MINISTRY EDUCATION AND SCIENCE,
YOUTH AND SPORTS OF UKRAINE
National aerospace university named after N.Ye. Zhukovskiy
“Kharkiv aviation institute”

TECHNOLOGY OF MANUFACTURING OF AIRCRAFT DETAILS WITH ALLOWANCE REMOVAL

Tutorial

Kharkiv «KhAI» 2012

УДК: 629.7.023-2.002(075.8)
Т30

Розглянуто загальні питання оброблення деталей планера ЛА з видаленням припуску, конструктивно-технологічні особливості ЛА як об'єкта виробництва, основні види заготовок і напівфабрикатів для виготовлення типових деталей. Викладено класифікацію заготівельно-оброблювальних процесів, структуру технологічного процесу оброблення різанням, режим різання й нормування операцій обробки з видаленням припуску.

Подано геометричні параметри системи різання, охарактеризовано технологічні особливості й конструкцію різального інструменту для основних видів обробки – точіння, свердління, фрезерування, шліфування. Описано особливості оброблення композиційних матеріалів, методи зміцнювальної обробки для підвищення міцності від утомленості деталей ЛА.

Наведено рекомендації щодо вибору типових траєкторій інструменту, технологічних параметрів чорнової, напівчистової й чистової обробки, а також створення типових циклів контурної обробки.

Дано аналіз основних напрямів інтенсифікації процесів оброблення з видаленням зайвого матеріалу, у тому числі на базі комп'ютерних інтегрованих технологій CAD/CAM.

Для студентів, що навчаються за напрямом «Авіа- та ракетобудування» й вивчають дисципліни, пов'язані з технологіями виробництва літальних апаратів.

Authors:
V.T. Sikulskiy, Yu.V. Dyachenko, V.V. Borisevich, S.D. Proskurin,
M.D. Tolmachev, C.M. Smal, I.O. Voronko, M.K. Heyshtor
Reviewers: dotsent I.A. Gritsenko, dotsent M.F. Savchenko

T30 Technology of manufacturing of aircraft details with allowance removal : textbook / V.T. Sikulskiy, Yu.V. Dyachenko, V.V. Borisevich and others. – Kharkiv: National aerospace university «Kharkiv aviation institute», 2012. – 196 p.
ISBN 978-966-662-271-9

Viewed are general questions on machining the details of the aircraft glider with allowance removal, design and technological peculiarities of the aircraft as the object of production, main types of workpieces and semimanufactured articles for manufacturing typical details. Described is the classification of workpiece-producing and machining processes, structure of technological process of cutting, cutting mode and regulating the operations of machining with allowance removal.

Given are geometrical parameters of the cutting system; characterized are technological peculiarities and design of cutting tooling for main types of machining – turning, drilling, milling, grinding. Described are machining peculiarities of composite materials, methods of strengthening machining for increasing the wear resistance of aircraft details.

Given are recommendations as to choosing the typical trajectories of tooling, technological parameters of rough, semifinishing and finishing machining, and creation of typical cycles of contour machining.

Presented is the analysis of main directions of intensifying the machining processes with allowance removal, including those based upon computer integrated technologies CAD/CAM.

Intended for students studying on the speciality of aviation and rocket construction and studying the subjects connected with aircraft manufacturing technologies.

Fig. 126. Tables 1. Bibliographic list: 38 titles

ISBN 978-966-662-271-9

Introduction

One of the main factors of the technological progress in mechanical engineering, as in other branches of industry is improving the production engineering. The peculiarity of modern production is using new constructional materials: heatproof, corrosionproof, composite, sintered, polymeric, etc.

Machining of these materials requires improving the existing technological processes and creating new methods that are based upon combination of mechanical, thermal and electrical activity.

The cutting process is accompanied by elastic and plastic deformation, breaking of the material, friction, wear of the cutting tool, vibration of separate parts and units and the technological system “machine – device – tool – part” (MDTP) in general. Knowing the regularities of these phenomena gives the opportunity to choose the optimal conditions that provide productive and quality part machining.

The cutting process is a sequence of extremely complex phenomena that depend upon the physical and mechanical properties of the material machined, quality of the cutting tool, cutting conditions, condition of the machine, and technological system rigidity.

Physical phenomena that influence the process of cutting determine the necessary basis for designing the tools, machines and devices, and also for creating more exact methods of machining. Basing upon the analysis of the physical mechanism of cutting, one determines the optimal cutting parameters, i.e. such combination of the cutting depth, feed and cutting speed for a certain type of the workpiece in the given technical requirements for the part machined, when the cutting properties of the tool and the capabilities of the machine and equipment are used maximally. Optimal cutting conditions provide maximum working efficiency, and therefore, the minimum self-cost of the production made.

It is emphasized on the tendency of increasing the amount of machining within the limits of using the monolith parts and joints of complex spatial forms in modern aircraft design, increasing the physical and mechanical properties of the materials used and raise standards to the weight efficiency of the products and accuracy of their machining. Thereby, the tasks on increasing the efficiency of machining are of great importance, and solving of which enables decreasing the labour and maintenance costs, increasing the productivity of certain operations, automation of the processes of machining of complex contour generating surfaces of the aircraft parts.

1 GENERAL QUESTIONS OF AIRCRAFT PART MACHINING BY MATERIAL REMOVAL

1.1 Design-technological peculiarities of the aircraft as the object of production

The objects of main production of the aerospace enterprises are in the first place the following types of aircraft: special and multi-purpose airplanes and helicopters, components of rocket and space systems - landing modules, rockets, upper-stage rockets, spaceplanes (Fig. 1.1).

According to ГОСТ (state standard) 2.101-68, an article is any object of production that is the subjected to manufacturing on the enterprise.

Let us give the terms and definitions of the main concepts according to ГОСТ 3.1109-82:

– part is an article made of the material uniform by its grade and quality without using any assembly operations;

– semifinished article is the object of production that is the object of further working on the consumer enterprise;

– workpiece is the object of production, from which one gets ready parts by changing its shape, size, accuracy, roughness or properties of the material;

– initial workpiece is the workpiece before its first step of machining;

– basic material is the material of the initial workpiece.

Among other articles of modern mechanical engineering, the aircraft as the objects of production have a number of unique peculiarities.

Large range and variety of parts of the airframe. The aircraft airframe parts differ by their purpose and type; they have many denominations – assortment. The number of parts in the aircraft airframe is more than hundreds of thousands items, furthermore, a large number of the parts of the same type, fastenings in particular, is used, which gives us the grounds to call the construction multipart.

Large spectrum of the materials used. The *spectrum* of the materials used in the airframe design equals several hundreds of grades. About 50% of the general number of the airframe parts are made of aluminum and magnesium alloys, 25% are made of the high-strength alloyed steels and titanium alloys. The use of composite materials in the aircraft design permanently increases. The thermal stress state of the spacecraft units operation in aggressive environment and in vacuum stipulates the necessity of using new materials with special maintenance properties (heat resistance, corrosion- and chemical resistance). These materials have low machinability with traditional cutting methods.

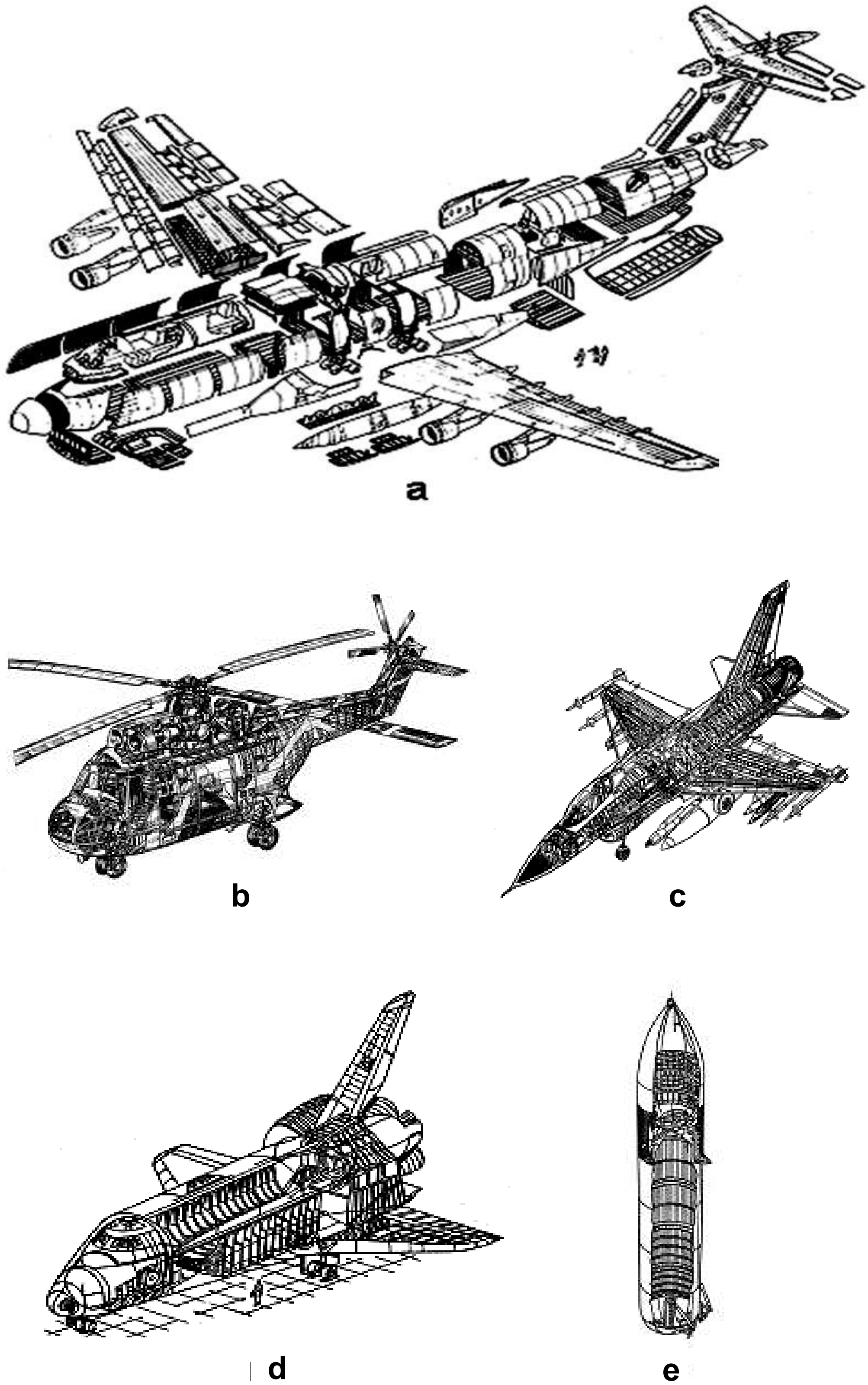


Figure 1.1 – Layout drawings of several modern aircraft:
a – heavy lifter; b – multipurpose helicopter;
c – supersonic fighter; d – aerospace plane;
e – upper-stage rocket of the rocket and space system

Complexity of the shapes, large size and high accuracy of the contour generating surfaces of the parts. Typical parts of the airframe and the elements of processing equipment have the bicurvature surface with changeable small and substantial curvature (frameworks of the cockpits, bulkheads, ribs, honeycomb units of the wing-flap system joints, control, template and gluing equipment, contact breakers, etc.). The length of the airframe parts (e.g., wing panel) are 30 m and larger, and the error of the bypass aerodynamic surfaces has been reduced to ±0,5 mm. The design and manufacturing method for production of the large-size parts of the complex special shape require using the special-purpose NC-machining technique, monitoring devices, special technological means.

High maintenance reliability of the parts. All aircraft parts should provide failure-free operation within the warranty period provided that working instructions are followed. Parts, units, compartments, assemblies (especially the blade of the helicopter) operate under the conditions of changeable cyclic loads. The life of the parts is increased by the technological methods of surface hardening, and the aircraft reliability at the stage of production is increased through controlling the critical parts and units using the nondestructive methods, and also by using complex imitational testing of the assemblies and products on special test benches.

High quality of the parts produced. Every part of the aircraft or of its system should be produced according to all technical requirements and conditions assigned in the design and technological documentation.

These and other design and technological peculiarities of modern aircraft have conditioned the aircraft production to separate into the independent engineering industry.

1.1.1 Standard categories of the airframe parts machined by material removal

Combining of the parts into categories is carried out according to the common principles of their production, uniformity of machinery used, and to the possibility of using the unificated equipment.

The airframe parts that are machined with removal of excess material are combined into the following categories:

– large-size parts of single- and bicurvature that are included into aerodynamic contour of the assemblies, - canopy frames, hatch and window fringing (workpiece materials are aluminum and titanium alloys);

– flat parts with curvilinear components – frames, ribs (workpiece materials are aluminum and titanium alloys and steels);

– large-size skin parts – panels and covering of single- and bicurvature shape with variable cross section made of aluminum alloys;

– large-size straight parts of great length – stringers, spars with constant and variable cross section along length (workpiece materials are aluminum and titanium alloys and steels);

– bulk part of average dimensions - walking beams, brackets, levers (workpiece materials are aluminum, magnesium, titanium alloys and steels);

– large-size parts of cylindrical shape – cylinders and shafts of undercarriage made of highstrength steel and titanium alloys;

– fittings – breechings, tee-pipes, nipples, sleeves of hydraulic and gaseus system (workpiece materials are aluminum, titanium alloys and steels);

– fastenings – bolts, screws, nuts, washes (workpiece materials are aluminum, titanium alloys and steels).

1.1.2 Semifinished articles and blank of the aircraft monolithic parts

The parts of modern aircraft are made of various metals and alloys. For example, for producing the airframe parts for an airliner An-148, the alloys of more than 50 grades are used, and 70% of the parts are made of aluminum alloys, 5% - of high-strength alloyed steels, 9% - of titanium alloys, 16% - of polymer composites, according to the data of Ukrainian science and technical institute of aviation technology, 2004.

Main types of initial airframe parts' workpieces for modern heavy transport and wide-body aircraft are the following: extruded section – 52,3%, plate – 7,5%, forging – 31,4%, casting – 2,1%, tube – 3,0%, bar – 2,6%, sheet – 1,1% [3, 11, 21].

Hot forged workpieces have the highest technological properties, therefore they are widely used for producing the heavy-loaded parts. For this type of workpieces, the stock utilization ratio is the relation of the part mass to the workpiece mass: $K_{s.u} = m_d / m_w$ = 0,7…0,8.

Cast products are used in the cases when parts made of cast workpieces correspond to the assumed loads and maintenance conditions, besides, the costs for producing the foundry equipment must be economically justified. For cast workpieces, $K_{s.u}$ = 0,8…0,9.

The material for the workpieces that are delivered to the enterprises of the corresponding branch of industry as tube-shaped product ($K_{s.u}$ = 0,8…0,9) and extruded sections ($K_{s.u}$ = 0,7…0,8) is the most effectively used. Sheet semimanufactured articles are used less rationally – about 40% of the material is wasted. Maximum chip wasting of the material occurs during manufacturing of monolithic panels from the plates and aircraft power parts of forged pieces.

Aluminum alloys are the most widely used aviation materials. They are divided into heat-strengthened and non-heat-treatable. The majority of the parts of the aircraft airframe produced from aluminum alloys are heat treated. Heat-strengthened alloys include deformed alloys, non-heat-treatable alloys include casting and weld alloys, and also the ones that are forged.

According to the RDC (research-and-development center) "Aviation materials" (Kyiv), about 40% of the general amount of high-alloy aluminum alloys and their semimanufactured articles used in the machine-building complex of Ukraine is used in the aerospace production.

The annual need of this branch in the semimanufactured articles is 16...19 thousand tons: extruded sections – 42%, forgings – 40%, plates – 9%, sheets – 6%, bars and tubes – 3%. The major amount of semimanufactured articles is produced of aluminum high-strength alloys Д16, В95, 1161, 1143, 2618, 1163, 1424, 1460, 1933. The ultimate strength of aluminum constructional alloys has nowadays increased from 420 to 600 MPa, and one seeks the possibilities of its further increase up to 700...750 MPa [11, 21].

Using the flat rolling method, the following semimanufactured articles may be produced out of aluminum alloys:

- plates 12...80 mm thick, 1000...2000 mm wide, 6000...30000 mm long, weighing up to 10 tons; delivered in hot-rolled, tempered and aged (naturally or artificially); alloy grades are АМг2М, АМцМ, АМг2Н, АМцН, АВТ, Д16АТ, В95АТ1, etc.;
- hot-rolled sheets 5...10,5 mm thick, up to 2000 mm wide, annealed sheets 0,5...10 mm thick with different degree of hardening; high-quality tempered sheets 0,5...3,4 mm thick, up to 2000 mm wide; sheet length is 2000...7000 mm depending upon the delivered state; alloy grades are АМг2М, АМцМ, АМг2Н, АМцН, АВТ, Д16АТ, В95АТ1 etc;
- strips for producing the roll-formed sections of aluminum grades А0, АД00, АД0, АД1and aluminum alloys АМц and АМг 0,25...2 mm thick and 150...400 mm wide; according to their state, they may be annealed or tempered.

Extrusion is widely used for producing the following semimanufactured articles:

- increased-strength bars and rods with the diameter 5...300 mm produced of В95, АК8, АК6, Д16 alloys, bars and rods of normal strength produced of Д16, АВ, АК4-1 alloys;
- edged and buttonhole-and-hinged sections up to 15 m length, and also large-size sections up to 30 m length with the cross-section area of 0,5…150 cm2;
- medium-size panels 960...2100 mm width, with the web thickness 2...15 mm, up to 12 mm long produced of Д16, Д19, АК4, АМг, В95Апч alloys, and large-size panels 350...1100 mm width with the surface thickness 5…50 mm, up to 30 m long produced of Д16, Д16ч, В95, В95Апч and АК alloys;
- hot-extruded tubes of circular and shaped sections produced of aluminum alloys; cold-worked tubes of 800 dimension types produced of aluminum alloys of 12 alloy grades, particularly those of 12...120 mm diameter with inner cladding.

The product mix of large-size *forgings* of the alloys Д16АТ, В95, АК4-1 with the plan projection area plan up to 28000 cm^2 with the surface thickness of 5...10 mm includes parts like wing spars, beams, brackets, and underframes.

High strength casting alloys ВАЛ8, ВАЛ10, ВАЛ14 for production of brackets, frames, casing.

Deformed *magnesium alloys* МА2, МА8, МА14 in the form of forgings sections, sheets, tubes are used for production of not critical parts, e.g., fuel tanks and pipelines, casting magnesium alloys МЛ6, МЛ10, МЛ14 are used for production of parts that function under the low static and cyclic loads.

Aircraft production is highly interested in *titanium alloys* because of their high strength and heat resistance. During the implementation period their strength was increased from 400 to 1200...1300 MPa [11].

By extrusion one produces bars for forged parts and fasteners, cold- and hot-deformed tubes and forgings made of ВТ3, ОТ4, ВТ8, ВТ16, ВТ18 alloys.

When flat rolling method is used towards ВТ, ВТ1-0, ОТ4-0, ОТ4-1, ВТ6, ВТ14, ВТ20 titanium alloys, the following items may be produced:

- plates 11...150 mm thick, 400...1700 mm wide, 1500...7000 mm long;
- sheets 0,3...10 mm thick, 400...1200 mm wide, 1500...5000 mm long;
- strips 0,3...1,5 mm thick, up to 600 mm wide coiled;
- foil 0,05...0,08 mm thick, up to 300 mm wide coiled;
- hot-rolled bars produced of ВТ3-1, ВТ8, ВТ9, ОТ4, ВТ16, ВТ18 titanium alloys for the forgings made by hot- and cold- heading; bar assortment: diameter – 5...55 mm, length – 1,6...3 m, crosscut shape – hexahedral, square, circle;
- cold-deformed tubes produced of ВТ1-0, ВТ1-00, ОТ4, ОТ4-1, ОТ4-0 alloys with 6…130 mm outer diameters and 0,8...10 mm wall thickness; hot-deformed tubes produced of ВТ6, ВТ3-1, ВТ14, ВТ22 alloys with 32...325 mm outer diameters and 2,5...30 mm wall thickness; welded tubes produced of ВТ1-0, ОТ4-0 alloys with 25...100 mm diameter and 1,5 and 2 mm wall thickness.

Forgings are produced of ОТ4, ВТ3-1, ВТ6, ВТ8, ВТ9, ВТ20, ВТ22 titanium alloys up to 800 mm long, with the projection area up to 15000 cm^2, 6...24 mm web thickness and mass up to 2500 kg.

Cast articles produced of ВТ5Л, ВТ9Л, ВТ21Л titanium alloys are used as the workpieces for the parts like beams, fittings, and brackets.

Structural steels are used during production of motor assemblies and parts of the airframe: wing spars, frames, struts, bolts, pins and other strengthening articles. The strength of structural steels has increased from 1200 to 1800...2000 MPa.

Deformable steels 30ХГСА, 12ХН3А, 18Х2Н4ВА, 38Х2МЮА, 38ХА, stainless steels 4Х13, ВНС, ВНС come in the form of sheets, sections, bands, wires, bars, forgings and tubes.

Cast workpieces of 35ХГСЛ, 27СНМЛ, ВНЛ, ВНЛ structural alloyed and high-alloy steels are used for producing frames, brackets, chassis parts.

While producing the parts of hot-forged workpieces one widely uses

30ХГСА, 12ХН3А, 38Х2МЮА, 38ХА structural steels, and 18ХГТ, 4Х13, ВНС, ВНС stainless steels.

1.2 Classification of the blanking and machining processes

Main manufacturing of the companies in the aerospace field uses a large number of various processes independently from production volume. All these processes are divided into three interconnected groups: blanking, working and machining processes, mounting and assembling, and adjustment and testing processes (Fig. 1.2).

The classification is based upon dividing each class into subclasses, groups, subgroups and initial processes that consist of mechanical, physical, chemical and or combined actions independently of the fact whether these actions involve human activity.

Blanking and machining processes class, depending on influence on initial materials, is divided into two interconnected subclasses: forming processes and the processes of imparting necessary physical and mechanical properties to the parts.

A numerous groups of the processes that deal with blanking and removing of excess material are subclasses of forming processes and may be classified according to the type of energy led to the machining area, and it may be divided into the following *subgroups*: mechanical, electrical, electrical and chemical, chemical, acoustic, heat and radiation processes.

Every subgroup may be divided into separate processes by their physical and chemical homogeneity (see Fig. 1.2), that, in their turn, are classified by the type of working. *Particular process* is a complex of machines' and staff interactions that are homogenous by their physical and chemical essence.

In the basis of every particular process there lies a certain physical theory. The examples of separate processes may be such processes as processing by cutting, cold and hot metalworking, electrophysical and electrochemical processing, etc.

Main terms and definitions according to ГОСТ 3.1109-82 are given below.

Production process (PP) is the part of the manufacturing that contains purposeful actions on changing and (or) determining the condition of the article being produced (object of labour). Objects of labour include workpieces and products.

Manufacturing method is the group of rules that determine the sequence and content of the actions during forming, working or assembling, moving, including technical control, testing in the producing or repairing PP and that are set independently of the denomination, dimension type or version of the item.

Operating condition is the set of parameter values of PP within a certain time period.

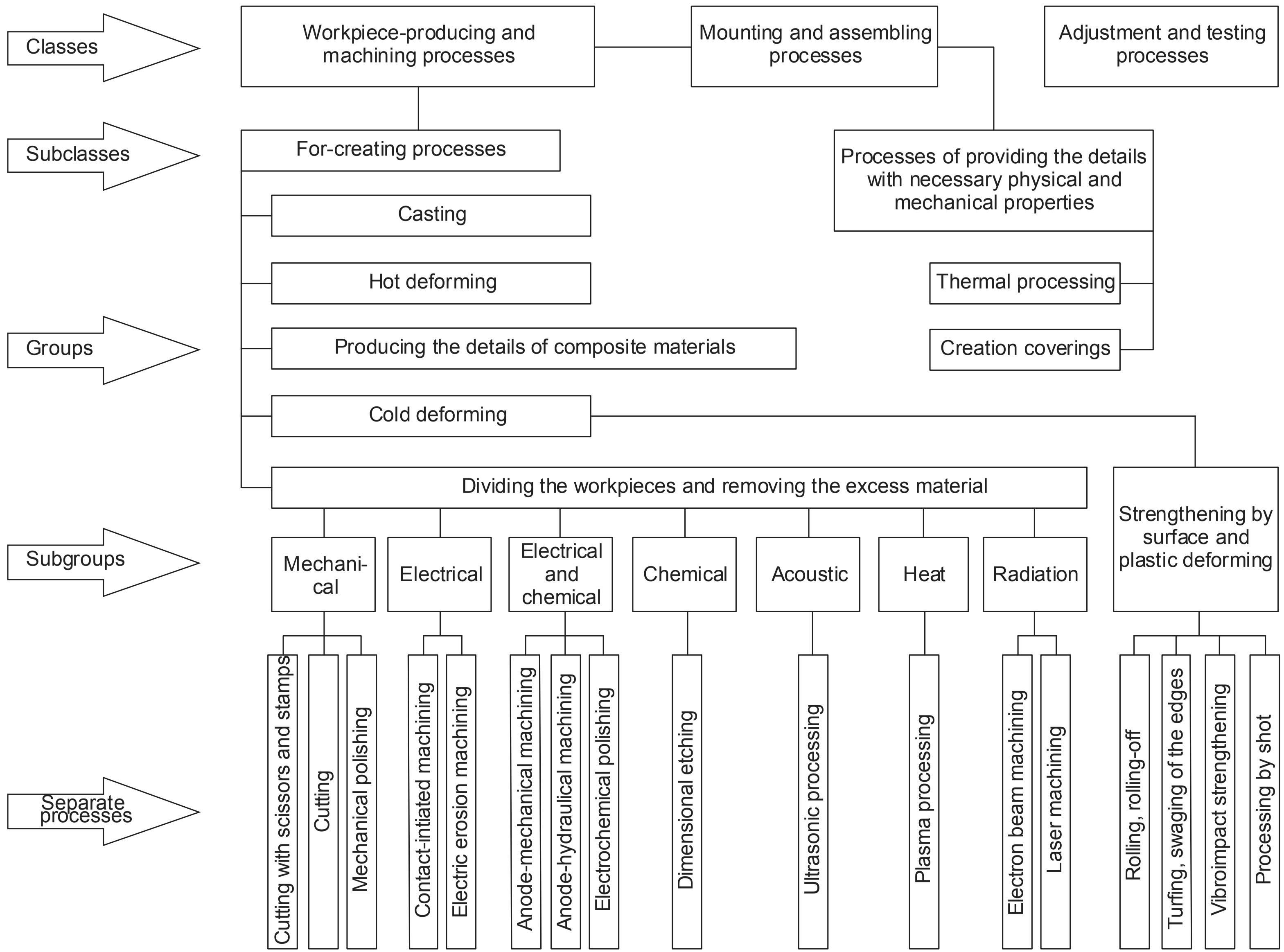


Figure 1.2 – Classification of the processes that divide the semimanufactured articles and removing the excess material

Machining is the action aimed at changing the properties of the object of labour while carrying out the PP. During rough machining the main part of allowance is removed and due to finishing machining one reaches the required accuracy and roughness parameters of the machined surfaces.

Machined surface is the surface acted upon during processing.

Mechanical processing is processing carried out by plastic metal working or cutting (machining).

Plastic metal working is the type of processing that includes plastic deforming or separating of the material. Separation of the material is carried out under pressure, and without any chip formation.

Cutting is the type of processing, under which one creates new surfaces by separating the surface layers of the material with chip formation. Creation of surfaces is carried out with deforming and breaking of the material surface layers.

Electrophysical machining is the type of machining, under which the workpieces change their shape, size, and surface roughness by using electric discharges, magnetostrictive effect, electronic or optical radiation, and plasma stream.

Electrochemical machining is the type of machining when the workpiece changes its shape, size and surface roughness as the result of dissolving its material in the electrolyte under the impact of electric current.

Coating deposition is the type of machining that includes creating the surface layer of homogeneous material.

Laboriousness of passenger aircraft manufacturing by certain types of machining and working is given on the diagram in the Fig. 1.3 [11, 21].

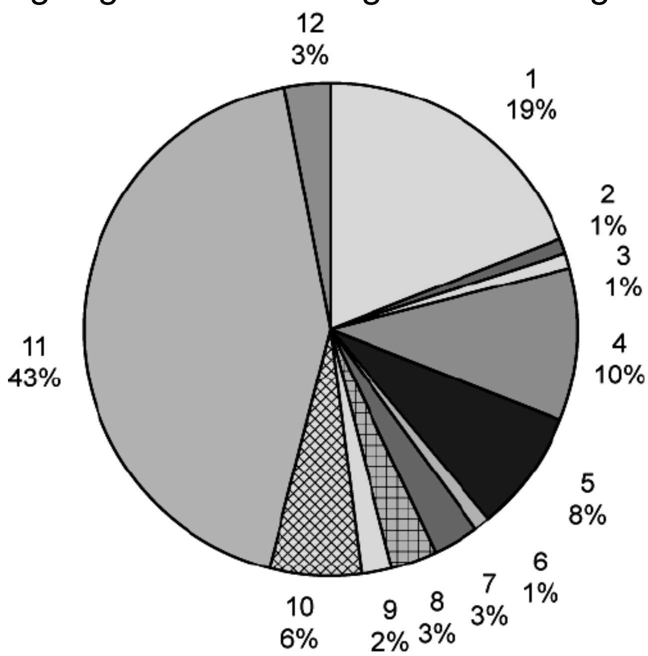


Figure 1.3 – Laboriousness of passenger aircraft production:
1 – cutting; 2 – casting; 3 – forgings; 4 – preparatory forging and welding; 5 –mechano-assembling; 6 – thermal processing; 7 – galvanic coating; 8 – varnish-and-paint coating; 9 – composite materials' machining; 11 – adjustment and testing; 12 – others

The most universal process in modern production, particularly in the aviation industry, is the process of part production by removing the surface layers of the workpieces – material machining or cutting. In this case, new surfaces of the parts are created, and they have the given shape, certain accuracy and necessary quality. The laboriousness of cutting is about 20% of the total laboriousness of modern aircraft production (see Fig. 1.3).

1.3 Structure of the manufacturing method of cutting

The process of aircraft production is a complex of machines' and workers' interoperation in order to transform the initial materials and semi-manufactured articles into the parts different in their properties and function. They form the parts of the aircraft that are finished in constructional and technological sense.

It is necessary to consider production process from the two aspects - physical and functional.

From the first aspect one considers physical nature of process – transformation of initial material, semifinished products, workpieces into part according to certain stages of manufacturing process (Fig. 1.4).

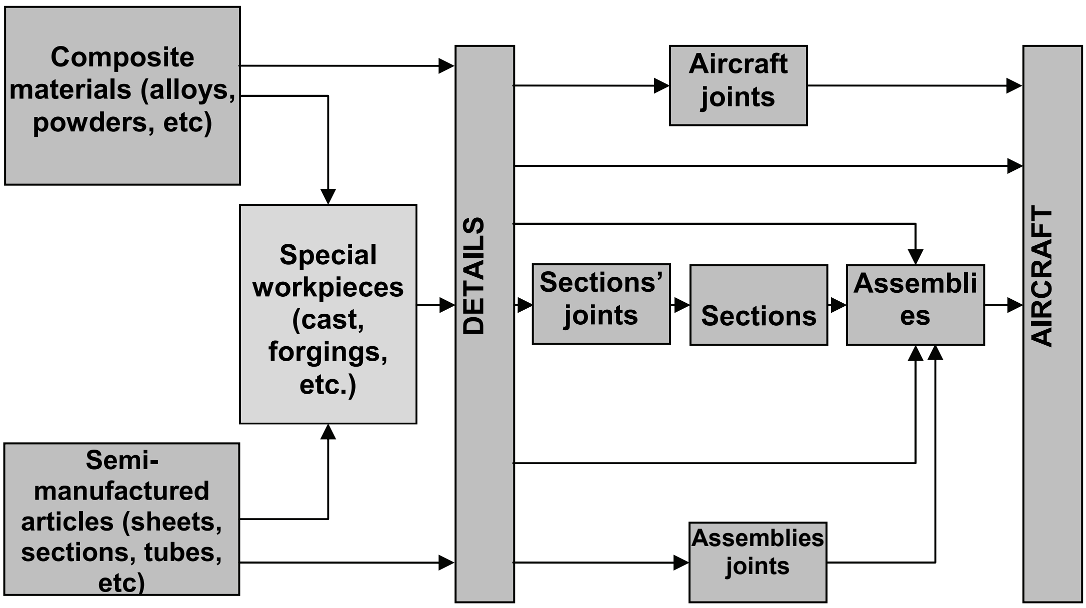


Figure 1.4 – Transformation scheme of the initial materials, semimanufactured articles and workpieces during aircraft airframe production

In functional aspect, one views the structural connections and dependences between the parts of the PP that comprise the process of the product manufacturing. The structural scheme of the PP of cutting process with excess material removal is shown in the Fig. 1.5.

The PP of cutting is the sequence of technological and auxiliary operations. Let us define the terms and definitions of the main notions according to ГОСТ 3.1109-82.

Processing operation is the completed part of the PP that is carried out on a single workplace.

Processing operation is the main unit of production planning and records. Basing upon these steps, the laboriousness, machining self-cost, time and cost regulations are calculated, the necessary number of workers, machines, devices and tools is determined, and production scheduling as well as quality and period of execution of works is carried out.

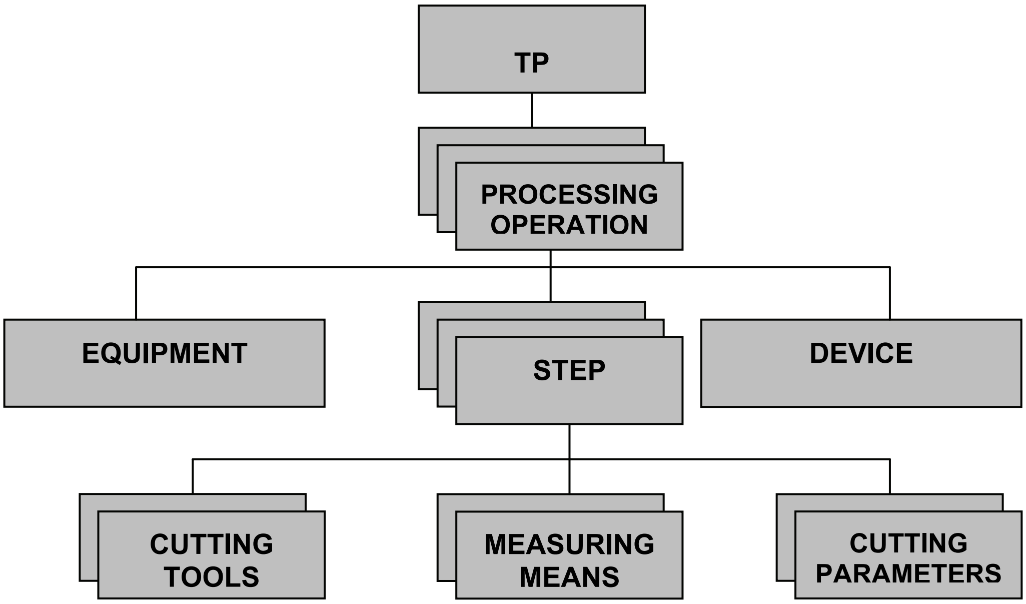


Figure 1.5 – The structural scheme of the PP of cutting process

Production techniques is a set of the means of production necessary for carrying out the PP: production equipment, production accessories (including the devices and tools), and also the means of mechanization and automation of production processes.

Production equipment includes the means of production accessories, into which one places the materials or workpieces in order to carry out a certain part of the PP, means of their operation, and also production accessories.

Devices are the production accessories used for setting or directing the object of labour or operating tool during the processing operation.

Operating tools are production accessories used for direct influence on the object of labour in order to change its properties.

Means of mechanization and automation are the auxiliary technological equipment, and they combine the features of equipment and accessories.

Means of mechanization and automation include various manipulators, processing robots and transport systems, mechanized and automated operational storages.

Processing operation cycle is the period of calendar time from the beginning till the end of the processing operation that is periodically repeated independently of the number of the simultaneously produced items.

Production time is the period of time, in which the items or workpieces of certain denomination, dimension type and perfomance are periodically produced.

Production rate is determined by the number of items or workpieces of a certain denomination, dimension type and perfomance that are produced per unit time.

Besides processing operations, in certain cases (e.g., by stream production, especially when processing in flexible technological complexes) the PP includes auxiliary operations (transportation, inspection, marking, etc.) that do not change size, shape, outlook or properties of the article machined but are necessary for carrying out the processing operation.

Installation is the part of the processing operation that is carried out by permanent fixation of the workpieces or assembly items.

Position is the settled location of the permanently fixed machined workpiece with the device relatively to the tool or immovable part of the equipment during certain part of the operation.

Setup is preparing the production equipment and accessories before carrying out the processing operation: installing the devices, switching the speed or load, setting the given temperature, etc.

Update is additional adjustment of the production equipment or accessories during the processing operation in order to refresh the values of the parameters received during the setup.

1.3.1 Elements of the production step

Let us give the terms and definitions of the main notions according to ГОСТ 3.1109-82.

Production step is the completed part of the processing operation carried out with the same means of production equipment with constant process parameters and equipment.

In the case of cutting, the production step is the completed part of the processing operation carried out on one or several surfaces of the workpiece with one or several tools operating simultaneously, without alterations, or with automatic change of the machine operating mode.

Automatic change of the machine operating mode in the middle of one production step may occur during machining of the workpieces with NC machines. In case of using the usual metal-cutting machines, production steps are, as a rule, carried out by constant process parameters.

Elemental step is the part of engineering step that is carried out with one tool over one area of the surface of the workpiece treated per one machining pass without changing the engineering mode of the machine.

The duration of the elemental step is determined by the length of the areas on the machined surface that are machined with constant load and corresponding prime machining time.

It is convenient to use the notion of the elemental step when one determines processing operations and calculates the prime time of processing the workpieces on the NC machines, when the machine mode of operation changes in the middle of the production step.

Auxiliary step is the completed part of the processing operation that includes the action of a person and (or) equipment that are not followed by the changes of shape, size and surface roughness of the object of labour, but that are necessary for conducting the process step.

Machining pass is the completed part of the process step that includes a one-time moving of the tool relatively to the workpiece that is followed by changing the size, shape, quality of the surface or properties of the workpiece.

Auxiliary pass is the completed part of the process step that includes a one-time moving of the tool relatively to the workpiece that is not followed by changing the shape, surface quality or quality of the workpiece, but that is necessary for preparing the machining pass.

Technique is the complex of a person's actions of one purpose during the process step or its part.

The processing operation is finished if the part of the PP is fulfilled without proceeding to machining another item.

E.g., machining of the stepped shaft (Fig. 1.6) on the turning machine is a single processing operation if it is carried out in the following sequence:

the workpiece is installed, its end surface is undercut with the cutter 2, and the largest diameter of the shaft is turned with the cutter 1 (Fig. 1.6, b);

the workpiece is unloaded, turned over and installed again, the central hole is drilled with the drill 3, the shaft is machined from the other end with the cutter 4, the groove is cut with the cutter 5, the chamfer is formed with the cutter 6 (Fig. 1.6, c).

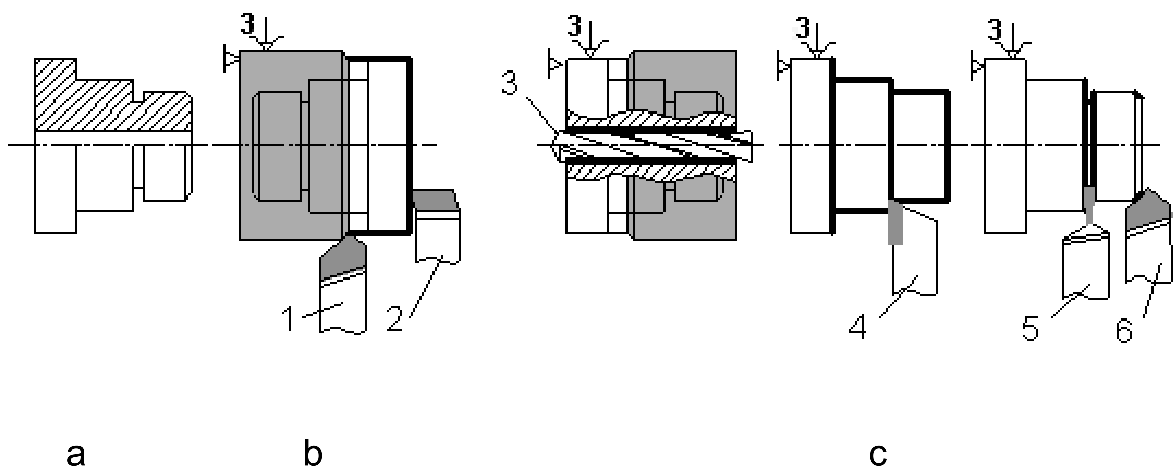


Figure 1.6 – Machining of the stepped shaft:
a – shaft; b – first installation, number of steps is 2;
c – second installation, number of steps is 4

Shaft machining similar in content may be carried out in two similar turning operations if the second installation and machining of the other end of the shaft will go not right after its first end is machined, but there will be a break to process all the workpieces of the batch (i.e., all the workpieces are at first machined from one end, and after that all of them are machined from the other one).

The given example shows that the content of the operation is determined not only by solely technological estimations, but also taking into account the organizational expediency.

1.4 Technological characteristic of types of production

One of the main principles of carrying out the PP is *the principle of combining technical, economical and organizational tasks* that are solved in certain situations in production conditions.

The planned PP should provide fulfillment of all accuracy and quality requirements to the product that are provided by the engineering drawing and technical requirements by the least labour spending and minimal self-cost, and it should also provide production of the goods in the amount and terms specified by the product release program (production program).

Let us give the terms and definitions of the main notions according to ГОСТ 14.004-83.

Product release program is the list of products specified for a certain enterprise that must be produced or repaired with referring to certain production volumes for each item within the planned time period.

One may reach the least amount of expenses during production if the PP carried out fully corresponds to a certain type of production and its conditions.

Production type is the classification category of production that is determined by the width of the assortment, regularity, stability and product volume of production.

Production volume is the number of products of a certain item, dimension type and version that the company or its subdivision produces or repairs within the planned time period.

Operation assignment coefficient ($K_{o.a}$) according to the state standard ГОСТ 3.1108–74 is defined as the ratio of all processing operations carried out or that must be carried out within a month, to the number of working places.

There are the following types of mechanical production: single-type, batch and mass production.

Single-type production is characterized by the wide product mix of items produced or repaired, and small volume of their production. All-purpose machinery is used, and it is placed in the premises according to the work group. As a rule, special devices and tools are not used; the necessary accuracy is reached with the trial machining method using marking and temporary measuring. Qualification of the workers is high, design documentation is shortened and simplified; work quota setting is research and statistic.

Mass production is characterized by short range of product mix and large production volume of the items that are noninterruptibly produced or repaired within a long time. For mass type of production, $K_{o.a} = 1$, i.e. the same constantly repeating operation is performed in the majority of workplaces.

Special highly productive equipment is used simultaneously. It is placed according to the stream principle (i.e., along the course of the PP fulfillment). In many cases, the equipment is connected by means of transporting devices and assembly-lines to the automatic intermediate check stations and intermediate storage and buffering facilities of the workpieces.

In mass production, the following is used:

– highly productive automatic and semiautomatic multispindle machines, multioperational NC machines, automatic lines and automated computer-controlled production systems;

– highly productive technological equipment, tools made of synthetic ultra-hard materials and diamonds and shaping tools of all types;

– accurate individual initial workpieces with minimal allowance for machining (accuracy is reached with the methods of automatic dimension getting on presetting machines).

The workers' average qualification in mass production is lower than in single-type production, but highly qualified machine adjusters work in the premises. Design documentation for mass production is developed in part; technical regulations are thoroughly calculated and verified experimentally.

Batch production is characterized by the limited product mix of the items produced or repaired in production batches that periodically repeat, and by comparatively large volume of production.

Production batch is the set of workpieces of the same denomination and dimension type that are subject to process simultaneously or noninterruptibly within a certain period of time.

Batch volume is the total number of the items of certain denomination, dimension type and method of production that are produced of repaired according to the permanent design documentation.

Depending upon the number of items in the batch or series, there are small-batch ($K_{o.a}$ = 20…40), medium-batch ($K_{o.a}$ = 10…20) and large-batch ($K_{o.a}$= 1…10) production.

Batch production is the main type of modern machine building; the companies of this type produce today 75-80% of the whole production. Here, all-purpose, specialized and partly specialized equipment is used. Widely used are NC machines, machining centres, adjustible automated NC lines.

The equipment in the premises is placed by their technological groups, taking into account the areas of main transportation directions in object-closed areas. Group directions and direction-changeable automated lines are combined.

Universal-assembly equipment and readjustment equipment are widely used, and this allows sufficient increase of the equipment coefficient of batch production. Initial workpieces are hot and cold rolling, accurate casting, forged pieces and precision forging. The necessary accuracy is reached both with methods of automatic dimension getting and trial machining methods.

Qualification of the workers is generally higher than in mass production, but lower than in the single-type one. Along with the labour of staff and highly qualified adjusters that operate on the complex all-purpose machines, the labour of the staff-operators of a lower qualification is used – they operate on the adjusted machines. Design documentation and technical regulations are developed in detail for the most complex and critical workpieces.

Depending upon the batch of the workpieces and production organization, the mode of the batch production PP may vary significantly, approaching the mode of mass (in large-batch) or single-type (in small-batch) type of production.

1.5 Accuracy of workpiece dimensional machining

When solving the problems of accuracy, the technologist should provide accuracy of the parts required by the designer, and at the same time get high productivity and economy of their production. Besides, the technologist should research the actual accuracy of the PP set and analyze the reasons of inaccuracies' appearing during machining.

Accuracy of the part is the level of correspondence of the part to the requirements of the drawing and technical conditions according dimensions, geometrical shape, rigidity and mutual allocation of the surfaces machined.

In production conditions, one solves a number of technological tasks referred to *accuracy categories*:

− required (standard, design) accuracy is set by designer during the development of the drawings, basing upon the conditions of the items' functioning; it may be reached with one of the two essentially different methods of machining: trial machining and measuring method or method of automatic obtaining of dimension on the adjusted machines;

− actual (production, received, real) accuracy is determined by measuring the geometrical parameters of the parts after machining;

− expected accuracy is calculated in order to evaluate the accuracy of the technology developed and device of the machine designed or chosen.

Accessible accuracy of processing corresponds to the limiting possibilities of this operation is that the highly skilled worker can get on the faultless machine with unlimited labour and time expenses.

Economic accuracy of the technological operation is the accuracy, by which the expenses on machining of the surface in a certain way will be lower than the expenses on machining of the same surface in any other way.

When designing the PP, one uses data from the works [15, 22], where the classes of accuracy and rigidity are given which is economically reasonable for different methods of machining.

1.5.1 Types of inaccuracies of machining during allowance removal

When evaluating the accuracy, one usually speaks not about the correspondence of the parameters of the real and given parts, but about their differences.

Numerically, the accuracy may be presented with machining inaccuracy by a certain parameter $\Delta = A_r - A_n$, wherein A_r is the real value of the parameter; A_n is the given nominal value of the parameter.

One of the main statements in the machine-building technology is the following: technology chosen for part production should provide only that level of accuracy that was set by the designer.

The essence and aim of machining of each surface includes sequential specification of the workpiece parameters to get the given part accuracy.

Refinement is the ratio of the workpiece inaccuracy $\Delta_{workpiece}$ to the part inaccuracy Δ_{part}: $\varepsilon = \Delta_{workpiece} / \Delta_{det\,ail}$.

Each operation of machining of the given surface should have r*efinement*, more than one, i.e. the next operation of the PP should provide higher accuracy than the previous one. If the specification equals to one or less, such operation is unnecessary.

Operational inaccuracies may be systematic and random.

Systematic inaccuracies may be of two types:

−constant, the value of which doesn't change during machining;

−changeable, the value of which in the process of machining is changed according to a certain law related to the mechanism of operation of each factor.

In the first case, the inaccuracy is called constant systematic inaccuracy, and in the second case – functional inaccuracy.

Main initial systematic machining inaccuracies are the following:

- Machine inaccuracy. It depends upon the accuracy of machine production and is detected during machine operation under load.
- Tool inaccuracy. It influences the accuracy of machining with the dimensional tools (drill, reamer, tap) and shaped tools (shaping cutter of the shape, milling cutter, grinding disk), as the inaccuracies of other shapes are transferred directly on to the part.
- Device inaccuracy. It determines the installation accuracy of the parts machined and influences the machining accuracy as the initial geometric accuracy. When designing the devices, it is necessary to foresee their higher accuracy than the accuracy of the operation performed.
- Tool wear-out. In the process of cutting, it depends upon the method of cutting and has three distinctive zones: running-in (up to 4% of the way), normal wear (95-99%) and critical wear (less than 1%). Normal wear pace up to the given durability criterion is determined by specific tool wear-out (wear-out attributed to the way of 1000 m), which is a reference value [23].
- Inaccuracy of adjusting the machine to a certain size. It has a

significant influences on the accuracy of machining. According to the method of trial machining, the adjustment inaccuracy is defined as the systematic inaccuracy during machining of one part, and according to the method of automatic providing dimension it is the systematic error during machining of the batch of parts.

- Elastic deformations of the MDTP system. The MDTP system is generally characterized by its rigidity – the ratio of the component of the cutting force directed towards the normal to the surface machined to the shift of the tool blade relatively to the part in the same direction. On the one hand, the MDTP system rigidity influences machining accuracy through the system deformations, and on the other hand – through vibration of the systems. In order to reduce the influence of the MDTP system on the accuracy, additional supports are provided (support holders, vibration dampers), the geometry of the cutting tool and cutting mode are altered.
- *Thermal deformations of the tooling*. They significantly influence the machining accuracy. They largely depend upon the cutting modes and machining conditions; for the given machining conditions, they are considered constant systematic inaccuracies.
- *Basing and fixating inaccuracies.* They appear when the part is installed on the machine or machining device. Basing inaccuracy appears by automatic dimension getting as the result of mismatching of the installed and measured (design) bases; fixating inaccuracy appears as the result of part deformation during fixation.

When determining the operational inaccuracy, systematic inaccuracies are summed up geometrically and brought together to the direction that would be normal to the machined surface.

Systematic inaccuracies make up the base of the calculation and analytical approach to accuracy prediction, by which one studies the mechanism of action of a certain factor in order to get analytical dependencies for inaccuracies' calculation.

Random inaccuracies are the result of the impact of a great number of factors that are difficult to take into account and that make up the basis of the probabilistic approach to accuracy calculating.

1.6 Operational allowance and methods of the workpiece dimensions calculation

Let us define the terms and definitions of the main notions for this subsection according to the ГОСТ 3.1109-82.

Allowance is the layer of material that is removed from the workpiece surface in order to reach the required properties of the machined surface (size, shape, rigidity). General allowance is defined as the difference of the corresponding sizes of the workpiece and part.

Allowance tolerance is the difference between the greatest and the smallest value of the allowance.

Operational allowance is the layer of the material removed from the workpiece surface during one technological operation. The size sustained during this operation is called operational size.

Intermediate allowance is the allowance for a separate process step.

Operational allowance equals the sum of intermediate allowances for the process steps that make up a certain operation.

As one can see from the layout scheme of allowances and tolerances for machining of the shaft in two operations – turning and grinding (Fig. 1.7), the general nominal allowance for machining equals the sum of the nominal allowances for separate operations:

$$Z_{no\,min\,al} = D_{general}^{no\,min\,al} - D_{det\,ail}^{no\,min\,al} = \sum_{i=1}^{n} Z_{i\,no\,min\,al}\,, \qquad (1.1)$$

wherein n is the total number of the operations of part machining.

From this scheme, we can see that we should recognize the following allowances:

−minimal operational allowance $Z_{i\,min}$ – the difference between the smallest limiting size before processing and the largest limiting size after machining during a certain operation;

−maximum operational allowance $Z_{i\,max}$ – the difference between the largest limiting size before machining and the smallest limiting size after machining during a certain operation.

Minimal unilateral operational allowance for the performed process step in the case of sequential machining of the opposite surfaces is calculated by the following formula:

$$Z_{i\,min} = (Rz + h)_{i-1} + \Delta_{\Sigma(i-1)} + \varepsilon_i\,, \qquad (1.2)$$

wherein Rz_{i-1} is the height of the roughnesses in the previous process step; h_{i-1} is the depth of the defective surface layer in the previous step; $\Delta_{\Sigma(i-1)}$ is the total deflection of the surface position and shape for the step performed; ε_i is the inaccuracy of the workpiece basing on the step performed.

Maximum allowance for machining of the workpiece surface is calculated by the formula

$$Z_{i\,max} = Z_{i\,min} + T_i + T_{i-1}\,, \qquad (1.3)$$

wherein T_i, T_{i-1} are the allowances on the operational dimensions of the performed and previous machining process steps.

Allowance tolerance T_z, according to the definition given above is determined as the difference between minimum and maximum values of the allowance:

$$T_z = Z_{i\,max} - Z_{i\,min} = T_i + T_{i-1}. \quad (1.4)$$

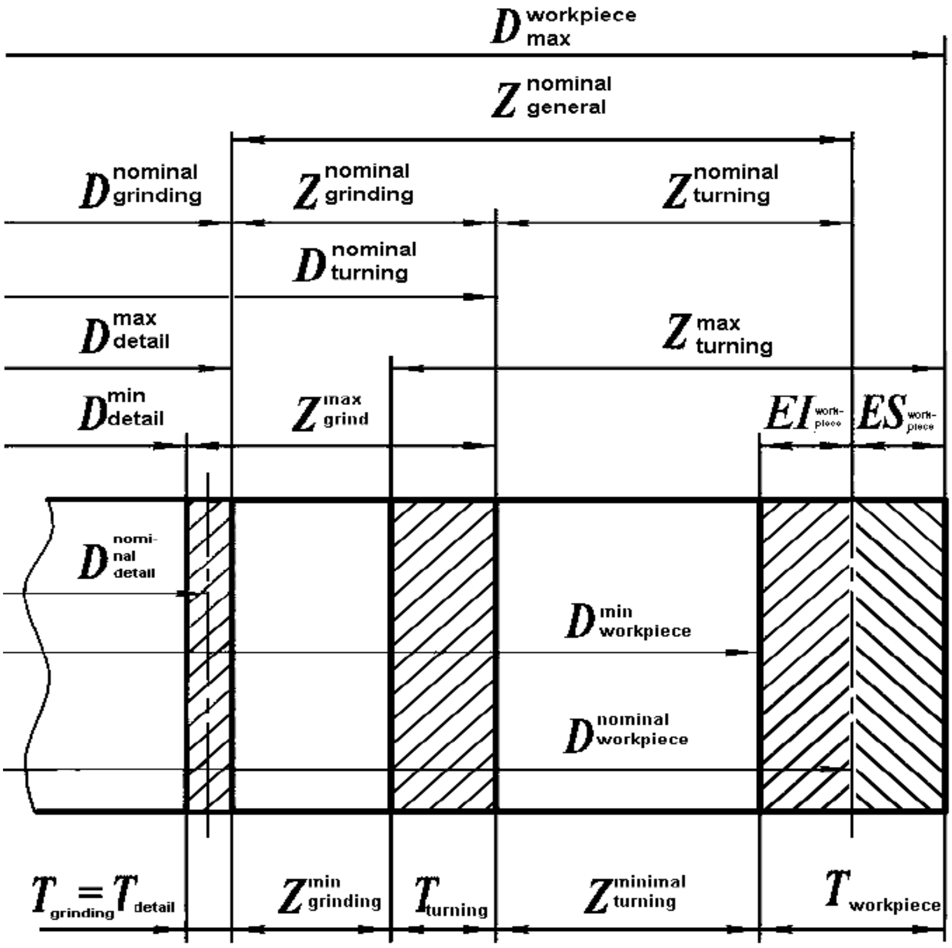


Figure 1.7 – Layout scheme of allowances and tolerances
on turning and grinding of the shaft

Nominal (calculated) operational allowance $Z_{i\,nominal}$ is determined as the difference of the workpiece nominal sizes before and after machining during a certain operation:

$$Z_{i\,nom} = Z_{i\,min} + T_{i-1} \quad (1.5)$$

When determining the nominal allowance for the first machining operation of the workpiece that has symmetrical position of the tolerance zone, one introduces into the formula (1.5) not the whole value of the tolerance range, but the value of its lower deviation (see Fig. 1.7).

In this case, the nominal operational tolerance for machining according to the inner and outer surfaces of the workpiece is calculated according to the formulas

$$Z_{i\,nom} = Z_{i\min} + EI_{i-1} + EI_i; \quad (1.6)$$

$$Z_{i\,nom} = Z_{i\min} + ES_{i-1} + ES_i, \quad (1.7)$$

wherein EI_{i-1}, EI_i are lower size deviations correspondingly on previous and performed steps; ES_{i-1}, ES_i are upper size deviations correspondingly on previous and performed steps.

The given formulas for allowances' calculation show that the allowance essentially compensates all inaccuracies of previous machining and the inaccuracies related to performing of a certain operation.

Application of extremely large allowances leads to non-productive wasting of the material because of chip formation and increasing of the laboriousness of cutting.

Small allowance doesn't provide removing of the defective layers of the material and reaching the necessary accuracy and rigidity parameters of the part surface machined.

1.6.1 Methodology of calculating the workpiece sizes

Assigning of the operational allowances for surface machining by choosing the final machining of this surface according to the economical accuracy of a certain operation.

The workpiece sizes are calculated by the following formulas:

– for outer surfaces

$$a_{min\,i-1} = a_{min\,i} + Z_{min\,i}, \quad (1.8)$$

$$a_{max\,i-1} = a_{min\,i-1} + T_{i-1}; \quad (1.9)$$

– for inner surfaces

$$a_{max\,i-1} = a_{max\,i} - Z_{min\,i}, \quad (1.10)$$

$$a_{min\,i-1} = a_{max\,i-1} - T_{i-1}, \quad (1.11)$$

wherein $a_{min\,i-1}$, $a_{max\,i-1}$ are correspondingly the smallest and the largest limiting sizes of the workpiece received during the previous process step; $a_{min\,i}$, $a_{max\,i}$ are correspondingly the smallest and the largest limiting sizes of the workpiece received during the previous process step.

For the steps of machining of the outer surfaces, the smallest size is determined by adding the allowance Z_{min} to the least limiting size according to the drawing.

While machining the inner surfaces, the largest size is calculable. The size on the previous process step is obtained by subtracting Z_{min}.

The given calculation and analytical method of determining the allowance is used for designing the initial workpieces and separate operations of large-batch and mass production, and also for the processes of machining of large and especially critical parts of the batch and even single-type production. In the conditions of single-type and batch production, in order to estimate the general and operational allowances, one often uses normative tables of allowances that are developed basing upon the large practical experience in production [15, 20, 22].

1.7 Mode of cutting and regulating of machining operations with allowance removal

1.7.1. Mode of cutting of machining operations with allowance removal

Terms, definitions and denominations of the general notions related to cutting are set by the ГОСТ 25762-83.

Cutting mode is the complex of the values of cutting speed, feeding and cutting depth. These factors depend upon the material of the workpiece and its properties on a certain machining operation, material and geometry of the cutting tool, type and nature of machining.

Cutting speed v is estimated by the empirical formulas for each type of machining; the formulas are as follows:

$$v = \frac{C_v}{T^m t^x S^y} K_{mv} K_{nv} K_{uv} . \qquad (1.12)$$

The value of the coefficient C_v and power exponents and also of the efficient life T of the tooling used for a certain type of machining is given in the reference literature [22]. Correcting coefficients are common for various types of machining: K_{mv} takes into consideration the quality of the material machined, K_{nv} is responsible for the condition of the workpiece surface, K_{uv} considers the quality of the tooling material.

Feed S is the ratio of the distance of a certain point of the cutting edge or workpiece that is passed along the trajectory of this point during feed to a certain number of cutting cycles of other movement. Under the cutting cycle one understands the complete revolution, move or double move of the cutting tool.

There are the following types of feeds:

– feed per revolution S_0, mm, is the feed that corresponds to one revolution of the tool or the workpiece;

– tooth feed S_z, mm, is the feed that corresponds to the revolution of the tool or workpiece per one angular step of the tool teeth;

– minute feed S_m, mm/min is the value of tool shifting per unit of time (it is the derived quantity).

For multi-blade tools, minute feed is calculated by the formula:

$$S_m = S_z z \ n , \qquad (1.13)$$

wherein z is the number of teeth in the tool; n – rotation frequency, min^{-1}.

Cutting depth t, mm, is the thickness of allowance that is removed in one machining pass of the tool (it is measured perpendicularly to the axis of the workpiece or to its surface).

Cutting parameters depend upon the constructional material of the workpiece.

1.7.2 Rating of machining operations with allowance removal

Time allowance, according to 3.1109–82, is the regulated time of performing of some amount of works in certain production conditions by one or several executors of certain qualification. In machine building, time allowance is usually determined for production operation.

Rated consumption of the working time is operational time, time of workplace adjustment, time for a break to rest and preparatory-finishing time.

Operational time allowance T_{op} is the time allowance set to carry out the processing operation. It includes main time allowance T_m and auxiliary time T_a:

$$T_{op} = T_m + T_a . \tag{1.14}$$

Main time T_m is the time, during which the size and shape of the workpiece is changed as well as the surface finish.

For all machining works main time T_m, min, is determined as the ratio of the distance passed by the machining tool to its minute feed:

$$T_m = \frac{Li}{S_m} = \frac{Li}{nS_0} = \frac{LZ}{nS_0 t}, \tag{1.15}$$

wherein $\boldsymbol{L}$ is the distance that the tool passes, taking into account the penetration and shifting values, mm; $\boldsymbol{i}$ is the number of machining passes; $\boldsymbol{S_m}$ is the minute feed, mm/min; $\boldsymbol{n}$ is rotation speed of the spindle or tool, min^{-1}; $\boldsymbol{S_0}$ is the feed per one revolution of the spindle/tool, mm/rotation; $\boldsymbol{t}$ is cutting depth per side, mm; $\boldsymbol{Z}$ is allowance per side, mm.

When calculating the main time by the formula (1.15), one calculates the cutting parameters $\boldsymbol{v}$, $\boldsymbol{n}$, $\boldsymbol{S_0}$, $\boldsymbol{t}$ using the corresponding formulas of the theory of cutting or find them in the tables of specifications given in the reference technical literature [22, 15].

Auxiliary time allowance T_a is the time allowance for carrying out the actions that provide performing of the processing operation or process step and that are repeated with each item or with their certain quantity.

Auxiliary time includes the following:

– time for the workpiece installation and removal;

– time for approach the tool to the workpiece, engagement and release of the feed, returning of the tool in the initial position;

– time for moving and changing the operating mode of machine mechanisms, tool changing, check measurements.

Time of the workplace maintaining $T_{maintain}$ is the part of single-piece time spent by the performer to maintain the equipment in the operable mode and doing up the workplace. Time of the workplace maintaining is divided into servicing time and organizational time.

Servicing time $T_{servicing}$ is the time spent for maintaining the equipment during performing a certain work (dull tools' replacement, tool adjustment, and machine update in the process of operation, chip removal, etc.).

Servicing time is determined in percentage of T_m.

Organizational time T_{org} is the time spent on doing up the workplace during the work shift (tool placing and taking away at the beginning and in the end of the shift, equipment inspection and testing, its oiling and cleaning, etc.) Organizational time is determined in percentage of T_{op}.

Personal time T_{rest} is the part of single-piece time spent by the worker on their personal needs and additional rest during heavy work. Personal time is provided for all types of works, excluding non-stoppable ones. It is determined in percentage of T_{op}.

Single-piece time T_{art} is the period of time that equals to the ratio of the cycle of processing operation to the number of items simultaneously produced or repaired.

Single-piece time allowance T_{art}, min, is calculated by the formula

$$T_{art} = T_m + T_{auxiliary} + T_{maintenance} + T_{rest} = T_{op}\left(1 + \frac{\alpha}{100} + \frac{\beta}{100} + \frac{\gamma}{100}\right), \tag{1.16}$$

wherein α is the ratio of the workplace maintenance time to the operational time, %; β is the ratio of the workplace organizational servicing time to the operational time, %; γ is the ratio of the personal time to the operational time, %.

In single-type and batch machine-building the workplace maintenance time isn't divided into organizational and servicing time, so the formula for calculating the single-piece time is simplified and is as follows:

$$T_{art} = (T_m + T_{auxiliary})\left(1 + \frac{K}{100}\right), \tag{1.17}$$

wherein K is the percentage of the operational time for servicing and organizational maintenance of the workplace, rest and personal use.

The values of the coefficients α, β, γ, K are taken so that they correspond to the standards [23].

Preparatory-finishing time allowance T_{p-f} is the time allowance for preparing the workers and means of production to performing the processing operation and returning the means of production into the initial condition after the step is finished.

In the T_{p-f} regulations, time spending is provided for the following actions:

– getting the materials, tools devices, documentation for production and work order;
– learning the documentation for production, getting the necessary instructions;
– installing the tools and devices, machine adjustment for a certain

working parameters, removing the tools and devices;

– turning in the ready items, rest of the materials, devices, tools, design documentation and order.

Preparatory-finishing time is calculated once for the whole batch of the articles that are nonstoppingly machined without break according to the given work order, independently of the number of items in this batch. The value of T_{p-f} is determined according to the regulations, including the dimension types of the machining equipment and devices, size and shape of the workpiece.

Single-piece-calculable time allowance T_{a-c} is made up of the preparatory-finishing time for the batch of the articles machined T_{p-f} and single-piece time $T_{artificial}$:

$$T_{a-c} = T_{artificial} + \frac{Tp-f}{n}, \qquad (1.18)$$

wherein $\boldsymbol{n}$ is the number of workpieces in the lot machined.

Time allowance for the workpieces' batch T_{batch} is calculated by the formula

$$T_{batch} = T_{p-f} + T_{artificial} n . \qquad (1.19)$$

Test questions

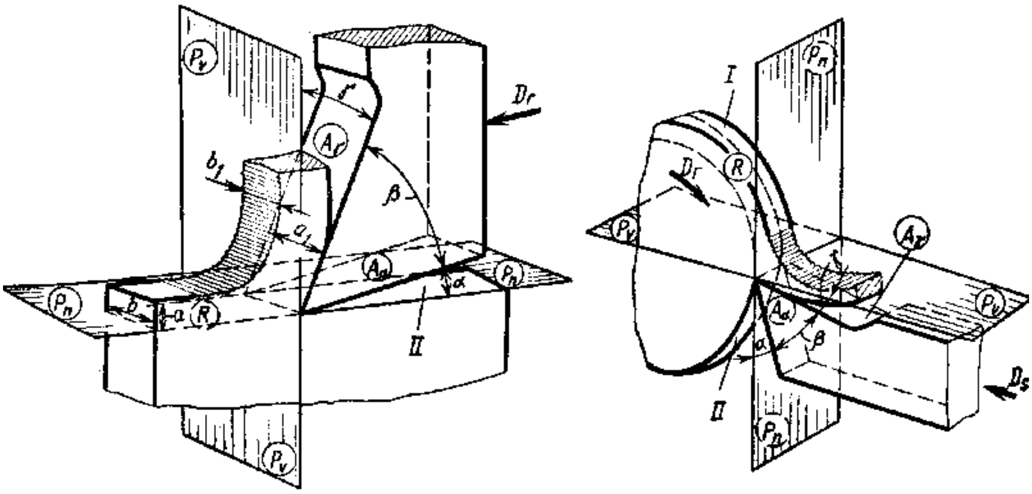
1. Name the design and engineering peculiarities of the aircraft as the object of machine-building.
2. Enlist typical classes of parts of the aircraft airframe that are machined with removal of extra material.
3. Give the characteristics of the principal scheme of turning the initial components into the aircraft airframe.
4. Describe the structure of the group of processes of semi-manufactured products' separation and removing of extra material.
5. Give the characteristics of the PP components.
6. What elements are involved in the process step?
7. Name the technological peculiarities typical for each type of machine-building.
8. Give the definition of the general and operational allowance.
9. Give the expressions for calculating the minimal and maximum operational allowances.
10. Write down the expressions for calculating the sizes of the inner and outer surfaces of the workpiece.
11. Draw the placement scheme of allowances and tolerances for turning and grinding of the shaft.
12. Enlist the accuracy categories of the part.
13. Give the definitions of reached and economical accuracy.
14. Name the types of inaccuracies during part machining.
15. Enlist the main systematic inaccuracies of machining with extra material removal.
16. Name the parameters of the cutting mode.
17. Enumerate the components of the regulations of single-piece time.

2 GENERAL INFORMATION ON MATERIAL CUTTING

2.1 Geometrical cutting parameters

Formation of part shape during the cutting is carried out by removing the surface layers of the workpiece material.

Let us consider the main terms and definitions used in the process of cutting under the condition that the tool and the workpiece are in a static instantaneous position (Fig. 2.1).



a b

Figure 2.1 – Geometrical parameters of the cutting system:
a – flat surface machining; b –bodies' of revolution machining

According to the ГОСТ 25751–83, cutting tooling has the following general design elements:

– *tool blade* is a wedge-like element of the cutting tooling for penetration into the workpiece material and separating the layer of material;

– *rake face* of the cutting surface A_γ is the surface of the tool blade that in the process of cutting contacts with the layer that is cut and with a chip;

– *clearance face* A_α is the surface of the tool blade that in the process of cutting contacts with the surfaces of the workpiece machined;

– *cutting edge* is the edge of the tool blade that is formed by the intersection of the rake and clearance surfaces; if the tool has several cutting surfaces, the most stressed one is called the *main cutting edge*.

Machined surface ***I*** is the surface of the cut layer of the workpiece that is partially or fully removed during machining (*a* and *b* are thickness and width of the cut layer).

Machined surface ***II*** is the new surface that is formed on the workpiece as the result of cutting after the chip removal (a_1 and b_1 are thickness and width of the chip).

Cutting surface ***R*** is the surface that is formed by the cutting edge in the resulting cutting motion. It may be flat, spiral, or screw-shaped.

In the processes of machining, static and kinematic angles of the cutting blade are considered; they determine the position of rake and clearance surfaces of the tool relatively to the mutually perpendicular planes – main plane and plane of cutting.

Main plane P_v is the coordinate plane drawn across a certain point of the cutting edge perpendicularly to the direction of the speed vector of the main or following cutting motion in this point.

Cutting plane P_n is the coordinate axis that is tangent to the cutting edge in a certain point and perpendicular to the main plane. In Fig. 2.1, a, the cutting plane goes through the cutting edge and coincides with the cutting surface, and in Fig. 2.1, b, it is tangent to the spiral cutting surface.

Kinematic angles depend upon the position of the cutting plane and may vary in value from the static sharpening angles of the tool. These angles are visible in *main sectional area* that is perpendicular to the line of intersection of the main plane and cutting plane.

Rake angle γ is the angle in the main sectional area between the rake edge of the blade and main plane. Angle γ influences the process of chip formation and strength of the cutting blade.

Clearance angle α is the angle in the main sectional area between the clearance surface of the cutting plane. To cut friction, clearance angle is taken more than zero.

Edge angle β is the angle in the sectional area between the rake and clearance surfaces of the blade.

Because of the cutting tool interaction with the material processed, the following cutting schemes are considered:

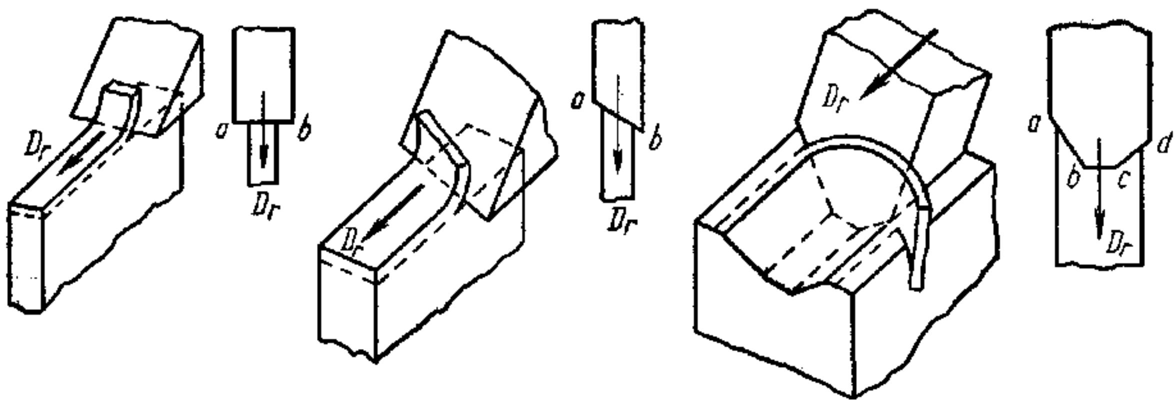
Free orthogonal cutting (Fig. 2.2, a). Only one straight-edge cutting edge takes part in the operation; it is perpendicular to the direction of the velocity vector of the tool D_r. The direction of moving of material particles that surround the cutting blade is the same in all points.

Oblique cutting (Fig. 2.2, b). In this case, the velocity vector of the tool D_r is not perpendicular to the cutting edge.

Constrained (hampered) cutting (Fig. 2.2, c). Several connected cutting edges of the blade that have different directions take part in cutting.

As a rule, separate moves of the tool or part are often simple, but the resulting move is almost always complex (screw-like, spiral, cycloid and other surfaces).

By the character of movement of the tool all kinematic cutting schemes may be divided into several groups depending upon combining of revolutionary and linear moves.



a b c

Figure 2.2 – Main cutting schemes:
a – free orthogonal; b – oblique; c – constrained

2.2 Kinematic elements of cutting

Machining by cutting, according to ГОСТ 25762-83, has general kinematic elements and characteristics (Fig. 2.3).

Main cutting movement D_r is the straight-line or revolutionary move of the workpiece or cutting tool that is carried out with the highest speed during cutting. It provides a certain speed of the chip separation from the workpiece.

Main cutting movement speed v is the speed of a certain point of the cutting edge or workpiece in the main cutting move that equals to the ratio of the distance passed by the point of the cutting edge to the unit of time (m/min, m/sec).

Feed motion D_S is the straight-line or revolutionary movement of the workpiece or cutting tool, the speed of which is less than the main movement speed; it is used to spread the separating of the layer of the material on the whole surface machined. The feed motion may be constant or interrupted, and depending upon the direction it may be length, transverse and complex.

Feed rate v_S is the speed of a certain point of the cutting edge in the feed motion.

Main move speed and feed rate are in the *working plane* P_S.

In order to perform cutting, one has to apply to the tool the forces that depend upon the resistance of the metal to chip formation.

Cutting force P is the resultant of the three forces influencing the cutting tool during cutting.

For convenience of design calculations, the vector P is resolved on the components in the spatial coordinate system ***XYZ***, and the direction of coordinate axes are chosen taking into account the technological peculiarities of a certain type of machining (Fig. 2.4).

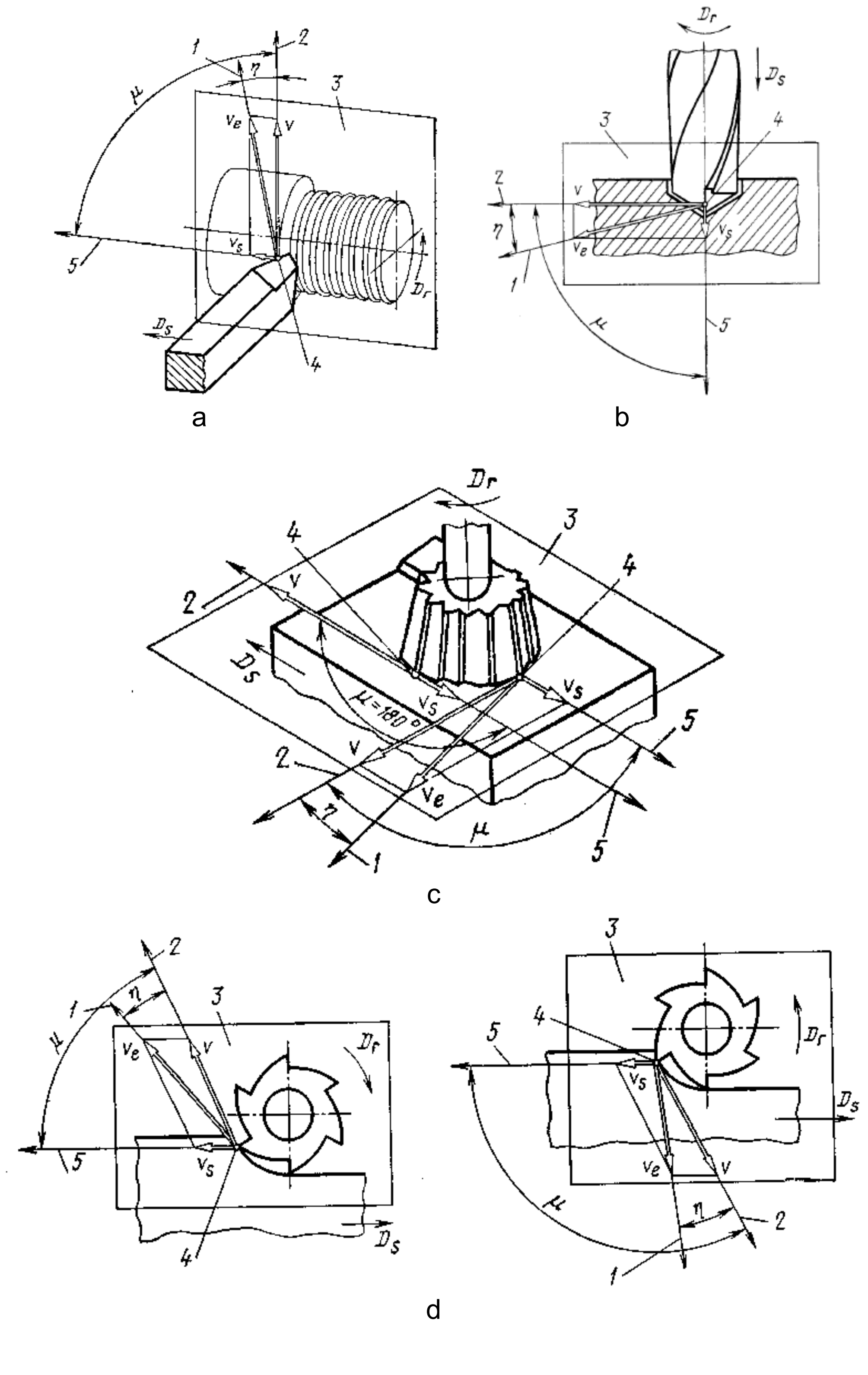


Figure 2.3 – Elements of motion during cutting:
a – turning; b – drilling, c – milling with the final milling cutter; d – peripheral climb and up milling; 1 – direction of the resultant move speed; 2 – direction of the main move speed; 3 – working plane P_s; 4 – certain point of the cutting edge; 5 – direction of the feed speed; η – cutting speed angle, μ – feed angle

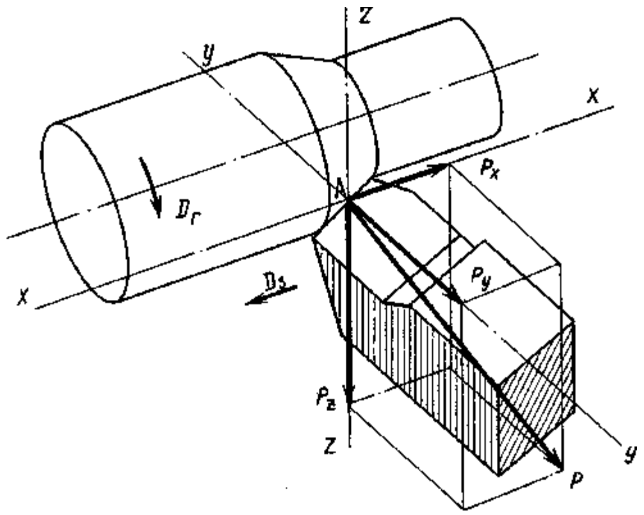


Figure 2.4 – Scheme of forces acting on the cutter and the workpiece

Each of the components of the cutting force has a certain value and technological meaning:

– *main (tangential) component* P_z is directed tangentially to the cutting surface and it coincides in direction with the vector of the main move speed. It is considered when one determines the capacity of the machine, sliding feed and resistance of the cutting tool to the bending in the plane ***YZ***;

– *axial component* P_x is parallel to the axis of the main revolutionary cutting move; it is considered during determining the durability of the longitudinal feed mechanism of the machine and resistance of the cutting tool to the bending in the plane ***XY***;

– *radial component* P_y is directed radially of the main revolutionary cutting motion in the top of the blade (perpendicularly to the workpiece axis); it is considered during determining the durability of the cross-cut load mechanism of the machine and resistance of the cutting tool to releasing pressure or part bending.

2.3 Chip formation

Cutting is the complex physical process, during which elastic and plastic deformations occur. This process is accompanied by friction, heat generation, buildup, chips shrinkage, workhardening of the surface machined and tooling wear-out. Knowing the physical nature of cutting and phenomena that accompany it allows controlling rationally this process and the quality of the surface machined.

For the first time, the process of cutting was researched by the professor of St. Petersburg polytechnic institute I.A. Timi, who had suggested the scheme of chip formation locating upon the visual observation of the process of cutting (Fig. 2.5).

In the initial moment, when the moving cutter under influence of cutting force touches the metal, elastic deformations occur in this metal (see Fig. 2.5, a). During its further moving, the cutter presses into the metal, causing its plastic deformation (see Fig. 2.5, b).

While the cutter is moving, the volume of plastically deformed metal increases, and inner stresses reach the values that exceed the ultimate tensile strength of the metal. At this moment, all plastically deformed material under influence of the forces is moved by the cutter in the form of the finally formed chip element (see Fig. 2.5, c). Then, the process of deforming continues, and new elements 1, 2, 3 of the chip are formed (see Fig. 2.5, d).

The volume of the metal that may be plastically deformed is limited with the rake face of the cutter blade from one side, and the plane O-O from the other, along which the formed elements of the chip are periodically moved or shorn. This plane is called shearing plane. The angle β_1 that determines the position of the shearing plane relatively to the direction of the tool movement is called the shearing angle, and the angle β' is called the angle of action.

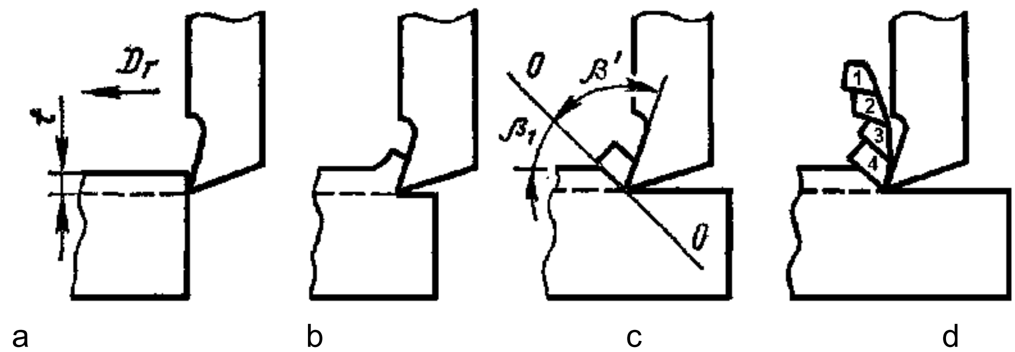


Figure 2.5 – Sequence of the chip elements' formation

Later during the research, it was determined that the largest deformations of the grains appear not in the direction of the plane O-O, but in the other direction determined by the angle θ (Fig. 2.6). The cut layer is additionally deformed due to friction of the chip against the rake face of the tool, and its final structure has the form of stretched grains.

Structured orientation of the deformed crystal grains is called texture, and the angle θ is the angle of texture.

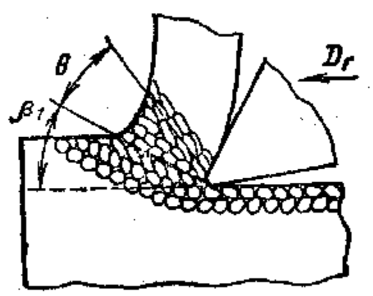
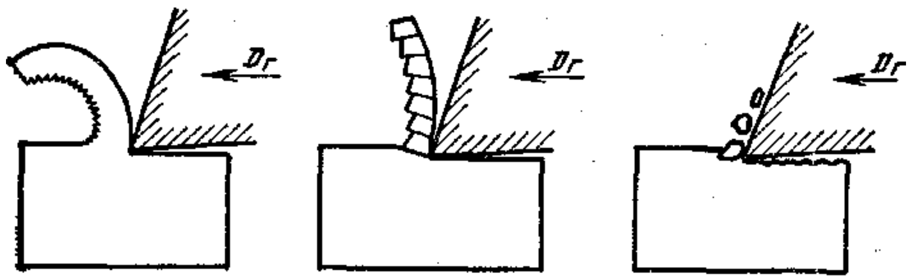


Figure 2.6 – Scheme of the plastically deformed area during cutting

Character of the deformation depends on the physical and mechanical properties of the material machined, geometrical parameters of the tool, cutting parameters and machining conditions. For the steels of medium hardness, the position of the O-O shearing plane is practically constant (β' = 30°). The angle θ depends upon the properties of the machined material and geometrical parameters of the tool. When machining brittle metals, the angle θ is close to zero, when machining ductile metals, it reaches up to 30°.

According to the still valid classification suggested by the professor I.A. Timi, as the result of machining of various materials, there may be the following types of chips: flow, discontinuous and crack (Fig. 2.7). Type of the chip generally depends upon the physical and mechanical properties of the machined material, cutting parameters and geometrical parameters of the tool.



a b c

Figure 2.7 – Types of chip: a – continious; b – discontinious; c – crack

Continious *chip* (see Fig. 2.7, a) is a solid band with smooth shiny outer side and dull inner side with feebly marked serrated dents. It is formed during cutting of ductile materials on high cutting speeds, small thickness of the cut layer and high rake angles of the tool.

Discontinious *chip* (see Fig. 2.7, b) is smooth from the outer side, but its inner side has strongly marked gaps – separate elements or elements that are connected into a band (articular chip). Such chip is typical for machining of the medium-strength materials by low cutting speeds, high thickness of the cut layer and small rake angles of the tool.

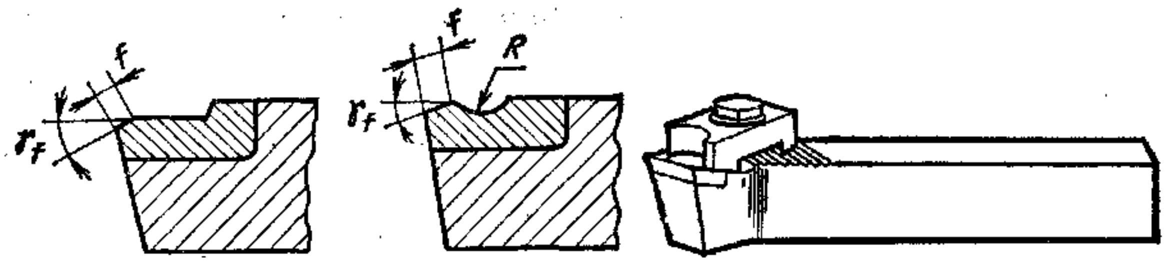
Crack chip (see Fig. 2.7, c) is formed during machining of brittle materials. The material cracks and breaks due to the force applied to the tool. If such chip is formed, the machined surface is rigid, with gaps and pits.

By changing the conditions and mode of cutting, one may get different types of chip. E.g., if one increases the cutting speed of the majority of carbonic and alloyed structural steels, discontinious chip turns into the continious one.

Continious chip that is formed during machining of most steels comes off in long bands or spirals. It winds on the machine mechanism, tool and the workpiece machined. It blocks the machine operation, may cause the worker's injury and damage of the machined surface. Such chip is especially prohibitive under automated production. In mass production, optimal is the chip of a spiral form 30…80 mm long.

A number of ways to control the chip are developed: adjustment of the cutting parameters and geometrical parameters of the cutting tool; artificial control using various devices.

In order to get consistent chip breaking, one cuts special bevels on the rake face of the cutter (Fig. 2.8, a) and grooves along the main cutting edge (Fig. 2.8, b). Bevel or groove increases the rake angle γ in the place where the chip comes off, which makes cutting easier. The chip comes of in the form of a spiral or breaks into separate rings. Attachable chipbreakers installed on the cutter may also be used (Fig. 2.8, c).



a b c

Figure 2.8 – Ways of chip breaking:
a – using the bevel; b – groove; c – attachable chipbreaker

Artificial chip breaking may be done also by changing the cutting kinematics – imposing axial vibrations on the uniform feed motion. Flow chip received during regular cutting turns into the chip with changeable thickness, breaks into parts and is easily removed.

2.4 Phenomenon of workhardening during cutting

During cutting, the radius of curvature of the blade top $r_{в}$ is always formed on the tool (Fig. 2.9). This is why only that part of metal that is subject to elastic and plastic deformation is turned into chip. The other part of metal, the thickness of which is consistent with the radius $r_{в}$, forms the machined surface. After the cutter has passed relatively to the already machined surface the elastic recovery of the deformed surface layer occurs on the value h_y – elastic aftereffect. As the result of elastic and plastic deformation, strength characteristics of the machined surface increase (ultimate tensile strength, yielding limit, hardness), and its plasticity decreases.

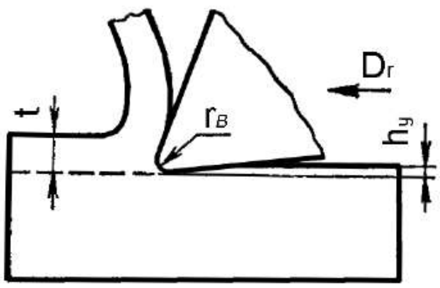


Figure 2.9 – Scheme of the surface layer formation

The complex of changes of the mentioned properties of the material is called hardening, or workhardening. Hardening is characterized by the depth and degree $i_h = HV_{surface} / HV_{init}$, wherein $HV_{surface}$ and HV_{init} are microhardness of correspondingly surface strengthened and initial materials.

Depth and degree of workhardening depend upon the physical and mechanical properties of the material processed, geometrical parameters of the tool, radius of curvature of the blade top, and cutting parameters.

The softer and more plastic is the machined material, the more it is subjected to hardening.

Plastic and elastic deformation of the metal also results in the mutually balanced residual stresses that appear as the result of the plastic deformation nonuniformity and significant heating of the working surface. Residual stresses may be tensile and compressive.

If the residual stresses exceed in value the ultimate tensile strength of the machined material, this may lead to formation of the surface cracks.

Hardening of the already machined surface is useful for finishing machining, if the residual stresses are contractible. But strengthening has also a negative consequence: if the surface layer is hardened after the rough machining, it is difficult to perform the finishing machining, as the degree of the tool wear-out and surface rigidity increase. The depth and degree of workhardening may be reduced by using the oily-cold fluid (MOP), increasing the cutting speed and by thermal processing.

2.5 Tool wear-out and durability

Tool wear-out during cutting occurs as the result of the friction between the chip and the rake and clearance faces of the blade and the workpiece surface. Friction occurs at high contact pressure and high temperatures.

Abrasive wear-out occurs as the result of scratching and erasing of certain surfaces of the tool with the hard inclusions that are present in the machined material.

Adhesion wear-out occurs because of the action of molecular cohesion forces – adhesion that shows up in cohesion of the surface layers of the tool blade with the machined material. The particles of the material are torn off the tool surface and removed with the chip.

Diffusive wear-out is the result of the tool material dissolving in the machined material. High temperature, large plastic deformations and interlocking in the contact induce the mutual diffusive dissolving of the tool and workpiece metals. The tools of hard alloys that work under high cutting speeds are subjected to diffusive wear-out most of all.

Oxidative wear-out occurs as the result of metal corrosion under the conditions of active cooling of the cutting area and gas saturation; the tool surface layers are destroyed because of oxide formation and irritation of the grains along with erasing.

All these types of wear-out are closely interconnected, and they generally affect the total wear-out of the tool. Specific impact of each of these types of wear-out depends upon the properties of the contact materials and interaction conditions (first of all, upon the cutting force).

As the result of work out (Fig. 2.10), there are a dimple with the depth h_d on the rake face of the tool and prominence with the height h_c on the clearance face, radial tool wear-out is determined by the value h_p.

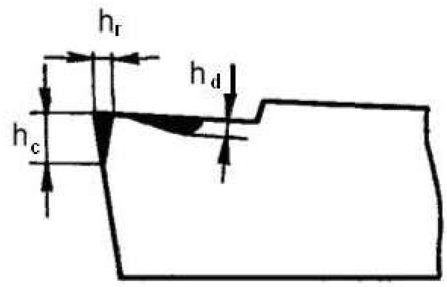


Figure 2.10 – General character of the cutting tool wear-out

Clearance face wear-out occurs mainly during machining of rigid brittle materials, and also ductile materials with the thickness of the cut layer less than 0,1 mm and at low cutting speeds.

Rake face wear-out dominates during machining of ductile materials with the cut layer thickness more than 0,5 mm and at high cutting speeds without cooling.

Clearance face wear-out of the turning cutter h_s has a certain pattern (Fig. 2.11).

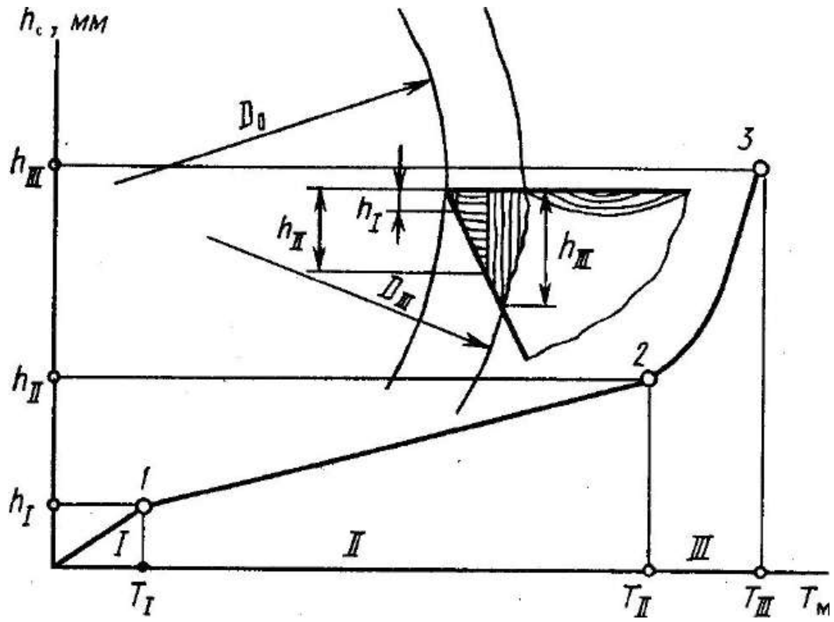


Figure 2.11 – The diagram of the cutter wear-out

At the beginning of the work the cutting edge of the tool is worn in and somewhat rounded (***I*** is the area of initial wear-out of h_c = 0,05...0,1 mm). Continually, the value of wear-out reaches a certain permissible value without surface finish and accuracy reducing (***I*** is the area of normal wear-out of h_c = 0,3…0,5 mm).

During further machining, the wear-out value of the rake and clearance faces dramatic increases, and the cutting blade breaks (***III*** is the area of "catastrophic" wear-out).

Wear-resistance of the tool depends upon the physical and mechanical properties of the machined and tool materials, geometrical parameters of the tool, and cutting parameters. The cutting speed has the highest influence on the wear-out intensity.

ГОСТ 25751–83 gives the following notions and definitions concerning the cutting tool reliability:

– *dulling criterion* is the failure criterion that is characterized by the maximum permissible values of the cutting tool wear-out, after which it fails;

– *reliability failure* is gradual failure of the cutting tool that occurs after the dulling criterion is reached;

– *accuracy failure* is gradual failure of the cutting tool that occurs after the size, shape or position of the machined surface reaches the bounds of the tolerance zone;

– *reliability life* is the time of cutting with new or renewed cutting tool from the beginning of cutting and till the failure.

Wear-resistance of the tool is characterized by the reliability period ***T***, min, during which the wear-out reaches its maximum permissible value that is defined as the dullness criterion. If the value of the tool wear-out equals to the dullness criterion, the tool should be resharpened.

The following is taken as the dullness criterion: for turning and milling it is the clearance face wear-out of the cutter or miller blade; for cutting off and grooving it is the wear-out of the cutter angles; for machining of holes and for threading it is the wear-out of the cutting part of the tool in the bridge, angles, clearance face and band.

For finishing machining, one has developed the so-called technological dulling criterion. The tool is considered to be worn-out if the roughness of the machined surface and the accuracy of its size fail to meet the certain technical requirements.

Test questions

1. Name the design elements of the cutting tool.
2. What kinds of surfaces characterize the process of machining with a cutting tool?
3. What angles of the tool are viewed in the main cross-cut plane?
4. Name the kinematic elements of the tool during cutting.
5. What are the components of the cutting force?
6. Name the main types of chip and the ways of reliable chip breaking.
7. What does the depth and degree of workhardening during cutting depend upon?
8. What types of the tool wear-out may occur during cutting?
9. What parameter is taken as the tool wear-out criterion?

3 WORKPIECE LOCATING AND WORKHOLDING DEVICES

3.1 Locating of the workpieces during machining

Terms and definitions of the main notions of locating and datums are given in ГОСТ 21495-76 and ДСТУ 2232-93.

Locating (referencing) is providing of a workpiece or an item with the necessary position relatively to the chosen coordinate system.

Datum is the reference surface, axis, point that belong to the workpiece or item and that is used for locating.

By their purpose, the datums may be of three types: assembly, technological and measuring.

Assembly datums are used for determining the position of the part in the item. Assembly datums may be main and auxiliary. Main datum is used for determining the position of the certain part, and auxiliary datum if for determining the position of the part that is attached to the certain one.

The datum is called *technological (process)* if it is used for setting the position of the workpiece or item during its making or repairing.

Measuring datums are used for determining the relative position of the workpiece or item and means of measuring.

Independently of their purpose, the datums are also classified by the display character: they may be latent or real; by the degrees of freedom of the base part or workpiece assembly unit, the datums may be guiding, resting, double guiding and double resting.

Under the latent *datum,* one understands the datum in the form of a reference plane, axis or point (e.g., the part axis of symmetry). The datum that has the form of real surface, dimensional mark or the marks' intersection point is called real. Technological datums are always real.

3.1.1 Set of the datums of prismatic and cylindrical workpieces

In a simplified way, it is considered that the contact of the static bodies occurs in the supporting points that symbolize every connection of the workpiece with the chosen coordinate system. *The rule of six points*: For the full locating of the workpiece in space, it is necessary to have the set of three orthogonal planes that include six supporting points. Set of the datums is the complex of three datums that form the workpiece coordinate system.

The parts of airplanes, helicopters and aircraft made by dimensional machining are mostly of a complex geometric form. But it is possible to single out the typical geometric surfaces on the parts – flat, cylindrical, conical, etc. As an example, let's consider the set of the datums of prismatic (Fig. 3.1) and cylindrical workpieces (Fig. 3.2).

In order to remove three degrees of freedom from a prismatic workpiece (the possibility to move along the Z axis and rotation along X and Y axes), one should establish three rigid bidirectional constraints 1 – 3 between its lower surface and the XOY axis (see Fig. 3.1, a).

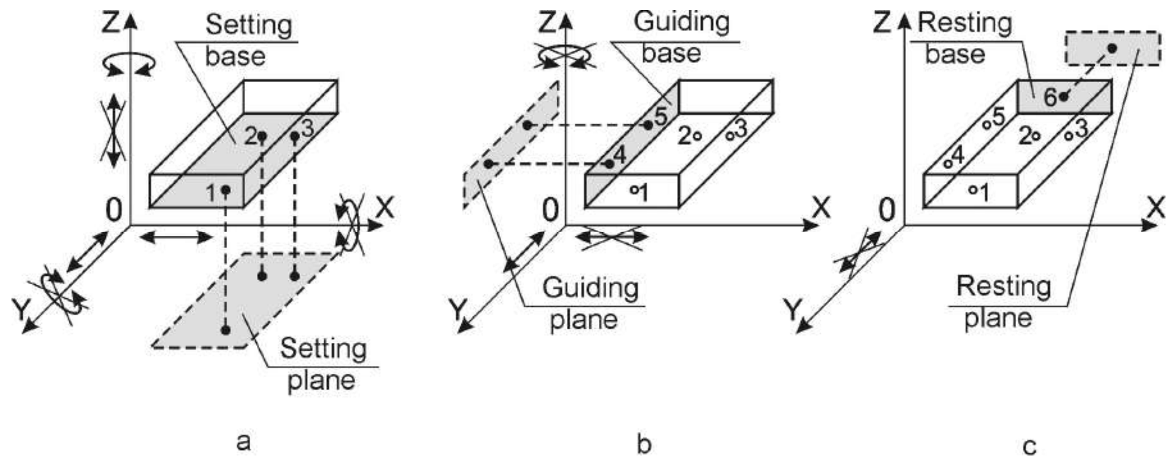


Figure 3.1 – Set of the datums of prismatic workpiece:
a – setting, b – guiding, c – resting

The datum used for applying the constraints that remove three degrees of freedom from the workpiece (moving along one coordinate axis and rotating around two other axes) is called the *position datum*.

In order to remove two more degrees of freedom from the workpiece (moving along the ***X*** -axis and rotation along the ***Z*** -axis are possible), one should establish with two rigid bidirectional constraints 4, 5 between its lateral surface and the ***YOX*** -plane (see Fig. 3.1, b).

The datum used for applying the constraints that remove two degrees of freedom from the workpiece (move along one coordinate axis and rotate along another axis) is called *the guiding datum.*

In order to remove one degree of freedom from the workpiece (moving along the ***Y*** -axis), one should establish one rigid bidirectional constraint 6 between its end surface and the ***XOZ*** -plane (see Fig. 3.1, c).

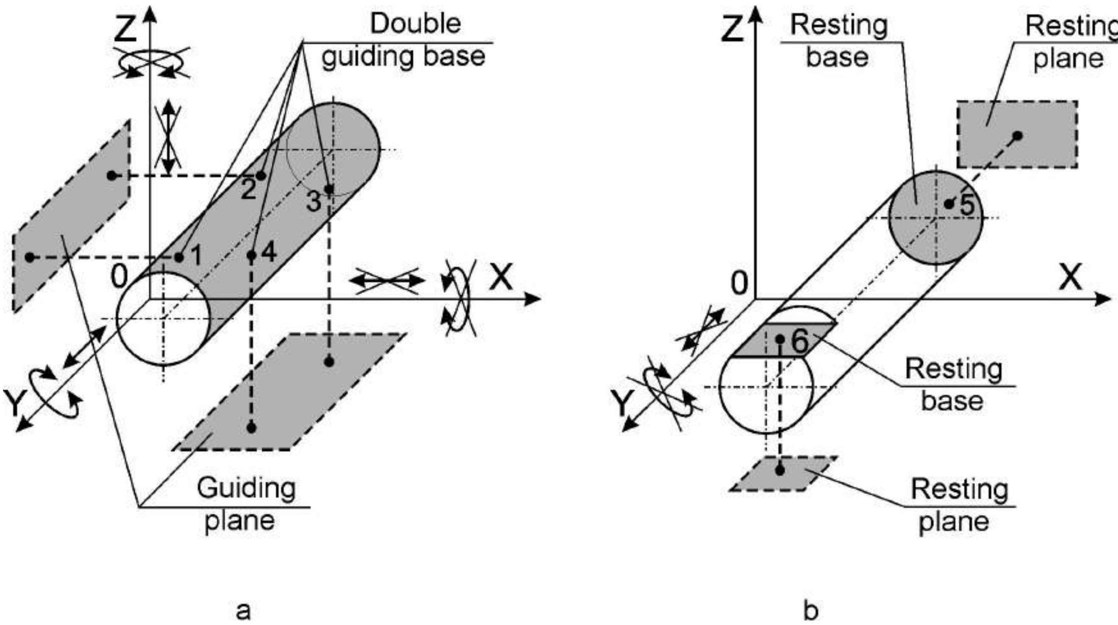


Figure 3.2 – Cylindrical workpiece full locating scheme:
a – double guiding base; b – resting bases

The datum used for applying the constraints that remove one degree of freedom from the workpiece (moving along one coordinate axis or rotation along the same axis) is called *the resting datum*.

For prismatic workpieces, it is recommended to choose the surface with maximum overall dimensions as a position datum, the surface with maximum length as a guiding datum, and the shortest surface of the workpiece as a resting datum.

In order to locate a cylindrical workpiece, its lateral area is joined with the constraints 1, 2 with the plane ***YOZ***, and with the constraints 3, 4 – with the plane ***XOY***, removing four degrees of freedom from the workpiece – the possibility of moving along the ***X*** - and ***Z***-axes, and also rotation along these axes (Fig. 3.2, a).

The surface of the cylindrical workpiece that has four supporting points is *the double guiding datum.*

To disable a cylindrical workpiece from moving along the ***Y***-axis, it is necessary to join its side with the constraint 5 with the plane ***XOZ*** (Fig. 3.2, b). In order to provide a certain position of the workpiece relatively to its own axis, the constraint 6 as a supporting point on the surface of a key groove, for example, should be foreseen. The workpiece planes that are bearing by one supporting point, according to the definition given above serve as resting datums.

3.2 Classification of workholding devices

Workholding devices are additional (auxiliary) devices for metal-cutting machines. Purposes of workholding devices are the following:

– installing the machined workpieces according to the technological process demands when running the machine;

– improving accuracy and stability of surfacing, which is carried out by proper locating, secure workholding of a workpiece and stiffening it while machining;

– increasing labour productivity, which is reached by eliminating the work layout before machining, adjusting the workpieces when installing them, cutting the machining floor-to-floor time in all machining technological operations.

All the devices are classified by the degree of specialization, number of installed workpieces, mechanization and automation levels, and machine types.

By *the specialization degree*, the devices may be multipurpose, specialized and special.

Multipurpose devices are devices for installing the workpieces of various constructions in the dimensions adjusting range. Usually, these devices are included in the tooling package that goes with the machine.

Specialized devices are devices for installing single-type workpieces, i.e. the workpieces that belong to one classification group that is singled out according to the constructional and technological characteristics adjacency.

Special devices are devices used for installing the workpieces of the same dimension type. They are used for installing a particular workpiece during a certain operation.

By the number of the workpieces installed, the devices may be one-position (for installing one workpiece), and multi-position (for simultaneous installation of several workpieces).

By the degree of mechanization and automation, the devices may be:

– manual, in which the workpiece attachment and detachment is carried out by hand;

– mechanized, in which the workpiece attachment and detachment is carried out by means of hydraulic, pneumatic or magnetic drives;

– semiautomatic, in which the certain operation algorithm performed is partly human-aided;

– automatic, in which the certain operation algorithm performed is not human-aided.

By the type of machine, the devices may be turning, drilling, milling, grinding, etc.

Despite the great variety of design of the devices used, all of them have the same structure, which allows to divide the devices by their function into several parts that are, as a rule, called elements.

Element is the part, assembly unit, or mechanism designed for carrying out a certain function in the device.

All elements may be combined into the following main groups: location elements, clamping accessories, guiding elements, frames. Elements of the group differ not only in size, but also in version. Depending upon the function, the structure of the device may contain the whole set of the elements or only separate groups of elements.

The elements are designed taking into account the requirements that are set depending upon the functions carried out. This allows to use general design methods for each separate group of elements.

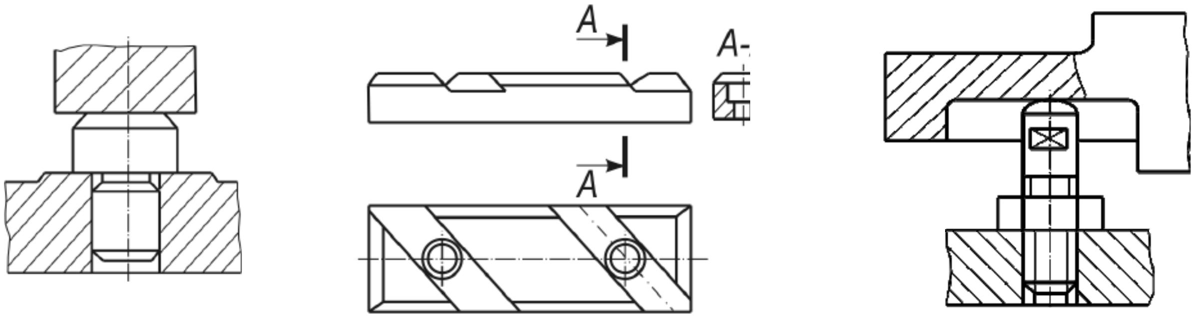
3.2.1 Location elements of workholding devices

When locating, the workpiece should be correctly oriented with respect to the machine movable operating elements. Workpiece orientation is reached by workpiece locating according to the rule of six points.

For locating the workpieces, one uses location elements of the devices that are fixedly connected with the device's frame. Location elements are bearing plugs, plates, rings, bushings, fingers and prisms.

Design types of bearing plugs are standardized and are called *"permanent support"*. Flat-head supports (Fig. 3.3, a) are used for pure locating of pre-machined flat surfaces, and sphere-like head and threaded-head supports are for rough locating.

Locating with the help of support plates is the most widespread way of locating the machined surfaces of the workpiece. Support plates may be of two types: flat and with skewed slots (Fig. 3.3, b). In the latter case, the support plates are more easily cleaned from the chips, which is why they should be used for installing on the horizontal plane, and flat support plates should be on the side surfaces.

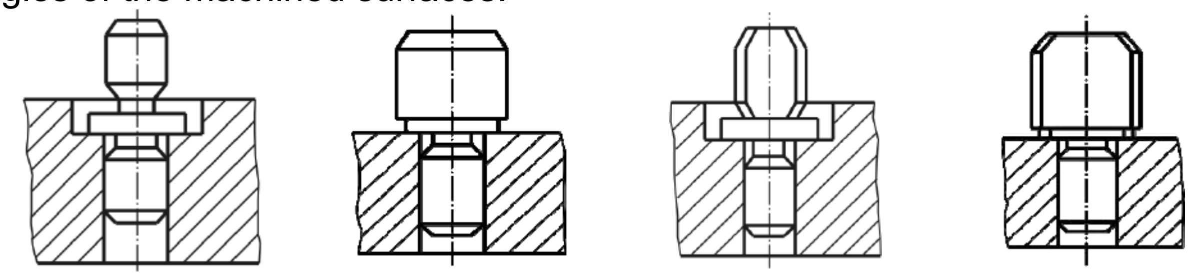


a b c

Figure 3.3 – Location elements for prismatic workpieces

Locating of the workpieces in the device is provided with main location elements, and as for using additional elements, they don't take part in locating, but provide more stability and rigidity to the workpiece. They are *movable supports* that are led to the workpiece after its locating on the main supports (Fig. 3.3, c). Installing *on a finger* in two holes and a plane is used for machining the workpieces like frames, plates. The advantages of this locating scheme are the simplicity of device, the possibility of holding to a principle of bases' stability for most operations.

Structurally, there are the following types of locating: installing on two cylindrical fingers; installing on one cylindrical and one truncated finger (Fig. 3.4). The range of implementation of such assemblies are determined by the accuracy of the diameters of the datum holes and their mutual location, accuracy of relative distances ensured during the operations, and revolution angles of the machined surfaces.



1 2 1 2

a b

Figure 3.4 – Location elements for cylindrical workpieces:
a – cylindrical finger; b – truncated finger; (1 – $D<10$ mm; 2 – $D=10...16$ mm)

In order to locate cylindrical workpieces, one generally uses *prisms* – location elements that have the slot-shaped working surface made up of two planes with the angle α between them. The prism determines the position of the workpiece axis that is perpendicular to the prism datum as the result of its matching with the axis of the angular slot. The angular slot axis is considered to be the one drawn through the intersection point of work planes perpendicularly to the prism datum plane.

In workholding devices, the prisms with the angles α that equal 60, 90 and 120^o are used. The most widespread are the prisms with $\alpha = 90^o$. In order to install the workpiece with finally machined datums, the prisms with wide supporting surfaces are used, and for rough machining, they should have narrow supporting surfaces.

3.2.2 Methodology of workholding devices' design

In order to design the workholding device, the designer should have the following basic material:

– working drawings of the part and initial workpiece;

– operation sheet with the draft of the workpiece machined for a certain operation with the scheme of locating and fixation;

– operation sheets of previous machining of datum surfaces, the usage of which is foreseen in a certain operation;

– annual production volume of the part;

– rated performance of the machine for which the device is designed.

Design of a workholding device is carried out in the following sequence:

– basic information is studied and variants of the device structural schemes are developed;

– technical and economical calculations are carried out for justifying the optimal variant of the device;

– constructions of the device optimal variant are developed.

Technical calculations are the ones that determine the accuracy of the workpieces' geometrical parameters performed and the reliability of their fixation in the device. Economical calculations are the evaluating of expediency of using the certain device and determining its efficiency.

One starts to perform technical calculations with determining the device accuracy. If the device doesn't correspond to the requirements of machining accuracy, this variant is unsuitable for production.

The next stage is determining the reliability of the workpiece fixation. After calculating the force necessary for the workpiece fixation, one finally chooses the constructions of the clamping device and the drive.

Design of the workholding device construction is carried out in a certain sequence. At first, one draws the outline of the workpiece machined in the projection bond. The projections are placed at such distance from one another, so that there is enough space for placing the corresponding elements of the device.

Then, one draws location and clamping elements on the workpiece projections, and if the device has guiding elements, one also draws them. After that, the construction of the device frame is formed.

General view of the device is drawn in the working position with all the necessary projections, cross-section and sectional views, which allows to represent the construction of all device elements in general, and also their interconnection. General view of the device is usually drawn on a scale of 1:1. Assembly drawing of the workholding device must contain the overall, setting (fitting) and connecting dimensions, and also the dimensions of guiding elements. Connecting sizes determine the surfaces that join the device with the machine.

3.3 System of modular accessories

Modular accessories (MA) are the devices assembled of the set of standardized elements - parts, joints, mechanisms. Elements of modular accessories are all-purpose, and the assembled device becomes special, as it is used for installing a certain workpiece during the operation performed. After the certain number of the workpieces is machined, one disassembles the device and uses its elements for assembling other devices. This way, the MA elements are reused for assembling the devices. This class of devices is widely used in single-type and short-run production.

Design and dimensions of the MA elements are determined by a number of standards. The main difference in the each series is the width of the fixed T-shaped slot in the MA elements: 8 mm (MA-8) – device manufacturing, 12 mm (MA-12) – machine-building industry, including aircraft construction, 16 mm (MA-16) – heavy machine-building industry.

The MA elements are divided into five groups:

1. *Basic parts* – square, rectangle and round plates, taper mandrels, corner plates, rings. Constructional peculiarity of these parts is that they have a grid of T-shaped and spline slots.
2. *Frame parts* – gussets, backings, wedges, plates. Parts of this group are used for making the frame of the device; they may perform the functions of basic parts or may be used as joining elements. They also have T-shaped slots.
3. *Installation and guiding parts* – dowels, pins, fingers, prisms, aligning bushings, positioning points. They are used for installing and fixation of the MA frame parts with respect to the basic parts, and also for regulating the operation dimensions of the device, workpiece locating and cutting tool guiding.
4. *Fixation and clamping parts* – hold-down tools and planks, bolts, screws, pins, nuts, washers. They are used for joining the elements of the device together and for fixation of the workpieces in the devise.
5. *Assembly items* – swivel work heads, supports, brackets, center stocks, clamping tools. They are used for mounting of more rational and compact MA with minimum amount of frame, fixation and clamping and other types of parts.

Nomenclatural and quantitative composition of the MA set depends upon the volume of production and makes up 4–20 thousand elements.

It is practically determined that the composition of the MA set parts is approximately the following: basic parts – 1%; frame – 15%; installation – 22%;

guiding – 4%; clamping – 5%; fixation – 53%.

Unlike special devices, the MA system eliminates additional improvement during the devices' assembly, as the MA elements are produced with increased accuracy of linear and angular sizes and centre-to-centre distances. Main linear and angular dimensions of basic and frame parts are produced according to the ***IT6*** class of accuracy. Parallelity and perpendicularity tolerances of the working planes, holes' axes, T-shaped and key slot correspond to the ***IT5*** class of accuracy. MA elements are expected to be used for a long maintenance period – up to 15 years.

Initial data for MA design are the method of machining, part drawing, operational drawing of the workpiece machining, type of the machine and the number of parts simultaneously machined in the device.

MA creation is made up of developing the layout chart of the device according to EP requirements, device assembling of the standardized elements, further adjustment of the operation sizes of guiding elements.

One begins the MA assembling with choosing the datum plate, the size of which should provide installation on its working surface of the parts and assembly items that take upon themselves the load from the cutting forces. Then, one installs on the locating plane workpiece locating and clamping elements, and rectangular supports, upon which the guiding planks with aligning bushings are fixed. If the workpiece is present, the MA assembling is significantly simplified.

In order to gain experience and simplify the re-assembling, one makes a photo of the MA assembly that has passed the maintenance testing and makes an album.

Comparatively to the production cycle of special workholding devices, the MA assembling cycle is 40–50 times shorter and is 10-15 times less laborious.

Test questions

1. Provide the classification of the datums by their purpose.
2. What datums form the set of datums for prismatic and cylindrical workpieces?
3. Enlist the rules for choosing the technological datums.
4. How are workholding devices classified?
5. What installation elements are used for locating of prismatic and cylindrical workpieces?
6. What principle lies in the basis of hold-down tools' construction?
7. Name the functions performed by aligning bushings of workholding devices.
8. What construction elements are placed on the workholding device frame?
9. Why does the MA system eliminate additional improvement during the workholding devices' assembling?
10. What are the advantages and disadvantages of using MA?

4 PREPARATORY OPERATIONS OF MACHINING

In blank department or shop rolled metal in the form of bars is straightened, roughed, cut, centered. Forgings are subjected to preparatory operations too: milling and centering of end surfaces, roughing and pre-turning of the holes. Preparatory machining operations for bars are usually performed in the following order: straightening, centreless roughing, parting, centering.

4.1 Straightening of solid workpieces

Solid workpieces in the form of large-sized forgings are straightened in the hot state on hammers; bars are straightened in the cold state condition on the presses with the help of prisms. The workpieces are previously checked in the centers, where the places to straighten are determined.

Bars of circular section are straightened on the special straightening machines (Fig. 4.1).

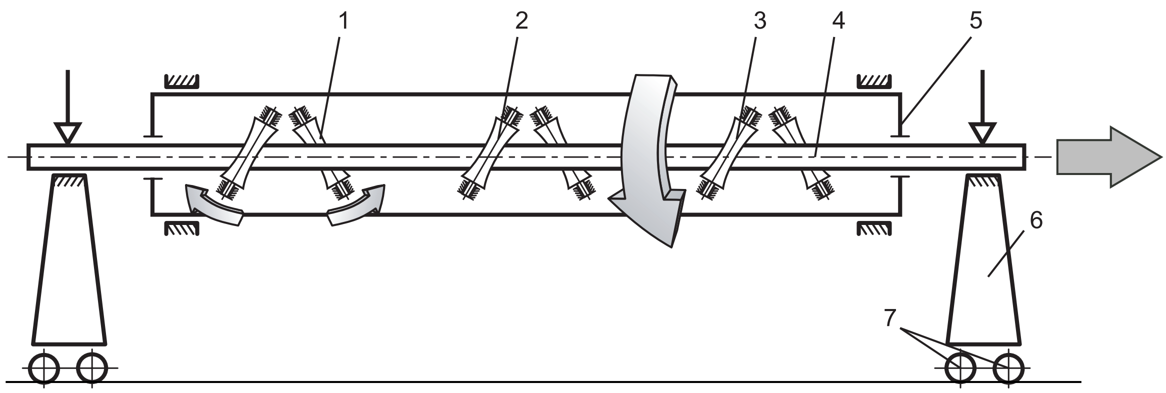


Figure 4.1 – Scheme of the straightening machine

Straightening is carried out with the help of three pairs of rollers 1, 2, 3 with concave surface. Rollers 1 load the bar 4 installed on special posts 6 with rollers 7. All three pairs of rollers are installed in the barrel 5 at an angle of 70° to its axis. During the barrel rotation, the rollers roll around the bar and straighten it. Feed speed of the bar is 5…30 m/min, depending on the barrel revolution speed; straightening accuracy is 0,1…0,2 mm per 1 m of the bar length.

4.2 Roughing of bars

In order to rough the bars with the diameter 15…80 mm and up to 7 mm long, the centerless roughing machines are used. Processing on such machining is carried out in the following way. Central gear wheel is the toothed wheel driven by the electric engine rotates two cutter heads. One head with the cutter performs rough machining, the other one – semi-final machining. The bar is loaded with the help of two rollers with large dent. Depending upon the revolution frequency of the rollers, the feed speed of the bar is 175…600 mm/min.

4.3 Parting of bars, shafts, tubes

Bars and shafts are cut on the hack-sawing machines, saws (circular, band, friction), turning and cutting machines or with abrasive wheel.

On the hack-sawing machines, the bar material is cut with the hacksaw blade that, under a certain pressure, performs mechanically driven reciprocal motion.

Cutting edges of the hacksaw blade teeth are directed in the cutting direction. The blade is pressed to the material cut only during the machining pass, and during the return pass it is lifted with the hydraulic mechanism. This results in the fact that the friction of the teeth and the material during the return pass is eliminated, the blade wear-out is reduced, and the sawing machine productivity increases.

Circular saws are produced in the assembly form. By design, the circular saw is a disc of carbon steel with inserted teeth or riveted toothed segments of high-speed steel. With the circular saw, the bars are cut one at a time or by batch method.

As the saw gets deeper into the material, the cut area of the workpiece constantly changes, which results in changing of the cutting force, provided that the saw is uniformly moved. Variable feed value in the each moment of time corresponds to the value of the area cut, so that the machine always operates under the same cutting force.

Band saws have the shape of a band 1,0…1,5 mm thick. Band saws are used mainly for cutting the bars of nonferrous metals.

Friction saw is a thin steel disc that, during feed and rotation, as the result of appearing friction, heats the particles of metal in the slit up to the melting temperature. Melted metal is removed from the slit with the disc that is cooled with air and water. To increase friction, thick denting knurling is provided on the surface.

Electric friction saw cuts the material by simultaneous operation of the friction saw and electric arc. The rotation disc is connected to one pole of the generator, and the cut material – to the other pole, and this way the voltaic arc is formed. The metal in the slit melts, and the rotation disc only removes the melted material.

Cutting machines are used for lengthwise cutting of round and hexahedral bars, and also tubes.

Cutting machines with two supports – rake and end ones – are produced serially. On these machines, two cutters operate simultaneously, which is why their productivity increases.

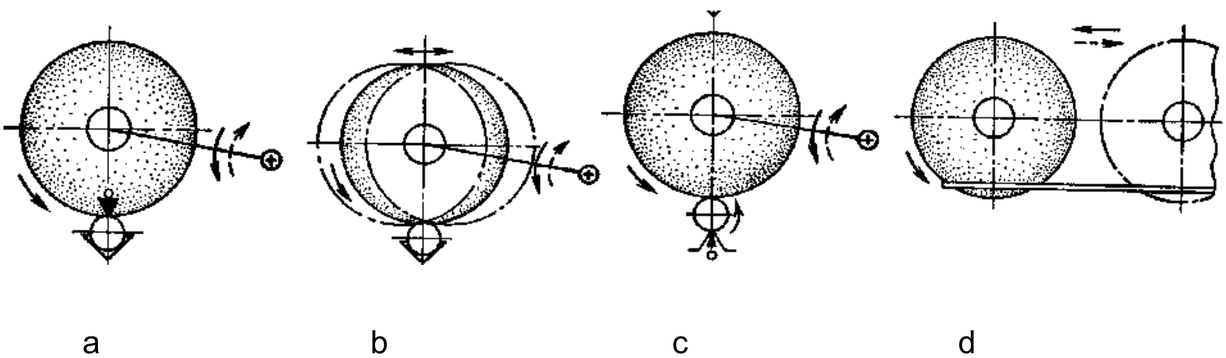
The productivity of cutting machines also increases thanks to the device that controls the cutting speed and keeps it constant. In the machines with constant cutting speed, as the cutters approach the bar axis, the revolution frequency of the machine spindle increases, which speeds up performance of the operation.

4.3.1 Cutting of the workpieces with abrasive wheels

Cutting of the workpieces with abrasive wheels is reasonable if one needs to separate the materials of difficultly machined heat-resistant and titanium alloys, dispersive-hardening steels, when it is impossible to use band or circular saws.

There are the following schemes of abrasive-cutting machines' operation:

1. *Pendulum* (see Fig. 4.2, a). The spindle with the disc is installed on one end of the lever (bellcrank), and the engine with the spindle drive – on the other one. The lever is rotated relatively to the immovable axis on the angle necessary to cut a bar, a section or a tube. Maximum diameter of the workpiece is 100 mm.
2. *With oscillating movement of the wheel* (see Fig. 4.2, b). Besides rotation and linear motion of the feed on the cut material, the cutting disc also moves reciprocally. As the length of the disc arc contacting the workpiece cut reduces, the temperature in the culling area lowers, and the quality of the end surfaces of the cut workpieces increases.
3. *With rotation of the disc and workpiece cut* (see Fig. 4.2, c). The cutting disc is moved only to the center of the workpiece of rolling and on the wall thickness during cutting the pipe workpiece, so maximum diameter of the workpiece increases up to 700 mm.
4. *With rotation and lengthwise movement of the disc* (see Fig. 4.2, d). Thin sheets and plates are cut during one machining pass, thick ones – during several machining passes with the cutting depth 3…6 mm. The length of the plates cut is up to 6000 mm, their thickness is up to 200 mm. Cutting of the workpieces is possible both single-piece and in package. Productivity of abrasive cutting is 0,8…15 cm^2/sec. Cutting parameters are the following: disc cutting speed is 50…80 m/sec, feed speed is 60…2500 mm/min.



a b c d

Figure 4.2 – Operating schemes of abrasive-cutting machines

Discs of electric corundum are used for cutting steel workpieces, discs of silicon carbide – for cutting the workpieces of titanium alloys and non-metal alloys.

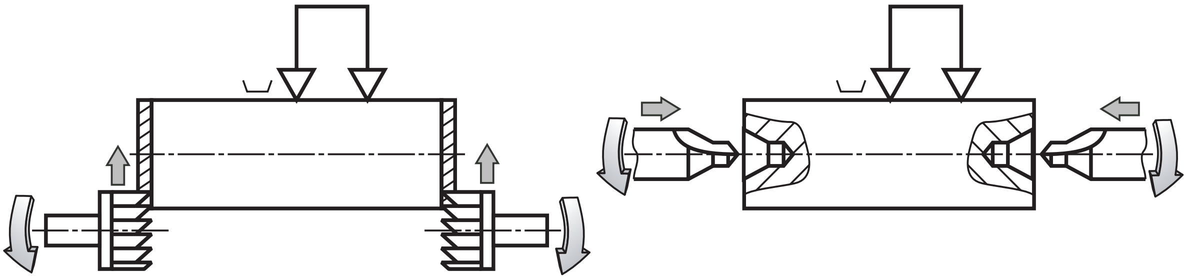
Cutting of sheets, plates, wires, tubes and other workpieces of high-strength alloys is carried out using electrophysical methods – anode-mechanical, laser and plasma.

4.4 Centering of the workpieces

On-centre holes in the parts like shafts are the basis for a number of operations: turning, threading, milling, slit cutting, and also for testing of the produced parts.

For centering the workpieces, one uses special combined (drilling and core-drilling) centering drills with the diameter 1…10 mm with the cone angle 60°, and also the drills with double cone (drilling, core-drilling and bevel formation) with the angles 60° and 120°.

The workpieces are centered on drilling, turning and turret machines, and in series and mass production – on special two-side centering machines, and also on turning-centering machines (Fig. 4.3). Centering of large workpieces is carried out on horizontal-drilling machines.



a b

Figure 4.3 – Operating scheme of a turning-centering machine

Turning-centering machines operate according to the following scheme:

– in the *"load – unload"* position, the workpiece is inserted into the jaws with self-centering prismatic grips;

– in the first position, both end surfaces of the workpiece are milled simultaneously (Fig. 4.3, a);

– in the second position, centering holes are drilled (Fig. 4.3, b).

Test questions

1. Name the types of preparatory operations.
2. List the methods of cutting the bars, shafts, tubes.
3. Give the cutting schemes of the workpieces' cutting with abrasive discs.
4. What equipment is used for the workpieces' centering?
5. Describe the operation principle of turning-centering machines.

5 WORKPIECE MACHINING BY TURNING

5.1 Purpose and main types of turning

Turning is widely used in producing the bodies of rotation of complex shapes and increased accuracy made of various construction materials.

By the nature of machining, there are the following *types of turning*:

– roughing – removing of the workpiece defective layers, cutting, cutting-off and facing, cutting of the surface peel and main (up to 70%) part of machining allowance;

– semi-finishing – removing of 20…25% of the allowance; surface finish R_z = 40…20, accuracy of 10 – 11 r; the class of accuracy (quality) gets the shape close to the part shape;

– finishing – surface finish R_z = 20…1,25, accuracy of 7 – 9 class of accuracy (quality); the workpiece gets the finishing shape and size;

– fine (diamond) turning – cutting of the very thin shaving; R_z = 0,65…0,32, accuracy of 5 – 7 class of accuracy (quality).

Turning may be carried out according to various cutting schemes (see Fig. 2.2): free orthogonal – e.g., for turning of the workpieces such as discs with cross-feed; oblique – it is the mist widespread cutting scheme; constrained – cutting-off, grooving, shape tool turning.

In order to turn difficult-to-cut material, *special technological* methods are used: turning with additional heating or deep cooling of the workpiece; vibratory turning with implementation of high-frequency or ultrasonic vibrations on the cutter; turning in various technological environments and vacuum.

5.1.1 Methods of turning

Turning is performed with turning cutters on various turning machines.

Cutter, according to ГОСТ 25751–83, is a single-point cutting tool for machining with linear or rotation main cutting movement and the possibility to provide the feed movement in any direction.

Main operations of turning are the following: external straight turning, cutting-off, facing, face grooving, external grooving, profiling, internal surfaces' boring and grooving, chamfering, internal and external threading with the cutter, etc.

Turning scheme of cylindrical surfaces and main moves during turning are shown in the Fig. 2.3, a.

Ways of conic surfaces' turning. In order to form a conic surface, the cutter should move at the required angle to the workpiece axis of rotation. Small taper angle α may be received by shifting the center 3 of the fixed back end of the workpiece 1 on the turning machine (Fig. 5.1, a). The value of the shift is determined by calculation.

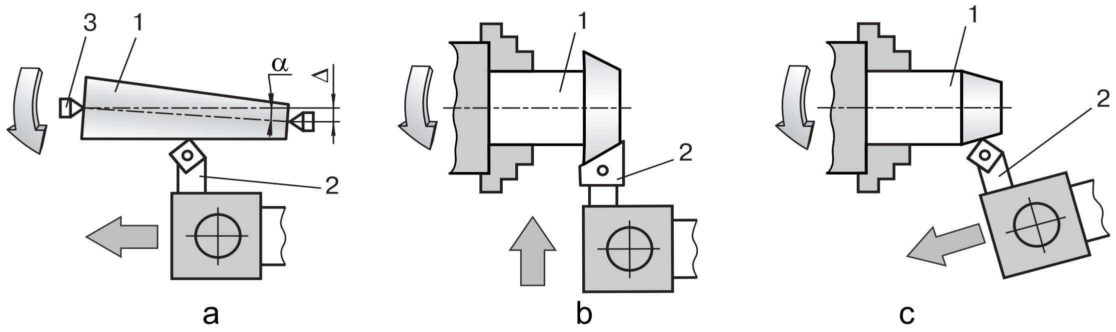


Figure 5.1 – Types of conic surfaces' turning

Short conic surfaces may be machined with the wide cutter with transverse feed (Fig. 5.1, b).

During machining of conic surfaces at large angle, moving direction of the cutter 2 is changed by rotating the compound rest (Fig. 5.1, c).

Ways of profiled surfaces' turning. One of the widespread ways is cutting with transverse feed of the shaping cutter 2 that has the profile of the part 1 outline (Fig. 5.2, a).

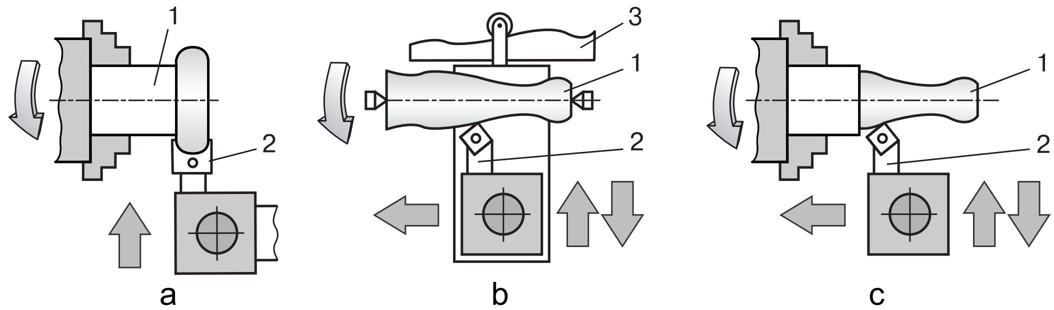


Figure 5.2 – Types of profiled surfaces' turning

Long profiled surfaces are machined with the help of templet tool 3 that, by constant lengthwise feed of the tool 2, is moved in the transversal direction in correspondence with the templet tool profile (Fig. 5.2, b). NC machines allow to set the tool trajectory by changing the feed value by two axes – longitudinal and transversal – simultaneously (Fig. 5.2, c).

Methods of internal surfaces' turning are shown in the Fig. 5.3:

– boring of the cylindrical surface 1 with lengthwise feed of the cutter 2 (see Fig. 5.3, a);

– cutting of the groove 1 of rectangular or shaped profile with transversal feed of the cutter (see Fig. 5.3, b);

– drilling of the hole 1 with the tool 2 with lengthwise feed (see Fig. 5.3, c);

– threading 1 with the cutter 2 (see Fig. 5.3, d) and tap 2 (see Fig. 5.3, e).

To achieve required accuracy of cutting it is necessary to provide firm cinematic connection of the spindle with the cutter. To ensure the full depth of the cut one needs to perform several machining passes, increasing depth of cut with each pass.

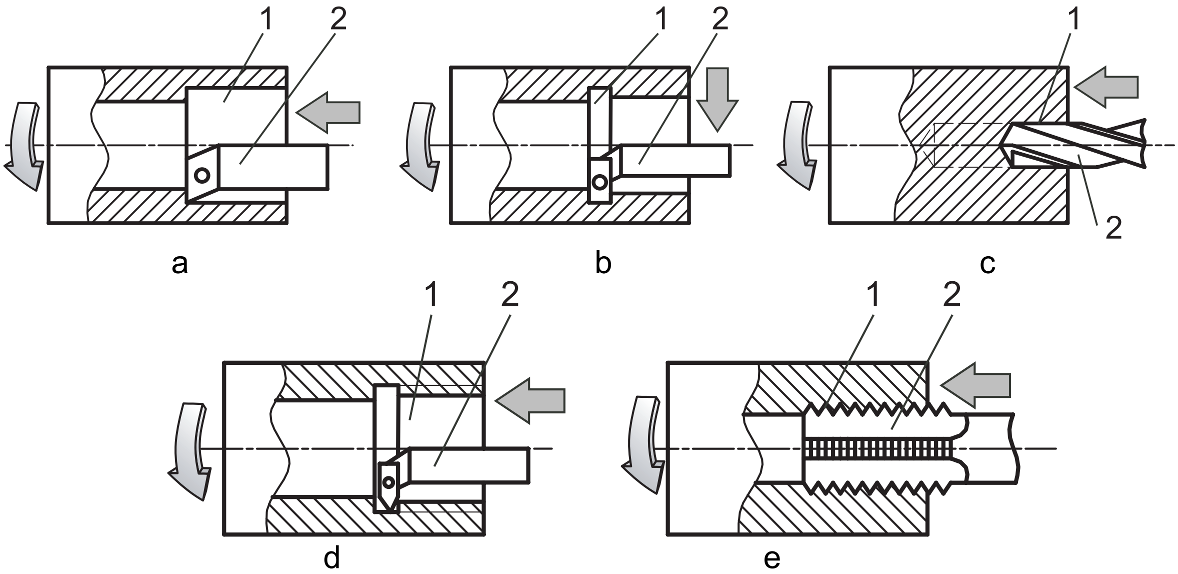


Figure 5.3 – Methods of internal surfaces' turning

Other types of turning. Due to plastic deformation of the workpiece surface layers, the following types of turning are used: production of riffling by knurling with the special roller (Fig. 5.4, a) and spinning of the part surface with the smooth roller (Fig. 5.4, b) in order to harden it and reduce roughness.

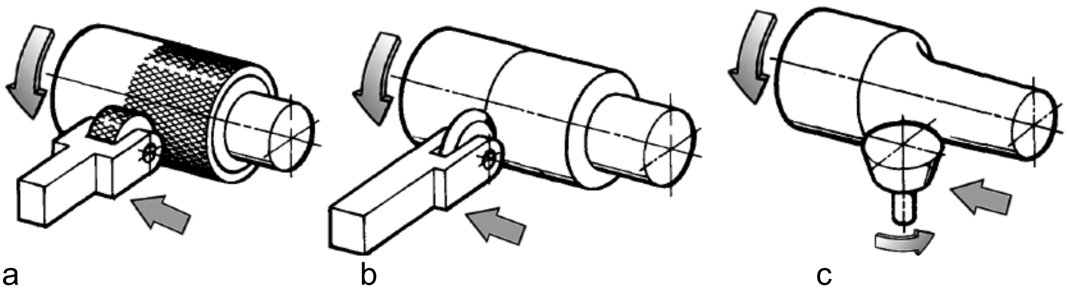


Figure 5.4 – Turning: a, b – with plastic deforming; c – with rotary tool.

One may also machine the surfaces on the lathes due to complex kinematic connection of the machine operating elements.

Turning with rotary tool (Fig. 5.4, c) is carried out with the help of three mutually concordant movements: rotation of the spindle with the workpiece, longitudinal movements of the carriage with the tool, and tool rotation. During rotation, form tool rolls over the surface machined.

5.2 Types of turning cutters

Large number of various technological operations performed on the turning machines defines the variety of designs of the cutters used.

According to design and technological features, turning cutters are classified as follows (Fig. 5.5).

Type of the cutter design is chosen taking into consideration the complex of technological and economical characteristics (type of the operation, properties of the material, geometrical parameters of the tool).

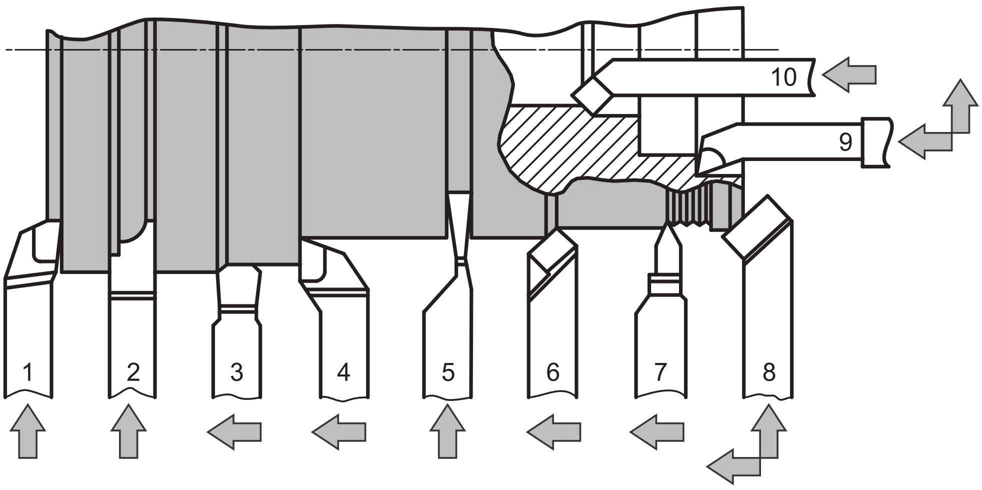


Figure 5.5 – Main types of turning cutters

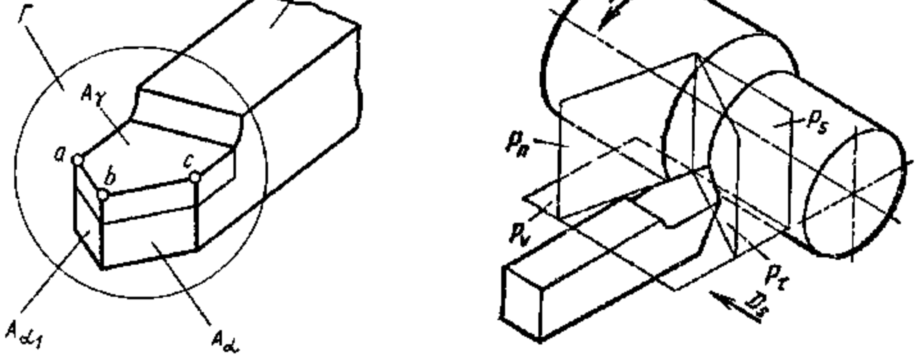
by purpose – straight-turning cutters 6, 8 and straight facing cutters 4, undercutting tools 1, cutoff and grooving cutters 5, boring cutters 10, 9, form cutters 2, threading cutters 7, finishing cutters 3; *by moving direction* – right-hand 6 and left-hand, radial and tangential; *by shape of the cutting part* – straight 6, 3, offset 1, 4, 8, 9, 10, tapered 5, 7; *by design* – solid, assembled with various methods of cutting inserts (tips) assembling, and cutter blocks

5.2.1 Geometrical parameters of the turning cutter

Turning cutter (Fig. 5.6, a) consists of the cutting part (point) *Г* and shank *К* (holder, shank end) for its fixation on the machine. It has the following standard geometrical parameters: *ab* is the end (auxiliary) cutting edge; *bc* is the side (primary) cutting edge; *b* is the point of the cutter; A_γ is the cutting face; $A_{\alpha 1}$ is the end (auxiliary) flank; A_α is the side (primary) flank.

Primary cutting edge that performs the main function of cutting is formed as the intersection of the cutting face and primary flank of the cutter. The intersection of the cutting face and auxiliary flank forms the auxiliary cutting edge.

The place of intersection of primary and end cutting edges is the nose of cutter (cutter point).



a b

Figure 5.6 – Elements and coordinate planes of the turning cutter

The combination of the angles that determine the positions of the cutter faces relative to coordinate planes is called *geometry of the tool*. The value of the angles is chosen depending upon the type of the cutter, its materials and the workpiece machined, taking into consideration the working conditions of the tool.

For measuring the angles of the turning cutter, one uses the following initial planes (Fig. 5.6, b): reference plane P_v, principal cutting plane P_n (their definitions are given in the section 2.1), and also orthogonal P_s and auxiliary orthogonal P_τ planes.

Reference plane P_v is parallel to the vectors of longitudinal and transversal feeds. Near the turning cutters, reference plane P_v coincides with the base plane of the cutter shank.

Principal cutting plane P_n is tangent to the cutting surface, and it crosses the primary cutting edge of the tool perpendicularly to the reference plane.

Orthogonal plane P_s is perpendicular to the projection of the primary cutting edge on the reference plane, and auxiliary orthogonal plane P_τ is perpendicular to the projection of the end cutting edge on the reference plane.

Fig. 5.7 shows the projection of the turning cutter and the workpiece on the reference plane:

P_n is the trace of the principal cutting plane; P_v is the trace of the plane that is parallel to the reference plane; ***I*** is the currently machined surface; ***II*** is the machined surface; R is the cutting surface. Main angles of the cutter (γ, α, β) are viewed in the orthogonal plane $N - N$, and auxiliary angles (γ_1, α_1, β_1) – in the auxiliary orthogonal plane $N_1 - N_1$.

In order to determine the position of the turning cutter sides relative to the coordinate planes, one uses six angles:

– *orthogonal rake angle* γ – the angle between the rake (face) and reference plane P_v;

– *orthogonal clearance angle* α – the angle between the main clearance side and the principal cutting plane (it is measured in the orthogonal plane; in Fig. 5.7, it is the plane $N - N$);

– *auxiliary orthogonal clearance angle* α_1 – the angle between the auxiliary flank and the plane that goes through the end cutting edge perpendicularly to the reference plane P_v (it is measured in the auxiliary orthogonal plane; in Fig. 5.7, it is the plane $N_1 - N_1$);

– *inclination angle* λ – the angle between the primary cutting edge and reference plane P_v (this angle is measured in the principal cutting plane P_n);

– *principal cutting edge angle* φ – the angle between the projection of the primary cutting edge on the reference plane and the direction of the feed;

– *end (auxiliary) cutting edge angle* φ_1 – the angle between the projection of the end cutting edge on the principal cutting plane and the direction opposite to the feed movement (these angles are measured in the reference plane $\boldsymbol{P_v}$).

Angles of the cutter that derive from the listed above are the following: cutting-point angle $\beta = 90° - (\gamma + \alpha)$, angle at the cutter point $\varepsilon = 180° - (\varphi + \varphi_1)$.

Rake angle γ has the most significant influence on the process of cutting. If the rake angle is positive, the cutter has the acute angle of cutting. At the same time, plastic deformation and cutting forces are reduced, but heat extraction becomes more limited, and the strength of the cutting tool is reduced because it is bending, and the probability of its breaking increases. Under negative values of v, the cutting angle becomes blunt, plastic deformation and cutting forces increase, but heat extraction becomes more intensive, and the strength of the cutting part increases, and it is under compression, which is a more favourable type of loading. By machining of nonferrous metals and alloys the rake angle is approved as being equal γ = 15…30°; during processing of tough-to-machine materials and quenched carbon steels, and also if there is a casting skin on the workpiece surface $-\gamma$ = 0…10°.

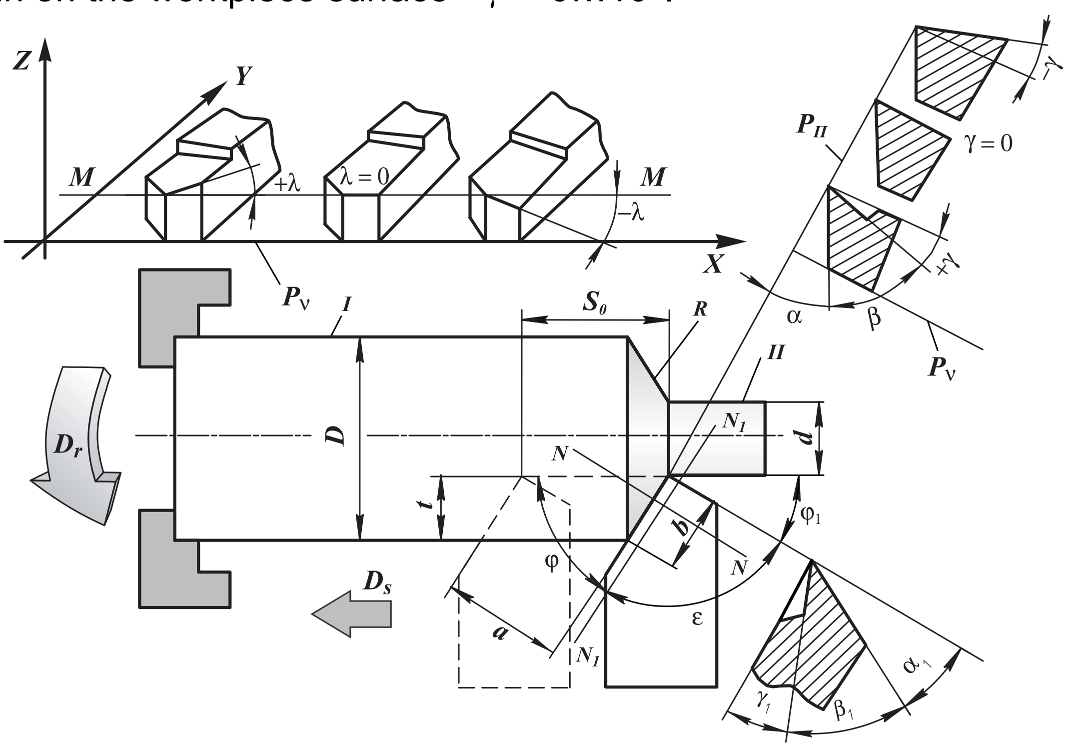


Figure 5.7 – Geometrical parameters of the turning cutter

Clearance angle α is used for reducing the friction between the clearance face of the cutter and the machined surface, it is chosen within 6 and 10°.

The angle that has a significant impact upon the process of turning is the *inclination angle* λ (in Fig. 5.7, it is the angle between the primary cutting edge and the plane $\boldsymbol{M - M}$, drawn through the point of the tool cutting part parallel to the reference plane $\boldsymbol{P_v}$). The angle λ is considered to be positive if the cutter point is the lower point of the cutting edge. The value and sign of the angle λ

influences the direction of the shavings' descent and workload distribution along the cutting edge. For roughing one uses positive angles λ. At the same time, the chips move towards the machined surface where it may wind onto the part and scratch the part surfaces. This is why for finishing machining one uses the cutters with negative angles λ (up to $-5°$), when the chip moves to the machined surface.

Principal cutting edge angle φ has a significant influence on the cutter durability and roughness of the machined surface. As the principal cutting edge angle gets smaller, the roughness of the machined surface reduces. Although, if the angle φ is small, there may occur vibrations, which results in reduction of quality of the machined surface and in the faster wear of the tool. The value range of the angle φ lies within 30 and 90°, depending upon the type of machining, type of the cutter, and roughness of the workpiece and the tool.

Cut layer thickness a is measured in the direction perpendicular to the cutting edge between the positions of the cutting plane per one rotation of the workpiece (see Fig. 5.7): $a = S_0 \sin \varphi$.

Cut layer width b is the distance between the points on the workpiece surface measured along the cutting edge (in width of the cutting surface): $b = t/\sin\varphi$.

5.3 Elements of the turning contour

Surfaces of the parts processed on the turning machines are divided into end surface planes perpendicular to the axis of rotation, coaxial cylinders, cones, spheres, tori and surfaces of rotation with rather curvilinear generatrix, and also helical surfaces that form the thread. The generatrices of these surfaces are straight lines, circles and lines

From the technological point of view, these geometrical elements and surfaces corresponding to them are divided into primary and auxiliary (Fig. 5.8).

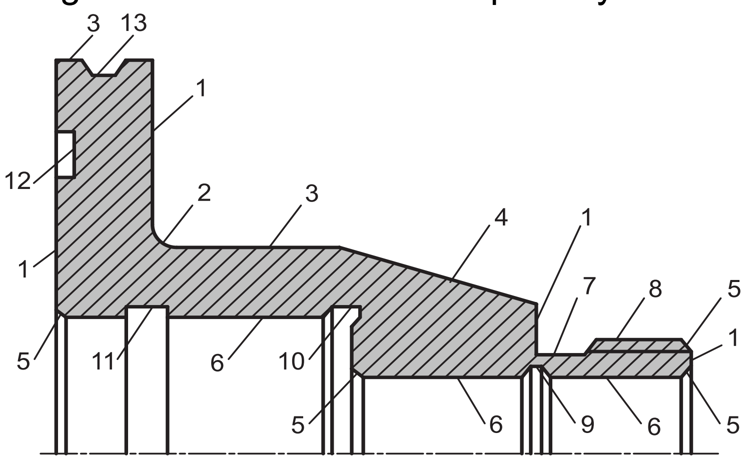


Figure 5.8 – Surfaces that form the part contour:
main: 1 – end surface, 2 – radius end surface, 3 – cylindrical outer surface, 4 – cone surface, 5 – chamfer, 6 – cylindrical opening; *auxiliary*: 7 – threading groove, 8 – threading surface, 9 – inner trapezoidal groove, 10 – angular groove, 11 – inner rectangular groove, 12 – end surface groove, 13 – chute

Main contour elements of the part are the generatrices of the surfaces that may be machined with the contouring cutter with the principal cutting edge angle $\varphi = 95°$ and end cutting edge angle $\varphi_1 = 30°$.

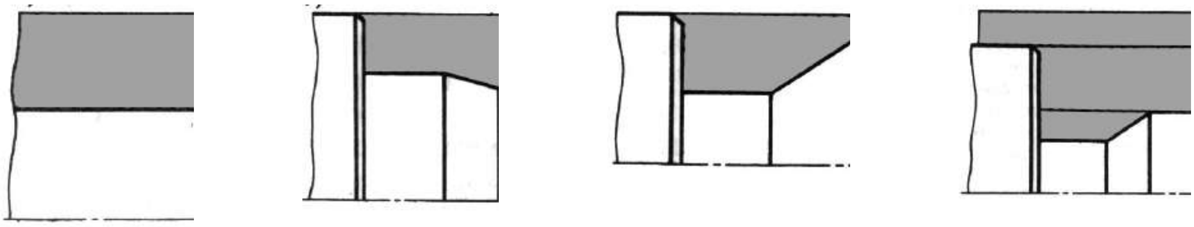
For machining of outer and end surfaces, one uses the straight-turning tool, and for inner surfaces – the boring one.

Auxiliary elements of the part contour are the generatrices of the surfaces, the shaping of which cannot be done with the cutter. Auxiliary elements of the contour include end surface and angular grooves for the polishing disc withdrawal, grooves on the outer, inner and end surfaces, threading surfaces, chutes for belts, etc.

5.3.1 Areas of turning

Every area of turning on the NC machines corresponds to one technological step and is formed depending upon the shape of rough or finishing contour of the part and technological possibilities of the cutting tool performing this step. For turning cutters, these technological possibilities depend upon principal and auxiliary cutting edge angles.

Areas of turning may be open, semi-open and combined (Fig. 5.9).



a b c d

Figure 5.9 – Areas of turning:
a – open; b – semi-open; c – closed; d – combined

Open area (see Fig. 5.9, a) is formed during allowance removal from cylindrical, and sometimes conic, surfaces. When choosing the cutter to machine this area, one doesn't apply restrictions on the principal and end cutting edge angles.

Semi-open area is the most widespread one (see Fig. 5.9, b), and its configuration applies restrictions on the value of the principal cutting edge angle.

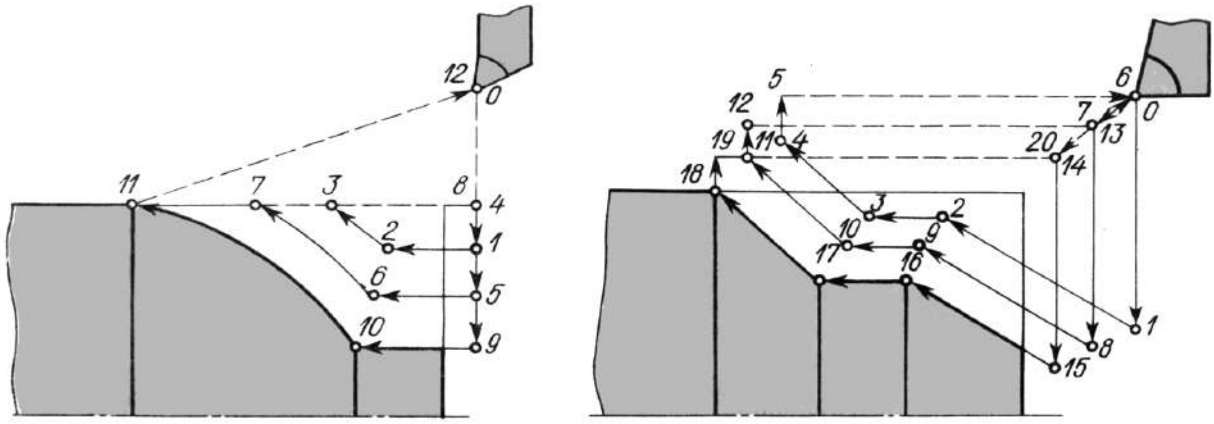
Closed area (see Fig. 5.9, c) is formed mainly during machining of auxiliary surfaces, and its shape applies restrictions on the values of both primary and end cutting edge angles of the cutter.

Combined area (see Fig. 5.9, d) is combined of two or three areas described above.

According to ГОСТ 25762-83, under *pass* one understands the one-side movement during reciprocal motion. Typical pass schemes during rough turning for allowance removal from the semi-open areas are shown in the Fig. 5.10.

Equidistant turning scheme (see Fig. 5.10, a) is used for machining of complex shaped parts. After each pass is performed, the tool is withdrawn from the area and approaches in the depth of the next step (auxiliary pass).

Contour scheme (see Fig. 5.10, b) is formed by repeating the tool machining passes along the contour of the machined part. Each machining pass along with the auxiliary one forms the trajectory of a closed cycle, the initial point of which shifts along a certain line, approaching the workpiece contour.



a b

Figure 5.10 – Typical turning schemes of semi-open areas:a – equidistant; b – contour

Most effective are the turning trajectories with the least number of machining passes of the tool. Contour turning passes' scheme is the most corresponding one for the standard cycle of NC machining.

5.3.2 Sequence of turning steps

After assigning the allowances on finishing machining of the part surface, general turning allowance is divided into several intermediate ones:

– rough machining of main surfaces, and the surfaces that require operating movements of the cutting tool in the direction of the headstock are machined first;

– rough (if necessary) and finishing machining of auxiliary elements, except for relief grooves for threading and polishing;

– finishing machining of main surfaces, particularly, facing and processing of outer surfaces;

– machining of auxiliary elements.

Steps during machining with the workpiece clamping in a chuck are carried out in the following sequence:

– centering (during drilling the holes with the diameter up to 20 mm);

– drilling;

– rough machining of main surfaces – facing (for forged workpieces – cutting off the allowance on all end surfaces), external turning, boring of inner surfaces;

– rough and finishing machining of auxiliary surfaces (in the cases when rough and finishing machining of main surfaces is carried out with one cutter, all auxiliary surfaces are formed after finishing machining);

– finishing turning of main inner and outer surfaces;

– machining of auxiliary inner and outer surfaces, particularly end surfaces, that do not require rough machining.

Operating reliability of the tool is reduced if the tool cutting edge is penetrated into the non-machined surface of the workpiece. This is why it is recommended to make one machining pass with the cutter on the end surface towards the workpiece axis of rotation, and one machining pass on the cylindrical surface in the direction parallel to the axis of rotation. Further direction of the cutter movement is chosen according to requirement of the minimum number of machining passes if the movement of the cutter is possible in the given directions and the cutting parameters are not changed.

During machining of narrow workpieces of large diameter (Fig. 5.11, a), the cutter should be moved perpendicularly to the workpiece axis of rotation, and during machining of wide workpieces (Fig. 5.11, b) – in the direction parallel to the axis of rotation.

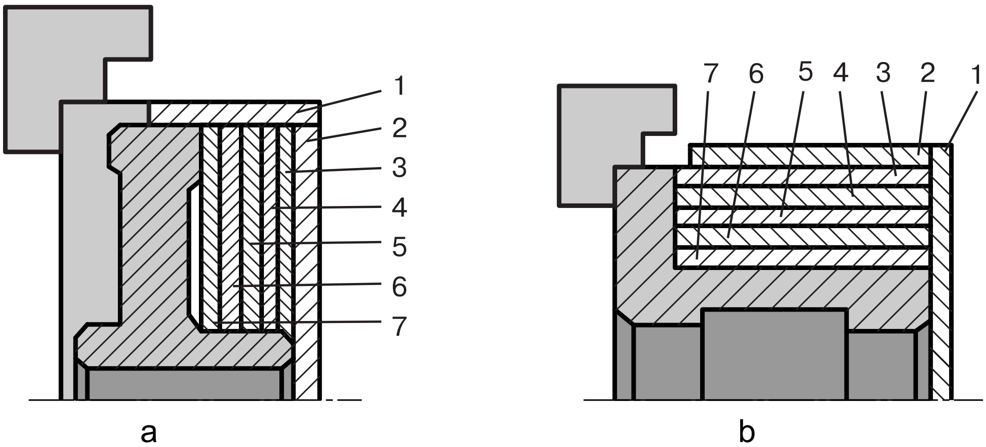


Figure 5.11 – Machining of the rolled workpieces in the draw-in gear:
a – narrow workpieces of large diameter; b – wide ones;
1 – 7 is the sequence of machining

Examples of the sequence of tool moving during machining of the stepped forgings in a chuck are shown in the Fig. 5.12.

Depending upon the value of allowances, one chooses the necessary number of machining steps for external machining and of internal end surfaces.

During rough boring of the workpieces, the allowance is removed with the cutter that moves in the direction parallel to the workpiece axis of rotation. Rough machining allowance of forged workpieces is cut during one machining pass.

During rough machining of stepped forgings, one at first removes the allowance on all end surfaces of the workpiece, and then machines the outer surfaces of the workpiece. If there is no opening in the workpiece, one begins machining of main inner surfaces with drilling.

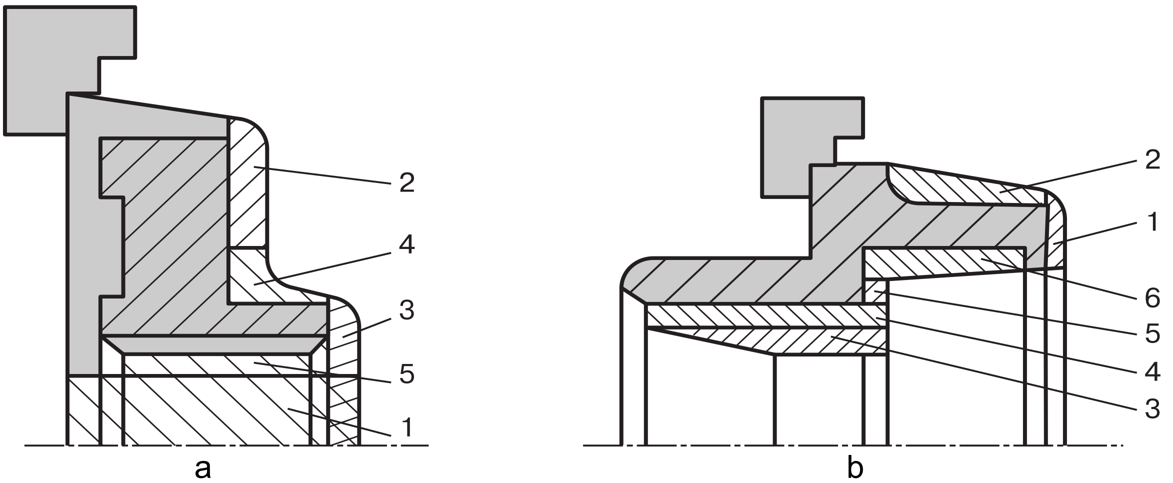


Figure 5.12 – Machining of forged workpieces: a – with flooding for the hole; b – with technological opening; 1 – 6 is the sequence of machining

5.4 Characteristics of the cutting parameters during turning

In the process of turning, there occurs rotatory motion of the workpiece and linear motion of the cutter feed. Each type of motion has a certain speed (see Fig. 1.7, a).

Cutting speed v during turning is the circular speed of the point on the largest diameter of the workpiece, m/min:

$$v = \frac{\pi D n}{1000}, \tag{5.1}$$

where D is the workpiece diameter, mm; n is rotation frequency, min^{-1}.

If the workpiece turning is longitudinal, the cutting speed is constant, if it is transversal (facing, cutting off), circular speed reduces towards the center of the part. During boring, the cutting speed is also chosen after the largest inner diameter.

Feed S is the value of the cutter cutting edge movement in the direction of feed movement D_S per unit of time or during one revolution of the workpiece. For cutting, there are the following types of feed: longitudinal, transversal and inclined – at a certain angle to the workpiece axis (it is used for external turning of conic surfaces). Numerically, the feed may be expressed in millimeters per minute (minute feed S_m) and millimeters per revolution (feed per revolution S_o).

Depth of cut t during external turning (see Fig. 5.7) is the size of the cut layer that is defined in the direction of the workpiece radius as the half-difference of the workpiece diameter D and machined surface diameter d. *Depth of cut* is chosen depending upon the type of turning (rough, semi-finishing, finishing).

When applying the cutting parameters to turning, the cutting speed is determined according to the following formula

$$v = \frac{C_v}{T^m t^x S^y} k_v , \qquad (5.2)$$

where C_v, x, y, k_v, m are the coefficients that consider the material properties and machining conditions in certain cases of turning at a certain tool life period T, min.

5.4.1. Sequence of choosing the cutting mode during machining

During machining, for initial data, one takes the physical and mechanical properties of the machined material, allowance and type of machining (rough or finishing).

Then, the cutting mode during turning is chosen in the following sequence:

- type of tooling and its grade are determined;
- geometrical parameters of the tool cutting part are chosen, taking into consideration the shape of the machined surface;
- depth of cut t is assigned;
- feed per revolution S_o is calculated using empirical formulas;
- life period T of the turning tooling is assigned;
- cutting speed v is calculated with the formula (5.2);
- nominal spindle speed n is calculated – $n = 1000v/\pi D$, and rotation frequency is corrected according the lathe certificate;
- according to the spindle speed, cutting speed is specified and the chosen mode is checked for cutting power;
- technological time of part machining is calculated.

Test questions

1. Name the main types of turning.
2. Describe the ways of outer surfaces' turning.
3. Name the methods of inner surfaces' turning.
4. Draw the main types of turning cutters.
5. Enlist the geometrical parameters of the turning cutter.
6. Name the main and auxiliary elements of the part contours during cutting.
7. Describe the open, closed and semi-opened areas during turning.
8. What are equidistant and contour schemes of turning passes?
9. Describe the sequence of technological steps of turning.
10. Name the cutting parameters during turning.
11. Describe the sequence of choosing the cutting mode during turning.

6 MACHINING OF THE HOLES BY DRILLING, CORE-DRILLING AND REAMING

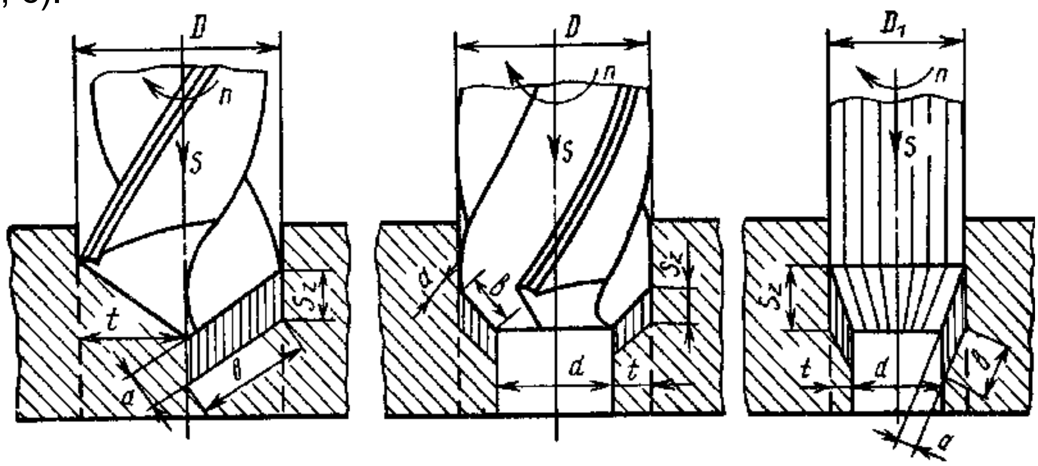
Drilling, core-drilling and reaming are widespread machining processes of blind and through holes with wide range of diameters. During these processes, two types of motions are carried out simultaneously: rotary motion of the tool or part (main movement) and linear motion along the axis (feed movement). Tools used for these processes, according to ГОСТ 25781–83, are called axial.

Drilling is one of the widespread ways of making holes in solid material with the help of drills. Drilling provides economic accuracy of machining within 11 – 13 class of accuracy and surface finish R_a = 5…10 mkm (Fig. 6.1, a).

Boring is the process of enlarging of the diameters or finishing of previously produced holes by means of single-point cutting tool.

Core-drilling is machining of cylindrical cast, forged or previously drilled holes with the core drill in order to impart them the right geometric shape, necessary size and surface finish. It provides 8 – 9 class of accuracy and surface finish R_a = 3,2…6,4 mkm (Fig. 6.1, b).

Reaming is a finishing of the holes in order to produce accurate sizes within 5 – 7 class of accuracy and surface finish R_a = 0,5…1,6 mkm (Fig. 6.1, c).



a b c

Figure 6.1 – Schemes of drilling (a), core-drilling (b) and reaming (c)

Cutting depth t, mm, at drilling equals $D/2$, and at boring of the workpiece of diameter d to the diameter D equals $t=(D-d)/2$, at core-drilling t = (0,05…0,1)D (D is the diameter of the core-drilled hole), at reaming t = 0,05…0,5 mm.

Feed rate S_0, mm/revolution, at holes' machining equals to the tool or part movement in the direction of the axis of rotation per one revolution.

Feed rate per flute (lip) of the axial tool $S_z = S_0 / z$, mm/flute, and minute feed $S_m = S_0 n = S_z z n$, wherein z is the number of tool flute (drills have two flute, core-drills – three-four flute, reamers – up to eight flute).

6.1 Main types of drills and their application

In aircraft part production, machining of the holes is carried out in a wide range of diameters D (from 0,1 to 100 mm) and cutting depths t (up to 100D).

There are about 30 types of drills of various design and function: twist (with helical flutes), straight flute drill, centering drills for machining of centering holes, gun and trepanning drills for deep hole drilling, special-purpose drill.

Twist (or spiral) drills are the most widespread. They are used for machining of the holes within 5…10 D depth.

6.1.1 Twist drills' design and geometry

Twist drills (Fig. 6.2) are used for drilling and boring of the holes with diameter up to 80 mm: with straight cylindrical shank D = 0,10…20 mm and taper shank D = 6...80 mm. Drill body consists of cutting and directional parts.

Small-size drills with diameters D = 0,1…1,0 mm (see Fig. 6.2, a) are produced of tool steels and P6M3 or P6M5K5 steel; with diameters D = 0,6…1,0 mm – of BK10M and BK15M strong alloys (see Fig. 6.2, b). For diameters D = 1,5…10,0 mm, one produces solid (see Fig. 6.2, c) and tipped solid drills – with strong-alloyed flute body with the length l_0 and steel shank part (see Fig. 6.2, d). Drills with diameter D = 6…80 mm are produced with taper shank (see Fig. 6.2, e). For drilling of difficultly machined materials, one uses twist drills with the diameters within 18…32 mm with cutting fluid (OCL – OIL-COOLING LIQUID) inner feeding (see Fig. 6.2, f).

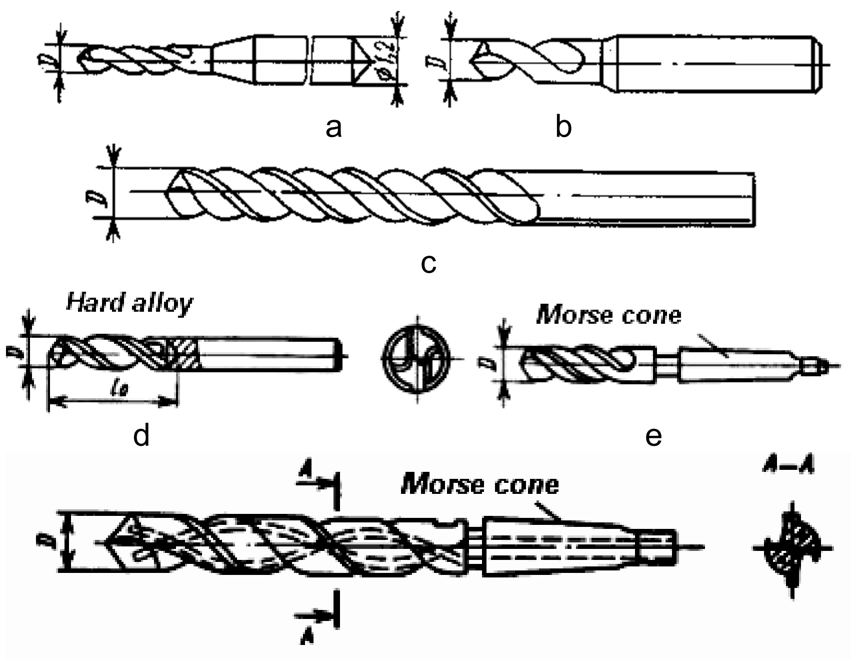


Figure 6.2 – Twist drills

Unlike cutters, front surfaces of drills are helical, main clearance surfaces (it is flank near lips) are usually conic, and auxiliary clearance surfaces are helical surface (margin) that provide direction of the drill during cutting.

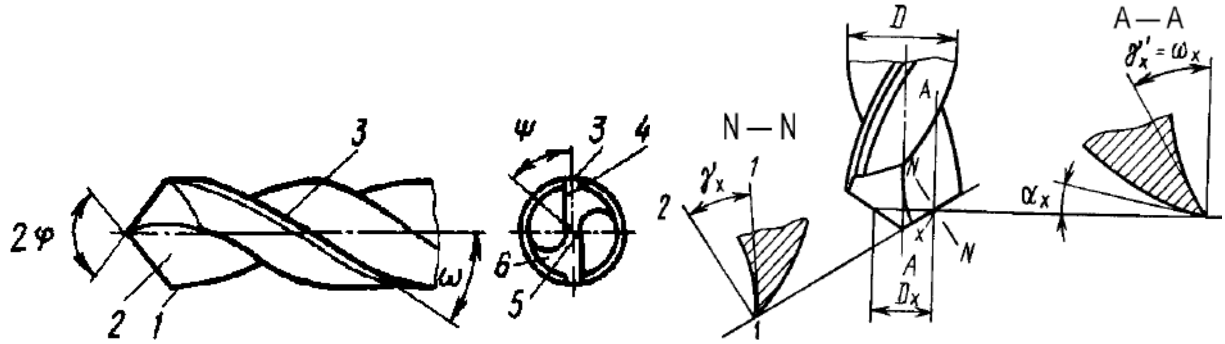
As the result of combining the rotary and linear motions of the drill (see Fig. 1.7, b), the trajectory of each point of the cutting edge is a helical line, and the cutting edge trajectory is a helical surface with the step that equals to the feed rate per revolution S_0.

Twist drill has two main cutting edges (cutting lips) 4 (Fig. 6.3, a) that are formed by crossing of front helical surfaces 2 of the flutes (faces), on which the chips are removed, with drill point surface 6 turned to the cutting surface. The transversal cutting edge (chisel edge) – web 5 – is situated in the intersection of both clearance surfaces. Two auxiliary cutting edges are formed by crossing of the faces with the margin surface 3. The drill margin provides direction of the drill along the machined hole during cutting and is a narrow strip on its cylindrical surface situated along the helical flute.

Drill sharpening geometry is characterized by the double cutting edge angle 2φ equals point angle, (peripheral) rake and clearance (lip relief) angles λ and α, and also by helix angles of the flute ω and by cutting (chisel) angle ψ. Standard drills have the angle 2φ with the value from 116 to 118°.

For drilling of highly strong materials, it is recommended that the point angle 2φ is increased up to 140°.

Rake angle λ is measured in the main sectional area N – N perpendicular to the projection of the main cutting lips on the main (diametrical) plane that pass through the tip of a drill point and axis (Fig. 6.3, b). The angle λ in this point is formed by the tangent 1 – 1 to the front cutting edge surface and the normal 1 – 2 in the same point to the surface formed by the rotations of the cutting edge around the drill axis.



a b

Figure 6.3 – Twist drill geometry

The angle λ depends on the helix angle ω of the flute. The points of the cutting edge lie on the helical lines of the drill front surface that have different angles ω, which is why the angle λ in different points of the cutting edge varies and changes similarly to the angle ω.

Lip relief angle α_x in the given point is the angle between the tangent to the clearance surface in this point of the cutting edge and the tangent in the same point to the circle formed by the cutting edge during its rotation along the drill axis. Lip relief angles are also changing: in the periphery α = 8…14°, near the transversal edge α = 20…25°.

In order to reduce the friction of the margins on the hole walls, one reduces the drill diameter in the direction of the shank, i.e. one forms the reverse taper. Reverse taper φ_1 is determined by the difference Δ of the drill diameters in the distance l_0 = 100 mm of the body length ($\varphi_1 = arctg\,\Delta/2l_0$). The value of reverse taper during machining of the holes in construction steels with the drills 1,0…20 mm in diameter range from 0,03 to 0,1 mm. At drilling of stainless and heat-resistant materials, it is recommended that reverse taper of the drills is increased up to 0,1…0,15 mm.

Angle ω is the angle between the drill axis and the tangent to the helical line of the margin. Along the cutting edges, the helical line slope angle changes – it becomes smaller towards the drill axis. The angle ω is chosen depending upon the drill diameter D and the properties of machined material: the smaller is D, the smaller is ω. For standard drills, ω = 18…30°. For drilling of ductile materials (aluminum alloys, low-carbon steels, copper), one uses the drills with ω = 35…45°.

For machining of the holes in high-strength material, the drills are sharpened in a special way, the aim of this is shortening of the transversal edge and creating more favourable angles near it (Fig. 6.4). Double sharpening, sharpening of the webs and margins is used for high-speed drills with diameter over 12 mm and strong-alloyed ones with diameter over 5 mm.

One uses different forms of drill cutting edge sharpening for machining of usual (see Fig. 6.4, a) and difficultly machined materials (see fig. 6.4, b – e).

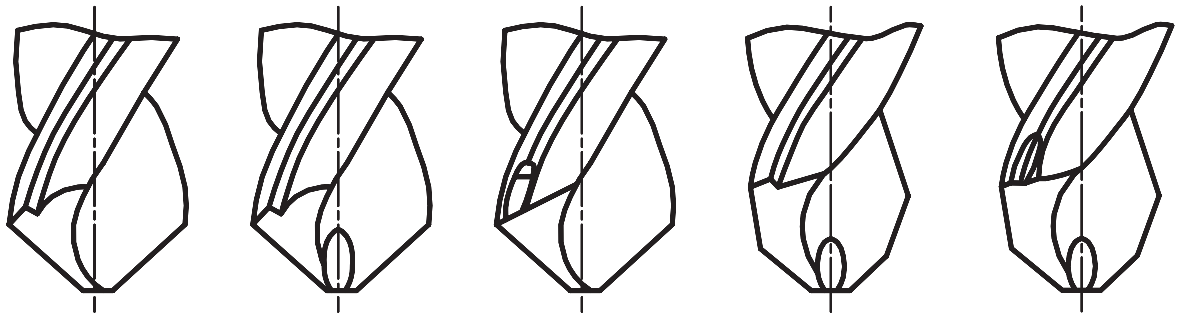


Figure 6.4 – Types of drill cutting elements sharpening:
a – single normal sharpening (N); b – single normal with web sharpening (NC); c – single normal with web and margin sharpening (NCR); d – double with web sharpening (DC); e – double with web and margin sharpening (DCR)

For drilling of the workpieces of high-strength materials ($\sigma_в \geq$ 1200 MPa), solid drills of ВК6М, ВК10М, ВК60М strong alloys should be used. Drill hardness may be increased if one reduces the length of the body, increases the shank diameter up to 0,4D, makes four directional margins and chooses the rational shape of flutes.

For machining of the holes in high-strength materials, it is reasonable to use twist drills of increased rigidity – with the drill shank diameter increased up to (0,3…0,35) D and sharpened webs.

Twist drills are used mainly with right-hand direction of the helical flute for right-hand cutting.

As OCL, by drilling of small-diameter holes ($D < 3$ mm), one uses oil-based fluids, and by drilling of large-diameter holes, aqueous emulsions are used.

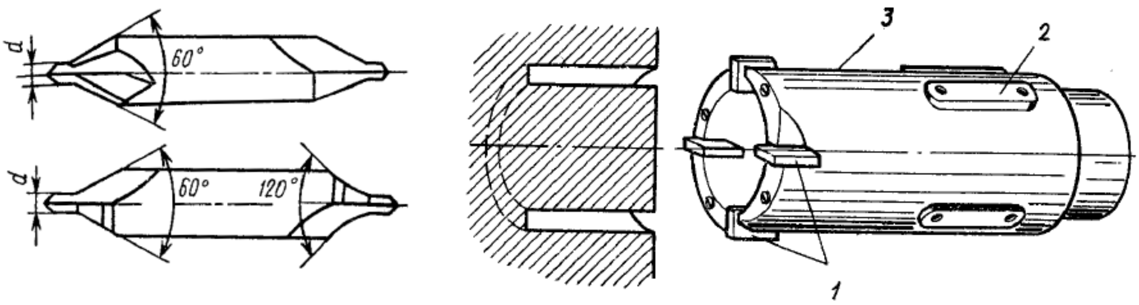
6.1.2 Design and geometry of special drills

Spade or flat, drills are simple by their design, but because of bad chipping removing conditions and difficult cutting conditions, they are used mainly for machining of the holes with the depth $l \le D$.

Centering combined drills are used for machining of central holes of 1…10 mm diameter. They may be of two types: with point angle 60° and with point angles 60° and 120° (Fig. 6.5, a).

Trepanning drills are used for machining of large-diameter through holes. *Trepanning* drill (Fig. 6.5, b) is the tube-like body 3 with cutting edges 1 fixed on the end surface and cams 2 placed for drill direction.

Deep-cutting drills. Deep holes ($l > 10D$) are usually machined according to 6 – 8 class of accuracy with severe requirements to the hole axis straightness, and hole and outer surface coaxiality.



a b

Figure 6.5 – Drills: a – centering; b – trepanning

Machining requires usage of special drills and machines. The machined part rotates, and the drill performs only linear motion.

For deep cutting, one uses simple double-cutting twist drills and special single-cutting drills. The design of the drill should provide forced supply of cutting fluid - OCL (oil-cooling liquid) to the cutting lips, free removal of chips, sufficient rigidity, and good basing on the hole walls.

Usual double-cutting drills are lengthened twist drills with two flutes (see Fig. 6.2, f), into which the central tail part channel of the drill is divided. OCL is supplied under high pressure to the central channel, and then it is extracted with the chipping by the helical flutes of the drill.

For deep cutting, the following special drills are generally used:

– double-cutting (two-edge) – auger and ejector drills;

– single-cutting (one-edge) – gun and cannon drills.

Auger (high-helix) drills (Fig. 6.6) are used for machining of the holes with 3…30 mm diameter and over 10 D length without periodical removing of the tool out of the hole. They have large helix angles (ω = 60°) that facilitates chip removal from cutting area. The flutes in the axial cross-section A – A have the triangle shape.

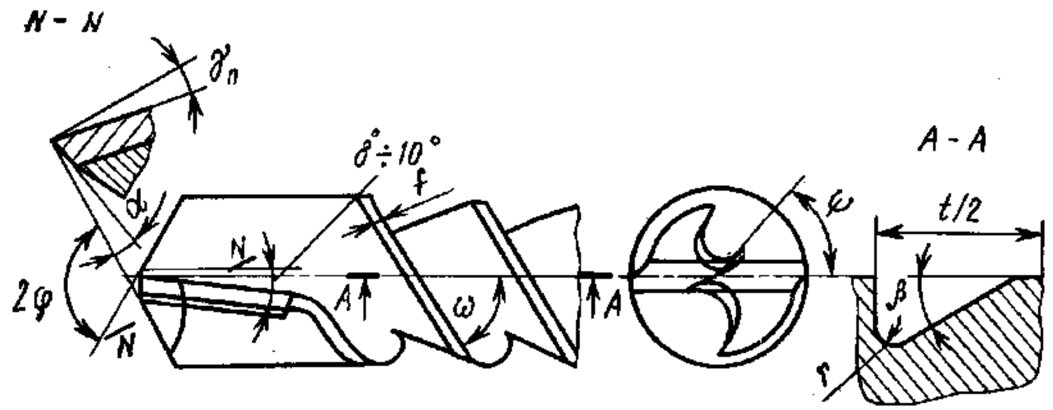


Figure 6.6 – Auger drill

In order to increase rigidity, auger drills are produced with (0,3…0,35) D shank and up to 0,1 D sharpened chisel edge.

Ejector drills (ejector or two tube system) (Fig. 6.7) are used for deep drilling of holes with the diameter D = 20…65 mm. Head 2 is screwed on the outer tube 3 that is the frame-carrier element. Cutting part 1 includes hardmetal plates situated in a staggered order, that is why the chipping is cut in the form of separate strips, broken up with the chip-breaking elements and is easily removed.

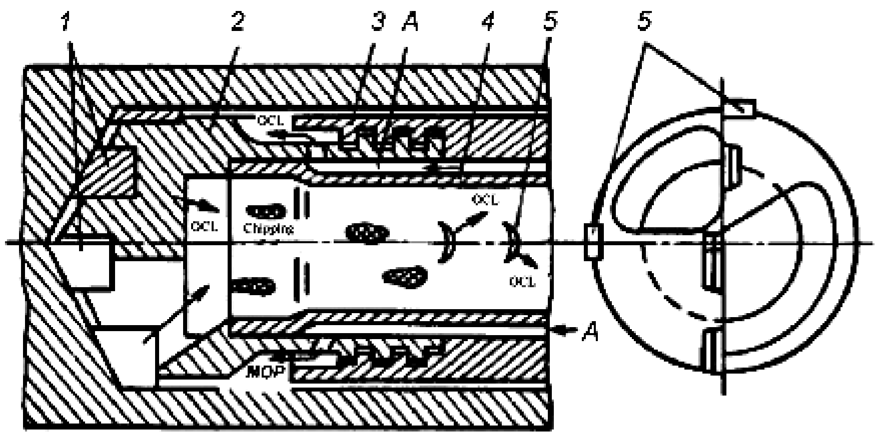


Figure 6.7 – Ejector drill

The peculiarity of ejector drills is the effect of sucking OCL extracted with the chipping as the result of vacuum inside the drill. Vacuum occurs because of the main flow *A* of the liquid is divided under the pressure of 2…3 MPa into two flows: main part of the fluid flows to the cutting area, and about 30% of the liquid gets through the slits *B* back into the inner channel of the tube 4. The vacuum that occurs between the flow of liquid with chip and the flow through the slits *B* improves the conditions of chip removal. In order to increase machining accuracy, hardmetal directional elements 5 are used.

Ejector drills operate on the cutting speeds v = 25…200 m/min and at feed rate S_0 = 0,15…0,7 mm/revolution. They provide 9 – 11 class of accuracy and surface finish R_a = 1,25…0,63 mkm.

Gun drills (Fig. 6.8) with the diameter D = 8…30 mm consist of the drill tip 1 and drill tube – stem 2.

In order to create favourable cutting conditions, main cutting edge is shifted on 0,2D from the drill axis.

The drill has inner channel of round or sickle-shaped cross-section for supplying the OCL under the pressure of 2 to 4 MPa. OCL is washed with the chips through the straight outer flute.

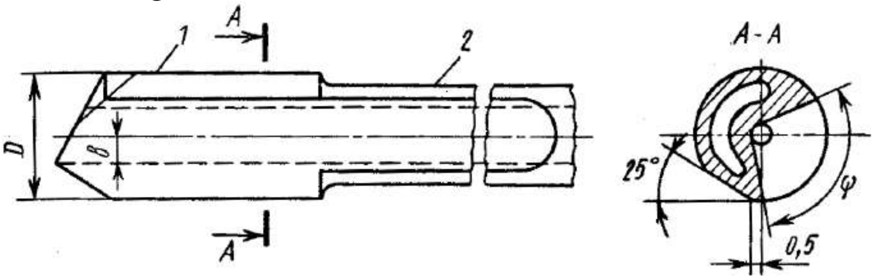


Figure 6.8 – Gun drill

Drills for vibratory drilling. Machining of the holes in the refractory and titanium alloys causes difficulties because of lack of tool rigidity, large values of cutting forces, bad chipping extraction and OCL supply to cutting areas conditions.

For deep drilling of the holes with the diameter 2…10 mm in reftactory and titanium alloys, vibratory drilling is rather effective. The tools used are hard-alloyed drills with straight flutes and inner OCL supply under pressure of about 10 MPa (Fig. 6.9).

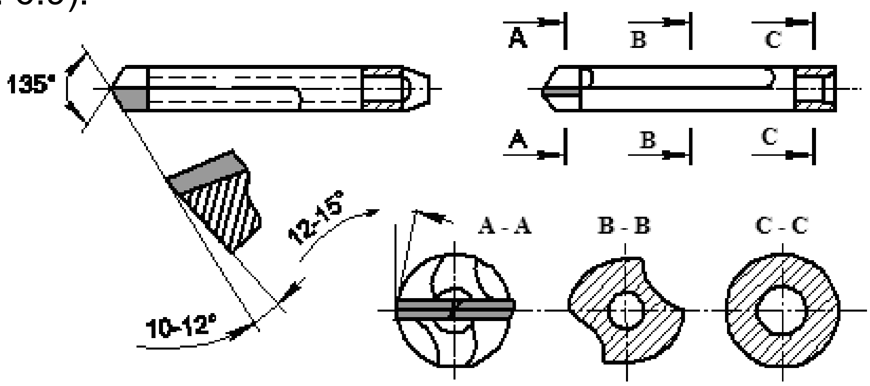


Figure 6.9 – Drill for vibratory drilling

Machining is carried out on the vibratory drilling machines; the tool, along with rotary and feed movements, performs vibratory movement along the axis with the amplitude 0,01 to 0,04 mm and frequency 100…200 Hz. At the same time, there is reliable chips breaking and the action of OCL is more effective.

6.1.3 Drill wear

Drill wear occurs as the result of friction between drill flank and surface of cutting, chips and front surface (face), margins and machined surface.

The drills may wear in the following way (Fig. 6.10):

- simultaneously on flank *A* and face *D* during machining of steels;
- on the angles *C* during drilling of brittle materials;
- on the margin *B* during drilling of ductile materials;
- on the chisel edge *E* in case of wrong drill sharpening.

During drilling of refractory alloys, the wear of the surface and margin of a tool occur. In this case, typical features of the wear are rounding of the blades on the angles and appearing of annular scratches on the margins because of the pickup of machined material on them.

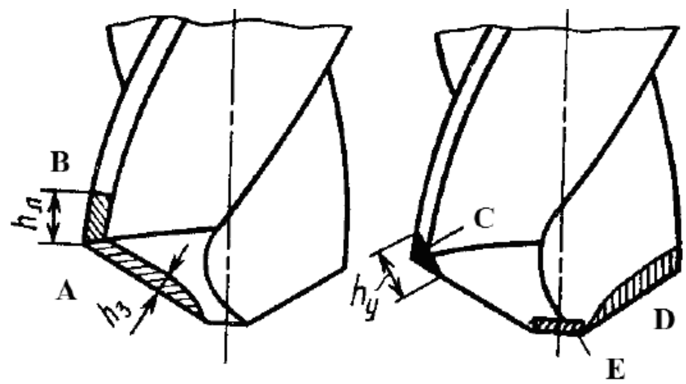


Figure 6.10 – Typical areas of the drill wear

The most dangerous type of wear is the one on the angles and margin, because in order to resharp the drill, one needs to grind off a significant part of it. Significant web wear leads to intensive grow of the axial force (thrust) P_0, and margin wear causes significant increase of twisting moment (torque) $M_{angular}$. At wear on the angles, both $M_{angular}$ and P_0 increase.

The size of the wear bevel on the flank h_c is more influenced by the cutting speed, and less influenced by the feed, so it is more reasonable to use drilling with greater feed rate and less cutting speed.

Permissible wear values depend upon the properties of machined materials, material of the drill and its diameter: at machining of constructional steels with high-speed drills, h_c = 1…1,5 mm; by machining of reftactory and titanium alloys, h_c = 0,4…0,8 mm. Large values of wear are typical for the large-diameter drills.

When the tool work-put reaches the predetermined value, one sharpens it in order to renew its cutting characteristics. Drills, core-drills and cutting part of the reamers are sharpened on their flank (main clearance surfaces) on the special sharpening machines.

6.1.4 Choosing the cutting parameters by drilling

The process of cutting during drilling is carried out under more critical conditions than at turning. It is conditioned by the following reasons: different deformation of the cut layer along the cutting edges because of rake angles γ and cutting speeds v changing; significant deformation of the material near the chisel cutting edge.

Based on the checking of the longitudinal durability of the drill as the clamped rod, the maximum permissible length of the drill body is equal to ten diameters; in case when the body is longer, the drill durability rapidly decreases.

Axial force P_0 defines the capacity of the feed. Under the conditions of large values of the force P_0 and the drill overhang, there may occur the longitudinal bend of the tool and its losing of durability.

The main part of the force P_0 (up to 60%) falls on the web. Sharpening of the web (see Fig. 5.4) allows significant reduction of the axial force P_0.

By the maximum value of the twisting moment (torque) $M_{angular}$, one makes strength and rigidity calculation of the spindle and elements of the drilling machine main move mechanism.

The values P_0 and $M_{angular}$ depend upon the strength of the materials machined, machining conditions, tool diameter D, cutting parameters (v, S, t), tool geometry (ω, φ, α), machining depth and tool wear.

To determine $M_{angular}$ and P_0, one uses empirical formulas calculation:

$$M_{angular} = c_M D^{x_M} S_0^{y_M} k_M ; P_0 = c_p D^{x_p} S_0^{y_p} k_p . \qquad (6.1)$$

The values of constants c_M, c_p, k_M, k_p and exponents are taken from the reference literature [23].

During machining with the axial tool, the feed rate is calculated with the formula $S_0 = c_x D^q$, where c_x is the coefficient that depends upon the properties of the machined material, q is the exponent.

The highest feed rates (*I*st group) are applied for drilling the holes in rigid workpieces, average feed rates (*II*nd group) – for drilling the holes in the nonrigid workpieces or for further threading with taps, and small feed rates (*III*d group) – for drilling of accurate holes with further machining with the core-drill and reamer.

Permissible cutting speed is calculated with the following formula

$$v = \frac{C_v D^{x_v}}{T^m S_0^{y_v}} k_v , \qquad (6.2)$$

where $k_v = k_m k_0 k_u k_l$; k_m, k_0, k_u, k_l are the coefficients that consider the properties of machined material, chemical composition of OCL, drill wear and drilling depth correspondingly.

The sequence of calculating of the cutting parameters during drilling:

- according to the depth and diameter of the machined hole choosing the drill series, shape and geometrical parameters of drill cutting part sharpening, type of tool material depending upon physical and mechanical properties of the machined material;
- determining the maximum permissible feed rates by the number of restricting factors, the following in particular: by the strength of the machine feed mechanism, drill strength, drill resistance to pressing;
- calculation of the cutting speed v and rotation frequency n with the formula (6.2) in correspondence with the taken tool resistance period T (T = 10…40 min);
- correction of the chosen values of S_0 and n according to the machine ratings;
- calculation of the torque $M_{angular}$ and axial force P_0 with the formulas (6.1), checking the cutting parameters according to the rated capacity of the machine;
- calculation of machine time of drilling, min: $T_{machining} = L/nS_0$, where $L = l + l_1 + l_2$; l is the hole depth; l_1 is the length of area to cut; l_2 is the overtravel length (usually, $l_1 + l_2 \approx 0,3D$, in case of blind hole machining l_2 = 0).

In case of holes' machining in high-strength materials in the NC machines, periodical withdrawal of the drill from the hole is foreseen, and the values of cutting speeds and minute feed rates are reduced by 12…15% in order to provide safe chipping removal and prevent the drill breaking.

6.2 Core-drilling

Core-drilling is the intermediate operation before reaming and finishing operation by machining of conic and cylindrical cavities with flat bottom, and also of both end surfaces.

As compared to drilling, core-drilling provides higher machining accuracy of the holes. This is explained by the larger number of cutting edges (three or four) operating simultaneously, smaller point angles (φ = 45…60°), lesser machining allowances (see Fig. 6.1, b), and higher tool rigidity. Unlike the drill, the core-drill has many cutting edges and increased diameter of the body, which increases the tool strength and provides its better direction in the hole.

6.2.1 Core-drill design and geometry

Core-drills may be classified in the following way:

- by their purpose: *cylindrical* (see Fig. 6.1, b) – for semi-finishing machining of cylindrical holes; *counterbores* (Fig. 6.11, a) – for machining of cylindrical holes with flat bottom; *countersink reamers* (Fig. 6.11, b) – for machining of conic area of the holes; *spot-facing drill* (Fig. 6.11, c, d) – for machining of flat surfaces adjoining the hole; *stepped* – for machining of cylindrical holes of several diameters; *combined* – combined drill and countersink tools, countersink core-drills, etc.;

– by the method of mounting: *shank-type* with the diameter 12…35 mm and *shell* with the diameter 25…80 mm;

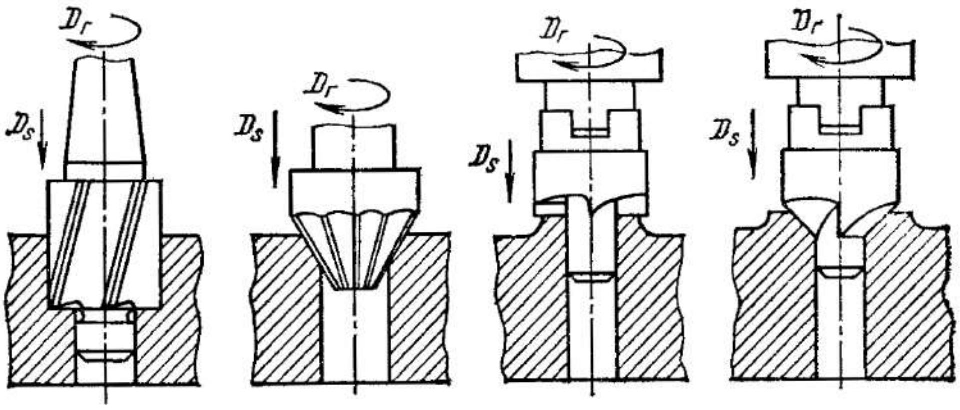
– by the design: *solid, shell, assembled* (with inserted cutting edges and multisurface plates).

The body of the core-drill is manufactured of high-speed steels and hard alloys.

For machining of the parts manufactured of ordinary constructional steels and titanium alloys, one uses carbide-tip core-drills. High-speed steel is used only for producing the small-size core-drills.

Similarly, one chooses the material for the drill cutting part by machining the parts of titanium alloys. The core-drills with the diameter over 10 mm are manufactured of grade of hard alloys ВК8, and the core-drills of smaller diameters – of high-speed steels.

Core-drilling of through holes of big length is carried out according to the drawing scheme, i.e. the core-drill is drawn through the hole. This significantly reduces deviation of the machined hole axis, lowers vibrations, enables removing large allowances. The designs of the core-drills allow to machine end faces, conic and shaped surfaces.



a b c d

Figure 6.11 – Types of core-drills

Cylindrical core-drills with the diameter 10…40 mm are most widely used in production. Solid cylindrical core-drill (Fig. 6.12) consists of the cutting part (drill point) 1, directional element 2, neck 3 and Morse taper shank 4.

Geometric parameters of the core-drill cutting part are chosen depending upon the type of machined material and purpose of machining; they are first of all determined by the sharpening angles of main cutting edges.

Core-drills manufactured of high-speed steels have the main cutting angle φ = 45…60°, and hard-alloyed ones – φ = 60…75°.

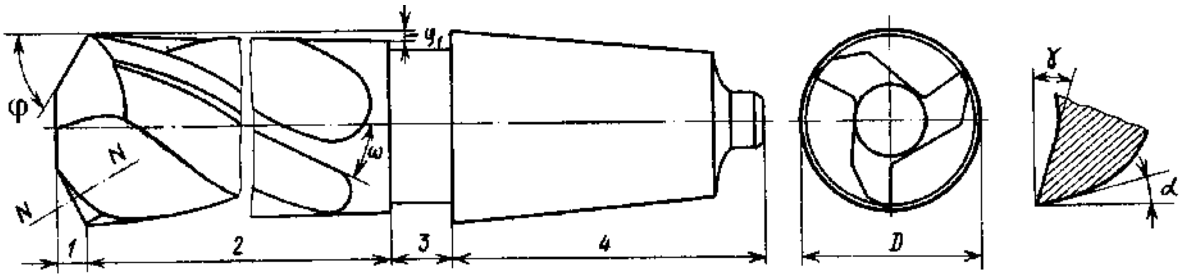


Figure 6.12 – Solid cylindrical core-drill

High-speed steel core drills with the rake angle γ = 0…8° are used for machining of high-strength materials, with γ = 25…30° – for machining of nonferrous alloys.

Relief (clearance) angle α = 8…10°, and the helix angle ω = 10…25°.

Counterbore (Fig. 6.13) is the type of the core-drill used for machining of cylindrical surfaces with flat bottom.

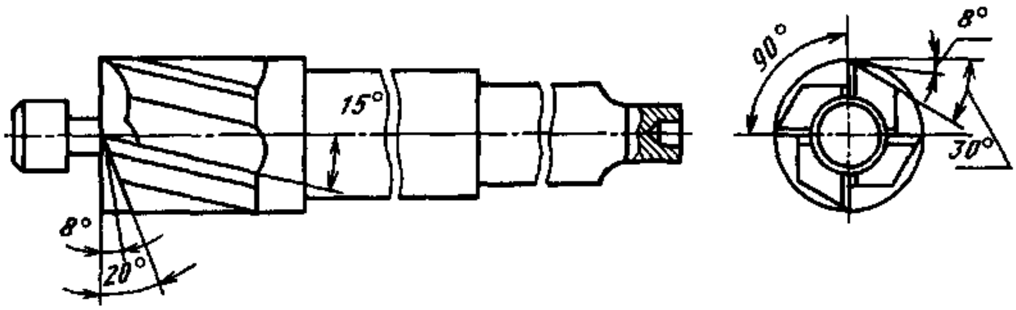


Figure 6.13 – Counterbore

Shell core-drills, both solid and assembled (Fig. 6.14), have four cutting edges. They are used for semi-finishing machining of the large-diameter holes (D = 32…100 mm).

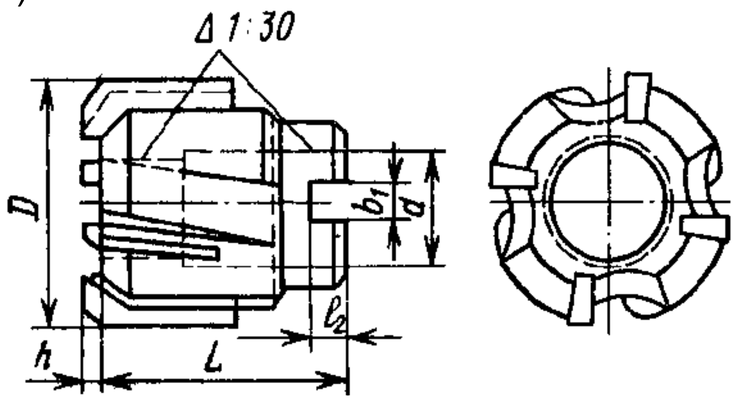


Figure 6.14 – Assembled shell core-drill

The core-drill, like the drill, is impacted by the torque $M_{angular}$ and axial force P_0 that are determined with the formulas

$$M_{axial} = c_м D^{x_M} S_0^{y_M} t^{z_M} k_м ; P_0 = c_p D^{x_p} S_0^{y_p} t^{z_p} k_p . \qquad (6.3)$$

Constants $c_{м}, c_{p}, k_{м} k_{p}$ and exponents are taken from the reference literature [23].

Permissible cutting speed by core-drilling is calculated with the formula

$$v = \frac{C_v D^{x_v}}{T^m t^{z_v} S_0^{y_v}} k_v \qquad (6.4)$$

Values of the constants C_v, k_v and exponents x_v, z_v, y_v, m can be found in the reference literature depending upon the tool durability period T (for core-drills, the durability period is 15…80 min).

The sequence of calculating the cutting parameters during core-drilling:

– choosing the core-drill material and geometrical parameters considering the particular machining conditions;

– determining the feed rate group, calculation or choosing by the standards of the feed per revolution S_0 value, mm/ revolution;

– calculating of the cutting speed v and rotation frequency n with the formula (6.4) according to the chosen durability period T;

– adjustment of the chosen values of load S_0 and rotation frequency n according to the machine ratings;

– calculation of the axial force P_0 and torque $M_{angular}$ with the formulas (6.3), checking the cutting parameters according to the rated capacity of the machine;

– calculation of machine (main) time of core-drilling, min: $T_{machine} = L/nS_0$, wherein $L = l + l_1 + l_2$; l is the hole depth, l_1 is the length of penetration area; l_2 is the overrun length (in case of machining of the blind holes, l_2 = 0).

6.3 Reaming

Reaming differs from core-drilling by comparatively small cutting depth t and special design of the tool – it includes the cylindrical sizing part, large number of cutting edges z (not less than six), and high accuracy of manufacturing. This is why reaming provides high machining accuracy.

By the shape of machined holes, there are cylindrical, conic and stepped reamers; by the way of using, there may be machine and hand reamers.

The body 5 of the hand cylindrical reamers (Fig. 6.15) consists of guiding cone 1, cutting 2 and sizing 3 parts and area of reverse taper 4.

The taper lead angle 2φ of hand reamers (φ = 0,5…1,5°) is significantly smaller than the one of machine reamers (φ = 15…30°).

On the clearance surface of sizing cutting edges, there is cylindrical margin of width f = 0,03…0,25 mm; this allows to keep the sizing part diameter unchanged during cutting.

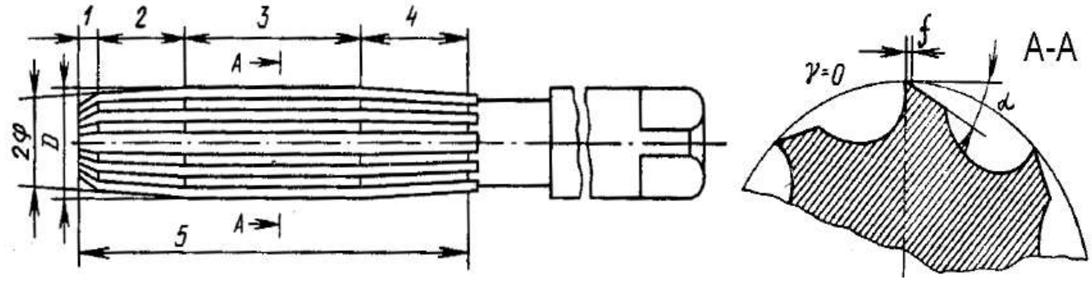
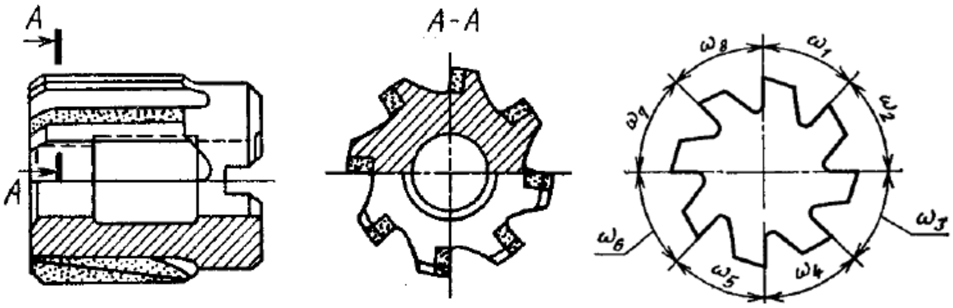


Figure 6.15 – Cylindrical hand reamer

Reverse taper makes up around 0,01 mm for hand reamers and around 0,07 mm for machine ones.

Like core-drills, according the *method of holding*, the reamers may be shank-type and shell. The latter may be solid and assembled – with inserted cutting edges (Fig. 6.16, a).

In order to increase the quality of reaming of difficult machined materials, one uses the reamers with uneven step and spiral placement of cutting edges.



a b

Figure 6.16 – Assembled shell reamer

Due to the uneven step of cutting edges placement (Fig. 6.16, b), vibration is decreased and machined surface finish is improved. The cutting edges angular step ω is chosen in such a way that each pair of the cutting edges would lie on one diameter. E.g., if the number of the reamer cutting edges z = 8, then by the average value of the angular step ω = 45°, one takes the following: ω_1 = 42°, ω_2 = 44°, ω_3 = 46°, ω_4 = 48°, ω_5 = 42°, ω_6 = 44°, ω_7 = 46°, ω_8 = 48°.

The layers cut with a reamer are very thin, that is why the tool wear occurs mainly on the clearance surface (flank).

At reaming, one uses the *technological criterion* of the wear – such wear value h_3, when reamer doesn't provide the necessary class of accuracy and the necessary quality of the surface layer. For different cutting conditions, magnitude of h_3 corresponds to the chamfer on the flank from 0,3 to 0,8 mm.

Average durability period T of the reamers that corresponds to the technological wear lies within 20…90 min, and large-diameter reamers have greater durability period than small-diameter ones.

Reaming is carried out in two steps, with allowance for rough reaming equaling 0,15…0,5 mm, and finishing one – 0,05…0,2 mm, depending upon the hole diameter and workpiece material. Before reaming, the hole is core-drilled.

Best centering and reducing of the hole breaking is reached by drawing reaming, by which the reaming rod is pulled.

For reaming, two groups of feed rates are predetermined: the first one is for rough reaming for further finishing one, and the second one is for finishing machining after the rough or single-step reaming.

The sequence of calculating of the cutting parameters for reaming, empirical formulas for determining the feed rate, cutting speed, axial force and twisting moment are the same as for drilling or core-drilling. The distinction is only in different values of constants and exponents.

6.4 Combined tooling

Combined tooling is used for combination several operations or technological steps. Such tools are used either for machining with similar tools that differ only by size (stepped drills or core-drills), or for machining with the tools of different types (drill and core-drill, core-drill and reamer, drill and tap, etc.).

Depending upon the machining conditions and design of the combined tools, machining is carried out according to the parallel or sequential scheme.

By machining according to the *parallel scheme* (Fig. 6.17, c), all cutting edges of the combined tool simultaneously take part in cutting, and by machining according to the *sequential scheme*, the tool cutting blades take part in cutting sequentially in groups (Fig. 6.17, a, b, d).

E.g., during machining with drill and tap (see Fig. 6.17, d), at first, the drill blades operate, and the tap follows them. Tools operating according to the parallel scheme (see Fig. 6.17, c) provide less deflection of the mutual position of the machined surfaces and higher machining efficiency.

Depending upon certain conditions (type of the tool, peculiarities of sharpening, position of the cutting blades in space), combined tools are manufactured to be solid or assembled (see Fig. 6.17, b).

Both solid and assembled tooling is manufactured on the basis of standard tools or equipped with replaceable perishable plates which makes such tooling significantly cheaper and expands the area of their usage.

Main attention by combined tooling operating is paid to their correct sharpening, assembling, effective chip removal and rational cooling. During sharpening and assembling of the tools, one should control the cutting edges' overlapping on one another in the places of joint, or else the chips may enter there or the surface may not be machined properly.

Chipping-separation flutes on the cutting blades help to remove the chips effectively (Fig. 6.17, b). In all cases, when arranging the chip removal, it is necessary to avoid the appearing of opposite and colliding flows of chipping.

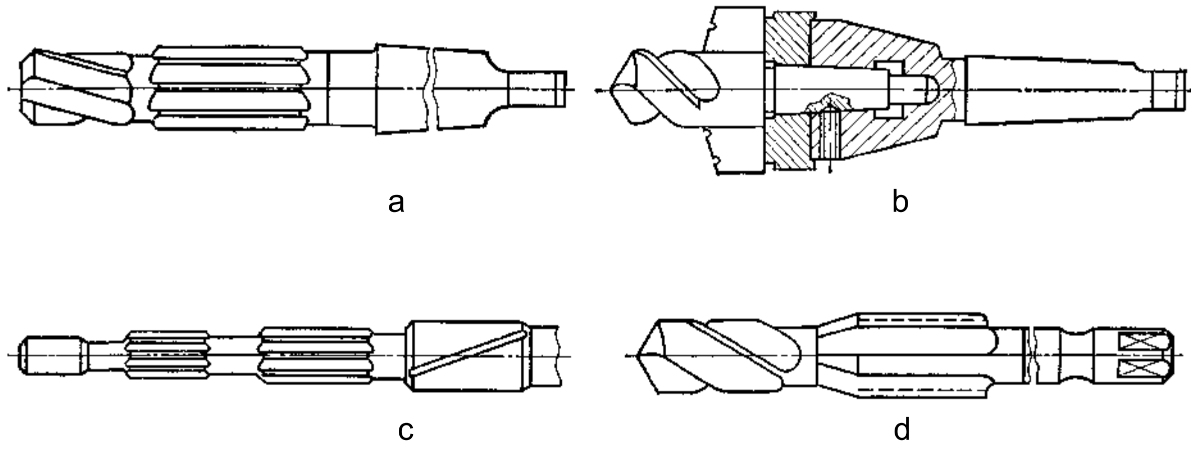


Figure 6.17 – Combined tooling: a – core-drill and reamer; b – drill and drill; c – reamer and reamer; d – drill and tap

Constructional difficulty and high cost of combined tooling is justified only in the case of their using in large-scale and mass production.

Test questions

1. As the processes of hole machining, what economic accuracy parameters have the drilling, core-drilling and reaming?
2. Give the main geometrical parameters of a twist drill.
3. What types of the drill cutting part sharpening are used for drilling of high-strength materials?
4. Name the main types of special drills and their geometrical parameters.
5. What characteristic areas of the drill wear? What does the permissible wear depend on?
6. What is the sequence of calculating the cutting parameters by drilling?
7. What types of core-drills are used for machining of the holes?
8. What geometrical parameters does the cutting part of the core-drill have?
9. What is the sequence of calculating the cutting parameters at core-drilling?
10. Name the parts of the body of a cylindrical reamer.
11. How can one increase the reaming quality of heavily-machined materials?
12. What is the essence of the technological criterion of the reamer wear?
13. Give the examples of combined tooling for parallel and sequential schemes of holes' machining.

7 MACHINING OF THE WORKPIECES BY MILLING

7.1 Purposes and main types of milling

In aircraft manufacturing milling is a widespread machining process of production of flat and shaped surfaces with the multiple-tooth cutter – milling cutter or mill.

Considering the practice, it is reasonable to perform 55 – 60% of milling works on the NC machines. In order to improve the service and increase the effectiveness, these machines are usually grouped into specialized workshops.

Kinematics of milling is characterized by two movements (see Fig. 2.3, c): fast rotation of the tool about its axis – cutting; linear movement of the workpiece fixed on the machine table – feed. During rotation of the milling cutter, the teeth sequentially engage workpiece and remove the allowance of the machined material.

In the process of milling, there are the following ranges of operation conditions:

- *hogging (skinning}* – machining with large and nonuniform allowance over 8 mm, and also machining of the defect surface layer of hot-forged workpieces (scalping);
- *rough* – machining with relatively uniform allowance, without skin, with the depth of cut from 3 to 8 mm;
- *semi-finish* – machining with uniform allowance and depth of cut from 1,5 to 3 mm, and height of microroughnesses of the machined surface not more than Rz = 40 mkm;
- *finish* – machining with uniform allowance and depth of cut up to 1,5 mm, and average maximum height of the profile of the machined surface not more than Rz = 20 mkm.

From the point of view of programming peculiarities, it is acceptable to classify milling operations according the number of axes of the NC machine that are simultaneously used for the certain operation.

During the so-called *2,5-coordinate (2,5D)*, or flat, machining, not more than two axes are used simultaneously. The third one serves as the installation axis for tool advance and withdrawal. 2,5-D milling is used for machining of cylindrical and flat surfaces (outlines), the guides and generatrices of which are parallel to the tool axis. In this case, machining is carried out with the side surface of cylindrical or conic milling cutters. Another purpose of 2,5-coordinate milling is machining of the surfaces that are perpendicular to the tool axis.

3-coordinate (3-D) milling with simultaneous use of three tool axes is used for solid machining of the surfaces with the tool axis remaining unchanged in space. Other types of multiaxis milling are considered to be specialized.

7.2 Types of milling cutters and their geometry

Edge tool, according to ГОСТ 25751–83, is the cutting tool with the certain number of cutting edges of a certain shape. Cutting teeth of the edge tool are used for removing a specified layer of allowance from the workpiece. Among all types of edge tooling, milling cutters have the greatest variety.

By the shape of cutting teeth, milling cutters may be of two types:

milled (unrelieved) – milling cutters with the teeth, the clearance surface generatrix of which is the straight line (Fig. 7.1, a);

form-relieved – milling cutters with the teeth, the clearance surface generatrix of which is the Archimedean spiral; the clearance surface blade shape provides constancy of the cutting edge profile during the re-sharpening of the cutting edge (Fig. 7.1, b).

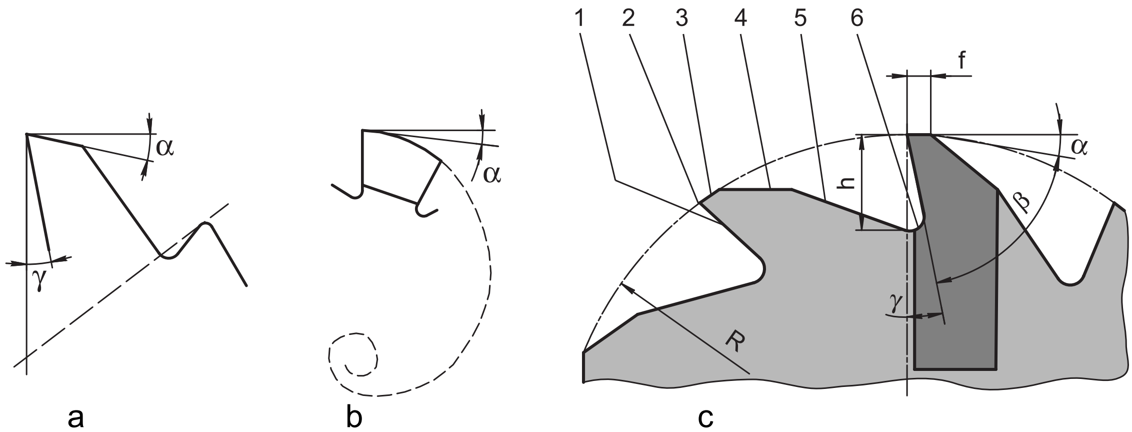


Figure 7.1 – Elements of milling cutter tooth: a, b – shapes of teeth;
c – comparison of the elements of the turning cutter and tooth of the milling cutter

Milling cutters of the first type are more easily manufactured, they provide higher durablity and smaller height of microroughnesses. But when the tooth face of such milling cutters is sharpened, the profile of the tooth cutting edge changes, which is why such tools are used for milling of the planes.

In form-relieved milling cutters, when the tooth face is sharpened, the profile of the tooth cutting edge remains unchanged. Such tools are used for milling of the shaped curved surfaces.

Similarly to the turning cutters, the surfaces and cutting edges of the milling cutter teeth (Fig. 7.1, c) have the following names: 1 – tooth face A_γ; 2 – main cutting edge; 3 – land of the tooth A_α; 4 –clearance surface A'_α; 5 – heel; 6 - fillet.

Shape of the machined surface and type of equipment determine the type of the milling cutter used. In order to reduce main cutting time and wastage of tooling material, one chooses the smallest milling cutter diameter if it is possible, rigidity of setup, the type of workpiece engage, and shape and dimensions of the machined workpiece.

There are the following types of milling cutters:

– *by the placement of cutting teeth* on the frame – slab (cylindrical) cutter (Fig. 7.2, a), peripheral (circular) cutters – one-sided (for slotting and slitting), straddle mills (Fig. 7.2, b), end (Fig. 7.2, c), face cutter (Fig. 7.2, d, e), form mills with convex and concave profiles (Fig. 7.2, f);

– *by the direction of the teeth relative to the axis* – straight tooth (plain) cutter (Fig. 7.2, b, e); with helical cutter (Fig. 7.2, a, c, d);

– *by the way of installation on the machine* – arbor-mounted types (Fig. 7.2, a, b, f), cylindrical- or tapered-shank (Fig. 7.2, c, d, e) – with conic or cylindrical shank end fixed directly in the machine spindle with the help of collet;

– *by the type of tool material* – high-speed steel, carbide, diamond, el'bor borazon material;

– *by design* – solid (usually manufactured of high-speed steel), brased-tip cutter (carbide), round and multy-edge indexable-insert cutter (see Fig. 7.2, d, e).

Arbor-mounted milling cutters (see Fig. 7.2, a, b, f) are installed on the mandrel, and for machining of several surfaces, there may be a set of milling cutters on one mandrel.

For all types of milling (see Fig. 7.2), depth of cut t is the distance between the surface to machine and already machined surface, width of cut B is the size of the surface machined during one machining pass.

When machining with cylindrical, face, width of cut, end, form and other milling cutters, the parameter measured by the direction parallel to the milling cutter axis is the depth of cut (axial engagement) B, and the parameter measured by the direction perpendicular to the milling cutter axis is the width of cut (radial engagement) t.

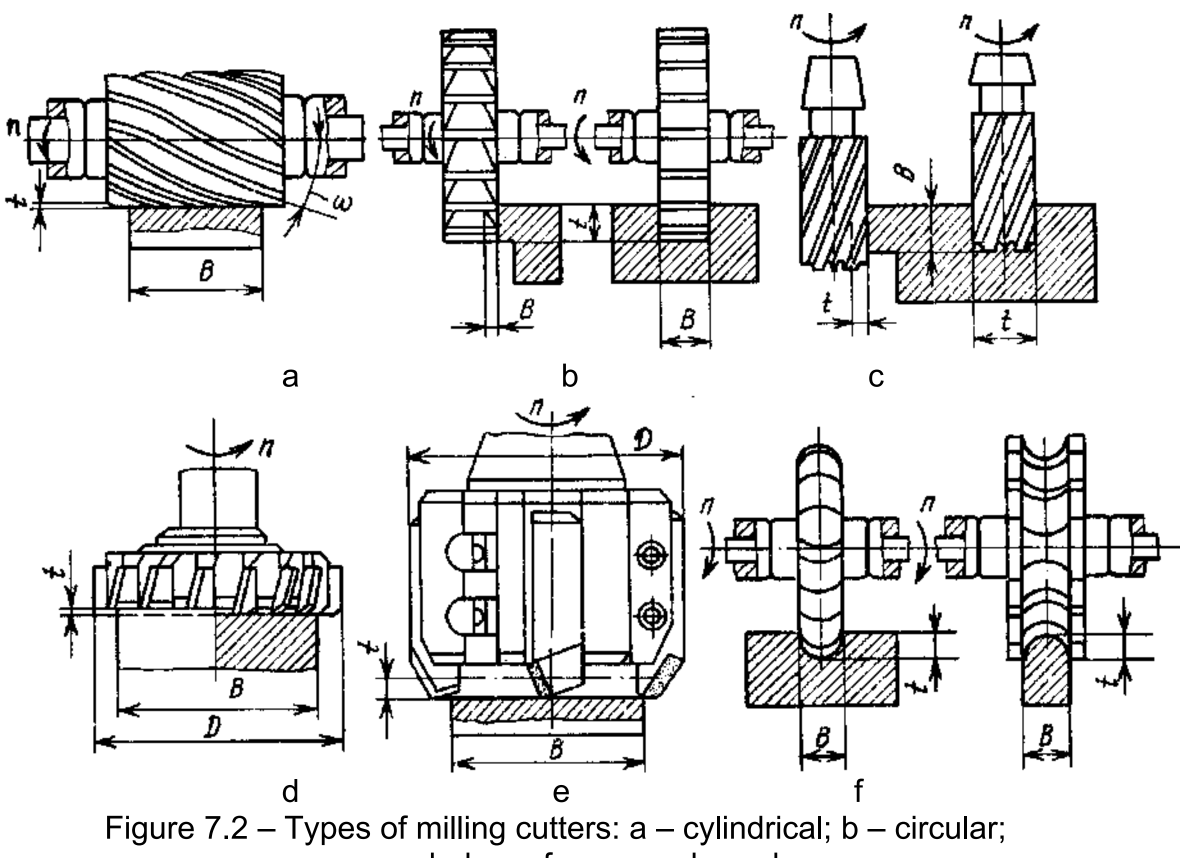


Figure 7.2 – Types of milling cutters: a – cylindrical; b – circular; c – end; d, e – face; e – shaped

Milling cutters are machined with serration (type ***I***) and large (type ***II***) teeth. In case of using the serration milling cutters, the volume of flute will be smaller, and permissible tooth load will be reduced. That is why for rough machining one uses milling cutters of type ***II***, and for finishing and semi-finishing – milling cutters of type ***I***.

According to ГОСТ 25751–83, by the direction of rotation, milling cutters may be of right-hand and left-hand cutting. *Right-hand* milling cutters are the ones that rotate clockwise during machining if one looks at them from the side of fixation part. *Left-hand* milling cutter rotates counterclockwise during machining if one looks at it from the side of fixation part. Choice of the type and size of the milling cutter depends upon the certain machining conditions (size of the machined workpiece, grade of the machined material, value of machining allowance, etc.).

7.2.1 Types and areas of milling

All numerous milling operations may be divided into two main types of machining:

– *face milling* performed with the teeth situated on the milling cutter end face (Fig. 7.3, a);

– *peripheral milling*, when cutting is carried out with the teeth situated on the cylinder generatrix (Fig. 7.3, b).

Other types of milling are the combinations of these two types.

Face milling cutters. These tools are used for machining of flat surfaces on horizontal and horizontal-milling machines and provide higher productivity than cylindrical ones. The milling cutter D should be about 20% larger than milling width B (see Fig. 7.2, d, e). Each tooth of the face milling cutter (Fig. 7.3, a) may be viewed as an offset turning cutter that has main cutting edge with the main cutting edge angle φ = 30...90° and auxiliary cutting edge with the angle φ_1. Joining of main and auxiliary cutting edges looks as the transition cutting edge with the angle $\varphi_0 = 0,5\varphi$.

Solid face milling cutters are manufactured with the diameter D = 40…100 mm, and assembled – with the diameter D = 80…630 mm with the teeth of fast-cutting steels or hard alloys.

In production, widely used are face milling cutters with multisurface hard-alloyed plates, and also with the teeth of ultra-hard materials (UHM).

Milling cutter teeth are produced of fast-cutting steels of Р6М3, Р6М5К5, Р9К10, Р14К5Ф5 grades, and also of hard alloys of ВК8, ВК10, Т14К8 grades.

In order to increase durability against wear-out, the working surfaces of the milling cutter teeth have the multi-layer wear-resistant coating applied on them. One has mastered series production of face milling cutters with the diameter 125…800 mm with clamped-on round and multi-surface plates of superstrong materials based upon boron nitride that have reduced end surface teeth outrun – within 0,002…0,012 mm.

Cylindrical (slab) milling cutters. Such cutters are used for machining of the surfaces on horisontal-milling machines. They are manufactured with the diameter 40…250 mm and up to 160 mm long; they may be solid or assembled.

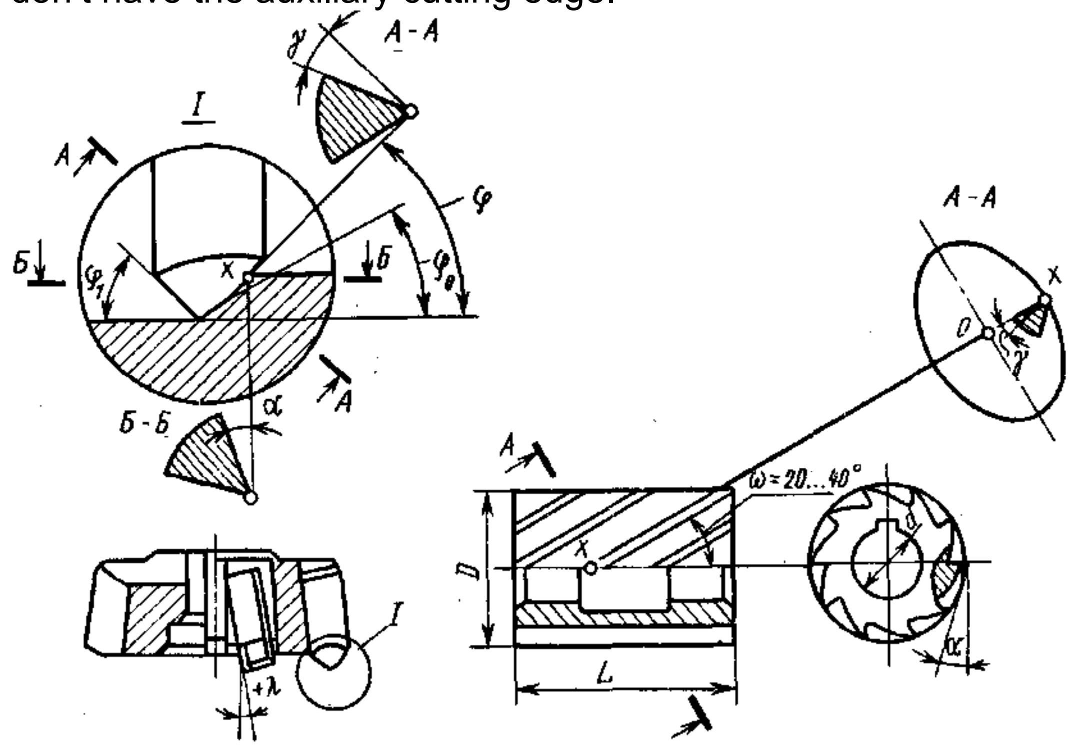
Geometric parameters of the cutting blade of a cylindrical milling cutter (Fig. 7.3, b) are the following:

– *radial rake angle* γ – the angle in the main sectional area A – A between the tangent to the tooth face in the given point x of the blade and cutter radius in the same point;

– *slope angle of the screw line* ω = 20…45°;

– *clearance angle* α – the angle in the end surface between the tangent to the clearance surface and the tangent to the circle formed with the rotation of the point x about the milling cutter axis (α = 15…25°).

Main cutting edge of cylindrical milling cutters may be straight-line (along the cylinder generatrix), inclined to the cylinder generatrix, or screw-like. Milling cutters don't have the auxiliary cutting edge.

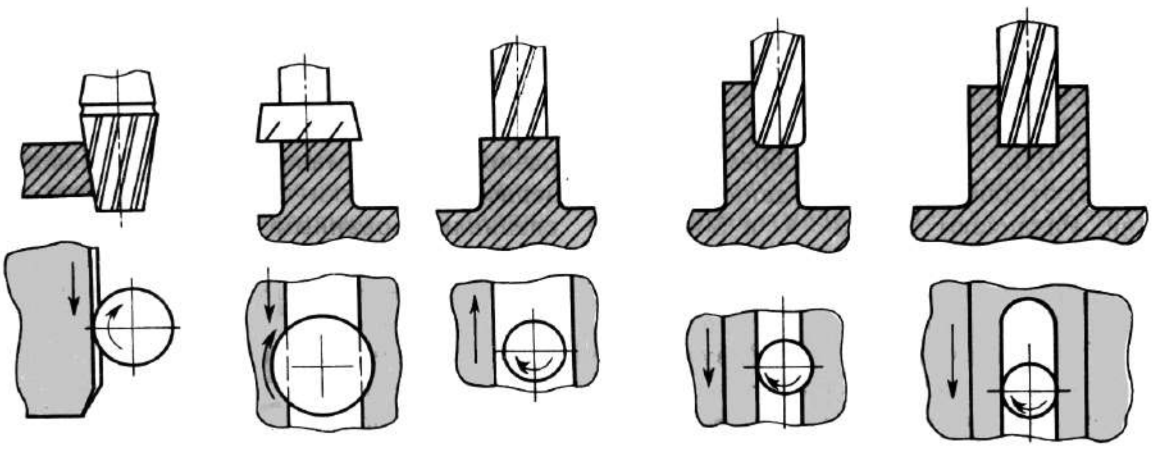


a b

Figure 7.3 – Geometry of the face (a) and cylindrical (b) milling cutters

During milling, there are certain *machining areas* (Fig. 7.4) – open, semi-open, closed and combined.

To the *open* areas (see Fig.7.4, a – c) belong the machining areas that do not apply any limitations on moving of the milling tooling along its axis or in the plane perpendicular to it. In *closed* areas (see Fig. 7.4, e), movement of the milling tooling is limited in all directions. Combined areas are formed with the described ones as the result of combining several machined surfaces of different types.



a b c d e

Figure 7.4 – Machining areas during milling:
a – c – open; d – semi-open; e – closed

In case of slab machining, inner joints with constant radius are formed at the expense of the corresponding configuration of the milling tool. In order to provide manufacturability during the part production, such joints should be done with the same, typical for a certain contour or workpiece, radius.

7.2.2 The milling cutter path planning

To program milling, typical strategies of milling cutter *path planning* are used.

There are two main strategy of milling cutter path planning: zig-zag and spiral [4].

In case of *zig-zag strategy*, during machining, the tool performs movements in opposite directions along parallel rows.

Zig-zag strategy has several variations depending upon the order of bypassing of machining boundaries:

- without bypassing of machining boundaries (Fig. 7.5, a);
- with the pass along the boundaries at the end of area machining (Fig. 7.5, b);
- with preliminary pass along the boundaries (Fig. 7.5, c).

Preliminary cut-through of boundaries (see Fig. 7.5, c) provides cutting symmetry for the tool during this machining pass, and also makes the tool working conditions easier during further machining at the beginning and in the end of every row.

Main disadvantage of the zig-zag strategy is the changeable character of milling: along one row, machining is performed in the direction of feed, along the next one – in the opposite direction, which has a negative influence upon accuracy and quality of machining.

In case of *spiral strategy*, machining is carried out in circular moves of the tool along the external boundary of the area on different distances from it.

Spiral strategy provides the best machining at the expense of unchangeable milling direction.

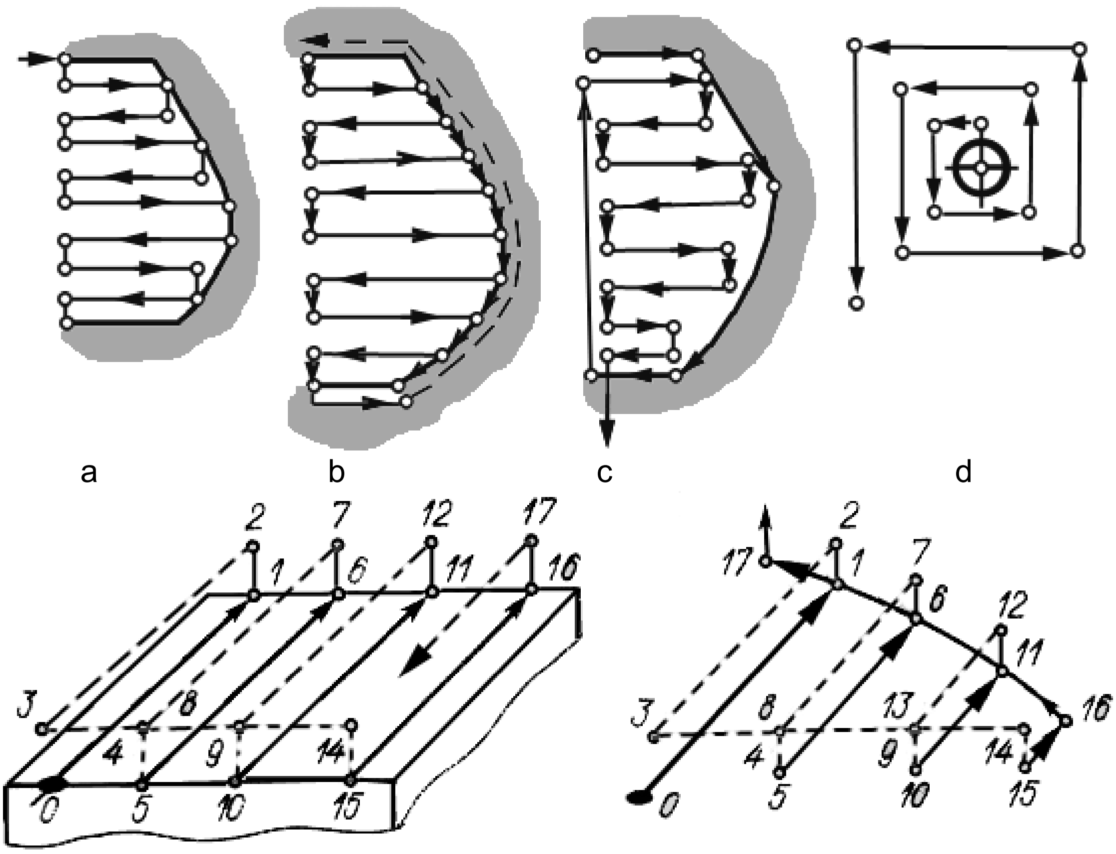


Figure 7.5 – Typical strategy of tool path:
a, b, c – zig-zag; d – spiral; e, f – E-strategy

Spiral strategy has two main types, one of which is characterized by moving the tool from the center of the area to the periphery (Fig. 7.5, d), and the other, on the contrary, from the boundary of the area to its center. When using these strategies, consider that during machining of the wells with thin bottom in the parts manufactured of aluminum alloys, there may occur tearing of the bottom at the end of machining according to the strategy “from periphery to center”.

The character of milling may be kept constant with the help of the strategies of E-like type. After the tool has performed the machining pass along the row, it is withdrawn on a small distance from the machined surface and sent back in a speeded feed. The E-like type strategy may have the same variations as the zigzag-type one: without bypassing of boundaries (Fig. 7.5, e); with the pass along the boundaries at the end of area machining (Fig. 7.5, f). A considerable disadvantage of this strategy is the large number of auxiliary passes.

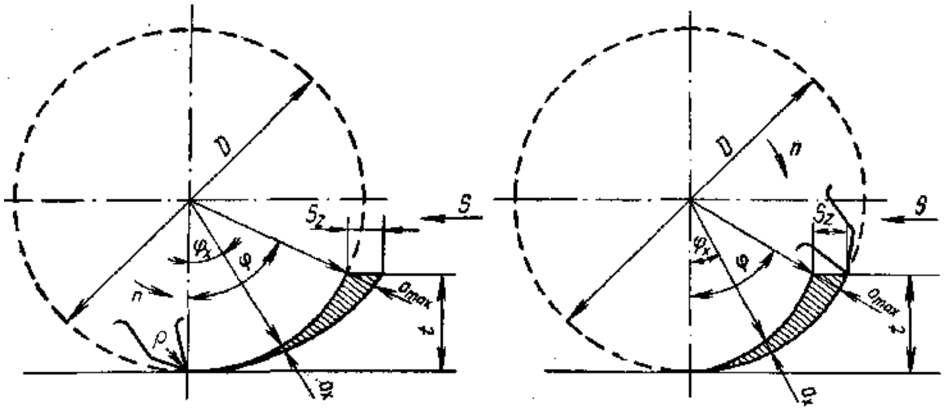
7.2.3 Cutting strategies during milling

At milling with cylindrical, circular, shape milling cutters, one uses two cutting strategies for allowance removal: climb (down) and conventional (up) milling (Fig. 7.6).

Milling, at which the milling cutter and the workpiece move towards each other, is called *climb*.

Conventional milling is the process when the moving directions of the milling cutter and the workpiece coincide.

The alteration of cutoff thickness a depends on strategy: in case of climb strategy, a increases from zero to a_{max}, and at conventional strategy, on the contrary, it decreases from a_{max} to zero.



a b

Figure 7.6 – Cutting strategies during climb (a) and conventional (b) cylindrical milling

Maximum thickness of the cutoff for both cutting strategies $a_{max} = S_z \sin\varphi$, where the angle φ is the contact angle of the milling cutter tooth. Maximum cutoff thickness depends not only on the feed per tooth S_z, but also on the relation t/D: $a_{max} = 2S_z\sqrt{t/D - (t/D)^2}$.

Under *climb* cutting strategy, the load on tooth increases gradually. It is reasonable to use this strategy for rough operations, as the allowance is removed from under the crust. The disadvantage of this strategy is the fact that at the beginning of the work due to the blade rounding with the radius ρ of the milling cutter tooth blade, each tooth doesn't cut, but slides on the machined surface, so hardening occurs. Hardening will be especially intensive at cutting of ductile stainless and other difficult-to-cut materials. This is why during finishing and semi-finishing milling of such materials, climb milling will be more effective, as the teeth sliding at the outlet is much lesser, and the milling cutters' durability increases twice or thrice.

At face milling independently of the rotation direction of the milling cutter, both cutting strategies – climb and conventional – are present.

In the part of the workpiece ***a***, where the main movement vector (of milling cutter rotation) D_r coincides with the direction of the workpiece feed movement D_s, conventional milling is performed. Correspondingly, in the part of the workpiece ***b***, where the main movement and feed movement vectors are directed towards each other, milling is performed according to the climb cutting strategy.

One should avoid the "undermine" of the workpiece; for this, in case the face milling cutter displacement, the part of the workpiece ***b*** should be wider than the part ***a*** (Fig. 7.7, b).

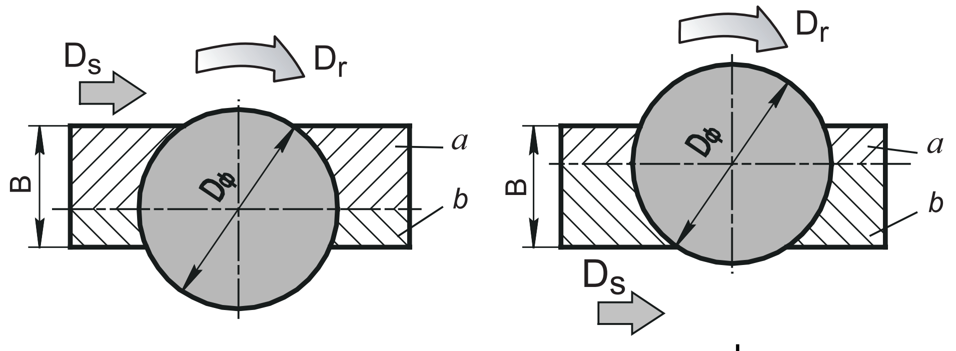


Figure 7.7 – Cutting strategies by climb (a) and conventional (b) face milling

Depending on the method of positioning the milling cutter relatively to the workpiece, *face milling* may be symmetric (Fig. 7.8, a) and non-symmetric (Fig. 7.8, b).

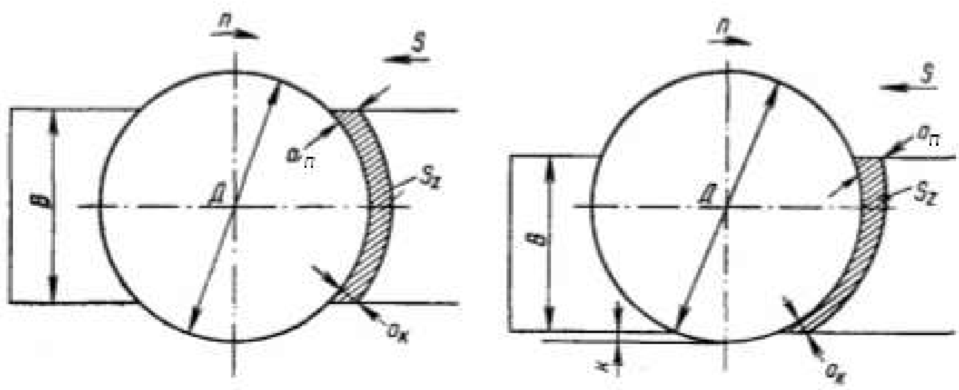


Figure 7.8 – Strategies of symmetric (a) and non-symmetric (b) face milling

During symmetric face milling, the initial a_n and final a_K values of the cutoff thickness are the same, and they depend on the relation B/D (optimal range is the following: B/D = 0,7…0,8).

Non-symmetric milling allows to reduce significantly the cut thickness a_K and, correspondingly, reduce normal and shear stresses on the teeth during the end of cut.

At small values of K, adhesion wear-out of milling cutters is significantly reduced and their durability is increased. For example, during machining of difficult-to-cut materials, if $K \leq$ 5…8 mm and $K/D \leq$ 0,05, the tool durability increases six times.

7.2.4 Wear-out and durability of milling cutters

The peculiarity of milling cutters' design and complex relative movement of the teeth determine a number of peculiarities of the milling. Unlike turning at milling, one observes cyclic change of heat and mechanical loads on the teeth, changing of the thickness and width of the cut. Besides, milling is characterized by interrupted character of teeth operation. When contacting the workpiece, each tooth is the subject to periodical dynamic and thermal impact, after which there goes the period of unfeed and cooling.

Duration of cutting equals several hundredth or thousandth of a second, so in a second, the process is performed several times, and it may cause mechanical and thermal fatigue of the tool.

Periodic penetration of the milling cutter teeth in the machined material lead to impact loads and may cause forced vibrations.

As the result of periodic dynamic and heat digging, there occurs the milling cutter teeth' wear-out. The character of the milling cutters' wearing differs from the character of the cutters' wearing, as the thickness of the cut layer during milling isn't significant. Because of this, the wearing occurs mainly on the clearance surface $h_з$ and is limited.

Wear-out criterion for all types of milling cutters is the size of wear-out chamfer which ranges from 0,3 to 1,2 mm depending upon the cutting conditions and properties of the materials.

If there is no oxides' crust on the workpiece surface, conventional milling is accompanied by less intensive wear-out than the climb one, which is why the milling cutters' durability will be two – four times higher.

Besides gradual wear-out, the milling cutter teeth may get broken down because of their brittle and plastic breaking.

Brittle breaking occurs under the influence of the maximum tensile stresses and it is the result of initiation and development of cracks. The most frequently the brittle breakings of hard-alloyed milling cutters and milling cutters with teeth of superstrong materials occur. Here, there may be breaking in the form of crumbling and shearing.

Crumbling shows itself in detachment of small particles near the cutting edge and is usually refered to surface defects of the tool material, heterogeneity of microstructure and residual stresses. Crumbling fairly depends upon the sharpening angle β, and it may occur even at little values of feed per tooth S_z. Cutting ability of the milling cutter with crumbled teeth is renewed after its sharpening.

Shearing is separation of large amounts of tooth that exceed the volume of the wedge near contact of the tooth face with the chip that occurs during cutting with too high values of S_z and insufficient angles β, and also because of low durability and ductility of the teeth material. When shearing occurs, the cutting ability of milling cutters is not renewed.

Plastic breaking is characterized with the flow of thin layers of tool material along the clearance surface and sinking of the tooth point, and occurs at too high cutting speeds and very high temperature.

Permissible wear-out $h_з$ depends upon the properties of the workpiece and milling cutter materials, machining accuracy requirements and quality of the layer surface, and equals h_3 = 0,3…1,2 mm. For milling of refractory and titanium alloys, h_3 = 0,5 mm.

Wear-resistance of the milling cutters varies greatly and depends upon the properties of machined material, cutting speed, type and diameter of the milling cutter, type of machining (rough, finishing). E.g., the durability period of face milling cutters of strong-alloyed materials T = 90…240 min.

At milling of the workpieces of refractory and titanium alloys, the durability period of milling cutters T may be increased three – five times by using intermediate strengthening heat treatment of the workpieces.

7.3 Cutting parameter during milling

Cutting parameter during milling is determined by the following parameters:

- cutting move speed v, m/min;
- feed movement speed: feed per tooth S_z, mm/tooth; chip feed S_o, mm/rotation; feed rate S_m, mm/min;
- depth of cut t, mm;
- milling width B, mm.

Feed per tooth S_z is the value of move of the machined workpiece or milling cutter at the time of rotation per one tooth.

Chip feed S_0 is the feed that corresponds to one rotation of the tool or workpiece, i.e. the value of movement of the machined workpiece or milling cutter at the time of rotation per single rotation.

Feed rate S_m is the magnitude of displacement of the machined workpiece or milling cutter per one minute.

Dependence of diferent types of feeds looks as follows:

$$S_z = S_0 n = S_z z n, \qquad (7.1)$$

where n is the milling cutter rotation frequency, min^{-1}; z is the number of milling cutter teeth.

Permissible cutting speed v depends upon many factors, and is determined with the formula:

$$v = \frac{c_v D^z k_u k_м k_\varphi k}{T^m t^x S_z^y B^q z^\eta}, \qquad (7.2)$$

where c_v is the coefficient that characterizes the machining conditions (materials of the workpiece and milling cutter); k_u, $k_м$, k_φ, k are the coefficients that consider correspondingly the constructional peculiarities of the tool, condition of the workpiece material, influence of the main cutting edge and the condition of the workpiece surface layer (scale, workhardening).

Values of constants and exponents are taken from the technical reference books [23].

Cutting speed v and durability period T, the same way as at cutting, are bound with the dependency $v = AT^{-m}$, where m is the index of relative durability.

Dependency (7.2) allows to optimize the elements of the cutting parameter and evaluate their mutual impact. E.g., in case of increasing the milling cutter diameter D, cutting force P_z is reduced, heat stress of the process gets lower, and so, permissible cutting speed v increases.

Milling width B has minimum influence on the cutting speed v. Only under the conditions of heavy heat withdrawal and small rigidity of the system, e.g., during machining with disc-type milling cutters, the wear-out intensity increases.

At conventional milling of the workpieces that do not have oxide surface crust, the cutting speed obtained with the formula (7.2) may be increased by 30…50%.

High efficiency of conventional milling is typical for more ductile materials that strengthen a lot during the process of chip formation at milling of the workpieces of refractory and titanium alloys with fast-cutting tools, one should provide intensive supply of OCL.

Efficiency of milling of the workpieces manufactured from refractory and titanium alloys and high-strength steels often gets lower because of vibrations.

The causes of vibrations may be the following: too big volume of cutoff – milling width B, feed S_z and especially the depth of cut t; change of the cutting intersection during the machining; radial and end surface outrun of the milling cutter teeth caused by low quality of sharpening, and also by mandrel deflection; periodical excitation during cutting and exiting from contact of certain milling cutter teeth; insufficient rigidity of the technological system.

To increase vibration resistance of the process during the semi-finishing and finishing machining, it is reasonable to use the strategy of conventional cutting, the milling cutter with nonuniform step and minimal teeth outrun, increase the system rigidity by using of milling cutters with small outrun of the teeth, short mandrels and strong fixation of the workpieces.

7.3.1 Methodology of applying the cutting parameter

Main criteria for choosing the rational cutting parameter for milling are the same as for other types of machining: maximum possible depth and width of cutting, technologically permissible feed and the corresponding cutting speed.

The sequence of applying the cutting parameter during milling is the following:

1. Choosing the design and geometry of the milling cutter and grade of the tooling material. For milling of steels with $\sigma_в \leq$ 1400 MPa, one uses milling cutters with the teeth of fast-cutting steels of P9M4K8 and P6M5K5 grades, and

also of strong alloys of ВК8 grade during rough machining and ВК3М, ВК6М grades during finishing machining. At machining of superstrong materials that have $\sigma_в$ > 1400 MPa, the milling cutters should be equipped with the plates of strong alloys of ВК group.

2. Choosing the depth of cut t. The value t is chosen depending upon the machining allowance, capacity of the drive and rigidity of the machine, and the way of the workpiece fixation.

3. Choosing the feed per tooth S_z. Main factors that limit the value S_z are the properties of machined material, material strength and teeth outrun, rigidity of the milling cutter mandrel and technological system, machining accuracy and surface layer quality requirements.

4. Choosing the durability period T. This value usually lies within 60 and 180 min. E.g., for machining of the workpieces of refractory and stainless steels, for face milling cutters one takes T = 60 min, for cylindrical and disc-type ones T = 90 min, for face milling cutters with insert teeth T = 120 min.

5. Calculating the permissible cutting speed v with the formula (6.2) or choosing it from the reference literature [23].

6. Calculating the rotation frequency of the milling cutter, min^{-1}: $n = 1000v / \pi D$.

7. Correcting of the values n and S_m according to the machine ratings in the direction of reducing.

8. Calculating of cutting power N_p and comparing it with the machine capacity (the condition $N_p < N_{cm}$ should be satisfied).

9. Calculating the milling machine time: $T_{machine} = Li / S_m$, where $L = l + y + \Delta$; l is the length of machining pass, $y = \sqrt{t(D - t)}$ is the length of penetration area; Δ is the length of overrun area (up to 5 mm); i is the number of the tool machining passes.

Test questions

1. What types of machining are there during milling?
2. Name the categories of milling depending upon the number of axes of coordinate moves.
3. Name the main geometrical elements of the milling cutter cutting edge.
4. In what way does one determine the width and depth of milling for main types of machining?
5. What machining areas are there during milling?
6. Name two typical cutting strategies during milling.
7. What peculiarities of tooling wear-out are typical for milling?
8. What does the durability of milling cutters depend upon?
9. What determine the cutting parameter during milling?
10. Provide the sequence of applying the cutting parameter during milling.

8 ABRASIVE METHODS OF MACHINING

Abrasive methods of machining that are based upon using abrasive tooling are widely used in aerospace technologies. The fields of their application are significant: in casting, welding and workpiece-producing workshops they are used for cutting off the intakes, weld dressing, cutting of superstrong materials; in machining workshops – for sharpening of blade cutting tooling, grinding, honing, superfinishing, polishing.

There are special methods of abrasive machining – wet blasting, vibroabrasive machining.

Abrasives are fine-grained materials in the form of microchips, polycrystals or their fragments with sharp sides that have high hardness and are able to cut. Abrasive tools may be with bonded grain (grinding discs, heads, bars, segments, belts) and in the form of unbonded grain (pastes, suspensions, powders).

8.1 Grinding and abrasive tooling

Grinding is one of effective methods of finishing and fine finishing of different surfaces. The peculiarity of grinding is simultaneous microcutting with several grains, each of which has several cutting blades. Rounding radius of cutting edges of abrasive tools, unlike the blade ones, is close to zero.

Abrasive tooling is characterized by the type of material, shape and size of the grains, type of bond, hardness and structure (Fig. 8.1).

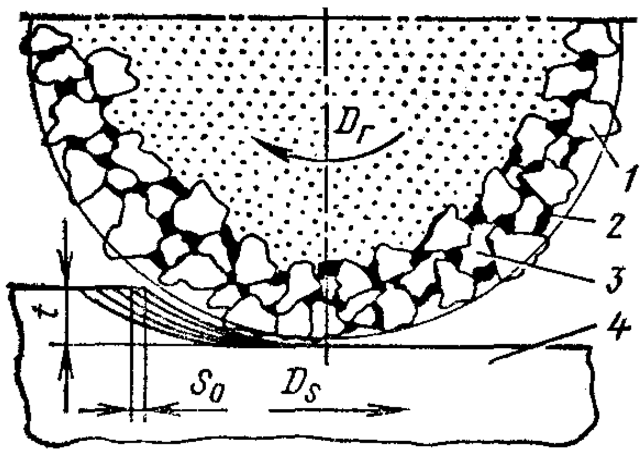


Figure 8.1 – Design of a grinding disc and strategy of allowance cutting:
1 – grains; 2 – bond; 3 – voids; 4 – workpiece

Abrasive materials. Abrasive materials are divided into artificial (synthetic) and natural. For manufacturing of abrasive tooling, one mostly uses artificial abrasive materials: electrocorundum, silicon and boron carbide, synthetic diamonds, cubic boron nitride.

Over 70% of abrasive tooling is manufactured of *electrocorundum* produced by melting of argil in electric furnaces. Main component of electrocorundum is crystalline aluminum oxide. Depending upon its content and admixtures, electrocorundum has different colors, structure and properties.

There are several types of electrocorundum: normal – grades 12A to 16A; white – grades 22A to 25A; chromic – grades 32A to 34A; titanous – grade 37A. Electrocorundum grains of 43A to 45A grades are separate crystals with large number of cutting sides. Stronger grains of chromic and titanous electrocorundum, and also of monocrystalline alumina have high cutting characteristics and are used for grinding of products of superstrong alloys.

Silicon carbide is the chemical compound of silicon and carbon produced by melting of silica sand and coke. Grains of silicon carbide have higher hardness than the grains of electrocorundum. Two types of silicon carbide are used: black and green. The disadvantages of silicon carbide are high fragility and low strength. This material cannot be used for machining of steel workpieces, but is quite appropriate for abrasive machining of parts manufactured of cast iron, bronze, titanium and refractory alloys and for sharpening of hard-alloyed tooling.

Boron carbide is the chemical compound of boron and carbon produced by melting of boron anhydride with oil coke. Boron carbide has high hardness and fragility and is used in the form of a powder for fine finishing and during ultrasonic processing of fragile materials.

Synthetic diamonds are produced in the form of fine crystals with their usual size not exceeding 1 mm. Synthesis of diamonds takes place under the influence of high pressures and temperatures on graphite. Synthetic diamonds, depending upon hardness, are divided into five grades: of usual hardness – AC2, of increased hardness – AC4, of high hardness – AC6, monocrystal – AC15 and AC20.

Cubic boron nitride (CBN), or el'bor borazon material, is the abrasive material, the hardness of which is close to the hardness of a diamond, and heat resistance is twice as high – up to 1600 °C. CBN may be of usual (ЛЗ) and increased (ЛП) strength. CBN, like diamond, has exceptionally high abrasive properties and by durability, it considerably exceeds all known abrasive materials.

Granularity of abrasives. By the size of grains, abrasive materials are divided into four groups: screened sizes – numbers from 200 to 16 (the ones that have the grains of main fraction with the size 2000…160 mkm); microgrits – numbers from 12 to 3 (grains with the size 125…28 mkm); classified flours – from M63 to M14 (grains with the size 63…10 mkm); thin classified flours – from M10 to M1 (grains smaller than 10 mkm). Granularity of diamonds and CBN is marked with the fraction, the numerator of which contains the largest size of grain of main fraction in micrometers, and the denominator – the smallest one.

Diamond abrasives are divided into two groups: microgrits – from 630/500 to 50/40, classified flours – from 60/40 to 1/0. CBN powders, depending upon the size of grains, methods of their control and receiving, are divided into three groups: screened-size grains with the granularity from ЛЗ

315/250 to ЛЗ 200/160, microgrits – from ЛЗ 160/125 to ЛО 50/40, classified flours – from ЛМ 40/28 to ЛМ 5/3.

Bonding substances (bonds). The bond initially impacts the operating efficiency of abrasive graining. Three types of bonds are used: non-organic, organic and metal.

Non-organic bonds may be ceramic, magnesite and silicate. The most widespread type of bond is ceramic one that consists of fireclay, feldspar, and talc. About 60% of all abrasive tooling is manufactured of it. These tools are heat-resistant, strong, resistant to chemical and moisture actions.

Organic bonds are bakelite (B), glyptal (G) and vulcanite (V). Bakelite bond is manufactured of phenolic-formaldehyde resin. Grinding tooling on such bond is strong, elastic and able to operate on high circular speeds, but their chemical and heat resistance is not high.

The discs on glyptal bond have increased elasticity, and they are used for finishing operations. Vulcanite bond has high strength and elasticity and is used for manufacturing of thin cutting discs.

Metal bonds MI and МК that consist of metal base (copper, tin and aluminum powders) and the filler are used in diamond discs. These bonds provide high productivity and efficient usage of diamond discs.

Structure of abrasive tooling is characterized by the percentage of abrasive grains and is determined by the relation of the volumes of grinding material, bond and voids in it.

According to the structure, there are four types of abrasive tooling: of solid structure – numbers from 0 to 3, medium-solid – from 4 to 6, open – from 7 to 12, high-porous – from 13 to 18. Zero structure has the highest volume of grains. The choice of tooling according to its structure depends upon its purpose, properties of machined material and other machining conditions. Tools of medium-solid structure are the most frequently used.

Hardness is an important feature of abrasive tooling. Hardness of abrasive tooling is the ability of the bond to resist to penetration of other body into it. There are seven classes of hardness, and they are given in the Table 8.1. When choosing the abrasive tool by its hardness, one considers physical and mechanical properties of machined material, and requirements for machining accuracy and quality of the surface.

Table 8.1 – Hardness classes of abrasive tooling

Hardness class	**Denomination**	**Degree of hardness**
Soft	M	MI, M2, M3
Medium-soft	CM	CM1, CM2
Medium	C	C1, C2
Medium-hard	CT	CT1, CT2, CT3
Hard	T	T1, T2
Super-hard	ДТ	BT1, BT2
Extremely hard	HT	HT1, HT2

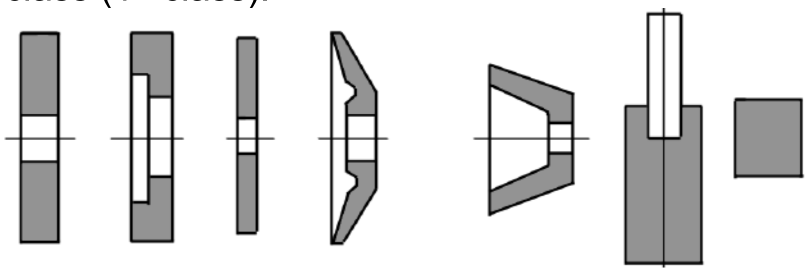
Classes of accuracy and unbalance of the discs. During manufacturing of abrasive tooling, the deviation of various parameters is inevitable: size, shape, placement of surfaces, etc.

Depending upon these deviations, there are three accuracy classes of abrasive tooling: АА, А, Б.

For abrasive discs, four classes of unbalance are set: 1^{st}, 2^{nd}, 3^{rd}, 4^{th}. In tool grading, the unbalance class of the disc is designated after the accuracy class.

Prototype of abrasive tooling. Solid and assembled tooling used for abrasive machining, depending upon their shape, are divided into flat abrasive circles of straight profile (ПП) and with recess (ПВ), discs (Д), plates (Т), conic cups (ЧК), cylindrical heads (ГЦ), honing bars (БХ), the shapes of which are shown in Fig. 8.2, and abrasive belts.

Let us give a particular example of grading of the grinding disc: *ПП 500x60x305 34A 40 СТ2 6 К5 35 m/sec A 1 class.* Here, the following is indicated: type of the disc (ПП) and its size (500x60x305), grade of abrasive material (34A), granularity and granularity index (40), hardness (СТ2), structure (6), type of bond (К5), permissible circular speed (35 m/sec), accuracy class (A), unbalance class (1^{st} class).



a b c d e f g

Figure 8.2 – Shapes of abrasive tools:
a – ПП; b – ПВ; c – Д; d – Т; e – ЧК; f – ГЦ; g – БХ

Grading of diamond and CBN discs differs from grading of abrasive ones. The geometrical size of the disc is followed by its characteristics, e.g., *АС4 100/80 150 М15*, where АС4 is the material of grains (synthetic diamond); 100/80 is the granularity interval, mkm; 150 – relative diamond concentration; М15 – bond material (М - metal).

8.2 Types of grinding

By *peeling* grinding, economic accuracy of machining corresponds to the 6 – 9 accuracy classes, roughness R_a = 1,2…2,5 mkm.

Finishing grinding provides economic accuracy of 5 – 6 accuracy classes, and roughness R_a = 0,2…1,2 mkm.

Depending upon the type of machined surface (external or internal) and its shapes, there are kinematic grinding strategies – machining of rotation bodies, flat, threaded, toothed, splined, and profiled surfaces.

Main movement during grinding is rotation of the grinding disc with the circular speed v_k , m/sec:

$$v_k = \frac{\pi D_k n_k}{6 \cdot 10^4}. \quad (8.1)$$

According to the technological conditions, there are the following types of grinding: common (v_k ≤ 35 m/sec), speed (v_k = 40…55 m/sec), high-speed (v_k ≥ 60 m/sec).

The main cutting move, conditioned by the disc rotation, and the feed movement provide continuity of the process of cutting and multi-step machining during grinding.

In grinding, there are three types of feed:

1. Feed in tangential direction relatively to the disc rim. At circular grinding, this type of feed is determined by the circular rotation speed of the part v_∂, m/min.

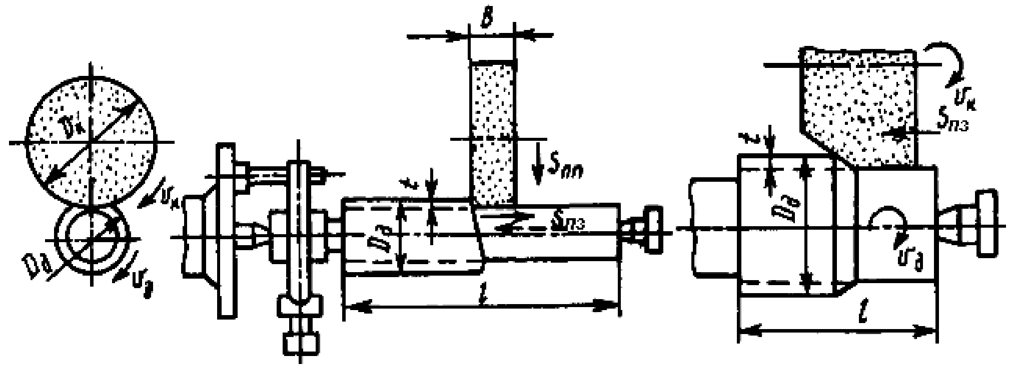
2. Feed in the direction coinciding with the rotation axis of the grinding disc. at circular grinding, this type of feed is called longitudinal S_{long}, and it is measured in the parts from the width B of the grinding disc per one revolution of the part, mm/rotation.

3. Feed in the direction perpendicular to the machined surface. It is called transversal S_{trans} (S_t), and it is defined as the magnitude of displacement per one pass of the disc (mm/pass) or double pass of the table (mm/double pass). For circular grinding, if there is no longitudinal feed, this type of feed is set per one rotation of the part (mm/rotation).

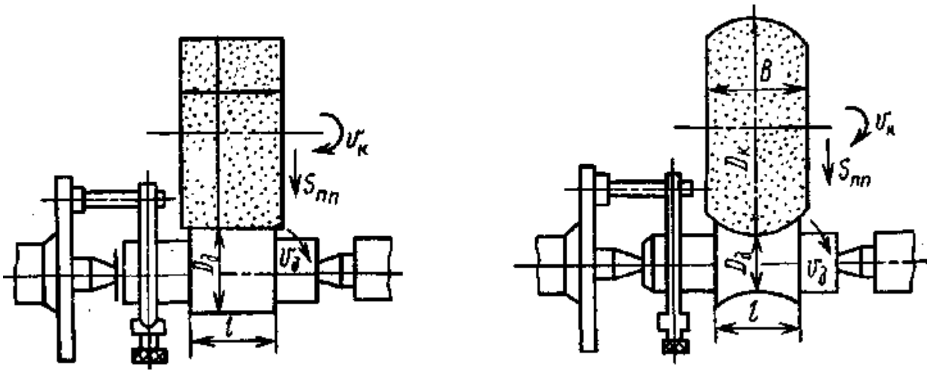
Main types of grinding with abrasive discs are the following: external and internal circular; centerless; flat. Special types of grinding are: gear grinding, cutting grinding, spline grinding, grinding of working parts of cutting tooling. Center grinding is used for machining of external cylindrical, conic and profiled surfaces.

External circular grinding has three classes:

1. Longitudinal (or multi-step) with flat disc (Fig. 8.3, a, b);
2. Subsurface with flat disc with conic bevel (Fig. 8.3, c);
3. Plunge (Fig. 8.3, d, e) with flat of profiled disc for the parts with straightforward or curvilinear generatrix.
4. Internal circular grinding has two types – cartridge (Fig. 8.4, a) and planetary (Fig.8.4, b).
5. Internal circular cartridge grinding is used for machining of small workpieces, and internal circular planetary – for machining of heavy and bulky workpieces.
6. In both cases, there is longitudinal feed of the grinding disc along the grinding hole axis: in the first case – with the movement of spindle head, in the second one – with the movement of the table. Usually, the diameter of the disc at internal grinding is 0,7…0,9 of the workpiece hole diameter. Depending upon the hole diameter, in case of preliminary grinding the depth of cut is 0,005…0,02 mm, in case of finishing grinding it is 0,002…0,01 mm.

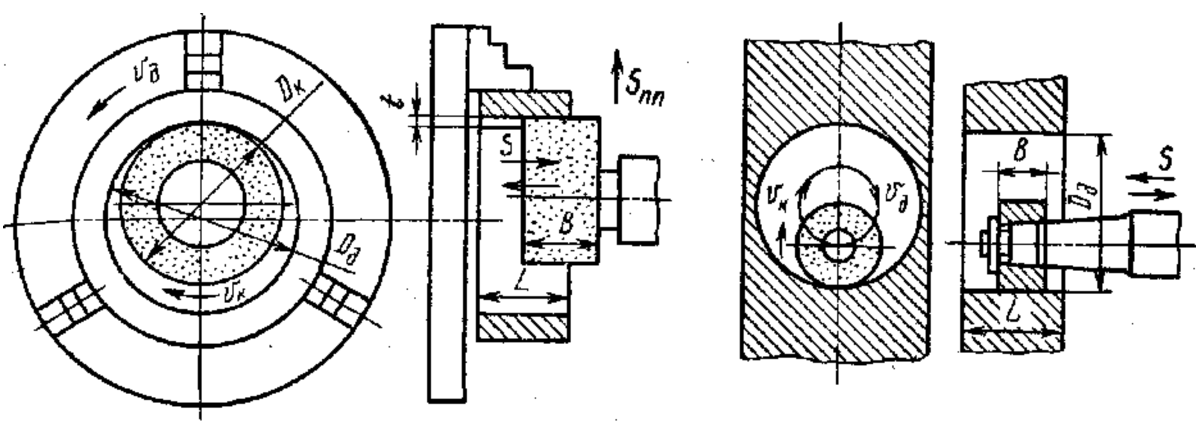


a b c



d e

Figure 8.3 – Strategies of external circular center grinding



a b

Figure – 8.4 – Strategies of internal circular grinding

By *centerless* external grinding (Fig. 8.5), the workpiece 1 is installed between the grinding 3 and control 4 wheels, and at the bottom it is supported by the rest (knife) 2. Longitudinal movement of the workpiece is provided by such placement of discs when their axes form the little angle ν.

Flat grinding (Fig. 8.6) is usually used for machining of flat surfaces. The workpieces are usually installed and fixed on the magnetic gripping plate. If the ground workpiece is non-magnetic, vacuum tables are also used.

Flat grinding may be performed both with periphery and with the disc end surface. Compared to grinding with the disc end surface, grinding with its periphery has the following advantages: more accurate machining, better quality level of machined surface, possibility of machining of small-hardness workpieces.

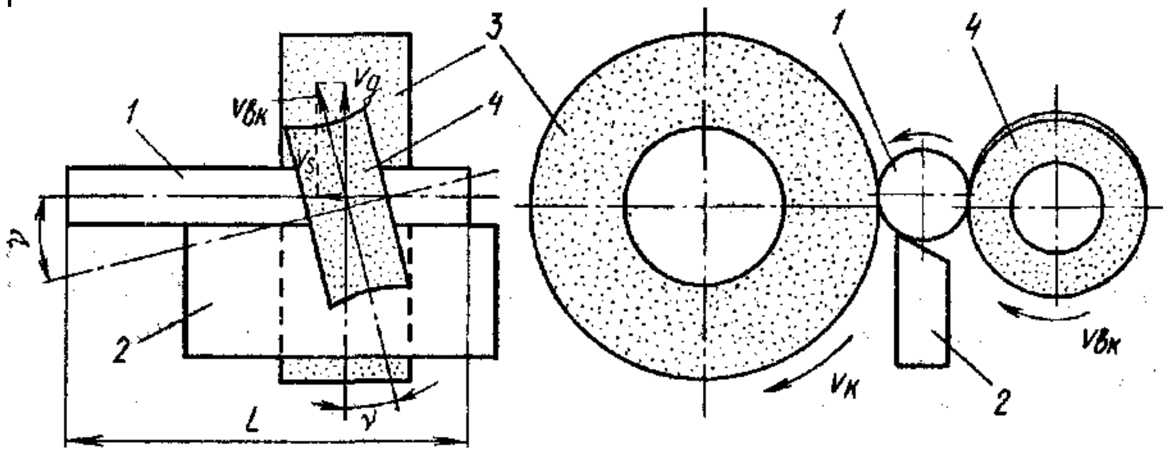
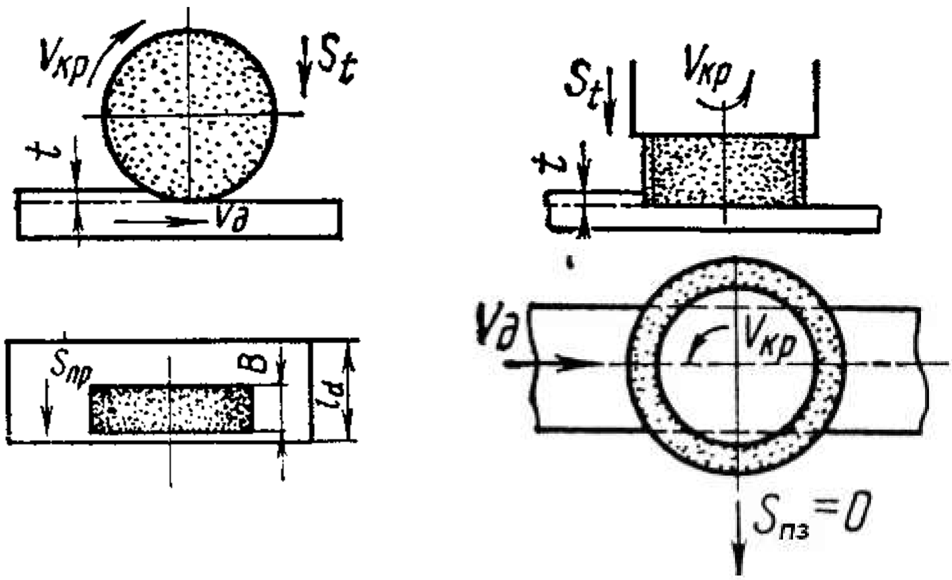


Figure 8.5 – Strategy of centerless external grinding

At flat grinding, reciprocal motion of longitudinal feed and interrupted movement of transversal feed S_{trans} is carried out either by the workpiece, or by the grinding disc. Disc feed movement on the depth of cut S_t takes place in the extreme position of the table to the extent of machining of the whole area.

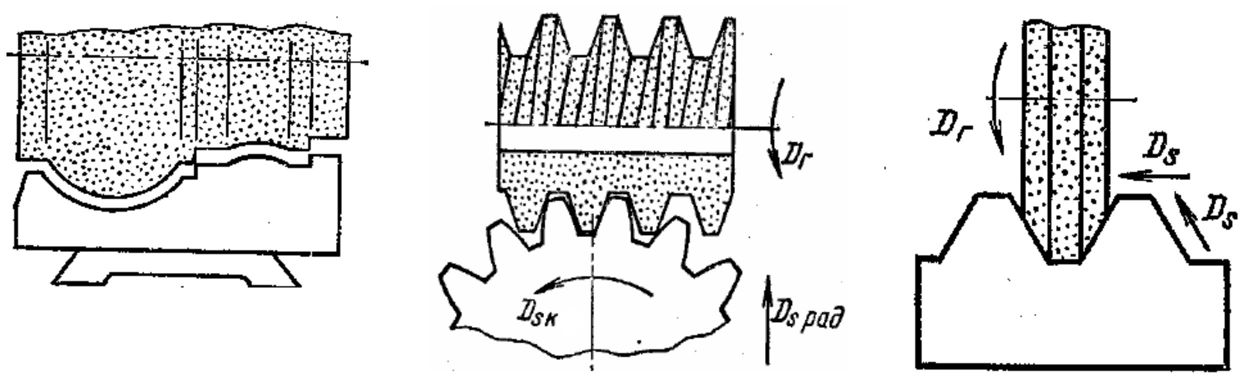


a b

Figure 8.6 – Strategies of flat grinding:
a – with disc periphery; b – with disc end surface

If the workpiece is narrower than the disc, vertical feed movement is performed on each double pass of the workpiece.

Profiled grinding of shaped surfaces. There is a big variety of parts with shaped (profiled) surfaces that require high roughness and accuracy parameters. They are toothed discs, spline shafts, cams, profiled cutters, etc. All these surfaces are processed on special grinding machines with special discs of complex profile (Fig. 8.7).



a b c

Figure 8.7 – Methods of profiled grinding:
a – copying; b – rounding of profile; c – equidistance method

Profiled grinding of shaped surfaces is usually carried out with the following technological methods:

– copying, when the profile of the grinding disc corresponds to the part profile;

– rounding of profile on the workpiece at the expense of relative rounding movement of the disc working surface;

– equidistance method, by which the feed movement of the disc is performed along the trajectory that is equally remote from the generatrix of the ground profile.

8.2.1 Belt grinding

Belt grinding provides high quality and accuracy parameters of the part shaped surfaces' machining due to close contact of flexible abrasive belt with the machined surface. The following elements are used as supports: contact discs or plates with riffling covered with rubber, profiled locating blocks.

During belt grinding (Fig. 8.8), machining of the detail 5 is performed with abrasive belt 2 set on the control 1, clutch 3 and driven 4 wheels, and the belt moves with high speed (30…50 m/sec).

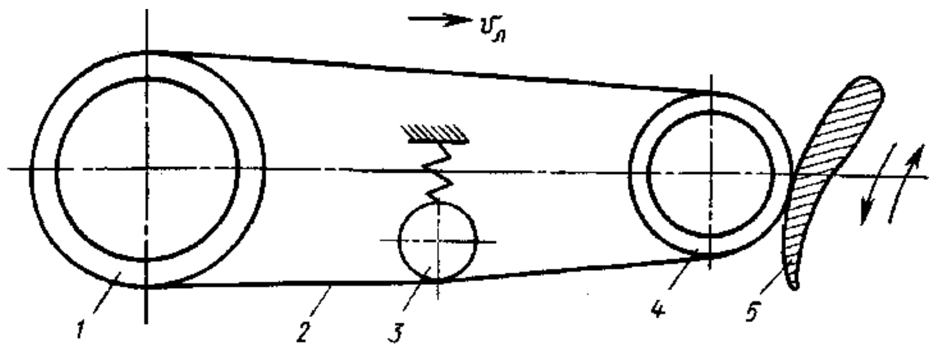


Figure 8.8 – Strategy of belt grinding on contact wheel

During removing of small allowances (finishing operations), the part, with slight force, is pressed to the abrasive layer of the belt on the free area between the clutch roller and the contact wheel. Such grinding is the most productive, as in this case, the area of contact of the abrasive belt and the part increases.

The process of belt grinding may be controlled by changing the tension of the belt, grinding parameter (speed, feed), belt characteristics (type of base, glue, abrasive granularity). It is recommended to set the value of pressure of the machined surface on the abrasive belt during machining of the workpiece of steel alloys within 0,05 and 0,2 MPa, and for the workpieces of aluminum alloys – not more than 0,04 MPa. Cutting speed during machining with abrasive belts is chosen depending upon the machined material, type of machining (rough or finishing), and other factors. For rough grinding of steel external surfaces, when $\sigma_в$ > 1000 MPa, recommended cutting speed is 25…30 m/sec, and for grinding the surfaces of aluminum alloys – 45…50 m/sec.

Abrasive belt consists of the base, layer of abrasive grains and glue bond. The base for the belt is hard paper and cotton and synthetic cloth. Abrasive belts are manufactured 6…2200 mm wide and up to 15000 mm long.

The working surface of the belt is several times larger than the working surface of the grinding disc, which provides better heat dispersion, reduces the chance of burns' appearing, allows mechanization and automation of the process of finishing machining of complex surfaces and also machining of hard-reachable places. As tool balancing is excluded and the belt is easily changed, one needs less time for machine adjustment.

Unlike disc grinding, during belt grinding, there occurs compression tension in the surface layer. Belt tension is the important characteristic that influences the process efficiency. Optimal value of tension force is 10…60 N per 10 mm of the belt width. As OCL, during belt grinding, mineral oils, kerosene, emulsions, fatty pastes are used.

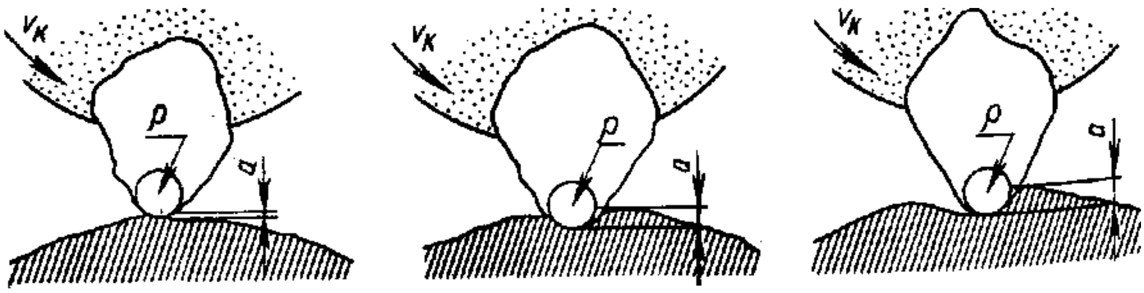
8.3 Process of cutting during grinding

Mechanism of chip formation during grinding doesn't have any essential differences from the process of chip formation during machining with blade tooling, but it has its own peculiarities conditioned by high deformation speeds, large negative radial rake angles, small thicknesses of cutoffs and shortness of contacts of grain points and workpieces. About 20 times more energy is needed for removing the unit of volume by grinding than by turning and milling.

A large amount of smallest chip is formed during grinding, the sizes of which vary from the several tenth of micrometer to the several tenth of millimeter. Size and shape of the chip depend upon the shape of grains and location of their points on the working surface of the disc and upon the process kinematics. Cutting is performed only by those tops of the grains that are situated the highest over the bond.

Efficiency of grinding largely depends upon the thickness of the cut layer and the cut area. These values determine the feed on the grains that, in the total, determins the cutting forces, disc durability and quality of the surface layer. Main part of the grinding energy is spent on overcoming the friction forces between the machined surface and grains, and also with bond.

Depending upon the relation between the cutoff thickness $\boldsymbol{a}$ and the radius ρ of the grain, the following (Fig. 8.9) may occur on the top of abrasive during the tool movement relatively to the machined surface: sliding of the grain over the machined surface (if $\boldsymbol{a} \leq \rho$); plastic deformation ($\boldsymbol{a} < \rho$); cutting ($\boldsymbol{a} \geq \rho$). Peculiarities of grinding are high specific cutting work and local heating of the metal in the cutting area. Significant plastic deformation of the surface layer occurs: heated and heavily loaded surface layers of metal are stretched in the direction of cutting.



a b c

Figure 8.9 – Interaction of abrasive grains and the workpiece
a – sliding of the grain; b – plastic deformation; c – cutting

The same way as during turning, the resultant $\boldsymbol{P}$ of normal and tangent forces acting upon the working surfaces of the disc is the sum of the forces $\boldsymbol{P_z}, \boldsymbol{P_y}$ and $\boldsymbol{P_x}$ (Fig. 8.10).

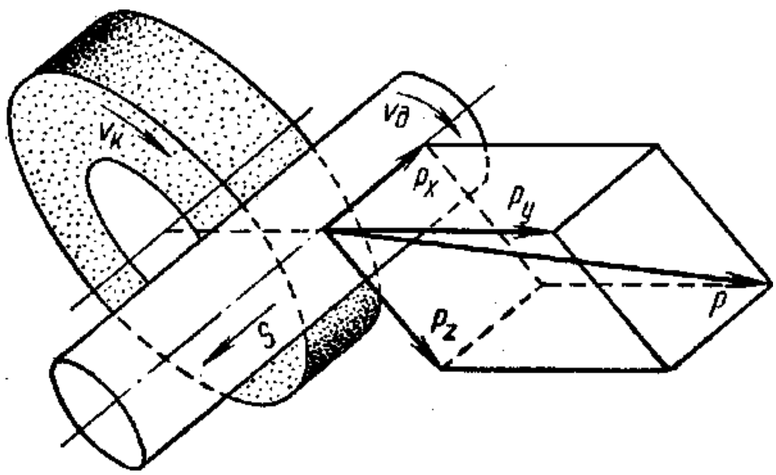


Figure 8.10 – Cutting forces during grinding

Tangential force $\boldsymbol{P_z}$ determines the cutting capacity. Radial force $\boldsymbol{P_y}$, causing elastic deformations in the technological system, significantly impacts machining accuracy and vibration resistance of the process. Axial force $\boldsymbol{P_x}$ determines the capacity of feed drive.

Considerable rounding radiuses ρ on the grains, large negative radial rake angles γ and small cutoff thicknesses result in the fact that force P_y is 1,5 – 3 times larger than the force P_z.

Under the conditions of insufficient hardness of the technological system, there may appear vibrations that increase roughness of the machined surface and cause its waviness (faceting of the parts). At forced vibrations, due to the disc misbalance, the surface roughness increases several times. In order to prevent part faceting caused by the waviness of the disc surface and changing of the contact place of the disc and the item, it is recommended to change the rotation frequency of a circle or the part from time to time.

Increase of the part rotation frequency and longitudinal feed results in reducing the heat impact of the disc upon the part and changing the correlation between the heat factor and plastic deformation of the compression in the favour of the latter.

This is why after machining the value of stretching residual stresses in the part reduces, and compressing ones – increases.

8.3.1 Wear-out and durability of abrasive tooling

During operation of abrasive tooling, the geometry of their surfaces changes at the expense of wear-out. General waste of abrasive tooling is made up of the value of wear-out during work and the volume of removed part during its periodic correction in order to renew its cutting ability and geometric shape.

Frequency of correction depends upon the disc durability period T - time of its operation between two corrections. The value of T for different grinding conditions varies within 5…60 min. The lesser value of T is referred to the internal and profiled grinding and machining of superstrong materials.

Depending upon the conditions of grinding, the disc may operate both in self-sharpening and blunting modes.

Self-sharpening is the ability of the disc to stay in the operable condition due to formation of new cutting edges. If the disc voids during grinding become clogged up with chip and wear-out products, the disc loses its cutting ability before its grains get blunt. The durability bound of the disc in this case is the time of its “glazing”, i.e. the time of clogging of the voids with chipping.

Typical types of disc wear-out are the following: rubbing off of the grain points; breaking and crumbling of the grains; rubbing off of the bond; tearing off of the grains; clogging of the voids and space between grains with the particles of grained material (“glazing” of the disc). Depending upon the certain grinding conditions, there may be all types of wear-out or one of them will dominate.

For soft discs, typical is shearing of corbelled points of grains and breaking-out of the grains that are not strongly enough held with the bond, or are wrongly placed relatively to the forces that act upon them; for hard discs, it is mostly blunting of the tops of abrasive grains and partial breaking-off of the grains that received cracks during correction.

Relation of the abrasive disc wear-out to the time of cutting is called *wear-out speed*. The highest relative spending and maximum wear-out speeds are typical for grinding of difficult-to-cut metals.

As the wear-out criterion, one takes indirect signs of reduction of cutting properties: increase of capacity, appearing of vibrations, appearing of burns, changing of shine of the part surface.

Disc durability depends upon the properties of machined material, hardness of the technological system, degree of disc misbalance, cutting parameter, part diameter, hardness and granularity of the disc.

Increasing of the disc misbalance degree, part speed v_d, longitudinal feed S_{long} and depth of cut t results in the increase of the feed on abrasive grains, and the disc durability is reduced.

Grinding of the items manufactured of refractory and titanium alloys is more complex due to adhesion, diffusion and chemical interaction of the materials, and also because of rubbing off of carbide inclusions that is included in the alloy.

With this all said, the disc durability is also impacted by the pickup of the alloy particles on the contact areas of the grains due to adhesive interaction of the metal with grains. This 10 – 15 times reduces the disc durability compared to grinding of the parts of constructional steels.

OCL (its composition and method of feed) plays a very important part in the process of grinding. OCL extracts heat from the cutting area, reduces friction, and cleans the disc working surface; surface-active admixtures simplify the process of chip formation. Usual method of feed the OCL – pouring from above – is not always effective. Best results are received by supplying the flow of the OCL under the pressure within 1…1,5 MPa on the working surface of the disc.

8.3.2 Choosing the tooling and purpose of the cutting parameter

Choosing the abrasive tooling to a great extent influences the indices of grinding efficiency, tool wear-out, economy of the process and quality of machining.

Grinding efficiency is determined by the volume of the workpiece material V_M removed per unit of time (mm^3/min), and efficiency of fine finishing processes – by the area of the surface machined per unit of time until it reaches the necessary parameters of roughness and machining accuracy.

Effectiveness of abrasive machining depends upon the specific efficiency $q = V_M / V_a$, where V_a is the wear-out volume of the disc per unit of time.

By grinding of the parts of carbon steels with electrocorundum discs, the value q is kept within the range of 50…80, with the parts of fast-cutting steels it is 6…12, of titanium alloys – 0,5…5.

For preliminary grinding, the discs with grit numbers 50…40 are used; for finishing, they are 25…12.

For grinding of the items stainless and refractory steels, one uses the discs with high cutting characteristics manufactured of monocrystalline alumina with the hardness M3 – CM2, with grit numbers within 16…25, of open structure, using the OCL of sulfofresol and kerosene. For grinding of the parts of titanium alloys, discs of silicon carbide of medium hardness are used.

When choosing the disc hardness, one should follow the disc *self-sharpening rule*: for hard materials, soft and medium-soft disks should be used; for ductile materials and alloys – disks of medium hardness.

Sequence of applying the cutting parameter during grinding:

1. Depending upon the properties of machined material and technical requirements, choose the characteristics of the disc and it circular speed V_k. For finishing grinding, first choose the disc granularity, and then – parameters that provide surface grinding of a certain quality.
2. Choose the depth of cut t (cross-load S_t): for semi-finishing grinding t = 0,05…0,10 mm/double pass, for finishing – t = 0,005…0,02 mm/double pass.
3. Determine the longitudinal feed S_{long}, mm/rotation; that is expressed in the quotients from the width of the grinding disc B: for semi-finishing grinding S_{long} = (0,4…0,8)B, for finishing – S_{long} = (0,1…0,3)B.
4. Determine the part circular speed v_d (or speed of the table at flat grinding) and adjust this value according to the kinematic characteristics of the grinding machine.
5. Choose the type of the OCL.
6. Calculate the force P_z and capacity needed for grinding.
7. Determine the machine time of grinding T_{mach}, min. For internal circular grinding by the method of longitudinal feed

$$T_{mach} = \frac{LZ}{S_{long} n_d Bt},$$

where L is the displacement of the table which is several millimeters longer than the workpiece machined; Z is machining allowance, mm; n_d is the part rotation frequency, min $^{-1}$.

8.4 Methods of abrasive machining

Methods of abrasive machining are divided into two groups:

- machining with free abrasive – confrication, polishing, hydroabrasive, vibroabrasive and ultrasonic machining;
- machining with the tooling with bonded abrasive – honing, superfinishing, confrication with abrasive bars.

Confrication method provides the highest indices of accuracy and surface layer quality. The process usually consists of several steps: preliminary, intermediate and final.

Confrication admixtures that are put on the lap disc are used in the form of pastes and suspensions with the concentration of abrasives (fine microgrits and classified flours) from 3 to 30%. The pressure acting upon the part isn't high – up to 0,05 MPa. During the relative movement of the lap and the part, there occurs removal of the thin layer of the material. At preliminary operations, one uses soft porous laps, and at finishing – the hard ones, usually made of glass. In order to get the surface roughness parameter R_a = 0,02…0,04 mkm, diamond paste mixed with kerosene, oleic and stearic acids is used.

8.4.1 Honing

Honing is machining operation that allows to get high accuracy of the holes (up to the 7^{th} accuracy class), small roughness parameter of the surface (R_a = 0,3…0,08 mkm), and special grid of machined surface microprofile for holding the oil. Honing is used for machining of the holes with the diameters within 2…1000 mm.

Machining is performed with fine-grained abrasive bars fixed in the honing head – hone. With honing, one can correct the deviations of the shape that appear as the result of preliminary machining within the allowance to remove; however, deviations of the position of hole axis are not corrected because the tool is hinged.

During machining, the hone receives the rotation movement D_r, axial feed movement D_s, and radial movement of bars' feed (Fig. 8.11, a).

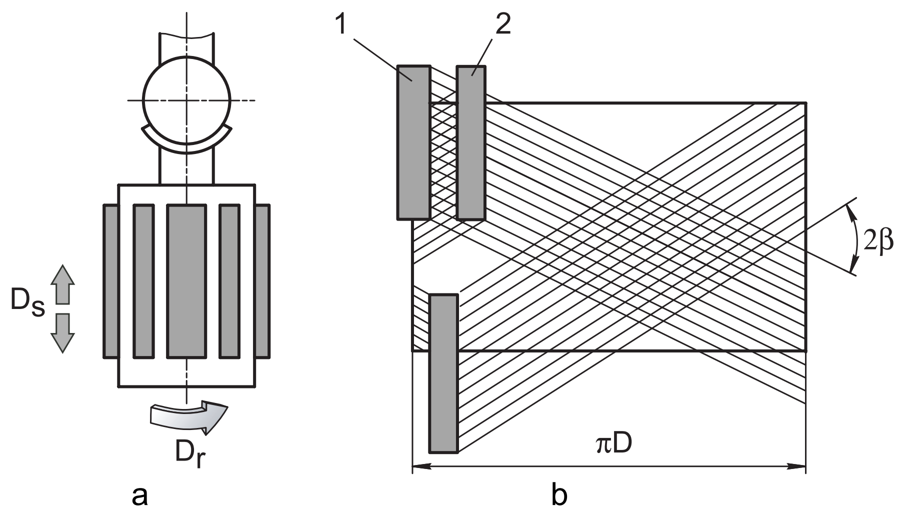


Figure 8.11 – Strategy of the process of honing:
a – honing head; b – grid marked with the bars;
1, 2 – positions of the bar at the beginning and in the end of the double pass;
β – angle between the trajectories of the bar move

The totality of these three moves creates conditions for cutting and self-sharpening.

Fig. 8.11, b shows the evolvent of the inner cylinder of the workpiece surface. In order to provide the straightforwardness of the hole axis, the bars are installed in the extreme top and bottom positions with overrun. The tracks of machining trajectory are of grid character. Abrasive bars always work with shift, as the track of turning is formed during reversal of the hone axial move. The pressure of the bars on the machined surface is created with hydraulic, pneumatic and mechanic devices.

There are two types of honing – preliminary and final. One leaves 20 – 30% of the whole machining allowance for final honing.

Cutting speed during honing is the geometric sum of the hone circular speed v and speed of its linear motion v_l:

$$v = \sqrt{v^2 + v_l^2} = v\sqrt{1 + (tg\,\beta)^2}\ , \qquad (8.2)$$

where $\beta = arctg(v_n / v)$ is the slope angle of the cutting speed vector.

Efficiency of honing depends upon the characteristics of abrasive bars and pressure on the bars. Optimal machining parameters are the following: pressure on the pars – 40…60 MPa; for steel, the cutting speed v = 45…60 m/min, for aluminum alloys it is twice as high. The harder is the machined workpiece, the higher should be the grinding speed.

The temperature in the area of cutting during honing doesn't exceed 150°C and doesn't influence the structural changes of the machined surface. Honing is followed by the cooling with high spending of the OCL (50…60 l/min) for timely removing of the slime and chip from the machining area. The mixture of kerosene and spindle oil most became the most widespread one for OCL.

Together with abrasive bars of electrocurundum and silicon carbide, diamond bars became largely widespread, as their durability is many times higher. Also, the efficiency of honing increases too due to the fact that the pressure on bars at diamond honing is higher – 120…250 MPa.

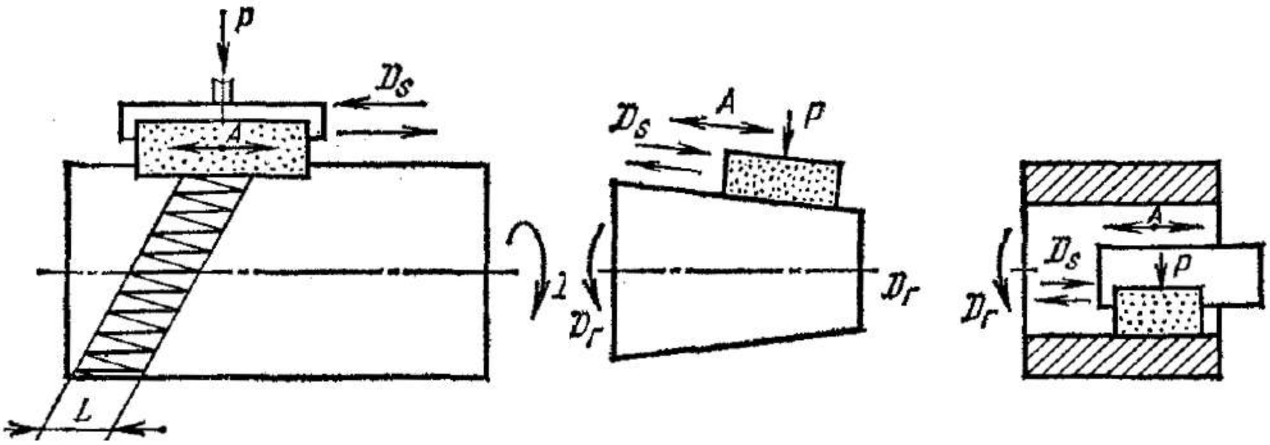
8.4.2 Superfinishing

Superfinishing is the process of thin fine finishing of the workpiece surface with the bars of various abrasive materials.

During superfinishing, the workpiece performs rotary motion D_r, and the elastically fixed workpieces perform reciprocal motion D_s along the generatrix of the machined surface (Fig. 8.12). Also, the bars vibrate, the frequency of vibration is up to 50 Hz and amplitude L = 2…5 mm. The pressure P = = 50…300 MPa acts upon the holder with bars. In order to remove the products of machining and receive thin oil film, one uses various OCL of small viscosity.

Number of bars for superfinishing is from one to four, depending upon the diameter of the machined workpiece. The bars have square section, but before the machining they are shaped into the curvature that corresponds to the curvature of the machined surface. The principle of choosing the characteristics of abrasive bars is the same as for abrasive discs and honing bars.

For machining of steel and aluminum workpieces, the following cutting parameter is used: workpiece rotation speed V_w – from 30 to 45 m/min; moving speed of abrasive bars along the generatrix – up to 0,5 m/min; pressure on the bars P – 50…150 MPa; vibration amplitude L – up to 5 mm.



a b c

Figure 8.12 – Strategies of superfinishing of the surface:
a – external cylindrical; b – external conic;
c – internal

As the result, at superfinishing, a very small allowance is removed (5…10 mkm) and at the same time high surface roughness parameter R_a = 0,16…0,02 mkm is reached. As the crest is removed from the working surface, there is going to be the moment, when the pressure will be insufficient for the bars to overcome the thin film of oil, and machining comes to an end.

8.4.3. Polishing

One of the widespread methods of reducing the roughness of the machined surface is polishing. This method allows to reduce the roughness to minimum value, i.e. polish the surface until it gets high luster. Responsible elements of the parts are subject to polishing, and it is also used in decorative purposes.

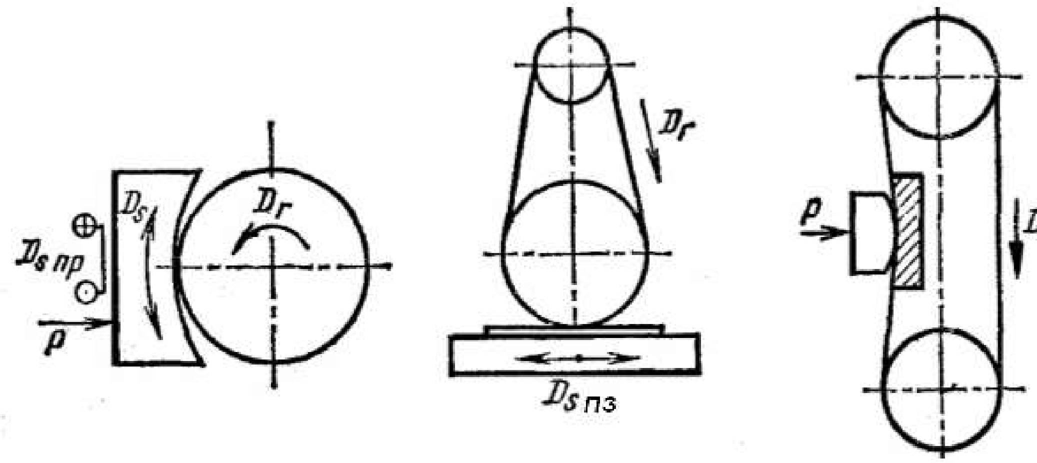
The parts are polished with elastic discs (rough felt, felt), abrasive belts, abrasive-fluid suspension.

Elastic discs are interlaced with abrasives of different granularity using the gluing substance. Polishing is carried out in two-three steps, sequentially using the abrasives with smaller grains.

For polishing the parts of non-ferrous metals, one uses the discs of soft felt. The discs are interlaced with the pastes of necessary granularity. Bonding materials for the pastes are wax, paraffin, fats. In order to increase polishing quality, one adds active acids to the pastes. For pastes of high and medium granularity, it is stearine acid, and for fine-grained SOI paste – the mixture of stearine and oleic acids.

During polishing with elastic discs (Fig. 8.13, a), the allowance of 0,005…0,015 mm is removed, with the speeds up to 50 m/sec. The workpiece pressed with the force $\boldsymbol{P}$ to the polishing disc performs the feed movement $\boldsymbol{D_s}$ according to the profile of the machined surface.

In production, polishing with abrasive belts is widely used (Fig. 8.13, b, c). The abrasive belt moves with the speed of the main movement $\boldsymbol{D_r}$. In the place of contact with the workpiece, the belt is supported by special rest of corresponding profile (see Fig. 8.13, c).



a b c

Figure 8.13 – Schemes of polishing: a – with elastic disc; b, c – with abrasive belts

The design and elasticity degree of the rest are the main factors that determine the contact area of the ribbon and the workpiece, process efficiency and roughness of the machined surface. The belt speed depends upon the machined material: in case of polishing the parts of non-ferrous alloys, the belt speed is 40…50 m/sec, of steel alloys – 15…20 m/sec, of difficult-to-cut alloys – about 10 m/sec.

The pressure of the part on the belt depends upon the machined material and area of the contact and is 3…25 MPa. Polishing with abrasive water-resistant belts is performed with cooling with different types of emulsions.

Abrasive-fluid polishing is successfully used for machining of the workpieces of complex configuration (machining of profiled stamps, forms for pressure die casting, decorative polishing). Abrasive-fluid polishing of the workpieces is carried out in the special cameras with the flow of liquid saturated with abrasive with the speed about 50 m/sec and under pressure of 10…100 MPa.

Vibroabrasive machining of the parts is performed in containers filled with abrasive grains and fluid. Relative movement of the abrasive grains and machined surfaces occurs at the expense of passing vibrations to the container in different directions.

Test questions

1. What main abrasive materials are used for abrasive machining?
2. In what groups are abrasive materials, diamonds and CBNs divided according to the values of their granularity?
3. What parameters of hardness and structures characterize abrasive tooling?
4. Give the characteristics of main schemes of internal circular polishing in the centers.
5. At the expense of what does the longitudinal movement of the workpiece occur at centerless external grinding?
6. What technological parameters does the scheme of flat polishing possess?
7. Give the characteristics of the scheme of belt grinding on the leding contact circle and provide main technological parameters of the process.
8. Give the characteristics of the scheme of cutting forces during circular grinding and name the forces acting on the disc operating surface.
9. What is self-sharpening of the abrasive disc?
10. By what parameters is the grinding efficiency evaluated?
11. Name the sequence of applying the cutting parameter for the process of grinding.
12. What design and technological peculiarities does the process of honing possess?
13. Characterize the main schemes and give the technological parameters of superfinishing.

9 ELECTROEROSION MACHINING OF METALS

9.1 Mechanism of the workpiece metal

The process of electroerosion (electrospark, electrical-discharge) machining (EEM) is based upon the phenomenon of erosion of the metals under the influence of electric current. Electric discharges that occur between two electrodes – electrode-tool (ET) and electrode-workpiece (EW) placed on a short distance from one another – break their surfaces.

Let us consider the mechanism of workpiece metal breaking under the influence of spark discharge. As ET and EW under voltage get closer to each other, there is a moment, when the electric field of maximum voltage is formed between the projecting zones of their surfaces that lie closest to each other (Fig. 9.1).

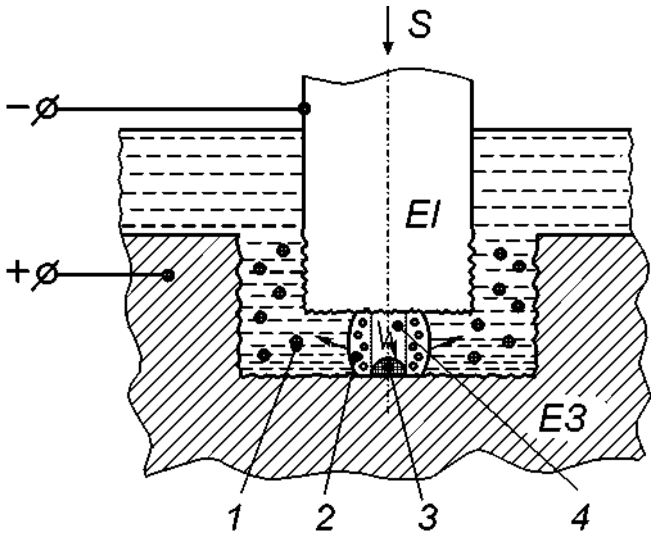
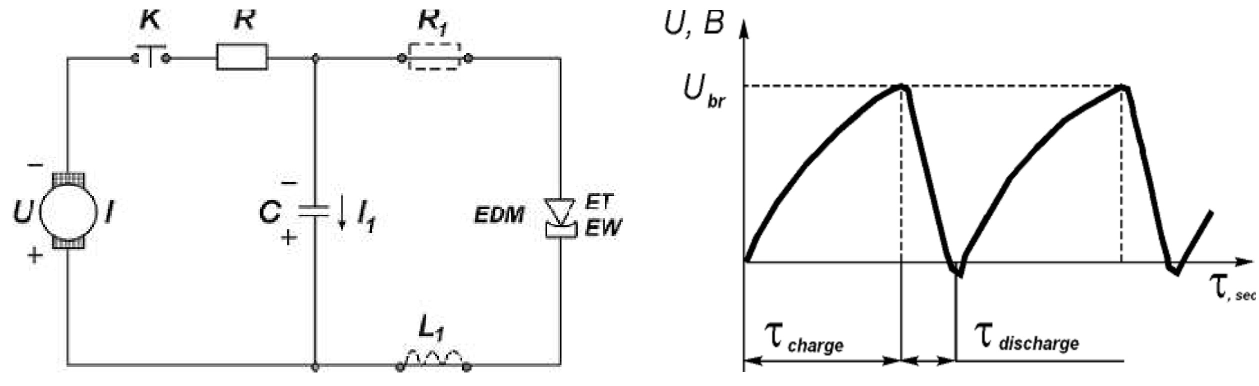


Figure 9.1 – Scheme of metal breaking during EEM

Electric breakdown occurs in spark gap (EDM gap) filled with fluid dielectric (water, kerosene, mineral oils, etc.).In the zone of breakdown and localization of the spark plasma channel of the discharge occurs 1, which is accompanied with the processes of melting, evaporating and ionizing of the working fluid substances. Electric discharge is created between the electrodes over the discharge channel, and heat energy is generated in the plasma. The EW material from the pit 2 is thrown into the EDM in the form of liquid drop. Generation of heat energy results in surrounding of the discharge channel with bubbles 3 – gas-like decomposition products of the working medium. The walls of the expanded bubble assist throwing of the working medium from EDM, the flow of which captures the particles 4 that were earlier thrown away from the pits, and removes them out of the EDM. So the phenomenon of electric erosion occurs which is used for removing of metal from the workpiece surface.

This way, if one creates in the circuit ET – EW such conditions, under which the spark discharge will periodically occur, then, after electrospark machining, the ET profile will be accurately reproduced on the workpiece surface or inside its body. In order to create the voltage impulses that follow one another after certain periods of time, electroerosion machines are equipped with impulse generators (IG). Impulses of little energy are received with the help of relaxation IG (RC and RLC), and powerful impulses – with mechanical IG.

Fig. 9.2 shows principal scheme of the RC-generator used as IG in the electroerosion machine of model 183. IG consists of the source of electric energy of direct current ***U*** (220 V), button K (Start), current-limiting charging resistor R and reservoir capacitor C connected in a parallel way with the EDM.



a b

Figure 9.2 – Scheme of the RC-generator: a – principal electric circuit; b – change of the voltage on the capacitor

Elements U, R and C make up the charge circuit, and C and EDM – the discharge circuit.

RC-generator operates in the following way. It is considered that at first the voltage on the capacitor C equals zero. After pressing the button K charge current I occurs in the circuit U–R–C, and voltage rises on the capacitor and EDM. When the value of voltage equals U_{br}, EDM breaks down. Charge current I_1 occurs in the circuit C–EDM, and the impulse energy accumulated in the capacitor is very quickly passed to the EDM. Due to the fact that the charge time of the capacitor is more than the discharge time (Fig. 9.2, b), the voltage on the capacitor falls, and the EDM stops discharging.

De-ionizing occurs (renewal of the EDM electric capacity) of the substance in the discharge channel, and the voltage in the capacitor begins to rise again due to its charging from the supply U. As the discharge circuit has certain inductivity L_1, the capacitor recharges during the discharge up to a certain negative value of the voltage, which makes de-ionizing easier. This way, the supply of unipolar impulses (impulses with the same polarity) periodically generates short-time discharges between the ET and EW, which allows to carry out selective erosion, i.e. to reduce considerably the erosion of one of the electrodes.

More intensive breaking occurs with the electrode connected to the positive capacitor coating (to the anode), and the electrode connected to the negative coating (to the cathode) defines the direction of the workpiece material breaking and specifies its shape. This is why two methods of connecting the electrodes to the circuit are used:

– direct polarity (ET works as cathode, and EW – as anode);

– reverse polarity (ET works as anode, and EW – as cathode).

The choice of polarity depends on the breaking speed of the workpiece metal and ET wear-out.

In order to increase the intensity of metal breaking, the EDM is filled with dielectric fluid, i.e. the process of EDM is performed in the bath filled with the working medium (kerosene, distilled water, solar oil, etc.).

ET material is chosen depending on material of the machined workpiece. For machining of steel workpieces, the following materials are used as ET: copper, brass, aluminum, graphitic EEG, copper-graphitic or coke-graphitic composition of AEC; for machining of hard alloys cast iron and aluminum are used.

During electroerosion machining, ET and EW do not have direct contact.

Main application of electroerosion machining is broaching of the holes and cavities of different shape depending on the shape of the ET cross section (independently of hardness and ductility of the material).

9.2 Technological methods of EEM

Technological methods of EEM provide realization of the necessary interconnection of electric mode with technological parameters of the process.

Electroerosion machining is carried out with profiled or non-profiled ET. Shapes and sizes of working surfaces of profiled ET are determined according to the given surface of the produced part, while the non-profiled ET have the simplest geometrical shape – in the form of a wire, rod or disc.

Shape formation of the machined part using the electroerosion method may be performed according to two methods.

The first method is copying of the shape of ET, i.e. production of such cavity or convexity that would be the mirror imaging of the ET working surface. This operation called broaching is performed only with linear movement of the ET. Separate case of the described process is broaching of different holes in the workpieces, by which only the shape of the ET cross section is copied. Fig. 9.3 shows the following: technological methods of EEM for the workpieces 1 applying the methods of direct (a – e) and reverse (f) copying of the shape with profiled ET 2; broaching of the holes with linear (a – c) and curvilinear (d) axes; volumetric shape-formation of the cavity (e) and internal surfaces (f).

The second method is mutual move of the machined part and non-profiled ET, by which the material is removed from the surface or the workpiece is cut (Fig. 9.4). In this method, one may distinguish two types of operations: cutting-out of parts with complex profiles and cutting of the parts 1 with non-profiled ET 2 (a, b); milling and boring of the workpieces with disc- and wire-ET (c, d).

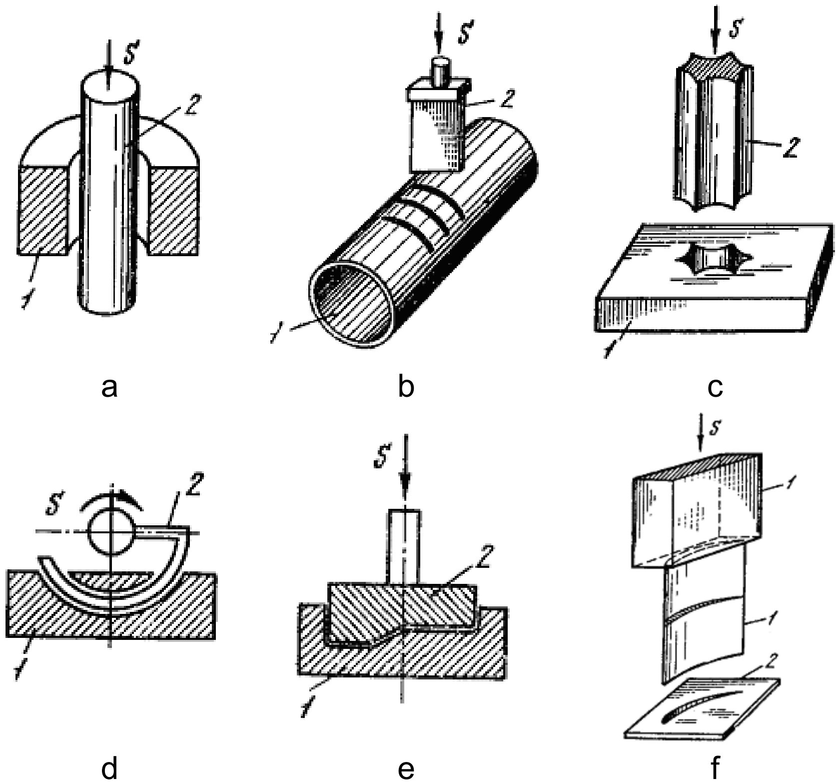


Figure 9.3 – Methods of the EEM processes with profiled ET

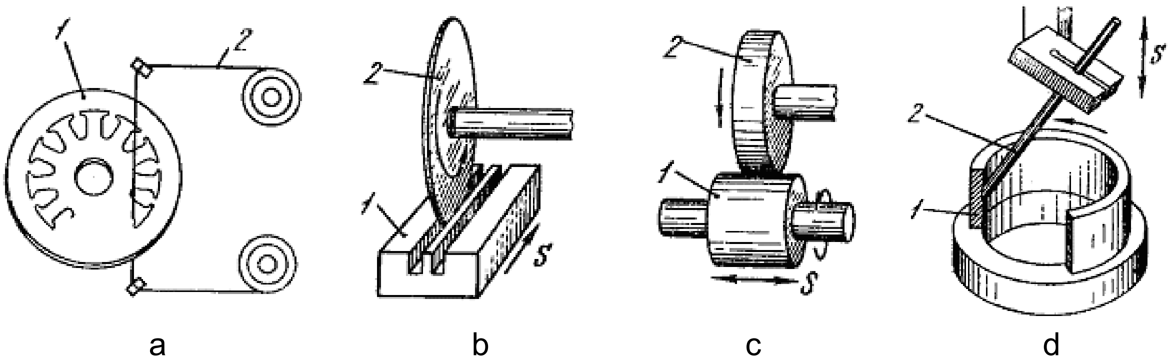


Figure 9.4 – Methods of the EEM processes with non-profiled ET

Technological method of EEM with profiled ET is the most widespread one. The shape of the ET corresponds to the shape of the machined surface that one needs to get.

In the technological method of EEM with non-profiled ET, machining with wire-ET became the most widespread. The advantages of this method are the following: possibility of cutting-out of complex contour sheet articles of high accuracy; availability and relative simplicity of automation of the load move according to the set program; simplicity of machine design. The disadvantage of this machining method lies in the fact that it may be used only for cut-out and cutoff works.

9.3 Technological parameters of EEM

Impulse energy that determines efficiency, accuracy and machining quality of the part surface is an important characteristic of the EEM mode. As the energy of the impulses rises, the process efficiency increases, but the quality of the machined surface gets lower.

Impulse energy equals to the energy accumulated in the capacitor, J:

$$A_i = \frac{CU_{br}^2}{2}, \qquad (9.1)$$

wherein C is the capacitance of the capacitor, F; U_{br} is the breakdown voltage, V.

It is determined experimentally that in the optimal mode the capacitor is charged up to the voltage that makes up 0,50 – 0,75 of the voltage of idle running (U = 180 V). This way, $U_{br} = (0,50...0,75)U$.

By the impulse energy A_i, the EEM mode is divided into three main groups: rough (5,0…0,5 J), medium-roughness (0,5…0,05 J) and soft (less than 0,05 J), which, according to the technological parameters, correspond to rough, finishing and fine finishing types of dimensional processing.

Efficiency of EEM

Efficiency of EEM is determined by the volume (mass) of metal removed from the machined surface per unit of time, mm^3/min (gram/min).

Machining efficiency depends upon electroerosion machinability, combination of material grades of ET and EW and capacity of impulse in the EDM. By constant impulse energy, the efficiency reduces as the machining area increases, which is explained by the fact that the speed of withdrawing the products of erosion from the EDM goes down. In this case, significant amount of discharges is followed not by removing of the metal, but by breaking of its small parts that were not withdrawn from the EDM.

In order to improve the conditions of withdrawing the products of erosion from the EDM, which stabilizes the process of EEM and increases its efficiency, one uses rotation or vibration of the ET in the direction of its loading or pumping of the working fluid.

Type and condition of the working fluid also have a significant impact on the technological parameters of the process of EEM. E.g., substituting kerosene with distilled water during machining of the articles of hard alloys and tempered steels with copper ET lowers the EEM efficiency, and with wolfram and hard-alloyed ET – increases it. During machining, ash content and viscosity of the working fluid increase, this is why the latter is periodically changed. Due to increase of working fluid viscosity, the products of erosion are withdrawn from the EDM more slowly, and this brings down the efficiency of EEM.

EEM efficiency is also influenced by the ET material, the properties of which set the breakdown voltage, and therefore, the energy of impulses, character of heat exchange in the EDM, de-ionization rate, etc.

All metals and alloys are divided into three groups according to their electroerosion machinability: a) well-machined; b) those that are lesser subjected to machining; c) those that are difficultly destroyed under the influence of discharges.

Different influence of impulse discharges on metals and alloys is determined by their thermophysical properties (temperatures of melting and boiling, heat conduction and heat capacity). Mechanical properties (hardness, ductility) don't affect the erosion effect. Relative machinability of some metals (machinability of steel is taken as 1 for convenience) is the following: magnesium alloys – 6,0; aluminum alloys – 4,0; brass alloys – 1,6; steels – 1,0; titanium alloys – 0,6; hard alloys – 0,5.

The higher thermophysical properties of the ET material and roughness of the working surfaces, the greater limiting capacity of EEM, as heat conduction determines the rate of heat withdrawal from the ET surface, and roughness – the actual area of the surface that conducts heat. If the roughness of ET and EW is the same, the limiting capacity will be maximum during machining with copper electrodes, and at lesser values – with aluminum ones.

Accuracy of machining

Accuracy of machining is influenced not only by the factors that are typical for any method of dimensional processing, but the factors typical only for EEM, e.g., initial inaccuracies, the complex of which defines the total inaccuracy Δ.

Initial inaccuracy Δ_{EDM} is the most significant one; it occurs because of the presence of the spark gap

$$\alpha = \alpha_{np} + \frac{2}{3} R_{z\max} + t , \qquad (9.2)$$

where α_{br} is the breakthrough spark gap for pure working fluid that depends upon the maximum voltage of the impulse generator; $R_{z\,max}$ is the height of irregularities of the surface that rises with the increase of the impulse energy; t is the total part of the spark gap filled with the products of erosion that increases when machining parameters increase.

Shape inaccuracy Δ_S is evaluated as the difference between the upper α_u and lower α_l spark gaps:

$$\Delta_S = \alpha_u - \alpha_l . \qquad (9.3)$$

In order to increase the EEM accuracy, one needs to reduce the difference of spark gaps, e.g., by introducing the fine finishing machining mode. By broaching of through holes, the inaccuracy of their shape may be reduced if one moves the ET beyond the limits of the EW lower surface, i.e. up to the full stop of electric discharges in the side part of EDM.

Quality of surface

By EEM, under the influence of electric discharges, typical irregularities are formed on the machined surface, i.e. the surface profile is the result of superposition of the large number of pits on one another (Fig. 9.5).

Machined surface roughness is evaluated by the height of crests in the place of superposition of pits that are formed on the part surface by electric discharge.

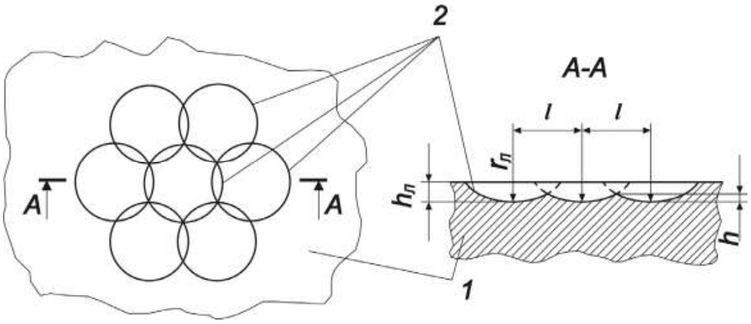


Figure 9.5 – Profile of the EW surface machined on the electroerosion machine: 1 - electrode-workpiece; 2 – pits

If one considers that the pit bottom is spherical with the radius r_p and the depth h_p, and the distance between the pit centers $l = r_p$, it will turn out that the height of the crests in the place of holes' superposition $h = R_{z max}$.

This way, according to the geometrical consideration,

$$R_{z max} = h \approx 0{,}33 h_p . \qquad (9.4)$$

So, the surface roughness is determined by the same machining conditions as the pit depth that may be calculated with empirical dependency

$$h_p = k A_u^n , \qquad (9.5)$$

where $\boldsymbol{k}$ is the pit depth coefficient that depends on the electric characteristics of the discharge and mechanical characteristics of the workpiece material; $\boldsymbol{n}$ is the nondimensional coefficient (for steels and hard alloys $\boldsymbol{n} =$ 0,38).

Control questions

1. Describe the phenomenon of metal electric erosion.
2. What technological parameters are influenced by the increase of impulse energy?
3. How do the machining parameters during EEM influence the roughness of the machined surface?
4. What factors influence the quality of surface machining with the method of EEM?
5. What factors influence machining accuracy during EEM?
6. What parameters does the efficiency of the workpieces' EEM depend upon?
7. Provide the examples of interconnection between electrical parameters and technological parameters of the process of EEM.

10 ELECTROCHEMICAL MACHINING OF METALS

10.1 General information on the process of electrochemical machining of metals

The process of electrochemical machining (ECM) is based upon the ability of metals to dissolve as the result of oxidative reactions that occur in the environment of electroconductive solution (electrolyte) under the influence of direct current. Such chemical process of metals' dissolution is called *electrolysis* (Fig. 10.1).

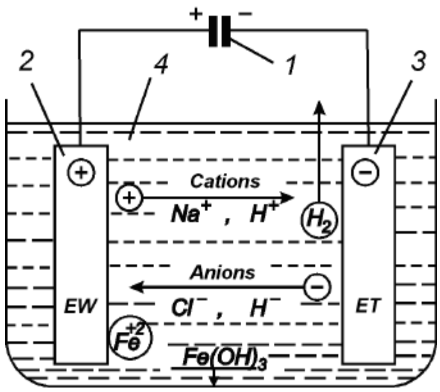


Figure 10.1 – Scheme of electrolysis

Let us view the move of ions in the water solution of sodium chloride NaCl – electrolyte that is most frequently used for ECM. From the power source 1, the voltage is supplied on the electrodes, the anions of hydroxyl and cations of hydrogen along with chlorine anions and sodium cations under the influence of the forces of electric field begin to move towards the cathode and the anode. Atoms of the surface layer of the anode 2, i.e. electrode-workpiece (EW), get additional negative charges from the anions of Cl and OH, and are transformed into positive ions of iron Fe^{+2}. The latter under the influence of cathode and anode reactions interact with the ions of OH^- and form the ferric oxide hydrate $Fe(OH)^3$ that precipitates in the form of inseparable chemical compound. In this way, there occurs electrochemical anode dissolution of iron. At the same time, on the cathode 3, i.e. on the electrode-tool (ET), hydrogen H_2 is extracted that leaves the electrolyte 4 in the form of bubbles. Reactions that occur on the cathode usually do not break it, i.e., the ET doesn't wear out by ECM.

From the scheme in the Fig. 10.1, we can see that electrolysis occurs in the EDM gap (EDM), where anode dissolution in the neutral electrolytes is accompanied by creation of metals' oxide hydrates that precipitate and clog the EDM. So, if passing of the electrolyte on certain areas of EDM is difficult or impossible due to some reasons, normal run of the ECM is violated in this case. In order to normalize the process of ECM, one particularly needs to remove the dissolution products (slime) from the EDM, which is possible to perform with the speed of electrolyte outflow equaling 5…20 m/sec. Such speeds allow machining at increased current density (up to 1 A/mm^2) and assist in cooling of the electrolyte that is heated under the powerful current.

10.2 Main schemes of the ECM processes

The dimensional ECM is the production of the part with the required shape and sizes due to anode dissolution of metal.

There are several schemes of the ECM.

1. Machining with unmovable ET. According to this scheme, one gets local relieves in the parts and holes in sheet metals, marks the information, removes the burrs, rounds sharp edges, sharpens the tooling.
2. Broaching of the cavities, hollows, holes. According to this scheme, one makes working hollows of forging dies, broaches holes, slots, airfoils of turbine blades.
3. Drawing of external and internal surfaces in the workpieces that have pre-machined surfaces, on which basing of the ET is possible. According to this scheme, one performs finishing of cylindrical holes, splines, screw grooves.
4. Cutting of the workpieces. Rotary disc serves as the electrode-tool. According to this scheme, one makes slots, chaps, undercutting of springs.
5. Grinding or polishing. One uses cylindrical rotary ET that performs linear motion along the workpiece. This scheme is used as the finishing operation by manufacturing of thin plates and parts made of ductile and high-strength materials.

Main technological characteristics of the ECM processes are productivity, dimensional and shape accuracy, and also roughness of machined surfaces.

The following factors influence the technological characteristics of the ECM processes: volumetric electrochemical equivalent of machined material k, composition of the electrolyte used and its specific electroconductivity χ, power source voltage U, anode current density i, coefficient of metal output versus current η, spark gap α, technological allowance Z.

According to the Faraday first law, the volume of dissolved metal V by electrolysis is directly proportional to the volumetric electrochemical equivalent k of this metal, current strength I and time τ, mm^3:

$$V = kI\tau . \qquad (10.1)$$

The volume of dissolved metal differs from calculated one according equation (10.1). It depends on anode current density which is defined by relation of current strength and area of anode , A/mm2 :

$$i = \frac{I}{F} . \qquad (10.2)$$

Efficiency of the ECM processes is evaluated by the coefficient of metal output versus current

$$\eta = \frac{V_a}{V} , \qquad (10.3)$$

wherein V_a is the actual volume of dissolved metal at transmitting of certain amount of electricity, mm^3.

Considering the equation (10.1) and coefficient η actual volume of dissolved metal, mm^3, is determined according to the formula

$$V_a = kI\tau\eta \, . \tag{10.4}$$

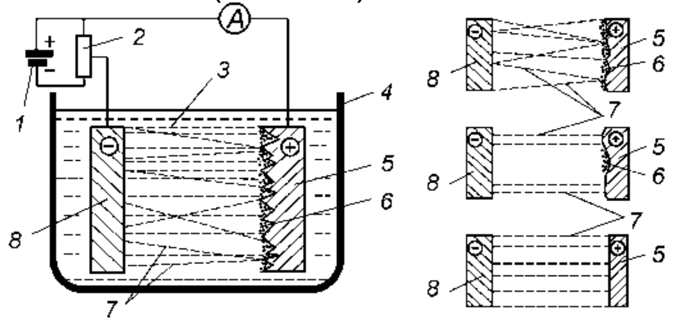
Actual volume of dissolved metal V_a is, as a rule, lesser than estimated volume V (for active dissolution, $\eta = 0{,}5 \ldots 0{,}9$, for passive one – $\eta < 0{,}5$).

Qualitative parameters of ECM processes largely depend on the application of the certain ECM technological schemes.

According to the technological conditions, the ECM operations may be divided for convenience into two groups:

1. ECM with low flux density (0,02…0,03 A/mm^2) in the stationary electrolyte (ECS);
2. ECM with high flux density (up to 1 A/mm^2) in the flowing electrolyte (ECF).

Fig. 10.2, a shows the principal scheme of the ECM in the stationary electrolyte (ECS) for the most typical operation – electrolyte grinding or polishing: 1 – power source; 2 – resistor; 3 – electrolyte; 4 – bath; 5 – electrode-workpiece (anode); 6 – film of dissolved metal (slime); 7 – electric lines of force; 8 – electrode-tool (cathode).



a b

Figure 10.2 – Principal scheme of ECM in the stationary electrolyte:
a – electric scheme; b – mechanism of projections' dissolution

Passing of electric current through the electrodes 5 and 8 and electrolyte 3 is accompanied by dissolution of the EW surface 5 in the electrolyte and formation of the film of dissolution products in the roughness cavities, which isolates them from current, concentrating its lines of force 7 on the unprotected projections of the EW surface (Fig. 10.2, b). Because of this, the projections dissolve quickly, and microroughness are smoothened.

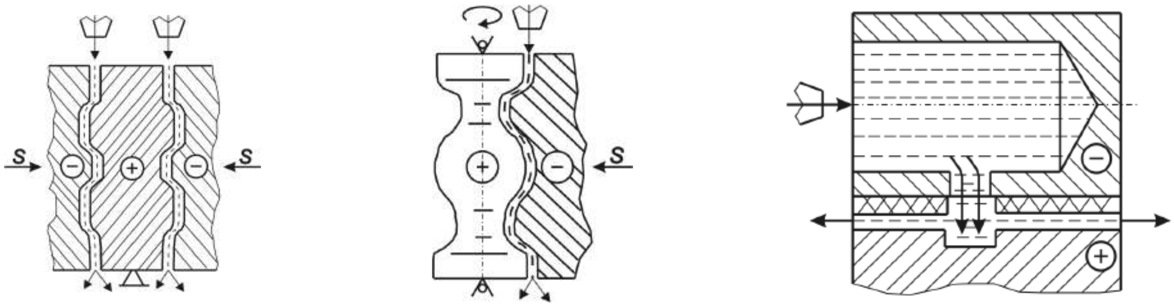
Unlike the mentioned above ECM process, dimensional ECF is performed at continuous and intensive renewal of the electrolyte that is pumped under pressure through the EDM. Forced removal of the electrolyte from the working area provides shape-formation of the machined surfaces with the EDM values lesser than during electrochemical etching and polishing.

According to this, anode dissolution of metal on the areas with minimal value of the EDM occurs on the initial machining stage more intensively than on the areas with high EDM values.

There exists the technological scheme of dimensional ECS with two movable ET placed on both sides of the workpiece (Fig. 10.3, a) that move towards each other with the feed S.

Fig. 10.3, b shows the scheme of electrochemical shape formation of profiled surfaces of bodies of revolution. In this case, work feed S is carried out by moving the ET in the direction of the rotated workpiece.

Grooving of different shapes may be carried out according to the technological scheme shown in the Fig. 10.3, c. During machining, EW and ET are immovable relatively to each other, so, the value of EDM will rise with increasing of the machining time. At such technological scheme not machined surfaces of ET are protected with the layer of dielectric.



a b c

Figure 10.3 – Technological schemes of the ECM processes in the flowing electrolyte

The advantage of the ECM is the possibility of receiving the surfaces of difficultly profiled parts with little roughness without using special tooling.

Disadvantages of the ECM are low specific efficiency and difficulty of its increasing due to the increase of the current density, sensitivity to changing of the electrolyte state and composition.

The advantages of the ECS are high efficiency that essentially doesn't have any limitations in increasing, full absence of ET wear-out, low surface roughness and high machining accuracy along with simultaneous increase of efficiency.

Disadvantages of the ECS are high energy intensity of the process, necessity of using special means for removing the slime and gas and providing intensive circulation of electrolyte.

10.3 Efficiency of the ECM processes

Efficiency of the ECM finishing processes is characterized by machining speed that is expressed in different units of physical values. So, at electrochemical etching, machining speed is determined by amount of metal removed per unit of time, and depending on the type of material machined, electrolyte composition and other factors, it ranges from 0,05 to 0,2 mm/min. Efficiency of electrochemical polishing is determined by a duration of the process, which may be at polishing of carbon steels – 5-10 min, aluminum – 2-3 min.

Efficiency of dimensional electrochemical shape formation is characterized by the speed of anode dissolution of metal which is expressed by linear (mm/min) or volumetric (mm^3/min) units.

At electrochemical shape-formation with stationary electrodes, when the value of EDM is changed during the process of machining, efficiency depends on many factors, with duration of machining being in the first place. So, as the time of machining increases, the value of EDM correspondingly increases and the speed of electrochemical dissolution decreases.

Volumetric electrochemical equivalent k for each type of metal has certain value, and therefore, it doesn't influence on the efficiency of the dimensional ECM. At increasing of the values of U, α, χ, η to their limiting values, one may significantly reduce or increase the efficiency of dimensional electrochemical shape-formation.

As the working temperature increases, electroconductivity and current density on the anode increase. Increasing of pumping speed of electrolyte in the EDM helps to remove the slime from the machining area more effectively, which also increases electroconductivity of the electrolyte layer in the EDM.

At ECM, the quality of machined surfaces is usually determined by their roughness.

Despite traditional processes of machining by cutting, when due to the force action of the cutter, deformed (stressed) layers of metal are formed on the machined surface, ECM doesn't cause any mechanical stresses in the surface layers. In many cases, this has a positive influence on the quality of machined surfaces.

In general, the quality of machined surfaces depends on combining the values of such parameters as composition of electrolyte, its temperature, pumping speed of electrolyte through the EDM and density of electric current.

Using the methods of dimensional EDM for machining of the parts of carbon and stainless steels, when the solution of sodium chloride serves as electrolyte, the surfaces with 2,5…1,25 mkm surface finish are produced.

Increasing of the electrolyte temperature mostly has a negative influence on the surface roughness. But in some cases, e.g., at dimensional ECM of parts of titanium alloys, the quality of machined surfaces is improved as the electrolyte temperature increases.

As the density of electric current increases, roughness of machined surfaces is reduced.

Test questions

1. What factors influence the technological characteristics of the ECM processes?
2. Name the peculiarities of the technological processes of dimensional EDM with the ET that moves in the flowing electrolyte.
3. Name the peculiarities of designing the ET for various ECM technological schemes.
4. What equipment parameters does the ECM efficiency depend on?
5. What are the advantages of dimensional EDM in the stationary electrolyte?
6. What are the advantages of dimensional EDM in the flowing electrolyte?

11 MACHINING OF THE PARTS OF COMPOSITE MATERIALS

Composite materials (CM) are structural materials that are made up of the matrix (base) and reinforcing agent distributed in it. As reinforcing agent, one may use fibers of glass, carbon, boron, organic fibers.

CM have a wide range of properties: specific strength higher than the one of structural metals; low sensitivity to stress concentrators; high corrosion resistance; radio transparency.

High CM indices of specific strength, roughness and fatigue resistance combined with particular properties – radio transparency, high damping ability, low heat conductivity – define their wide usage in the design of modern aircraft.

The design of transport aircraft An-124 created in the Antonov ASTC has a record number of parts, joints, assemblies of CM – over 4000 units per one product with general area of about 1500 m^2 and mass of 5600 kg (Fig. 11.1) [11, 21]. The volume of implementation of CM in the aircraft gliders constantly increases. E.g., the design of An-140 aircraft (model year – 2000) included 13% of CM parts from the whole amount of parts, and the design of An-148 aircraft (model year – 2004) had already 16%.

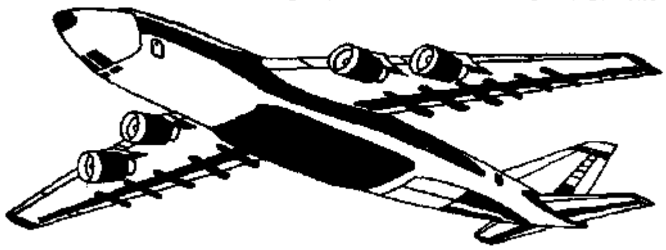


Figure 11.1 – Using CM in the design of the aircraft glider of An-124

Machining by cutting of CM is used at manufacturing of wide nomenclature of traditional parts – casings, skins, stringer and corrugated panels, splice plates, belts, multilayer panels with cell filling.

Technological units of CM – beams, frames, wing spars, assembly sections – have the increased volume of machining with removing of extra material.

Here, almost all present types of cutting are used: cutting out of the blanks, turning, milling, drilling, grinding, etc. Cutting of CM has a number of specific peculiarities that are conditioned mainly by the peculiarities of structure and properties of machined material: heterogeneity, low heat conductivity, presence of fibers, etc.

At the same time, the process of CM cutting is followed by the same phenomena as cutting of metals: chip formation, force and heat phenomena, intensive wear-out of tooling.

11.1 Peculiarities of machining the CM by cutting

11.1.1 Classification of structural plastics

Structural plastics, to which CM belong according to their classification characteristics, differ by composition as well as by physical and mechanical properties. Analysis of the properties and composition of structural plastics used allows determine main characteristics, according to which they should be referred to a certain group for cutting. In the first place, it is changing the properties of the reinforcing agent during heating, which determines the difference in the cutting conditions of these types of materials.

According to heat resistance of the reinforcing agent, structural plastics are divided into two classes: thermoplastic and thermoreactive (Fig. 11.2).

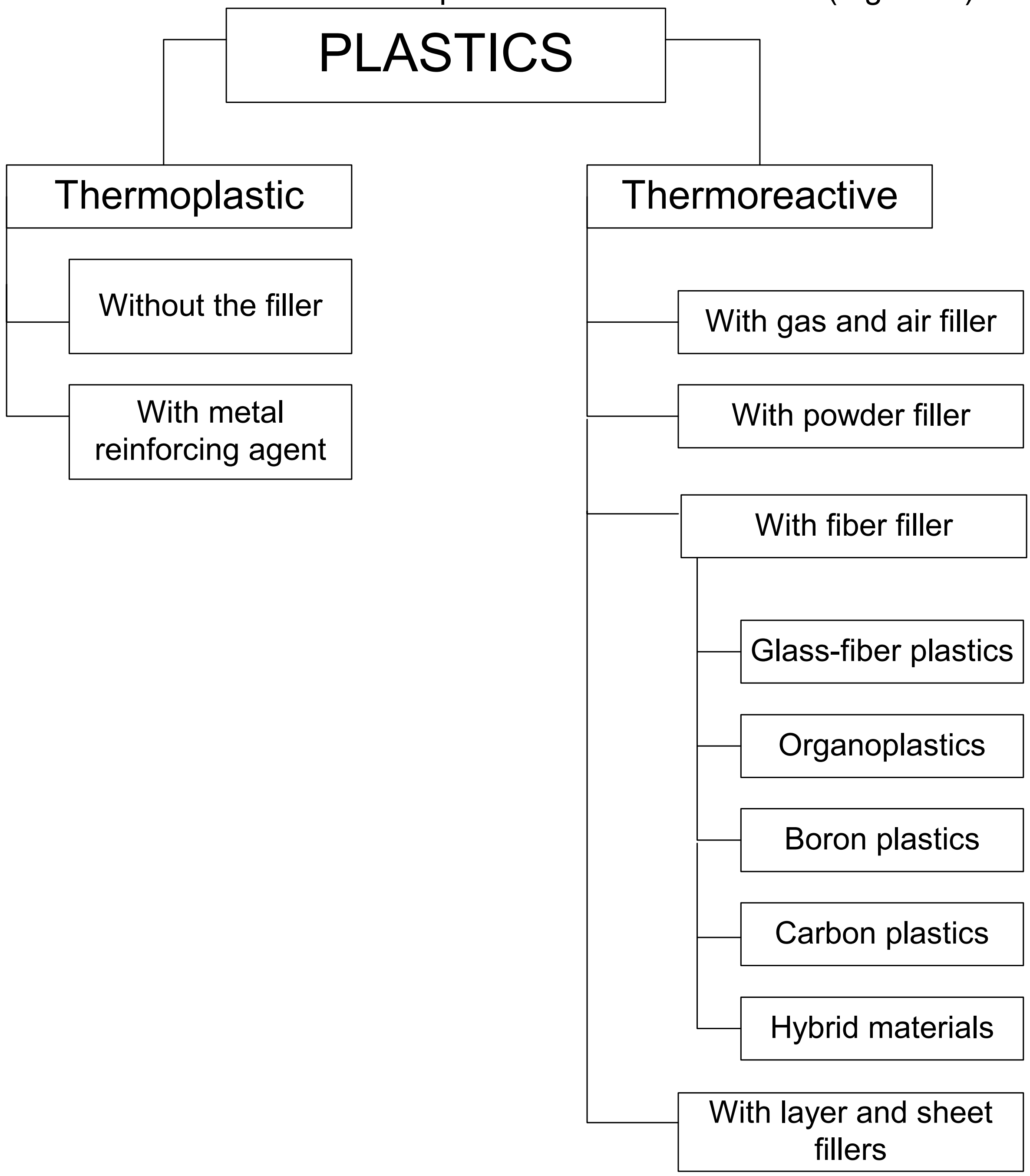


Figure 11.2 – Classification of plastics by their heat resistance

Thermoreactive plastics mostly have phenolic-formaldehyde resins as the reinforcing agent. These types of resins during manufacturing of the parts under the influence of heat and pressure are transformed to the irreversible state, i.e. they aren’t soften during heating.

Thermoplastic plastics, unlike thermoreactive ones, soften under the influence of increased temperature.

Each class of structural plastics, in its turn, is divided into groups by cutting machinability:

1. Thermoplastic plastics:
   - without the filler (perspex, fluoroplastic, kapron, vinyl plastics);
   - with powder-like metal filler (plastics based upon fluoroplastic or polystyrene with powder admixtures of copper, lead, molybdenum disulfide).
2. Thermoreactive plastics:
   - with gas and air filler (foam plastics, cellular plastics);
   - with powder filler (phenoplasts);
   - with fiber filler (glass-fiber plastics, organoplastics, boron plastics, carbon plastics, hybrid materials);
   - with layer and sheet filler (paper-based laminates, textolites).

Materials that belong to one group have similar structure, properties and aggregative state, that is why the particularities of their cutting are the same. This is true for all groups of materials except for the plastics with fiber agent, to which, according to the classification, CM belong. The thing is, such CM as high-strength glass-, ograno-, boron- and carbon plastics, while having the same fiber structure, differ a lot by their physical and mechanical properties.

Group of plastics with fiber filler may be expediently divided into a number of subgroups according to the composition and properties of the filler and the reinforcing agent, and also by the scheme of material reinforcement. When calculating the cutting parameter, these peculiarities are considered by introducing the correction coefficients. In all cases, the first-priority index of machinability is the influence of the machined material on the intensity of the tooling wear-out.

11.1.2 Peculiarities of CM cutting

Typical peculiarities of CM machining by cutting are the following:

1. Tendency to shearing of some types of CM during cutting, which leads to significant increase of the surface roughness, and also to crumbling of the surfaces of the machined workpiece during the tool penetration and removal. Tooling wear-out during machining increases this factor even more.
2. Heterogeneity of material composition and different hardness of its components, which makes it difficult to produce low surface roughness. This results in the fact that permissible level of tooling wear-out depends upon the *technological criteria of wear-out*, first of all, from the increase of the surface roughness.
3. Significant influence of material structure on the tooling due to the presence of components with high abrasive properties.
4. Low heat withdrawal from the cutting area because of reduced heat conductivity of CM, and consequently, overheating of the tooling cutting edges. Because of this, the criterion of maximum permissible cutting speed is often the

carbonization of the surface layer of machined surface. Besides, the temperature rise in the cutting area due to CM lowered heat conductivity favours its softening, and in some cases, its destruction as well.

5. Intensive dust formation, especially during cutting of thermoreactive CM, which leads to the necessity of forced removal of dust and chip from the cutting area with the help of special devices.

6. Difficulty with using the OCL due to hygroscopicity of machined material and its chemical interaction with the OCL, which causes changes of physical and mechanical properties of CM. During machining of thermoreactive CM, one shouldn't perform fluid cooling, as in this case the paste of dust-like chip is formed, and it sticks to the working surfaces of tooling and makes it difficult to machine. This is why at cutting of CM compressed air is the most frequently used medium for cooling.

Mentioned peculiarities of CM cutting indicate that simple application of cutting parameters used for metals for these materials is inadmissible.

During production of the items of CM, the following typical methods of cutting are used: the workpieces cutting off, turning, drilling, reaming and threading, milling and grinding.

11.1.3. Cutting of CM sheet workpieces

Sheet workpieces of CM are cut on the machines with band and disc saws, disc milling cutters, abrasive discs.

In order to avoid significant overheating, it is recommended not to carry out cutting of the CM sheets in large stacks. To avoid vibrations and cracking of the sheets, it is necessary to provide their firm fixation on the machine by applying wooden pads. During cutting of the CM sheets, special attention should be paid to the sharpness of cutting edges of wedge tooling.

Profiled cutting of CM sheets is performed with band fine-toothed saws (tooth spacing up to 5 mm) at the cutting speed of 1000…1500 m/min and feed speed up to 1 m/min.

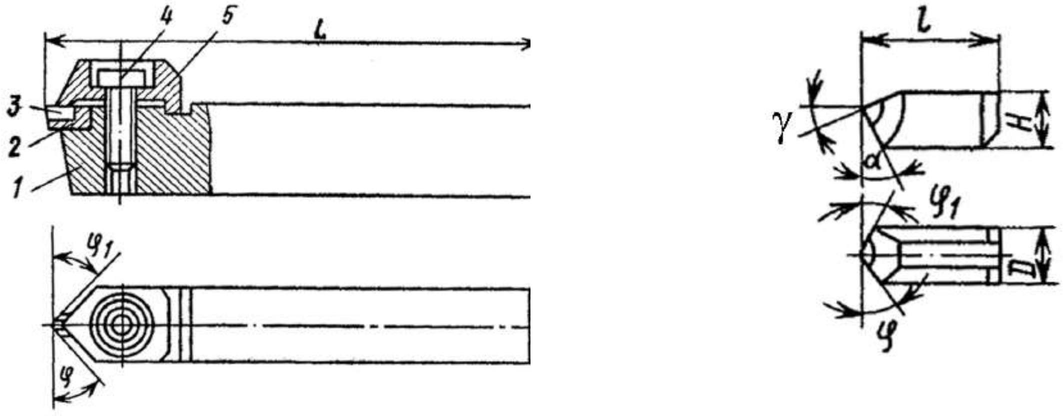
Straight cutting of CM sheets is also carried out with abrasive wheels with granularity of 24 – 46, diameter 300…350 mm and 3…6 mm thick with OCL cooling at such cutting parameter: v = 40…50 m/sec, S_0 = 0,3…0,6 m/min. The cutting scheme for the CM sheets is similar to the scheme of preliminary operations shown in the Fig. 4.2, d.

11.1.4. Turning of CM items

Turning of the parts of CM is performed with high-speed and hard-alloyed cutters; it includes thorough fine finishing of the tooling working surfaces with the paste of boron carbide. The values of cutting depth and load for turning of the CM parts is chosen on the basis of stable removing of chip without its winding on the part, or else there occurs softening of the machined surface and its cohesion with the chip.

For turning of the CM parts (e.g., glass-fiber plastic) that have an intensive influence on the tooling because of the presence of abrasives, one uses the cutting tooling supplied with plates of hard alloys of ВК3М and ВК6М grades.

For machining of the parts of especially strong types of CM, such as carbon plastics, diamond tooling is widely used (Fig. 11.3).



a b

Figure 11.3 – Assembled cutter with the insert of superstrong metal:
a – design of the cutter; b – parameters of the cutting element

Assembled cutter (see Fig. 11.3, a) is manufactured as case form 1, in which with the help of the screw 4 and special plate 5 (which serves as the chipbreaker), one fixes the cutter insert 2 or directly the cutting element 3 of cylindrical, prismatic or plate shape manufactured of superstrong metal.

Cutter insert is the metal casing with the crystals of synthetic diamond of АСПК or ПТНБ grade welded into the slot. Structural dimensions of crystal inserts are standardized (see Fig. 11.3, b): γ = – 5…8°; α = 10…12°; φ = 15…45°; φ_1 = 15…45°; l = 18…30 mm; D = 5…16 mm; H = 4…12 mm.

Cutting parameters for the parts of CM such as carbon plastics that are cut with diamond tooling has the following values: v = 800…1000 m/min, S_o = 0,04 mm/rotation.

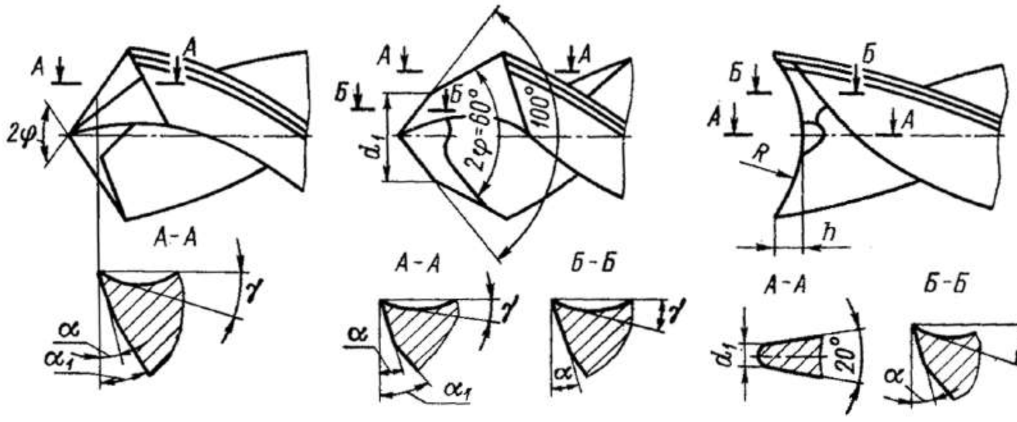
11.1.5. Machining of the holes in the CM workpieces

Drilling of the CM workpieces is one of the most widespread types of machining. Drilling is performed with the drills of high-speed steel, and also with the drills that have plates of hard alloys.

Fig. 11.4 shows the recommended shapes of sharpening of the cutting elements and the design of the drills of high-speed steels and hard alloys.

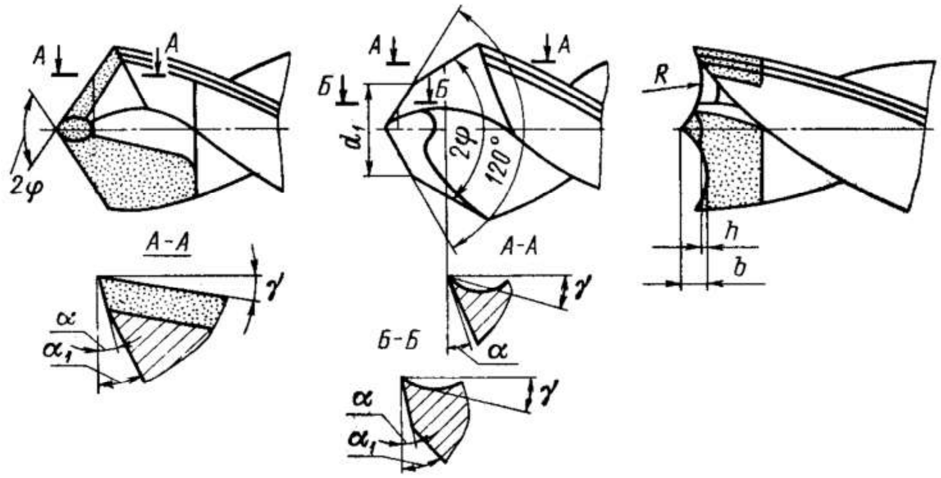
The drills of *high-speed steels* (see Fig. 11.4, a) with sharpening shapes of the cutting element of types NRD (normal recess), DRD (double recess) and RCE (with recess cutting edges) are used for drilling of the holes in glass- and carbon plastics; drills of hard alloys (see Fig. 11.4, b) with the shapes of sharpening – in glass-, carbon and boron plastics.

The point angle 2φ of the drill has the most significant influence on the machining quality of the holes and drills' wear-out. On should take into consideration that during drilling of thin stacks with the drills with sharp point, “pierced” holes are formed, so it is inexpedient to accept the value of the angle $\varphi < 110^{\circ}$.



1 2 3

a



1 2 3

b

Figure 11.4 – Sharpening shapes of the drills’ cutting element
of high-speed steels (a) and hard alloys (b):
1 – NRD; 2 – DRD; 3 – RCE

As the relief angle α increases, the friction force on the clearance surface becomes lower, which favours lesser crumbling of the reinforcing agent, and therefore, reduction of the hole surface roughness.

As the rake angle γ increases, the hole surface roughness increases as well, there occurs disheveling of the hole edges, especially when the drill angles exit the holes.

Reducing of the helix angles of the flute ω up to $10\ldots15^{\circ}$ and using the drills with wide polished flute improves removal of the chip and favours the increase of the holes’ machining quality.

In order to prevent the chip’ sticking to the tooling during drilling, it is recommended to apply molybdenum disulfide on the surface of grooves’ drills. It is not recommended to use cooling liquids during drilling, as the latter mix with the dust and form the paste that makes it difficult to drill.

Wear-out value of the drill is its important quality criterion. For the drill wear-out criterion, one usually considers the wear-out of the relief surface of the drill starting taper.

This way, for example, the drill wear-out up to 0,2…0,3 mm leads to the cracks formation on the parts of powder-like, and on the parts of fiber CM – of fringes and convexities. This is why the permissible wear-out value of the tooling for cutting the CM parts is much lower than the one for machining of metal parts, and it equals 0,1…0,15 mm for the drills.

Cutting parameter for drilling of the CM parts is chosen in such a way that it could provide the necessary level of the surface roughness and the tooling durability period. Excessively intensive machining mode makes it difficult to remove the dust-like chip, causes tool heating and further cohesion of the chip with the surface of the drill flutes. This is why it is necessary to withdraw the drill from the holes during machining.

Drilling at high feeds causes detachment of the material on the entry and exit ends of the hole, and at low feeds it causes fluffiness of the holes' surface. As the feed increases (over 0,3 mm/revolution), the quality of the holes decreases, and so, the durability of the joints is reduced. In the cutting speed range within 10…40 m/min, fluffiness of the holes' surface gets lower.

Core drilling of the pockets in the CM workpieces for countersunk rivets and bolts are recommended to be performed on the drilling and core-drilling equipment with combined tooling – drill-countersink reamer. For core-drilling of pockets, one uses four- and six-toothed core-drills. Increasing of the core drill teeth to six is favourable for reducing the surface roughness of machined pockets and increasing of tool durability. Cutting edges of core-drills should be greatly sharpened. Core-drill wear-out is detected due to fluffiness formation and faceting of the holes' surface.

Reaming of the holes in the CM parts is performed with machine reamers of standard design with the inserts of hard alloys. The reamers have the back or the back and front guide bushings that move along the rotary aligning bushings. Reaming at small feeds is not used, as in this case the hole machining accuracy is reduced, and their ovality and conicity increase.

It is recommended to use the following geometrical parameters for the body of the reamers and the cutting parameter: γ = 0, α = 8…10°, 2φ = 15°; v = 20…40 m/min, S_0 = 0,1…0,6 mm, t = 0,2...0,3 mm.

Machining accuracy of the holes is also influenced by the heterogeneity of metals in the drilled stack: for homogenous stacks (CM – CM) the accuracy is somewhat higher than for the mixed (CM – metal) ones.

Threading in the CM parts is performed with cutters, milling cutters, screw-thread dies. Usually, internal threading for the holding elements of CM is carried out with the taps.

High elasticity of CM during the process of thread formation causes grasping of tooling, which reduces the machining accuracy and leads to the defect as the result of getting the torn profile. In order to avoid grasping of tooling, the rake angle of the taps is done negative within the range of – 5 to – 10°.

In order to reduce the intensity of friction, one manufactures the tap nib as narrow as possible using minimum of them (2 or 3) with polished grooves and ground profile. Chromium plating of the taps' working surfaces also provides good results. External diameter of the taps should be increased by 0,05…0,15 mm, taking into consideration the shrinkage of the threaded holes. It is recommended to conduct chemical and thermal treatment of the taps by cyanidation and to use air cooling during machining.

During threading with the taps manufactured of high-speed steels, the speed shouldn't exceed 15 m/min.

11.1.6 Milling of CM parts

For machining of the parts manufactured of glass-, carbon-, organo- and boron plastics, milling is not a determinative operation, and it is used much more seldom than turning, drilling or cutting.

In order to reduce the CM detachment, this type of machining should be performed according to the scheme of conventional milling, i.e. the direction of miller rotation should coincide with the direction of the workpiece feed move (see Fig. 7.6, b).

Glass- and carbon plastics may be milled with hard-alloyed milling cutters. It is more reasonable to use the tooling of wolfram-cobalt hard alloys, with the alloys with lesser content of cobalt being more durable. It is practically impossible to mill boron plastics with hard-alloyed millers because of their catastrophically fast wear-out.

Geometrical parameters of the tool cutting element have a significant influence upon its durability (Fig. 11.5), which is why they should be chosen correctly. During milling of the CM parts, changing of the main clearance α and front γ angles of the milling cutter teeth influence the tool durability and chip formation at the same level as during turning.

Permissible wear-out value of the milling cutter mustn't exceed 0,5 mm for rough machining and 0,3 mm for finishing one.

The amount of chip during milling of CM parts is significantly higher than during machining of metal parts, which is why one uses milling cutters with wider grooves between the teeth. This doesn't reduce the tool strength, as the cutting forces during machining of CM parts are relatively small.

During milling of CM parts, rather effective is usage of the tooling that include inserts made of superstrong metals. In this case, the design of the tool doesn't practically differ from the design of the milling cutters of hard alloys, and interchangeable blades (e.g., of end milling cutters) are the inserts made of superstrong metals of the АСБ grade.

For milling of slots and drilling of holes in boron plastics and hybrid materials with boron fibers, one uses special tool supplied with the layer of synthetic diamond of Ac15 grade and of granularity not less than 400/315

(Fig. 11.6). The tool consists of the shank end 1 and cutting element 2. The layer of diamond 3 is applied on the end surface and side faces of the cutting element. Longitudinal grooves 4 on the side face and slots 5 on the end surface face 6 form the cutting edges of the tool.

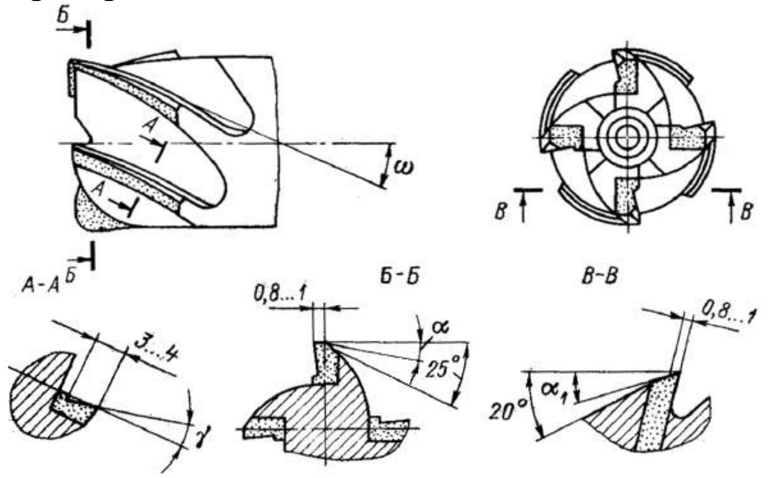


Figure 11.5 – Typical design of hard-alloyed end milling cutter

Cooling liquid is supplied to the area of cutting through the internal cavity and through holes of the mandrel. Recommended rotating frequency of the tool is 9000 min^{-1}, feed per revolution by the given granularity is not more than 0,015 mm/revolution.

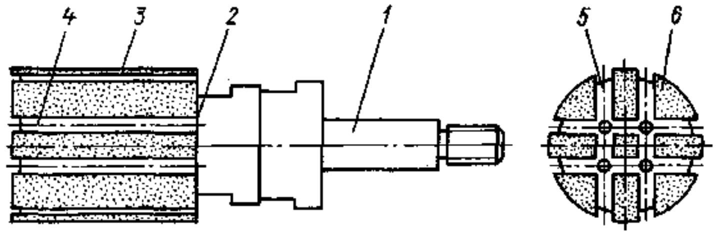


Figure 11.6 – Special tooling with diamond layer

Abrasive machining of CM parts has the following advantages compared to cutting with wedge tooling: lesser surface roughness, absence of scabbing and cracks.

High efficiency of abrasive machining may be reached only by choosing the correct characteristics of the disc for a certain type of CM. Carbocorundum and corundum discs are most frequently used for this purpose. E.g., for round external grinding of CM parts, one uses corundum discs with the granularity 60, hardness M1 by the following cutting parameter: t = 0,2…0,4 mm under the condition that the feed speed will not exceed 0,24 m/min, and disc cutting speed v = 30…35 m/sec.

11.1.7 Machining of parts of metal-polymeric CM

UkrRIAT together with ASTC "Antonov" have developed the technology of manufacturing of structural elements of sheet metal-polymeric CM (MPCM) of three-layer structure [11].

External metal layers of MPCM are produced of metal alloy Д16т, and the internal one is organopolymeric based upon the glue ВК-41, reinforced with two layers of glass fabric.

The use of layered MPCM in aircraft design allows to reduce the mass of the aircraft and to increase their resource, and as to reduce significantly the vibration and acoustic loads.

Compared to aluminum alloys, MPCM have lesser (on 10 – 20%) density, higher (by 10 – 20%) specific ultimate tensile strength, lower (in 10 – 15 times) speed of fatigue cracks propagation, and high damping ability.

Machining of MPCM parts by cutting consists of the following operations: cutting out and cutting of the parts at their external contour, milling, machining of the edges and drilling of holes. To perform these operations, one uses basically the same methods of machining as for CM.

For MPCM, the cutting parameter during milling may be the same as for the corresponding aluminum alloy (Д16Т), but with correction for the tendency of the material to layering. Milling is performed with two-toothed end milling cutters of high-speed steel of Р9Ф5К5 grade .

For machining of chamfers fine finishing of the surfaces and truncating of sharp edges, one uses manual means of mechanization with diamond and abrasive heads, and also small-toothed milling cutters of hard alloys with high rotating frequency – up to 18 000 min^{-1}.

The holes are drilled with diamond perforated drills of diameter up to 100 mm, hard-alloyed ones of diameter 6…30 mm, and also with the drills of high-speed steels of Р18, Р9Ф5К5 grades.

11.2 Chip and dust removing from the CM cutting area

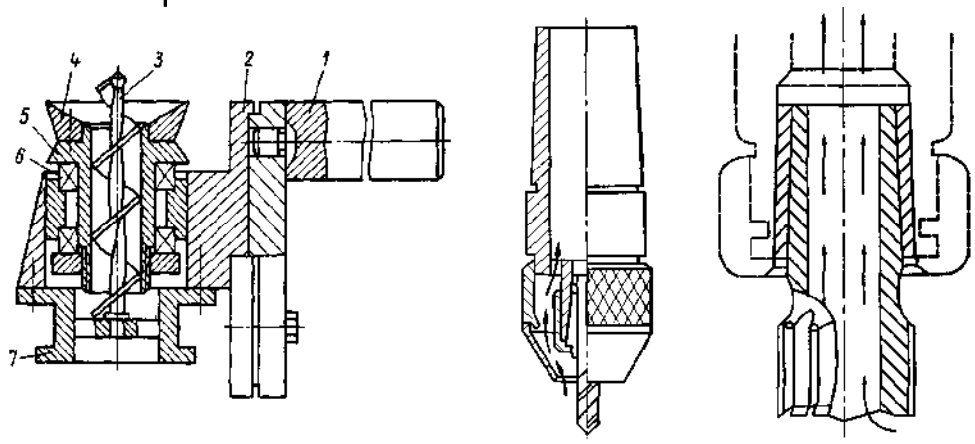
During machining of CM parts with diamond discs and drills, hard-alloyed cutting tooling, and also with the tooling of hard-alloyed metals, toxic dust and fine-crushed chip is formed. In order to remove chip and dust from the cutting area, exhaust ventilation and tooling of special design are applied.

In order to exhaust ventilation operated effectively one should have a certain system of pipelines and correctly designed catcher receivers in the working zone of the machine.

Such catcher receivers are used at cutting off of the workpieces, threading with diamond discs, grinding, when the chip is the disperse particles that move with high speed within a rather narrow area. By embracing this area with the corresponding catcher receiver, one may remove the wastes formed during cutting.

Special design of the tooling allows to catch chip and dust in the zone of their formation, i.e. directly in the area of cutting with the tool (Fig. 11.7). Fig. 11.7, a shows the design of special self-rotating cutter of hard alloy used for external turning of the CM workpieces.

Mandrel 1 is fixed in the tool-holder of the machine. Hard-alloyed self-rotating cutter 4 is installed in the bushing 5 that is joined with the frame 2 through bearings 6. By means of bolt auger 3 is firmly fixed to fitting 7 joined with casing 2. Fitting 7 is connected with the system of exhaust ventilation. In the process of machining, the cutter rotates, and the chip moves to the channel along the helical grooves of the auger. Exhaust ventilation connected to this channel facilitates this process too.



a b c

Figure 11.7 – Tooling of special design for machining of CM parts:
a – turning cutter with chip-withdrawal device;
b – collet draw-in gear with annular slot; c – hollow milling cutter

During drilling, the dust and chip are removed through the collet draw-in gear with the annular slot (see Fig. 11.7, b), and during milling – through the central hole in the tool (see Fig. 11.7, c).

In order to use manual means of mechanization, the workplace should be provided with the personal portable vacuum cleaner of FPGA-type.

The workers that perform the operation of mechanical machining should be supplied with the means of individual protection: respirator, protective goggles, gauntlets, and overalls.

Test questions

1. What conditions the usage of CM in the airframe design of modern aircraft?
2. Give the classification of structural plastics according to their heat resistance and cutting machinability.
3. What characteristic peculiarities of cutting are typical for conventional CM?
4. Describe the typical design of diamond tooling for turning of parts manufactured of superstrong CM, such as carbon plastic.
5. How do the geometrical parameters of the drill cutting edge influence the machining quality of the holes?
6. What sharpening shapes of the cutting element have the drills used for machining of the holes in the CM parts?
7. Name the peculiarities of milling of CM workpieces.
8. Describe the design of special tool with diamond layer for milling and drilling of the workpieces manufactured of boron plastics.
9. What peculiarities of cutting are typical for metal-polymeric CM?
10. What methods of withdrawing of chip and dust from the cutting area are used during machining of CM parts?

12 HARDENING TREATMENT USING THE METHODS OF SURFACE-PLASTIC DEFORMATION

12.1 Influence of the surface hardening on the resource of the aircraft parts

During aircraft running, the assemblies of the airframe are subjected to repeated high loads. Under such conditions the mechanism of influence of surface hardening on the material structural strength significantly differs from the one that takes place in the zone of small stresses typical for usual fatigue.

Formation of residual compression stresses in the surface layer is critical for increasing the fatigue resistance of the airframe parts. In the small-cycle zone of repeated high loads, the most important factor that influences the durability of high-strength materials is radical improvement of the surface microrelief.

Workhardening removes sharp cuts, provides most favourable surface microrelief, and by this the fatigue resistance of the surface layer is increased.

For B93, B95 and Д16 aluminum alloys the effect of workhardening at repeated high loads is very significant. For B93 and B95 superstrong aluminum alloys because of their high sensitivity to condition of the surface, the effect of workhardening is higher than for the less strong Д16 alloy.

Hardening treatment by the methods of surface-plastic deformation (SPD) may be applied to the parts of various shapes and sizes manufactured of various metals.

There exists a large group of the parts of small hardness, such as panels, walls, arcs, profiles, that are manufactured of superstrong steels, aluminum or titanium alloys.

Load-bearing parts, e.g. panels, cylinders, beams, posts, shafts, brackets, manufactured of superstrong alloyed steels and titanium alloys, may be hardened by the surface strainhardening both at all and at certain surfaces.

The shape of the hardened surface influences the choice of the method, means and parameters of SPD methods. This is why it may be used as the main principle for systematization of the local hardening technology. The surface geometry determines also the degree of stress concentration.

After hardening treatment of the part by the SPD methods, the surface microgeometry or roughness are changed. Also, some methods of hardening reduce the roughness of machined surface (drawing of the holes), the other ones increase it (bead blasting), but in all cases the parameters of initial and final roughness are interrelated.

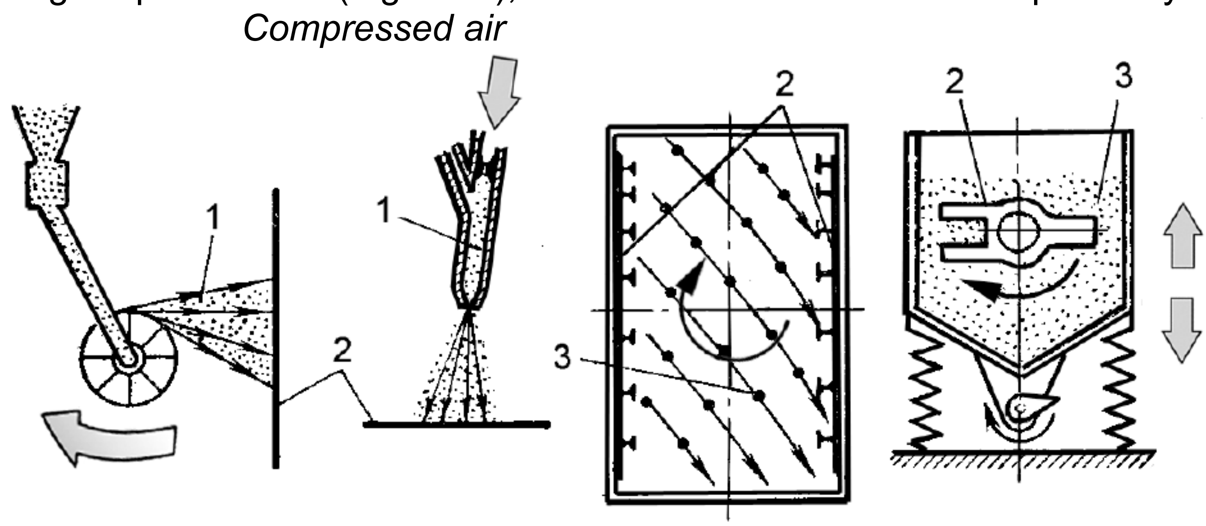
The lesser is the surface roughness of the parts before hardening, the more effective is the process of hardening.

The places of stress concentration should have the following surface roughness: for steel parts after machining – not less than R_a 2,5, and for the parts of aluminum alloys it is not less than R_z 40…20.

Depending on the shape, sizes and material of the part, requirements to the geometrical parameters and surface quality, production and other conditions, one may use various methods of hardening treatment by the SPD.

12.2 Impact methods of surface hardening

The method of hardening is chosen depending on the shape and sizes of the part, its working conditions and the condition of the surface layer, technological possibilities (Fig. 12.1), and also on the economical expediency.



a b c d

Figure 12.1 – Impact methods of hardening: a – flow and mechanical; b – flow and pneumatic; c – rotary-impact; d – vibration; 1 – beads; 2 – part; 3 – granules or balls

Independently of the variants of the technological scheme, there are two types of surface hardening of the parts:

– significant plastic deformation of the surface layer without removing of metal (surface hardening by vibration workhardening, pneumodynamic, vibroimpact, shot-blasting or hydro shot-blasting workhardening);

– insignificant plastic deformation with removing of metal with the depth 0,01…0,3 mm at small depth of workhardened layer (surface hardening by vibration grinding of hydroabrasive grinding and polishing).

12.2.1. Technological peculiarities of vibrohardening

The essence of vibrohardening is in the following. Working environment that consists of abrasive or metal particles (granules, balls) and parts under treatment placed in the vibroinstallation container (Fig. 12.2) perform mechanical vibrations with acceleration (10…15)*g*. Under the influence of these oscillations, the particles of the working environment get the energy enough to carry out plastic deformation of the part surface layer.

Main parameters of the SPD processes that determine the degree of workhardening, residual stress and surface roughness are the following:

− characteristics of the working environment (material and diameter of the balls; material, granularity and shape of the abrasive filler);

– amplitude and frequency of vibration that determine the speed and acceleration of vibrating particles;

– duration of the hardening process.

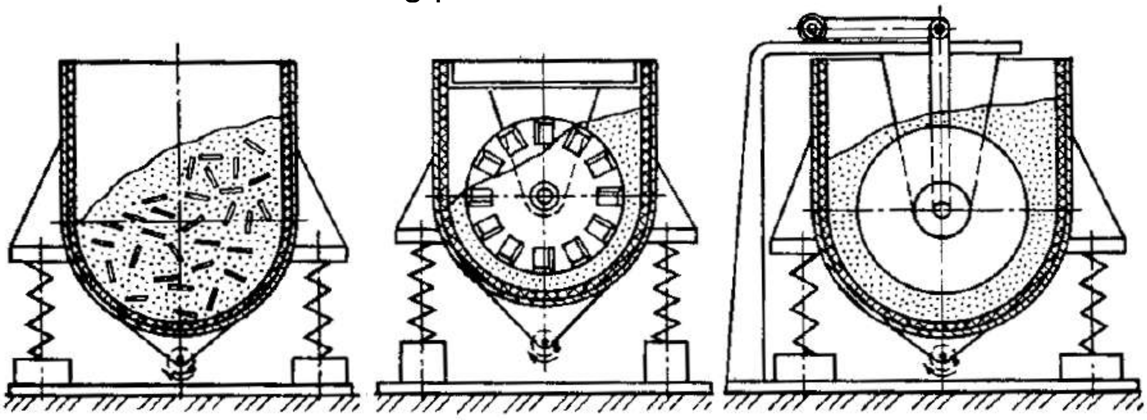


Figure 12.2. Methods of loading of the part during vibrohardening:
a – free placement; b – fixation in the reservoir; c – fixation on the isolated support

Depending upon the working environment used, vibrohardening may be carried out as the operation of vibrogrinding or vibropolishing.

Vibrogrinding is performed with abrasive granules with grains of dimension over 50 mkm and used for removing the defective layers from the part surface and providing roughness R_z 1,25. In the parts' surface layer, there occurs residual compression stress with small depth of spreading (up to 80 mkm).

Vibropolishing is carried out with abrasive granules with grains of dimension less then 50 mkm and used for providing surface finish of the part R_z 0,65 and greater. In the parts' surface layer, there occurs residual compression stress with small depth of spreading (up to 50 mkm).

Residual compression stress that occurs as the result of polishing with steel balls, compared to residual stress that occurs during vibrogrinding is somewhat smaller in its magnitude, but is spread on a significantly greater depth (over 200 mkm). The size of particles of the working environment also has a significant influence on the parameters of the workhardening and residual stress in the surface layer of the parts. The smaller the sizes of the particles, the smaller the workhardening and the residual stress.

Vibrohardening with steel balls provides the highest plastic deformation; it is called *vibroworkhardening* and marked as V.W. Vibrohardening in the filler of abrasive particles provides great removal of metal at small increase of its fatigue resistance; it is called *vibrogrinding* and marked as V.G.

Before hardening, the roughness of the part surfaces of steel shouldn't exceed R_z 20, of aluminum alloys – not higher than R_z 40. Surfaces of the parts with R_z 40 surface finish manufactured by precision casting are subjected to vibroworkhardening without their preliminary preparation.

It is recommended to perform vibroworkhardening of thin-walled parts, e.g. cylinders, landing gear struts, before the final finishing of the holes that in this case have the allowance, which allows to eliminate their chute-like shape (ovality) during grinding, if this ovality has occurred during treatment by SPD methods.

Vibroworkhardening of the internal cavities of the parts may be performed simultaneously with treatment of internal surfaces or separately from it. For this, the internal cavity is filled with the working environment by 70-80% and closed with the plug. Vibrohardening of the parts that severely differ from each other by the mechanical properties of the material, shape and mass, in one container is inadmissible.

In the process of vibroworkhardening, the working environment is formed with steel metal balls with diameter 4…6 mm that should be polished, clean and have no surface defects. During maintenance, the balls should be regularly washed in kerosene, sorted in 150…200 hours and culled. They should be stored in the bins in the aqueous solution of triethanolamine.

Intensity and quality of the hardening processes is controlled on the basis of determining the deformation of the reference specimen. The reference specimen for all hardened steel parts are manufactured of the 30ХГСА or 30ХГСНА steels and are obligatory polished, and for all hardened parts of aluminum alloys – of material similar to the material of the parts. Deflection of the reference specimen during one-side hardening treatment should be the following: in case of using the methods of V.G. – not less than 0,4 mm, the methods of V.W. – 1,6…3,0 mm.

If one accepts the efficiency of vibroabrasive treatment of the items of the 45 steel as the basic unit, then removing of the metal from the part surface manufactured of other materials under the same conditions will be approximately the following [25]:

- of aluminum alloys – 1,6;
- non-hardened carbon and alloyed steels – 1,0;
- hardened alloyed steels – 0,9…0,8;
- corrosion-resistant and refractory alloys – 0,8…0,7;
- titanium alloys – 0,6.

12.2.2 Pneumodynamic method of hardening

Pneumodynamic method of part hardening is based on using the cinematic energy of the balls or beads passed on to them by the flow of air supplied in the working camera under pressure 0,3…0,6 MPa.

Main parameters of pneumodynamic method of hardening are the following: air pressure; material and diameter of the balls (beads), their hardness; distance from the nozzle gap to the machined surface; length of the working area of the camera; residual stress of the balls (beads); machining time.

Pneumodynamic hardening is applied to the parts of aluminum alloys with the wall thickness not less than 4 mm and to steel parts with the wall thickness not less than 2,5 mm.

For pneumodynamic hardening treatment, the installation of БДУ-Е2М type is widely used (Fig. 12.3).

The installation consists of the system of loading 2, gathering 1 and cleaning 5 of the beads and working camera 10 connected to the main systems with the help of two sleeves: supplying of the air-bead mixture 7 and bead sucking 6. The mass of the beads loaded is up to 100 kg.

The working camera consists of the connecting pipe 8, nozzle 9 that supplies the particles on the workpiece surface 12, and exhaustion cavity 13, through the connecting pipe 4 of which the beads are withdrawn from the camera. In order to avoid the beads' getting out of the camera, brush sealing 11 is foreseen. The installation is mounted on the bogie 3, so it may be transported. Deforming bodies are the beads with the diameter up to 2 mm.

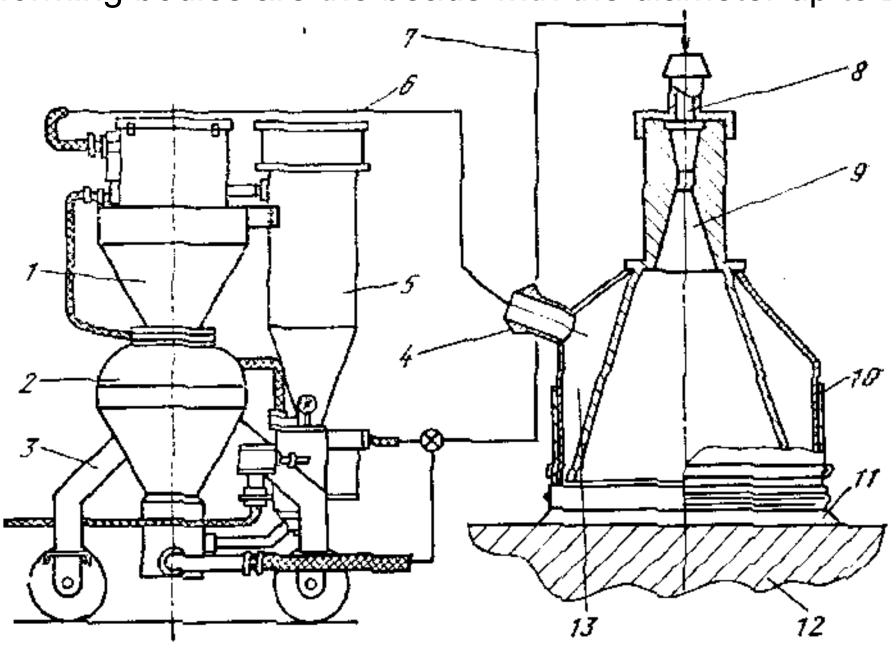


Figure 12.3 – Scheme of the pneumodynamic installation БДУ-Е2М

Pneumatic *portable* device (Fig. 12.4) is widely used as a means of local hardening using the SPD methods.

The device consists of the casing 1 and the handle 2. The working camera of the device is the channel in the casing between the profiled central body 6 and the side lid 8.

For storing the beads before using the device and gathering them after work, the catcher 3 with the shutter 4 are provided in the casing. The device has the set of elastic rubber heads 5, configuration of which depends on the shape of the surfaces 7 being hardened.

Compressed air is supplied into the working camera through the nozzle 9, exhaust air is withdrawn through the holes 10 in the side lids. After the device has finished working, the blocking of the profiled channel shutter 4 is opened;

the beads move to the catcher 3, and the exhaust air leaves through the side holes of the catcher.

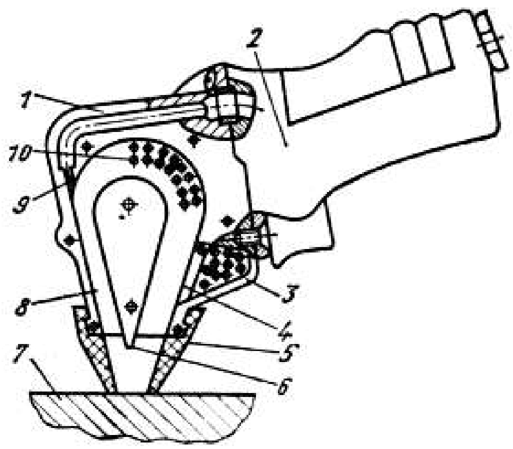


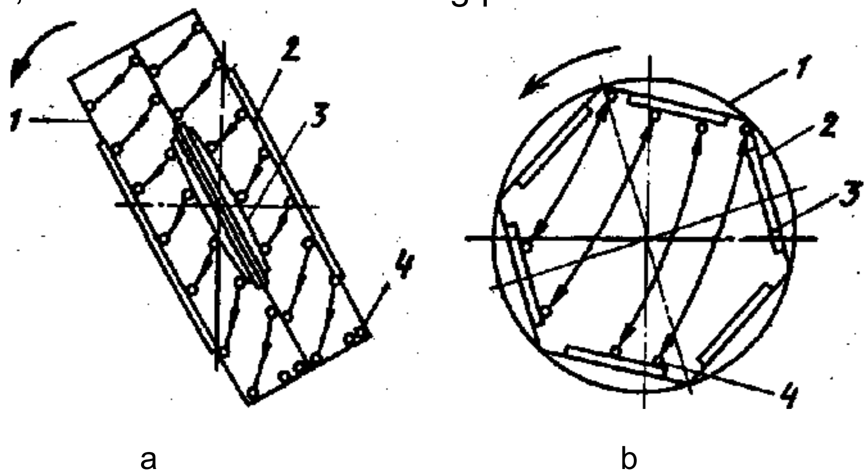
Figure 12.4 – Scheme of pneumatic portable device

12.2.3 Drum-impact methods of hardening

Drum-impact method of hardening (see Fig. 12.1, c) is used for treatment of aluminum, steel and titanium parts, such as panels, wing spar skins, belts, ribs, stringers, frames with smooth and ribbed surfaces [21].

Drum-impact hardening is provided by hitting of the granules of granular working medium with the surfaces of parts being treated. The parts are fixed inside the drum that rotates about the horizontal axis. The granular working medium gets the energy at the expense of centrifugal and gravitational forces as the result of the drum rotating (Fig. 12.5).

The drum 1 has the rectangular (see Fig. 12.5, a) or hexagonal (see Fig. 12.5, b) shape. The cavity of the drum is of a rectangular shape and it is divided with the central dividing plate into two working cameras. Parts being treated 3 are fixed on the removable panels 2 that close the holes of the working cameras, and on the central dividing plate.



a b

Figure 12.5 – Schemes of parts location in the drum:
a – in the two-chamber one; b – in the multi-side one

During rotation of the drum, the granules of the granular working medium 4 fall on the surfaces of the parts being treated, the surface layer of the parts gets plastic deformation that results in hardening. The part surfaces hardened in turn. In order to increase the uniformity of part treatment, the rotation direction of the drum is periodically reversed.

As the granular working medium, one uses the bricks of the B95-T1 alloy with the side size 2…5 mm. Treatment is performed dry with constant ventilation of the drum working cameras.

12.2.4 Vibroimpact method of hardening of long-length parts

The essence of vibroimpact hardening is in deformation of the metal surface layer as the result of hitting of the part with steel balls poured on its surface.

This method of hardening is performed on the special vibrator installation (Fig. 12.6) used for simultaneous treatment of internal and external surfaces of long-length parts, e.g. wing spars, propeller blades of helicopters, etc.

On the rigid platform 1 unbalanced guide vibrators 2 are fixed. Platform 1 with the help of elastic hangers 3, 5 is installed on the frame 4 fixed on the foundation.

The part is located in the special container 8, and on the surface being treated, steel balls 6 are poured. In order that the balls not fall down, the end surfaces of the container are closed with plugs.

The container with the part and balls is fixed to the platform with special pins 9.

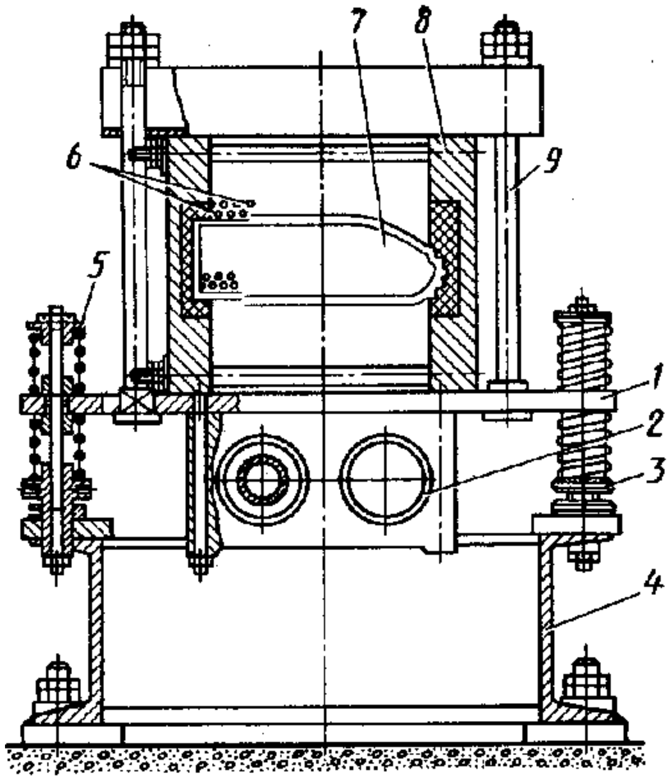


Figure 12.6 – Scheme of vibration installation

Vibrators 2 are simultaneously started with the direct current electric engine with regulated excitation frequency of 20…40 Hz. The process of hardening is performed minimally in two engineering steps. Vibroimpact hardening allows to make the depth of the workhardened layer up to 0,6 mm both on external and internal surfaces.

12.2.5. Shot-blasting method of hardening

Shot-blasting method of hardening is based on using the kinematic energy of metal particles (steel or porcelain balls, glass spheres, beads) that under pressure of the compressed air are supplied on to the surface of the machined part (Fig. 12.7).

Shot-blasting hardening of long-length parts, such as monolith ribbed panels and wing spars without shape formation is carried out in the special installations in the form of large cameras at vertical position of the part.

The distance from the nozzle to the machined surface is 200…250 mm, and the nozzle moves across the strength ribs with the speed of 0,5…0,9 m/min.

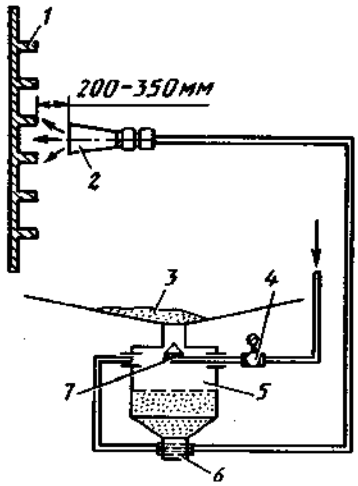


Figure 12.7 – Scheme of the shot-blasting processing in the camera:
1 – part; 2 – nozzle; 3 – bead collector; 4 – reducer-manometer;
5 – working bin; 6 – pipe adapter; 7 – bypass valve

Treatment is carried out in a closed cycle. As treatment environment, one uses steel cast beads of the ДСЛ grade with the diameter 0,8…1,2 mm, steel balls of construction steel of the ШХ-15 grade with the diameter 0,8…3,0 mm.

12.3 Static methods of surface hardening

12.3.1 Spinning with roller-type and ball rolls

Spinning not only increases the strength during dynamic loads, but also raises wearability and corrosion-resistance of such parts as landing gear struts, shafts and wheel hubs.

Depending upon these parameters, the depth of the layer with residual deformation is in the range from 0,01 to 05 mm and higher.

The process of spinning of external body of revolution is reasonable to perform on the turning lathes, internal ones – on the turret or drilling machines, and flat ones – on milling or planing machines.

Spinning is carried out with the speed 30…150 m/min and feed 0,1…0,2 mm/revolution, with intensive use of oil in order to reduce roughness of machined surfaces. Hardening of the surface layer depends less on the spinning speed, but is more dependent on the number of the working strokes.

In order to reduce roughness and to strengthen the parts with relatively correct surface shapes, one uses spinning with spring-actuated roller-type and ball rolls (Fig. 12.8, a – d).

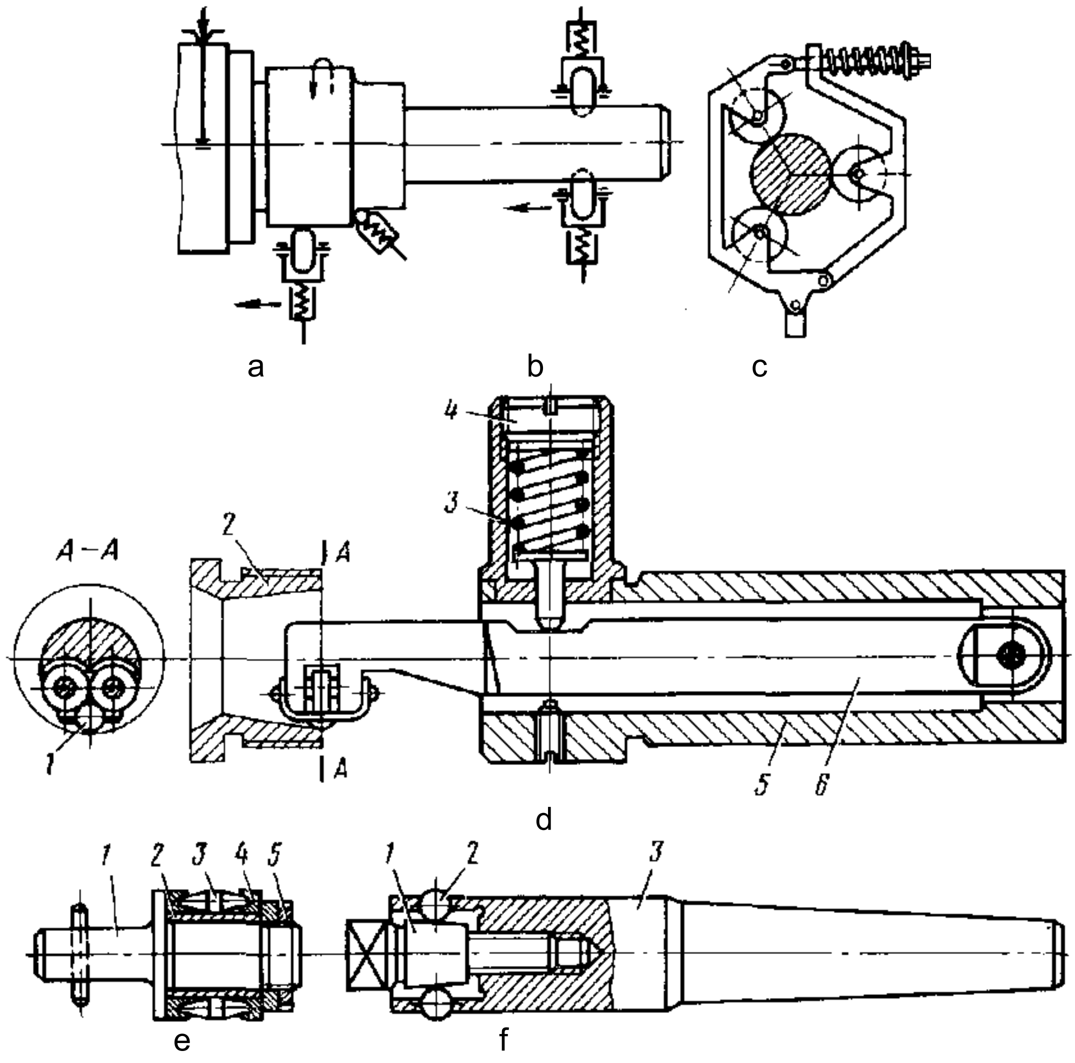


Figure 12.8 – Schemes of spinning and rolling:
a – one-roller, b – ball-type, c – three-roller runner;
d – ball runner (1 – ball, 2 – workpiece, 3 – spring, 4 – screw, 5- frame,6 - mandrel); e – non-regulated roller runner (1 – mandrel, 2 – bushing, 3 – roller, 4 – iron ring with sockets, 5 – check-nut); f – regulated ball runner

The part surfaces of high roughness are spinned with single-roll devices (see Fig. 12.8, a), and in other cases – with three-roll spinning tool (see Fig. 12.8, c).

For spinning of transitional and other similar zones, one sometimes uses balls instead of rollers (see Fig. 12.8, b, d). The pressure of the tool on the machined surface is in the range from 1,47 to 4,9 kN and is created with calibrated springs, pneumatic or hydraulic devices.

For calibration, machining and hardening, one uses both rigid non-regulated (Fig. 12.8, e) and regulated (Fig. 12.8, f) roll burnishers and spinning tools, in which the rollers or balls are firmly pressed by certain force to the machined surface.

One uses rigid roll burnishers for treatment of the holes with the diameter 6…500 mm and up to 3 mm long in parts of steel and non-ferrous alloys.

During spinning and internal roll burnishing, the diameter of the machined part changes in the range from 0,005 to 0,03 mm, but the inaccuracies of the geometric shape, such as ovality, conicity and waveness of the surface, are not removed.

Main parameters that characterize the process of treatment with roller are: radial force, longitudinal feed, circumferential speed, diameter of the roller and radius of its profile. The number of steps during roller treatment is not more than two. One should also take into consideration that if one doesn’t follow the optimal treatment parameters and exceed the optimal number of steps during rolling, this may lead to peeling of the machined surface and appearing of cracks on the surface layer.

12.3.2 Mandrelling, pressing of the edges

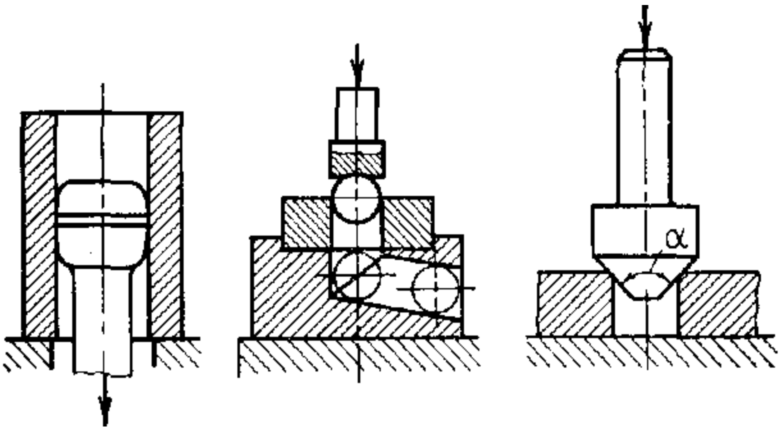
Mandrelling is an effective process of hardening the holes for bolt joints, especially in those cases when treatment occurs in the stack of parts without their further disassembling.

Mandrelling of the holes with the diameter up to 40 mm is carried out by pulling with interference fit of the special tool called mandrel through them (Fig. 12.9, a). Sizing is done in a similar way with the help of steel polished balls (Fig. 12.9, b). Mandrelling and sizing are performed on the presses, impact machines and other types of machines.

In order to reduce friction and roughness, the burnisher and the machined surface are oiled before sizing. Mandrelling may increase the machining accuracy of the hole per one class and reduce roughness from R_a 40 to R_a 0,32.

Sizing speed doesn’t have any insignificant influence on the accuracy and roughness of machined surfaces. The optimal interference fit value during mandrelling (up to 0,2 mm) is determined depending on the mechanical properties of the material, size of the holes, initial surface finish, and quality of lubricant.

The criterion for choosing the optimal parameters of mandrelling or sizing and also for rolling is the quality of hardening: the surface should be smooth, especially near the hole edges, where the concentration of stress is the highest.



a b c

Figure 12.9 – Schemes of the SPD processes of the holes:
a – mandrelling; b – sizing with the ball; c – pressing of the edges

Pressing of the hole edges with steel polished balls (Fig. 12.9, c) is used to increase the strength and durability of bolt and riveted joints, shanks with holes for supply of the oil, ears of hinge joints.

The edges of the holes are pressed statically or, if needed, with strong and sparse hits of the pneumatic hammer. Machine oil is applied on to the working surface of the swaging tools before pressing. After pressing of the hole edges, the surface should be shiny, with surface finish in the range from R_a 0,32 to R_a 0,16, without noticeable marks of shearing or metal detachment.

In order to increase the durability of especially critical application parts or to strengthen the holes allocated in the most loaded places, it is reasonable to combine the types of treatment – use mandrelling and pressing of the edges.

The effect from hardening remains at the temperature up to 200°C for aluminum alloys and up to 400°C for steels.

Test questions

1. How does the surface hardening influence the resource of the airframe parts?
2. What technological schemes of impact methods of hardening are used in aircraft production?
3. What parameters determine the process of vibrohardening?
4. What parameters characterize the pneumodynamic method of hardening?
5. Design the principal scheme of pneumatic portable device for local hardening treatment.
6. What scheme is vibroimpact hardening of long-length parts of the aircraft airframe performed according to?
7. Draw the scheme of shot-blastingtreatment of the parts such as panels.
8. What schemes are used for spinning of the shafts and rolling of the holes?
9. Draw the schemes of burnishing, sizing of the holes and pressing of the hole edges.

13 MANUFACTURING PROCESSES OF TYPICAL PARTS OF THE AIRFRAME

On modern machine-building productions, NC machines are the universal means of automation of controlling the technological machinery.

Control program (CP) put into the NC device of the machine sets the trajectory of the tool movement, power-operated actuators of the main movement and auxiliary devices that provide manufacturing of the certain part. Due to the equipment of the NC machines, control of the machine operation is automated and general technological possibilities of the machines remain or are expanded.

NC machines may perform cutting of two types:

- *profile (shape) cutting* – for machining of the surfaces of variable profile typical for milling and turning;
- *positional* – for formation of the surfaces with identical geometrical parameters, e.g. holes (these are mostly operations of drilling, threading and boring).

The usage of the NC machines has caused the appearance of the new group of machines – hybrid. Foreign companies mark hybrid machines with the abbreviation *MC* (Machining Center).

By hybrid machine one now understands the drilling-milling-boring machine equipped with tool magazine (carrier) and devices for automatic change of the tooling that allows to perform complex positional and *profile* machining per one control program (CP).

Hybrid machines appeared on the basis of both milling machines that typically have high power of the main move drive and drilling-boring machines that are characterized by high machining accuracy.

According to the technological possibilities, all models of multicenter NC machines may be divided into two groups:

1. Machines, design and structural configuration of which depends on the type of technological operation that is more important (usually, it is milling). The following machines belong to this group: ФП-27С, ФП27-4С, ФП-17СМН, ФП-7СМН, МА-655А, МА-655В, МА-655СМЗОА, ВФЗМ8, etc.
2. Machines that have the same technological possibilities as for performing a wide range of machining operations. The peculiarity of these machines is in the fact that machining is usually performed with the axial tool (drill, core-drill, reamer, etc.). Milling operations on these machines are carried out at lower cutting parameters than on the machines of the first type. The following machines belong to this group: АПРС-11, СМ400Ф4.5, СМ630Ф4.4, АГП630-800-1.3, АГПН630-800-1.3, etc.

13.1 Structural configuration of milling NC machines

By structural configuration one understands the combination of the machine units that characterizes their type, mutual location, connection and movement in order to provide the performance of the given technological process (TP) (Fig. 13.1).

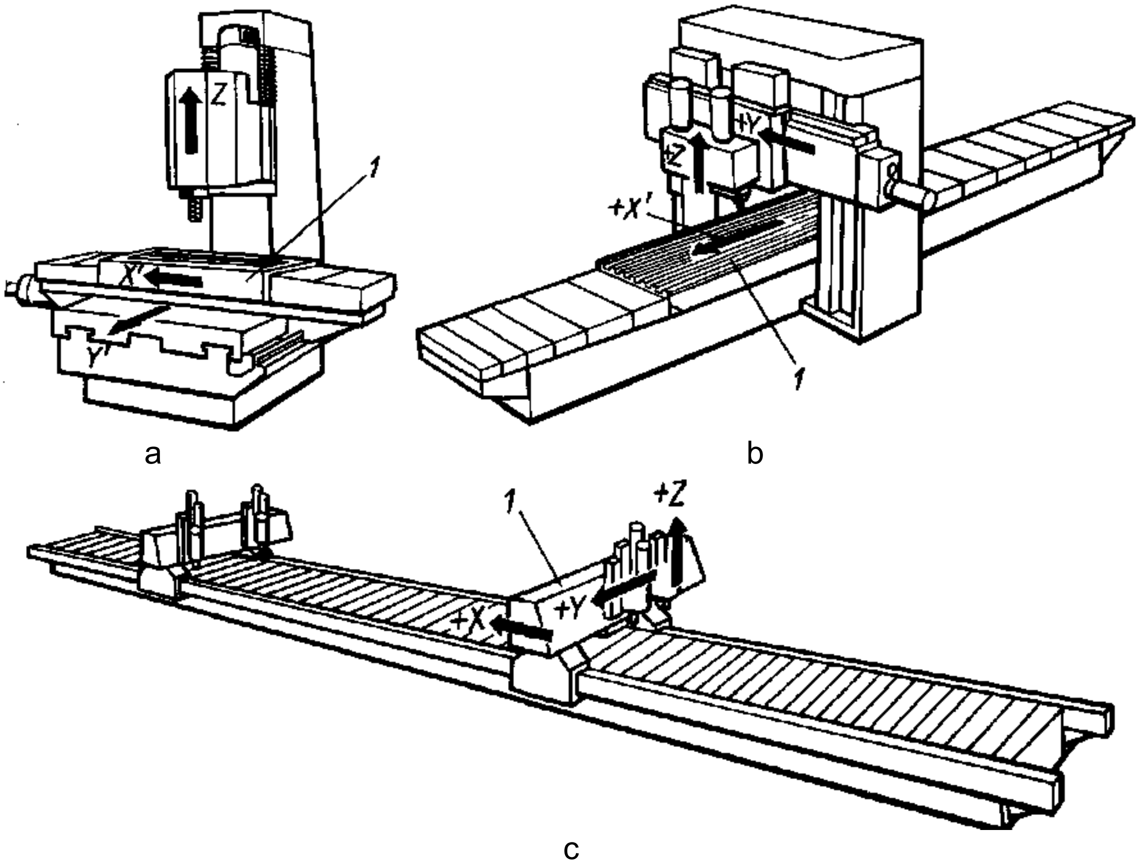


Figure 13.1 – Main types of structural configuration of milling NC machines with different direction of the movement stroke

For manufacturing of wide range of parts of aerospace production, one uses universal and specialized milling NC machines of the following structural configuration types:

1. With cross-like table 1 located horizontally along the coordinate axes X' and Y', and the immovable column that supports the spindle head that moves along the coordinate axis Z (see Fig. 13.1, a). Such type of structural configuration is typical for vertical milling machines, e.g. model MA-655, with transversal stroke length Y up to 600 mm and longitudinal stroke length X up to 2000 mm.
2. Portal-type with movable table 1 that moves along the coordinate axis X at the distance up to 10000 mm (see Fig. 13.1, b). One or two spindle heads move along the coordinate axes Y and Z. Machines of ФП-9М and ВФ-3М8 models have this type of structural configuration.
3. Portal-type with movable portal 1 that moves along the longitudinal coordinate axis X, with stroke length over 10000 mm (see Fig.13, c). Here,

the table of the machine is immovable, and the spindle heads move along the coordinate axis Z. Such structural configuration is typical for the machines of ПФП-5, 2ФП-231, 2ФП-242В models.

By *specialized* NC machines one understands the machines, the parameters of which (stroke length, speed of spindle rotation, structural configuration, number of coordinates of the working move) differ from the parameters of the machines of general purpose [12].

Accuracy and roughness requirements, maintenance conditions, control automation, safety requirements are common for both specialized and universal NC machines.

13.1.1 Vertical milling NC machines

In aerospace production, vertical milling NC machines of МА-655 і ФП-14 models are most frequently used.

Universal vertical milling NC machine *МА-655* with cross-like table (see Fig. 13.1, a) has three axis of the tool motion: X – longitudinal motion on 1000 mm Y – transversal motion on 500 mm; Z – vertical motion of the milling cutter head on 640 mm. Rotation speed of the spindle is 20…2500 min^{-1}. Working feed rate is adjusted from 0 to 2400 mm/min, auxiliary stroke speed is 4800 mm/min. The machine of МА-655СМН model is equipped with the device for changing the tooling with the help of the eight-position crown. The most widespread modifications of МА-655 machine are follows: МА-655СМЗОА – with the magazine for 30 tools, МА-655С2 – equipped with two-spindles, МА-655С5Н is five-axis machine.

Specialized machine *ФП-14* is used for five-axis machining of the workpieces manufactured of light alloys and high-strength steels with the surfaces of single and double curvature, such as brackets, fittings, ribs, cockpit canopy frames and hatches with theoretical contour. Structural configuration of this machine is similar to the structural configuration of the milling machine with cross-like table (see Fig. 13.1, a). Two rotary motions combined with three linear displacements allow to install the milling cutter axis perpendicularly to the machined surface. Maximum rotation angle of the milling cutter relative to the working zone of the table is $\pm 45°$. On this machine, one may machine the parts with the dimensions up to 900x630x400 mm with the accuracy ±0,03 mm at rotation speed of the spindle up to 3000 min^{-1} and linear feed speeds 2…2000 mm/min and angular feeds up to 120° per minute.

13.1.2 Portal milling NC machines

Portal milling NC machines, due to their rigid structure provide machining of large-size bulk workpieces manufactured of aluminum alloys and high-strength steels that have many pockets, openings and notches different by their shape and depth. NC machining of such workpieces is performed on the specialized machines with immovable portals of the ФП-2М and ВФ-3М8 model.

ФП-9М machine is one of the specialized machines of the first generation that are used on the aircraft-building plants. Its modification is the ПФ-9У machine with reduced rotation speed of the spindle for machining of the workpieces of high-strength steels and titanium alloys.

Machine *ВФ-3М8* belongs to the bed-type milling machines of current generation. Unlike ФП-9М, it has the cross bar immovable in height, device for automatic change of the tools with the help of the crown with eight positions, screw conveyer for removing the chip, wider table. Along with milling of the profiled surfaces on this machine, one may also perform drilling, core-drilling, reaming and boring of the holes. The ВФ-3М8 serves as a base for the following modifications: two-spindle machine ВФ-32 (see Fig. 13.1, b) for simultaneous machining of two workpieces with the dimensions 4000x1100x650 mm, three-spindle machine ВФ-33 for machining of three workpieces with the dimensions 4000x650x650 mm, machine ВФ-3М8Д with the table of the length up to 6000 mm.

Long-length parts, e.g. pressed panels of stringers and wing spars, are machined on the specialized milling machines with *movable portals* of the ПФП-5, 2ФП-231 and 2ФП-242В models.

Machine *ПФП-5* is the base machine for the three-axis machining with two portals simultaneously (see Fig. 13.1, c). On it, one may machine either one workpiece with the dimensions up to 20000x1400 mm with moving of one portal, or two workpieces, with each having the dimensions up to 10000x1400 mm with simultaneous moving of two portals. There are two milling heads installed on each portal: one has the rotation speed of the spindle 1500 min^{-1}, and the other has two speeds with the rotation speed of the spindle 1500 or 3000 min^{-1}.

Machine *2ФП-231* has two portals (see Fig. 13.1, c) of the higher technical level for three-axis high-productive machining of the workpieces of aluminum alloys that have the shapes up to 30000x1800 mm. One may perform complex milling and drilling machining of the part workpieces with external and internal profiled surfaces, pockets, cavities, undercuttings on it. The machine has immovable sectional bed, upon which there are the blocks of vacuum table fixed in the T-like slots for fixating of the workpieces. There are two portals above the table moving with length feed (X-axis), each of which has cross-feed carriage (Y-axis) that holds the milling head (Z-axis). There is a tooling storage magazine for 16 positions with the device for automatic tool changing attached to the portal. Basing upon the base machine 2ФП-231, the model 2ФП-131 was created, the length of its table is reduced to 1400 mm.

Machine *2ФП-242В* is the four-axis machine for machining of the part workpieces such as panels and wing spars with reduced scales. On each of the two portals, installed are two uniform milling heads with power drives by translational axes X, Z and angular *A* coordinate. On the machine, one may machine one workpiece with the dimensions up to 25000x2500 mm at operation of one portal, for identical workpieces with the dimensions of each one up to 12000x1150 mm or four reflection symmetric workpieces – two right and two left ones.

Typical unit of the mentioned milling machines with movable portals is the device for correcting of the scimitar shape. This device is necessary for tracking the real position of stringer feet and input the necessary corrections to the machining CP.

13.1.3 Cutting-out milling NC machines

Cutting-out milling machines are used for cutting out by milling with the end milling cutter of sheet workpieces in the stack up to 15 mm thick with any curvilinear external or internal contour, and also for drilling of the holes with the diameter up to 8 mm.

The base model for the specialized cutting-out milling NC machines is *РФП-1* with two movable portals of identical design (see Fig. 13.1, c). Based upon this model, there was created the one-portal machine *РФП-2* with shortened bed.

On the machine РФП-1, at moving of one portal, there cutting-out of the workpiece up to 11000 mm long and up to 2000 mm wide occurs and at moving of two portals simultaneously, cutting-out of two workpieces occurs, each of which is up to 5500 mm long and up to 2000 wide.

Similar operations are performed on the machine РФП-2, if the workpiece has a length up to 5500 mm and up to 2000 mm wide. Machining is performed with end milling cutters with the diameter 8…12 mm with deviation from the given contour up to 0,25 mm.

Specialized milling NC machine of the *РФП-6* model is created on the basis of the cutting-out milling machines. It is used for machining of honeycomb filler edges of volumetric shape with longitudinal and transversal lines, and also for milling of undercuttings on the edges of honeycomb filling with mushroom-shaped milling cutters.

Structural configuration of the machine allows to apply five-axis cutting at the same time: X – longitudinal movement of the portal, Y – transversal movement of the carriage with respect to the portal; Z – vertical movement of the carriage with respect to the portal; B – spinning of the carriage about the transversal axis with the angle ±32°; A – rotation of the carriage with the milling head with respect to the longitudinal axis at the angle ±135°.

Overall dimensions of the workpieces are as follows, mm: length – 6300, width– 1500; height – 350. The speed of work feeds along linear coordinate axes may vary uniformly, and it may reach up to 3300 mm/min, auxiliary feed is 4800 mm/min. The two-speed milling head has the power 6 or 3 kW with rotation speed being correspondingly 18000 or 9000 min^{-1}.

The machine is equipped with the NC device of H55-2 model; five-axis controlling is performed simultaneously with the help of thyristor transformers and direct current electric engines.

The NC device of H55-2 model provides automatic change of tooling, correction of the equidistance of tool path, switching of the spindle rotation speed, right and left tool rotation in particular, automatic return to the zero point of the machine along all coordinate axes.

13.1.4 Peculiarities of using end milling cutters

Standard end milling cutters of fast-cutting steels with 14…30 mm diameter are the most widespread tool for machining of wide range of parts of medium dimensions; they are centrally manufactured on the tooling plants.

Despite this, the design of standard end milling cutters (Fig. 13.2) has a number of disadvantages that stipulate bad removal of chip, insufficient bending strength of the milling cutter, etc.

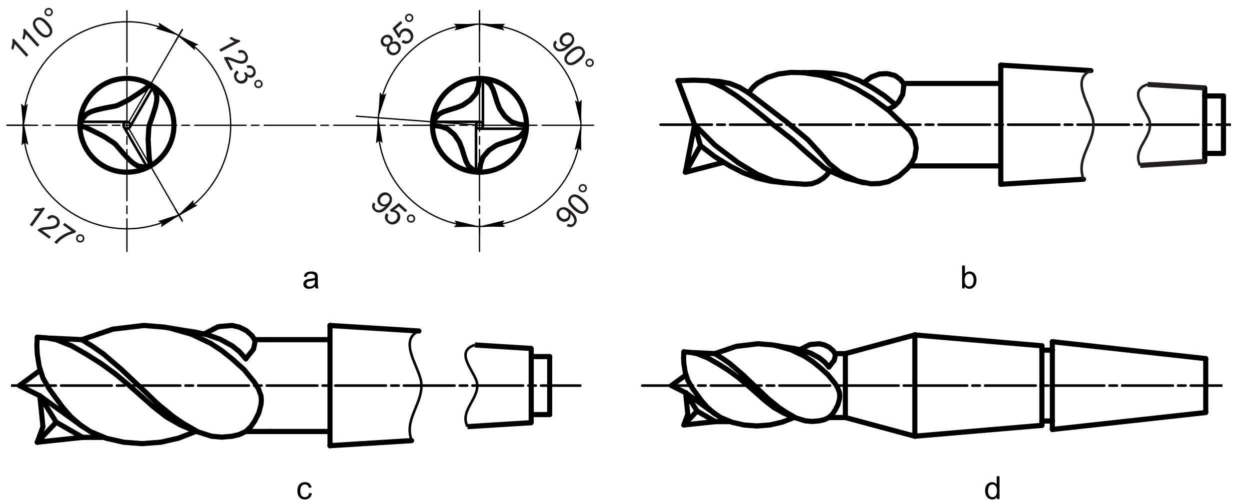


Figure 13.2 – Modifications of standard end milling cutters

On the aircraft building plants the designs of standard milling cutters are improved by the following operations:

– increasing the chip removal by changing the angle of the helical flute from 40 to 55°, expanding the helical flute and additional polishing of its internal surface;
– reducing the radial runout of the teeth from 0,2 to 0,05 mm;
– using the right-cutting milling cutters with left spiral and left-cutting ones with right spiral, due to which the workpiece is pressed to the machine bed plate with the help of the axial component of the cutting force;
– reducing the tool vibrations due to the asymmetrical location of the milling cutter teeth (see Fig. 13.2, a);
– sharpening of the chisel edge on the end surface of the milling cutter, which allows to perform vertical penetration into metal (see Fig. 13.2, b);
– increasing of rigidity of the tool cutting element by using the flute of variable depth (see Fig. 13, c);
– increasing of the tool overhang at the expense of strengthening cone application (see Fig. 13.2, d).

For machining of set walls on framed parts, one also uses form-milling cutters (Fig. 13.3), the generatrix shape of which corresponds to the configuration of the machined surface.

Using the milling cutters in the Fig. 13.3, a, b, one may perform layer machining of concave surfaces. Form-milling cutter shown in the Fig. 13.3, c, is used for machining of the surfaces with variable bevel and convex surfaces.

During 3-D three-axis milling, the tool movement is controlled simultaneously along three coordinate axes.

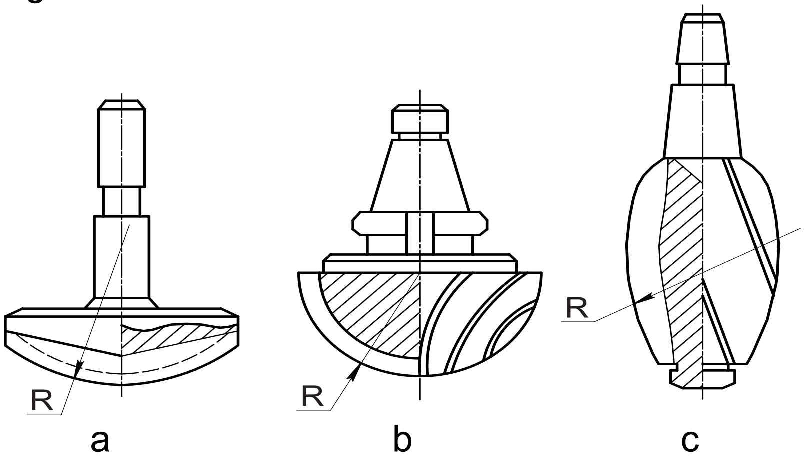


Figure 13.3 – Several types of form milling cutters

In accordance with the selected tool path (zig-zag or spiral), one calculates the stepover of the lines $\boldsymbol{A}$ of the tool path during performing of two neighbouring machining passes of the trajectory. The value of the stepover depends on the allowance on the height of the crest Δ_{crest} that remains on the machining surface between the neighbouring machining passes.

The stepover between the milling lines along the inclined zone of the plane (see Fig. 13.4, a) is calculated by the formula

$$A = \frac{2\Delta_{finning}}{\sin\alpha}\sqrt{\frac{d_r \sin\alpha}{\Delta_{finning}} - 1}\,. \tag{13.1}$$

where $\boldsymbol{d_r}$ is the diameter of the trajectory of the point of the milling cutter cutting edge that directly forms the shape of the machined surface: $\boldsymbol{d_r = d}$ for milling cutters without rounding of the end surface, $\boldsymbol{d_r = d - 2r(1 - \sin\alpha)}$ for milling cutters with rounding radius of the end surface $\boldsymbol{0 < r < R}$; $\boldsymbol{d_r = d \sin\alpha}$ for milling cutters with spherical end surface; $\boldsymbol{r = R - d = 2R}$ is the diameter of the milling cutter; α is the slope angle of the zone.

The stepover between the milling lines across the inclined zone of the plane (Fig. 13.4, b) for milling cutters with rounding radius of the end surface $\boldsymbol{0 < r < R}$ or $\boldsymbol{r = R}$ is calculated using the formula

$$A = 2\cos\alpha\sqrt{2r\Delta_{finning} - \Delta_{finning}^2}\,. \tag{13.2}$$

Usually, during three-axis 3-D machining, the cutting edge of the milling cutter moves on the surface with variable curvature radius ρ.

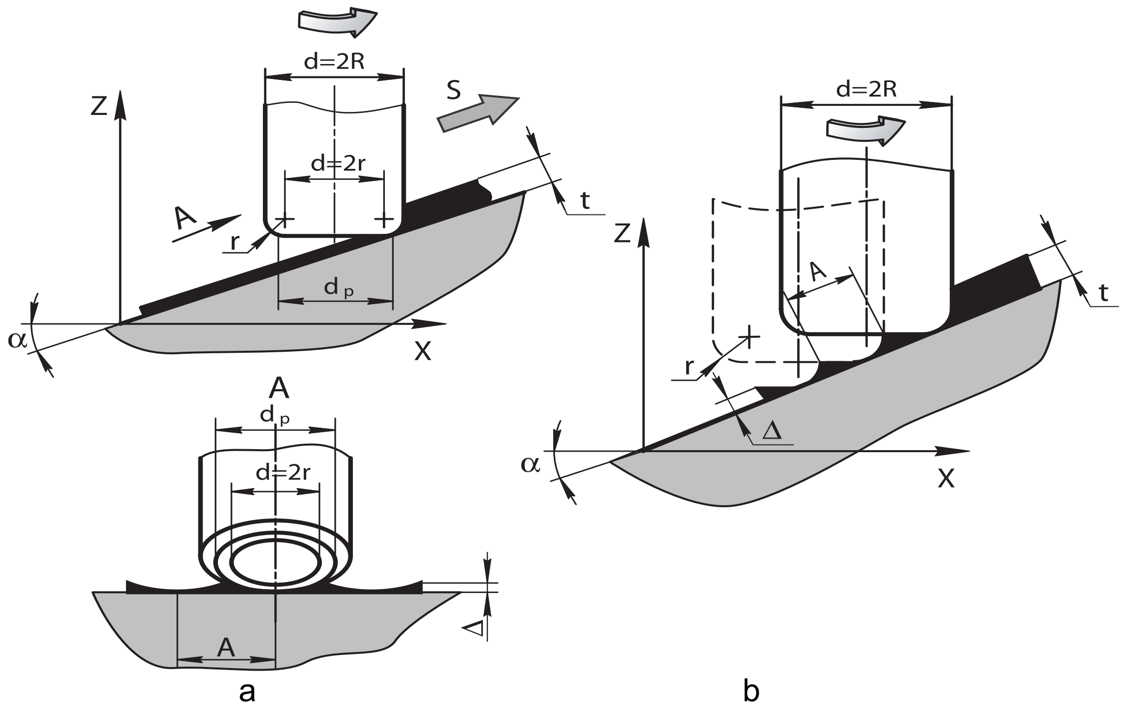


Figure 13.4 – Schemes of three-axis milling along (a) and across (b) the inclined zone of the surface

This way, the line stepover A of the tool path when performing the two neighbouring machining passes of the trajectory is determined according to the crest allowance:

$$A = \sqrt{\frac{8\Delta_{finning}}{1/R - 1/\rho}}. \quad (13.3)$$

In manufacturing practice, one usually takes the following correlation of machining accuracy and geometric parameters of the surface and end milling cutter:

$$\Delta_{finning} \approx 0{,}01R \text{ and } \Delta_{finning} < (0{,}01...0{,}001)\rho.$$

13.1.5 Peculiarities of machining on multipurpose machines

During process of aircraft manufacturing it is often necessary to produce complex case-shaped parts that require machining in six directions, and sometimes in ten and more directions (if the parts have inclined planes). Each of the faces of the complex casing has projections, pockets, slots, guide elements, ribs and other structural elements, i.e. each face of the case is the surface with several levels of depth and with complex contour. Besides this, case-shaped parts have a certain number of main and fixation holes (smooth, stepped, conic and threaded) that differ in shape, depth and accuracy.

Multi-purpose machines (MM) allow to combine milling of straight and curvilinear surfaces, centering, drilling, core-drilling, reaming, counterboring, boring, beading and rolling of the holes, threading (with taps, screw-thread dies, cutter heads, cutters), circular milling of external and internal cylindrical, conic and profiled surfaces and circular slots with finishing and disc milling cutters.

In order to reach high efficiency of MM, one tends to perform all machining of the workpiece on one machine in one or two installations. One, though, should also consider the risk of distortion of the part shape as the result of redistribution of residual stresses in the initial workpiece. In these cases, the technological process is divided into operations of rough (peel-off) and further machining. Rough machining is performed on powerful, especially rigid machines (either NC or universal), and after that the parts are heat treated in order to remove internal stresses. Further machining is performed on the multipurpose machine.

Planes are milled with the face and end milling cutters with carbide multisurface disposable insert (MDI). Usually it is carried out in two steps: the first step is rough milling; with large allowances it is reasonable to perform it with consequent passes of face milling cutters along the machined surface. Width of the surface is machined per one pass of the tool, and this means that the diameter of the milling cutter as well, is chosen in such a way that tool pressing out wouldn’t influence the accuracy of the finishing pass. If the allowance is large and not uniform, the diameter of the milling cutter should be reduced. For the second, finishing, machining step, one uses such milling cutter, the diameter of which allows to involve the whole machining area.

In order to get especially fine surface finish with small allowance, one uses face milling cutters with inserts of CBN and cemented oxide.

One machines open zones with end milling cutters not very often; they are mainly used in the cases when the same milling cutter is used for milling of other surfaces (recesses, slots) in order to reduce the range of the tools used.

Slots, windows and recesses are usually machined with end milling cutters that are equipped with carbide inserts.

In order to increase machining accuracy along the slot width and to reduce the range of the tooling required, the diameter of the milling cutter is selected somewhat smaller than the size of the slot. Machining is performed sequentially: at first, the middle zone of the slot is milled, then both sides, using the possibility of production of the slot width with high accuracy by application of the milling cutter-radius correction. At the end of the cycle, the correction is cancelled.

In order to increase the tool durability and improve chip removal during machining of blind slots, one uses end milling cutters with increased angle of the flute helix and polished flutes. To make penetration with axial feed easier, one uses the milling cutter with end surface teeth of special sharpening. The milling cutter with strengthened core of conic shape and flute with variable depth has increased hardness. At increased overhangs of the milling cutter that are conditioned by the workpiece shape, milling cutters with strengthening cone are used. One may reduce vibrations if milling cutters with variable steps are used- milling cutters with three or four teeth of unequal distance between them.

Circle milling is a new operation that became possible as milling and multi-purpose NC machines appeared. The holes in the case-shaped parts were usually machined by boring. On the NC machine, they may be milled if one sets circular feed for the milling cutter.

Analysis of the plans of milling operations shows that in modern conditions circular milling is chosen whenever it is possible to use it. It is limited only by the depth of the hole (that is conditioned by the length of usual end milling cutters and is equal to 60…80 mm), its diameter and machining accuracy. It should be noted that circular milling is especially successfully used for preliminary machining of the holes in cast workpieces (for removing of rough allowance).

Machining of the holes is the most widespread type of machining step on MM. There are the drilling and threading in fastening holes for bolts, screws and pins among them; drilling, core-drilling, reaming, boring of accurate fitting holes – smooth and stepped, machining of the holes in cast parts.

Coaxial holes in opposite walls of case-shaped parts are machined on the MM with cantilever-type fixed tools sequentially with the workpiece turn together with the machine table on 180°. Coaxiality of the holes depends on the accuracy of the dividing table. The inaccuracy of distribution shouldn't exceed half of the tolerance range for the deflection of mutual alignment and location of the holes according to the part drawing. In order to increase the hardness of the spindle joint, the holes are bored with constant hangover of the spindle by moving the table or machine post.

If accuracy requirements for machining of the holes with *axial tooling* aren't high, the operations are performed in the following sequence: at first, one machines all holes with one tool, then with another one (provided that change of the tooling on the given machine requires more time that positioning of the table). If accuracy requirements for diameters and shape of the holes are high, each hole is machined separately, with changing the tool for each hole, and the spindle moves only along the Z-axis. Otherwise, machining inaccuracy will increase due to positioning inaccuracy.

In order to reduce machining time for drilling with t*wist drill* and to increase the durability of the tooling, one uses fast automatic change of the cutting parameters. After accelerated advance of the drill to the workpiece, one throws in the work feed, and when the larger part of the hole is drilled, the feed is reduced in order to avoid the tool breaking because of the jump-like change of the stress during the drill leaving the hole. If there is a cast crust on the entrance or exit of the hole, the program should include the changing of the spindle rotation speed on these zones.

Due to the fact that during drilling on MM the guide bushing is not used as a rule, one widely uses predrilling of the holes with short hard drills – kind of marking for the allocation of the holes. If there is a cast crust, this operation allows to resolve other problems as well: to make tool penetration easier, to increase the durability of the drills with small diameters and at the same time to remove the chamfer at the hole entrance if it is provided in the drawing. Predrilling is reasonable to use for machining of the holes with the diameters 8…15 mm in the parts of ferrous metals.

For machining of the holes in case-shaped workpieces, rather effective is using the tooling that was previously applied only for drilling of deep holes, e.g. two-edged drills with mechanically fixed triangular-shaped carbide insert. Using of such drills along with distribution of the allowance along the width of the cut and internal advance of the OCL allows to increase the cutting efficiency three-five times compared to average twist drills.

Large number of machined surfaces, rough, semi-finishing and finishing passes during machining of each surface, large amount of tooling in the magazine make it difficult to choose the plan of machining of the part on the MM. It is necessary to choose the most effective variant. There are many opportunities to do this: one may, for example, do the whole machining of the part on one side and then turn it; one may firstly make rough machining of the part from all sides and after that do finishing; one may machine all planes and that process the holes. For the parts with coaxial holes, it is reasonable to use sequential machining from two opposite sides, etc.

The decision made is influenced by many various factors. There are several general principles, though, that should be followed: the higher is the accuracy of the structural element, the later one should foresee its machining; at first, rough machining should be planned, and after it – the finishing one; the lesser is operation time of the executive device (change of the tool, rotation of the table, etc.), the more frequently this device should function. The highest accuracy is reached when the part is machined with one installation. For the parts with big allowances, one should provide unloading operations, part of which is reasonable to perform on universal or specialized equipment.

When choosing the machining plan for the parts on multipurpose machines, first of all it is reasonable to use typical schemes that are given in the corresponding standard documentation [20, 21]. Usually, these documents recommend choosing the sequence of operation steps depending on the type of part and workpiece, type of the machined surfaces and accuracy of their machining, etc.

Example. Content and sequence of steps during machining of the part “case” on a multipurpose machine is the following (Fig. 13.5):

1) milling of the upper plane (zone A), face milling cutter;
2) milling of the upper shoulder (zone B), face milling cutter with straight angle inserts;
3) milling of the lower shoulder (zone C), face milling cutter with straight

angle inserts;

4) milling of the side surface (zone D), fast-cutting end milling cutter;

5) milling of the opening (zone E), fast-cutting end milling cutter with end surface teeth;

6) milling of the contour notch (zone F), fast-cutting end milling cutter;

7) milling of the longitudinal slot (zone G), end slot-milling cutter with carbide insert.

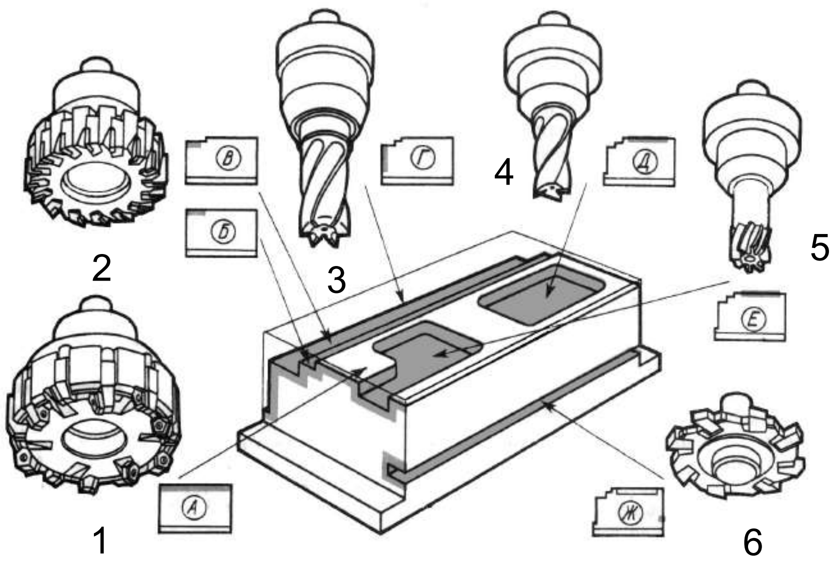


Figure 13.5 – Machining scheme of the case-shaped part: 1 – face milling cutter; 2 – face milling cutter with straight angle insert; 3 – fast-cutting end milling cutter; 4 – fast-cutting end milling cutter with end surface teeth; 5 – fast-cutting end milling cutter; 6 – end slot-milling cutter with carbide insert

13.2 Manufacturing of typical parts of the airframe on three-axis milling machines

13.2.1 Machining of forged stringer panels

Forged stringer panels belong to a large group of airframe structural parts of modern aircrafts. E.g., in the design of a wide-body aircraft Il-86, monolithic panels take up about 500 m^2 of the external surface of the wing and 200 m^2 of the fuselage surface [3].

Forged stringer panels are most frequently manufactured of aluminum alloys В95-Т and Д16-Т (Fig. 13.6).

End milling cutters are used for machining of the following surfaces in the stringer panel: side walls 1 lengthwise, end surfaces 4, shelves 3, scallops 2 of the stringer shelves, roundings of the shelves 5, cutouts and cutoffs 7, interstringer cavities 6 on the surface and zones of longitudinal joints. Scallop of the joints and interstringer cavities are machined up to the level with the stringer ribs without affecting the ribs.

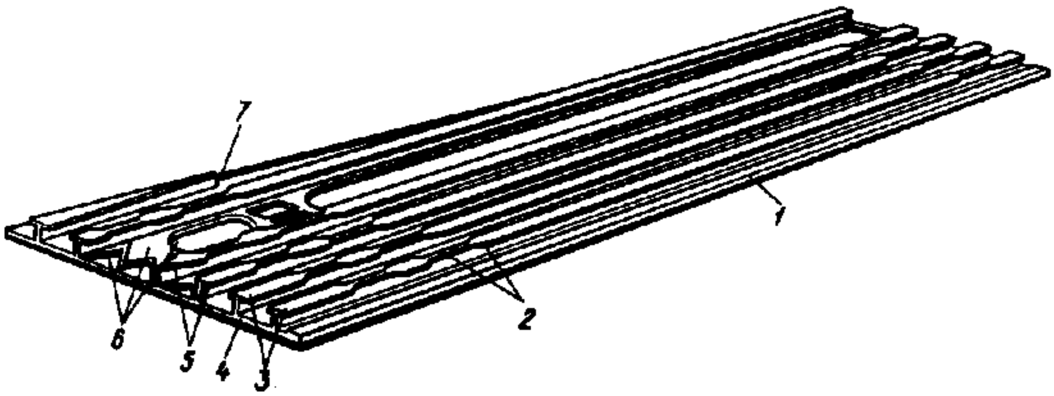


Figure 13.6 – Typical design of the stringer panel

Thickness of stringer panels varies from 2,5 mm in the zone of cavities between the stringers to 8 mm in the zone of mounting faces. Lower panels of the outboard wing have mounting holes with curvilinear contour.

After rough machining of longitudinal ribs and interrib cavities assembly hatches and mounting faces are machined, and after that finishing machining of the ribs is carried out.

Finishing machining of the stringer ribs is performed on lower working feeds in order to exclude mutual release of the rib and the tool and to reach high accuracy of manufacturing.

Windows and holes of the panel are machined in two stages: at first, one cuts the hole that is machined along the contour from the side of the stringers (internal contour), and after that one performs the edging for sealing from the side of the external theoretical contour.

For locating and fixing of the workpiece on the machine table, special cradles are designated; they allow to install the part in the machine coordinate system with high accuracy.

In order to increase the efficiency, such workpieces, due to their big length, are machined simultaneously with two portals, except some operations when the quality requirements for surface machining require the necessity of nonstop machining with one tool.

The part is divided into four sections, the first and the third of which are machined at the same time correspondingly with the first and second portal. The second section, the length of which should be at least 4500 mm, prevents the portals from collision, and it is machined simultaneously with the fourth section.

13.2.2 Manufacturing of rods of wing lift devices

Rods of lift devices are large-size highly loaded parts that are manufactured of steel and titanium forgings.

Construction peculiarities of these parts are ribs-runners formed with the arcs of circles, and also shaped pockets and blind slots (Fig. 13.7).

Parts such as rods are manufactured on the machines of MA-655, ФП-7М, ФП-17 models and ФП-27 with end and angular milling cutters with the body of fast-cutting steels or hard alloy ВК8.

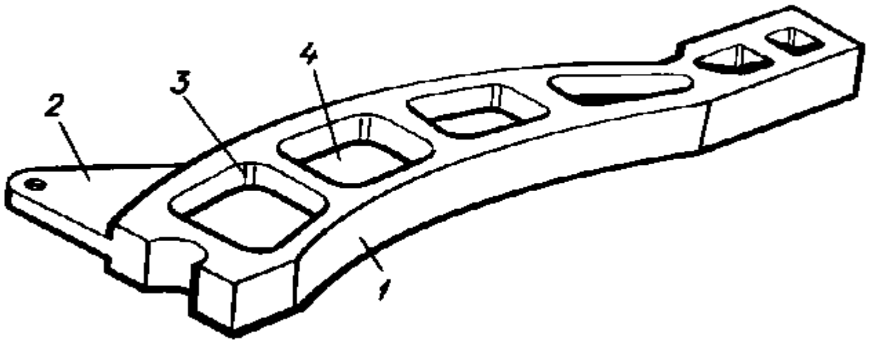


Figure 13.7 – Typical design of the lifting device rod:
1 – external contour; 2 – face of the eye;
3 – internal contours of the pockets; 4 – bottom of the pockets

Typical sequence of machining of rods:

- milling of the external contour from both sides;
- spiral milling for the milling cutter advance in the pockets;
- milling of the material monolith between the flanges;
- milling of the pockets on the external side and in the tail part of the flange;
- rough and finishing machining of the pockets for the angular milling cutter advance with finishing machining of the radii in the corners;
- preliminary and final milling of internal and external slots, ribs and cants;
- machining of the holes by drilling, core-drilling, chamfering, reaming.

The rod workpiece is based in the block-type devices with fixing on two holes. If the rod workpiece is a forging, it is preliminary machined on the NC machine along its contour from two sides.

After thermal treatment technological allowance on the flanges is removed on the turning-and-boring lathe of 1550 model with fine finishing with grinding heads or by machining on the specialized milling machine of model СШР.

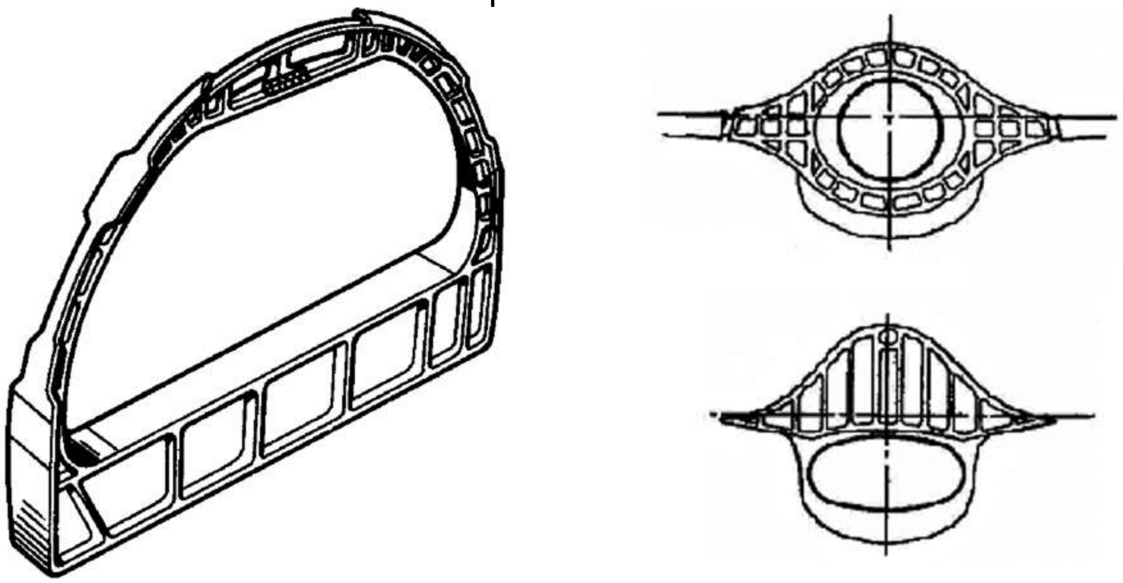
13.2.3 Machining of large-scale parts of the load-carrying airframe components

Manufacturing of large-scale parts of the load-carrying *airframe components*, in the first place, of fuselage load-carrying frame (Fig. 13.8) of monolithic workpieces on the NC machines, is a complex and laborious process.

When developing the process rout (PR) and operational plan (OP) of machining for these parts, one should consider plastic deformations (warpage) of the workpiece that occur as the result of redistribution of internal stress during removal of metal from it.

During milling of forged workpieces of average size, these deformations are, as a rule, rather small and they do not affect the accuracy of the workpiece shape. At the same time, the value of plastic deformations of large workpieces may reach 10 mm.

The effective method of shrinkage reducing and providing the required accuracy of parameters for part machining is in developing such PR, at which the workpiece material is removed layer by layer, interchanging these layers with respect to the neutral zone of the part.



a b

Figure 13.8. Typical load-carrying frame:
a – of passenger aircraft; b – of fighter

Typical sequence of machining of load-caring frame:

– preliminary machining of external contour with the allowance up to 5 mm with referencing on the holes prepared in advance;

– preliminary machining by the height of the reinforcing ribs, thicknesses of the surface and bosses, flange end surfaces;

– preliminary machining of the pockets with the allowances up to 3 mm on the surface and up to 5 mm on the contour, with machining being performed from the center of each typical element to its periphery;

– reinstallation of the workpiece and repeating of all previous operations on the opposite side of the workpiece;

– finishing machining of external contours and construction elements in the same sequence.

As a rule, if one sticks to the recommended sequence of milling and all technological conditions, one may receive the necessary geometry of the part after the preliminary machining. In order to provide roughness of the workpiece structural elements, additional clamping elements are used in the device during machining. Technological breaks are foreseen for reinstallation of clamping elements from one zone to another.

13.2.4 Machining of clasp ramrod joints

In the design of airframe, one widely uses clasp ramrod joints that are load-bearing elements. Their manufacturing has certain difficulties and it requires thorough preparation of production.

Fig. 13.9 shows typical design of clasps of wing leading edge flaps of the supersonic fighter. Interconnection of the clasps is ramrod type: by the hole with 0,5 mm gap, by the end surfaces – with fit *H11/∂11*. Material of the clasps is titanium alloy of BT5v grade. Semimanufactured article for clasps production is the accurate forged profile of fixed cross section with negative (see Fig. 13.9, a) or zero (see Fig. 13.9, b) sliding bevel.

The main operations during machining of clasps are milling of the zones step by step (see Fig. 10.8, c) and boring of the ramrod hole with the diameter 5 mm to the diameter $6{,}5^{+0{,}2}$ mm.

Milling of the zones is performed on the milling NC machine of model ФП-17M in the unified hydraulic device with the special milling cutter that has three sections.

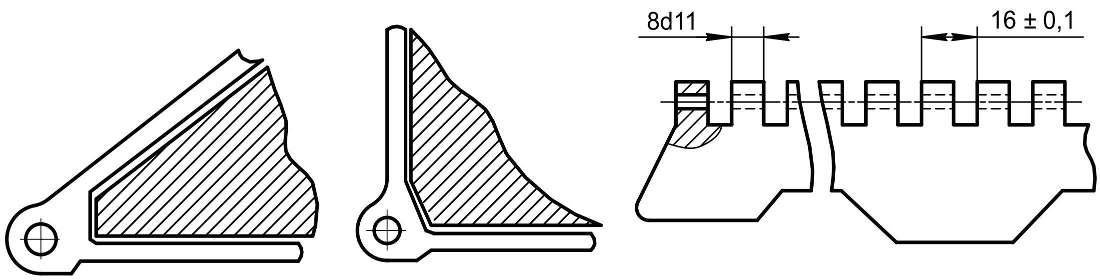


Figure 13.9 – Typical design of the clasp of wing leading edge flap

The cutting parameters during milling of the zones are the following: speed – 25 m/min; minute feed – 15 mm/min. Boring of the hole with correcting of straightness of its axis is carried out on the special horizontal drilling machine, using the conductor, with the drills of fast-cutting steel of P9K10 grade. The cutting parameters during boring are as follows: speed – 10 m/min; minute feed – 0,1 mm/min.

13.3 Manufacturing of typical parts of the airframe on five-axis milling machines

13.3.1 Pecluiarities of multiaxis milling

The number of parts, assemblies and equipment elements that have the surfaces that partly exceed the external aerodynamic lines, with variable sliding bevel, significant curvature and wide range of twisting of the normal vector exceeds 60% of the general number of parts that are manufactured with allowance removal [1, 11, 21].

According to the extended classification, there are follows typical objects of multiaxis milling:

– parts of fuselage bearing frame bound with the surfaces of double curvature (fringing of hatches, doors, pilot and flight navigator canopy frames);

– elements of wing framing with variable sliding bevel (joint fittings, ribs, carriages);

– elements of lift devices bound with linear surfaces (parts of leading-edge flap, flaps and deflectors);

– elements of 3-D line-forming equipment (models of the surfaces, pigs, form blocks, paste-up devices, bladed levers, unit dies).

Parts of the first two groups are manufactured of monolithic forged workpieces of different sizes. The elements of lift devices are the constructions that consist of the frame and honeycomb filling that are covered with thin sheet skin.

Earlier, the previous NC machining of such workpieces was carried out on the three-axis milling machines in several installations with further after-machining with manual tools.

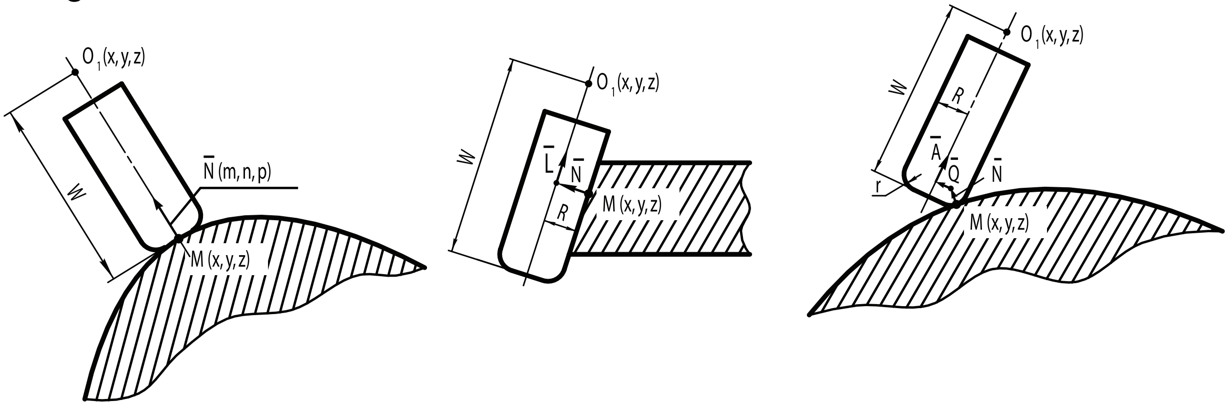
The ways of expanding the technological possibilities of three-axis NC machines by installing the rotary devices, using the barrel-like milling cutters and milling cutters with variable geometry gave positive results only for the parts with constant sliding bevel or with the sliding bevel with insignificant variations.

The methodology of multi-axis programming is implemented on the specialized NC milling machines of models ФП-11, ФП-14, МА-655С5Н of different modifications.

Main purpose of typical EP for manufacturing of the parts on multiaxis machines is to practically exclude the laborious manual adjusting works, increase the efficiency of machining, accuracy and interchangeability of the parts in the assemblies.

In order to perform multiaxis machining, one needs to calculate the quasiequidistant trajectory of the center movement , with respect to which the rotation of the tooling is carried out, adhering to the value of its overhang.

Calculation of linear coordinates depends on the type of NC machining, i.e. how machining is carried out – with end surface (Fig. 13.10, a), with periphery (Fig. 13.10, b) or with torus zone (Fig. 13.10, c) of cylindrical or conic end milling cutter.



a b c

Figure 13.10 – Main types of five-axis milling:
a – with end surface; b – with periphery; c – with torus zone

In Fig. 13.10 the following designations are given: x, y, z – coordinates of variable control point ***M*** of machining trajectory; W – overhang of the milling cutter end surface; m, n, p – components of unit vectors; $\overline{N}$ – vector of the normal to the machined surface in the control point; R – milling cutter radius; $\overline{L}$ – generatrix vector of the linear surface in the control point; r – rounding radius of the milling cutter; $\overline{Q}$ – milling cutter torus zone vector; $\overline{A}$ – direction vector of the milling cutter axis.

Machining on the multiaxis machines is followed by specific phenomena in the range of cutting parameters due to angular movements of the tooling.

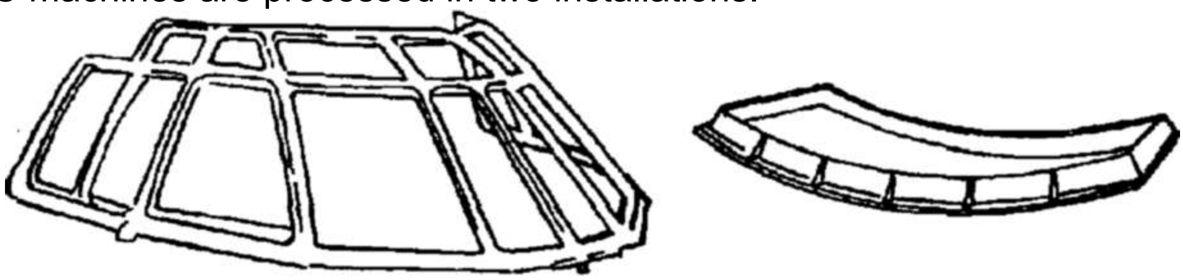
For example, during rotation of the tool in the plane in the direction of the feed, the angle of milling cutter tooth penetration into the metal is changed, i.e. tool geometry actually is changed that is, and nature of the cutting process itself.

At the same time, there occurs significant (up to two times) changing of the resultant feed as the result of algebraic sum of the angular movement speed and linear feed speed set according to the calculated parameters.

One of the main tasks during machining on the multi-axis NC machine is reducing to minimum the number of installations of the parts due to the complexity of their configuration and, correspondingly, the difficulty of locating.

13.3.2 Machining of the fuselage frame parts

Fig. 13.11 shows typical parts of the fuselage frame, NC machining of which became possible due to the usage of five-axis NC machines of models ФП-14, ФП-14МЛ, ФП-14В. The workpieces for these parts on five-axis NC machines are processed in two installations.



a b

Figure 13.11 – Parts of the fuselage frame:
a – pilot cockpit frame; b – hatch frame

During machining, one firstly forms the surface which reaches the theoretical contour. This surface is the part of the cone (pilot cockpit frame) or cylinder (hatch frame), into which the construction elements – fittings and undercuttings – are inscribed.

Machining is performed with the milling cutter with the diameter 50 mm, and during formation of the part external surface the milling cutter axis constantly turns according to the normal to the tangent of the theoretical contour in variable coordinates.

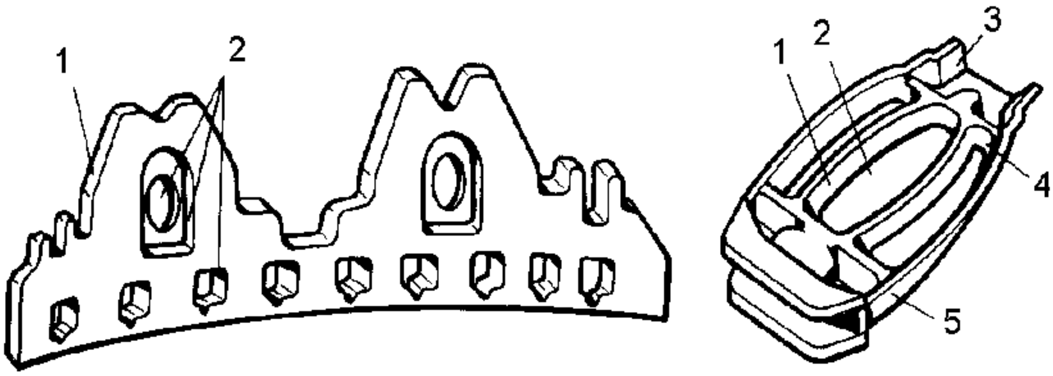
After that, one mills the internal side with the locating on the already machined surface of the theoretical contour and the equipment locating block, due to the high geometrical complexity of the reference surface, is machined according to the same CP as for the internal surface.

13.3.3 Machining of the wing framing parts

Five-axis machining of the wing framing parts of forged workpieces is performed on the five-axis milling NC machines of models ФП-14, ФП-14МЛ, ФП-14В.

Rack joint of the wing panel (Fig. 13.12, a) is machined along the contours and internal lines 2 located on the curvilinear surface 1. The cheek of the wing flap deflector carriage (Fig. 13.12, b) is machined along the external contour 5 with angularly set surface, internal contours 1 and bottom 2, and also along the internal contours with angularly set surfaces 3 and 4.

This part, enforced with stiffening rib, is limited by the contour with the linear surface with the edge height 50 mm, but the range of variations of the sliding bevel along the comparatively small area of the contour is very broad – from the zero sliding bevel to the 30° angle. The cheeks of the flap deflector carriage require high accuracy location of theoretical contour the with respect to the close tolerance holes.



a b

Figure 13.12 – Parts of the wing framing:
a – rack joint of the wing panel; b – cheek

Workpiece of the flap deflector carriage cheek is located in the device by two coordinate-fixing holes with the diameter 8 mm and is fixed through the previously opened attaching holes, which allows to perform machining in one installation.

Typical sequence of machining of the carriage cheek:

- milling of the external contour in the five-axis mode along the closed trajectory with the loop-like withdrawal of the milling cutter for its rotation outside the contact with the workpiece in order to avoid undercuts;
- height end surfacing of the surfaces' ribs in the five-axis mode;
- finishing the internal surface of the pockets in the three-axis mode with final formation of the surface thickness.

After that, one machines the internal contour 1 in the three-axis mode: preliminarily – with the milling cutter of 16 mm diameter with the allowance 1 mm and finally – with the milling cutter of 12 mm diameter.

13.3.4 Machining of the honeycomb filling

For honeycomb structures of the joints of lift devices of airplane wing and tail zone of the helicopter blade, it is necessary to machine the end surfaces of the honeycomb fillings that are directly connected to the elements of aerodynamic line formed with the percent surface.

Honeycomb blocks as workpieces for honeycomb filling are manufactured of foil АМГ2-Н 0,03 mm thick (cell with the size 2,5 mm) or polyamide paper called polymeric honeycomb plaster of mark ПСП-1, and also of foil of titanium alloys or corrosionproof steel [8, 11].

Machining of honeycomb fillings consists of operations of cutting the honeycomb blocks to form the workpieces, milling, cutting off of the contour allowance, flat and curvilinear grinding, making holes, slots, shoulders and slits.

These processes require special approach while choosing the cutting parameters, variants of locating and fixing the workpieces, machining schemes, design and shape of the cutting tool, methods of removing the dust and chip.

Cutting of the honeycomb blocks of aluminum alloys and their cutting off along the contour is performed on the band saws of ЛС-80-3 model with cutting speed 900 m/min and minute feed 300…600 mm/min.

Honeycomb blocks of titanium alloys or corrosionproof steel are cut on the anode-mechanic saw of 4822 type.

Milling of straight and curvilinear surfaces of the honeycomb blocks and the honeycomb end surfaces is performed on special NC machines of РФП-4, РФП-6 models. Honeycomb filling is milled with the special mushroom-shaped milling cutters of fast-cutting steel with the diameters 50 and 100 mm.

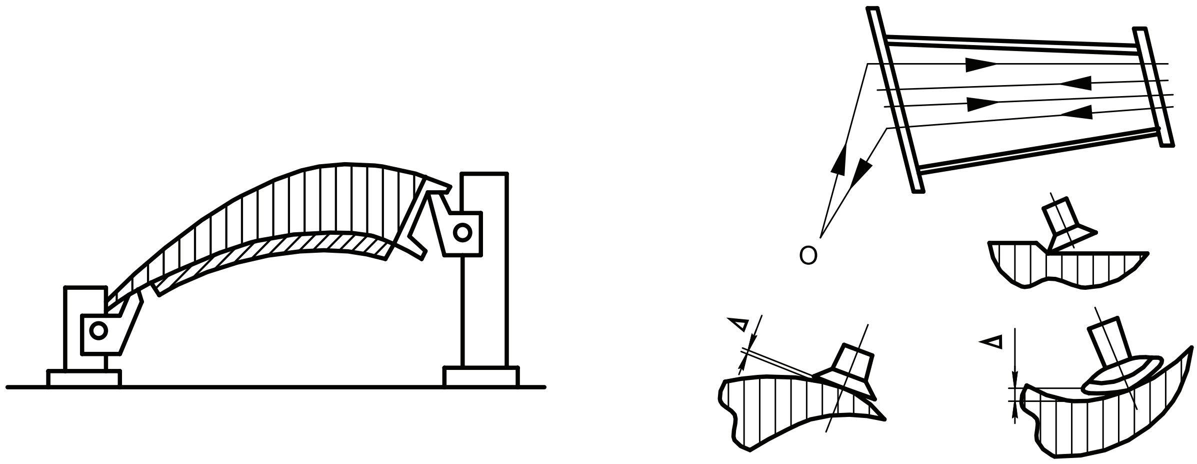
During machining of concave side, the honeycomb end surfaces are located on the plane; during machining of convex side, the honeycomb end surfaces are located on the technological work support according to already machined concave surface (Fig. 13.13, a).

If we consider accuracy, rational is the boat-type scheme of machining along the percent lines (Fig. 13.13, b). In this case, the faceting depth Δ on the convex and concave sides of the honeycomb filling doesn't exceed ±0,04 mm. Machining of convex surface of the honeycomb filling and manufacturing of the technological work support is performed according to one CP, which provides high accuracy.

The accepted cutting mode is the following: rotation speed of the mushroom-shaped milling cutter is 18000 min^{-1}, minute feed – up to 3500 mm/min. Before machining, the honeycomb block is fixed on the technological work support with the help of the special glue – polyethylene glycol [1].

Grinding is used for formation of the surfaces of high accuracy. Flat zones of the honeycomb blocks are ground on the belt grinding machines and curvilinear are ground on the special grinding NC machines. The cutting parameters are kept within the following range: cutting speed – 5…10 m/sec, minute feed – 3000…5000 mm/min.

Holes in the honeycomb fillings are made on the multipurpose drilling and milling machines with the drills of fast-cutting steels of P18 grade, using aligning tooling, with rotation speed of the tool not less than 1500 min^{-1}.



a b

Figure 13.13 – Locating (a) and machining (b) schemes of the honeycomb filling

13.4 Manufacturing of typical parts of the helicopter rotor blades

13.4.1 Peculiarities of the helicopter rotor blade parts

Parts of the helicopter lifting rotor (LR) and antitorque rotor (AR) blades operate under the conditions of cyclic loads, that is why they have increased reliability and durability demands.

Despite intensive usage of the polymer composites blades, using all-metal blades (AMB) in the constructions of lifting rotors of heavy transport helicopters like Mi-26 and universal helicopters like Mi-8 is more economically reasonable.

The most typical parts and units of AMB that determine its design and structural scheme, are butt part (blade tip), spar and tail unit.

Main load-bearing element of the LR blade (Fig. 13.14) is the spar 1 (steel pipe element of 40ХНМА steel or duralumin extruded one of АВТ-1 alloy or ПЕКЛО-33) that has variable cross section along the blade span.

Tip 2 with the eyes for hanging the blade on the LR bushing manufactured of high-strength 3ОХГСНА steel is fixed to the tube steel wing spar by argon arc welding, and to the extruded duralumin one – by means of bolts. Each tail unit of the blade has aluminum or polymeric honeycomb filling 3.

Besides the design of the tail unit of polymer composites, one has worked out the technology of manufacturing of metal compartment that is cheaper than the one of polymer composites. In this case, the skin and the ribs are manufactured of aluminum alloy АВТ-1 0,3 mm thick, and the honeycomb filling – of the foil Амг2-н 0,03 mm thick.

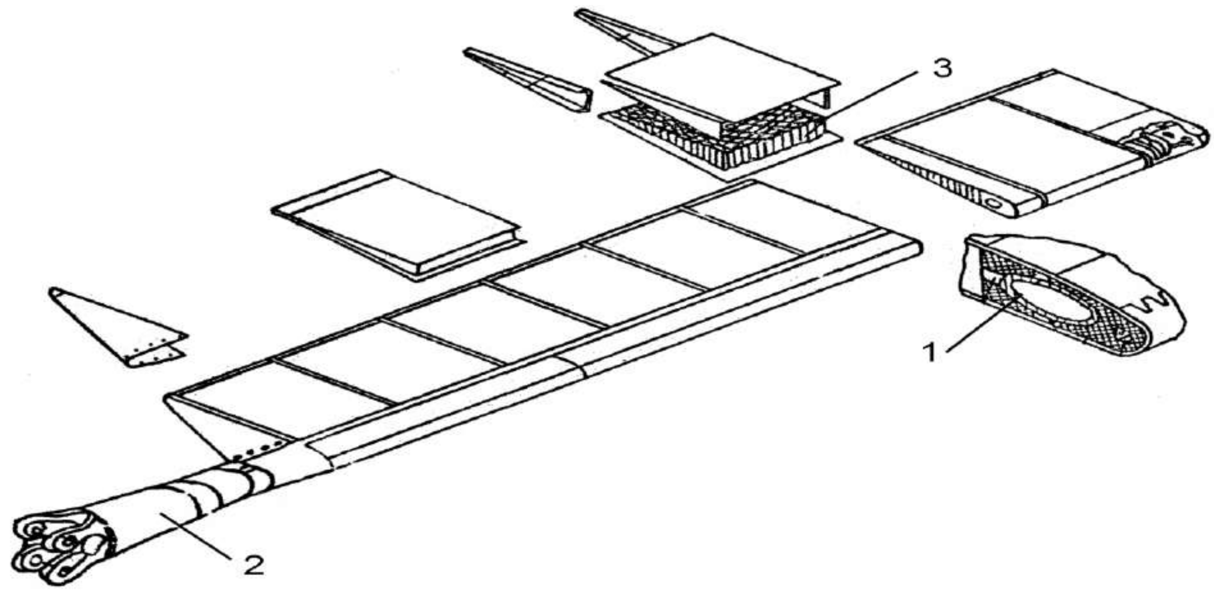


Figure 13.14 – Scheme of technological segmentation

13.4.2 Manufacturing of the blade tip

Manufacturing rout of blade tip production is the following:

– input X-ray cracks and hair line control of the workpiece (X-ray machine РУП-600);
– milling of eyes' and fork planes with milling allowance (milling NC machine of MA-655CMH model with tooling magazine);
– drilling, core-drilling, reaming of the holes in the eyes for hanging of the blade on the LR bushing; chamfering, counterboring of nests for the heads of bolts and nuts for mounting the extruded spar (vertical milling NC machine of model MA-655CMH with tooling magazine);
– heat treatment (induction furnace of УНКЗ-2 model);
– grinding of eyes' and fork planes (flat-grinding machine of 3П722ДВ model), blunting of sharp edges;
– sizing, burnishing of the holes (hydro-press of ЛС6-НА model);
– spinning of transitional fillets, vibrostrengthening of the tip (vibroplant of ВУД-630 model), washing;
– technical control (inspection NC machine of DELTA-AB model), weighing;
– corrosion-protection treatment – cadmium-plating (electroplating bath).

Operations of milling, drilling, core-drilling, reaming, counterboring are performed in one installation of the workpiece on the machine.

The processes of strengthening using the SPD methods are the final, they are carried out after machining, heat treatment and finishing machining of the tip.

13.4.3 Manufacturing of aluminum extruded spar

The spar workpiece of high-strength aluminum alloy of АВТ-1 or АД-33 grade is produced by hot extrusion in the mandrel die that at the output welds several metal flows together in the closed loop of constant cross section with inside webs or reinforcing ribs.

After the input X-ray defect control of the workpiece the spar workpiece is milled on the bed-type copy-milling machine of ВКФ-1 model equipped with two horizontal (for rough and finishing machining) and one vertical milling cutter heads. Milling is performed with form milling cutters. The spar workpiece is fixed on the machine table with hydraulic blank holders.

External contour of the spar has the zones with the constant cross section within its length and smooth transition zones. The thickness of the spar walls after milling varies from 3 mm in the overhang part to 20 mm in the butt part. After milling, the external surface of the spar is scraped and finished to the accurate cross section contour by means of portable pneumatic grinding machines.

According to the requirements of the blade aerodynamics, the spar has geometrical twistedness along its length. Spar twistedness is performed in the cold state on the installation of УЗЛ-1 model.

Assembled mandrel with the cord tension bracing in the zone of twisting is put into the internal channel of the spar. The spar is spinned with the rollers on the locating blocks, pressed with the force brackets through the hydrocylinder. Locating blocks are self-oriented with respect to the external contour of the spar and are rotated from the power hydraulic actuator with automatic calculation of the blade spring angle after removing the load. After moving on the step required, the spar is fixed with the force brackets, the twisting cycle is repeated.

After the operation of geometric twisting in the butt part of the spar, one performs drilling-out and reaming of the mounting holes of the butt part tip in two steps. After reaming, the holes are burnished, and their edges are pressed. For strengthening of the pressed spar, one uses shock-vibrating hardening in the impact machine of УБЯ-3-11 model.

After hardening and washing, the spar surface is counteretched in the acid solution in order to remove the thin film of oxides before applying the protective galvanic coating.

Before installing into the jig for assembling, the spar with the butt eng tip passes the geometrical control and gets weighted.

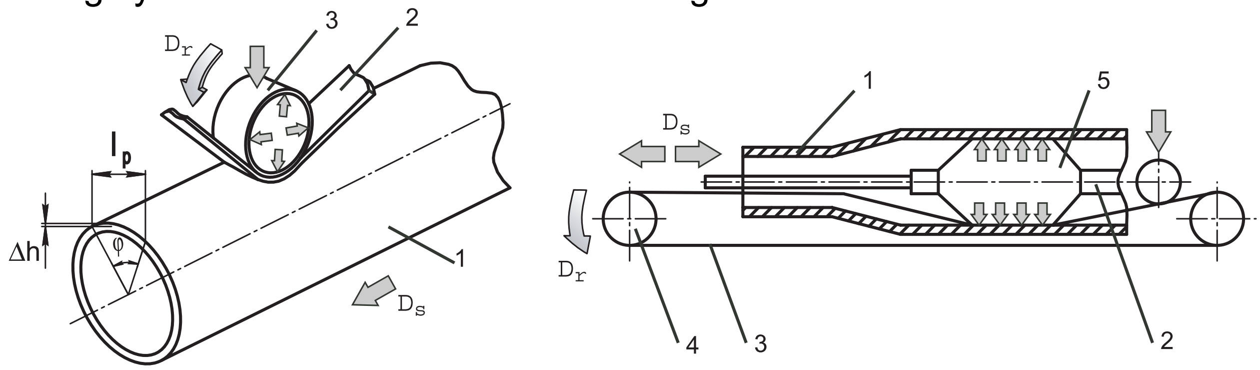
13.4.4 Manufacturing of steel pipe spar

For heavy helicopters, the AMB spar is manufactured of steel cold-rolled tube (40XHMA steel). Workpiece along its span has variable thickness and cross section shape (from the circular cross section in the butt to the oval one in its overhang part).

After the input X-ray control and quenching, the workpiece is ground on the external and internal surfaces on the specialized belt-grinding machines of СШСЗ models (external milling) and СШСВ (internal milling).

Layer grinding of the external wall of the spar 1 (see Fig. 13.15, a) is performed with the abrasive belt 90…100 mm wide. The belt is pressed to the machined surface with the pneumatic contact roller 3.

During machining, the spar 1 workpiece is moved along the longitudinal axis of the machine with the feed 5…25 m/min and in the breaks between the working cycles it is turned on the certain angle.



a b

Figure 13.15 – Grinding scheme of the steel pipe spar

Hydraulic system of the machine follows the part profile through the rollers, by the move of which the pressing force of the abrasive belt (0,2…1,2 MPa) is adjusted depending upon the radius of curvature of the spar cross section. Technological parameters of belt grinding are the depth ***h*** and width ***l*** of the removed metal layer.

Fig. 13.15, b shows the grinding scheme of the internal surface of the spar workpiece on the machine of СШЛВ model.

Before grinding, the workpiece 1 installed in the drive support holders and pressed in the machine draw-in gear, has the abrasive belt 3 90…100 mm thick drawn through it with the help of the bar 2, and the belt's ends are glued together. The drive pulley 4 on which the abrasive belt is fixed is actuated with electric engine. The belt is pressed to the machined surface with the elastic element 5 filled with compressed air through the shank 2. Air pressure in the elastic element is 0,03…0,08 MPa, the movement speed of the belt along the grinding layer at the expense of the pressing element feed is 5…6 m/min, and main movement speed of the grinding belt is 20…25 m/sec.

In order to increase fatigue strength of the steel spar under dynamic loads, one uses rolling with the rollers, shock-vibrating and pneumodynamic machining.

The workpiece of the pipe spar 2 (Fig. 13.16) is spinned in two machining passes during the up and down rotation of the roller 3 and the spar. Rotation speed of the runner is 2500 min^{-1}, of the spar – 5…6 min^{-1}, length feed of the runner is 0,1…0,2 mm/rotation. The spar surfaces of cylindrical and oval shape are spinned with three- or five-layer roller runners 3.

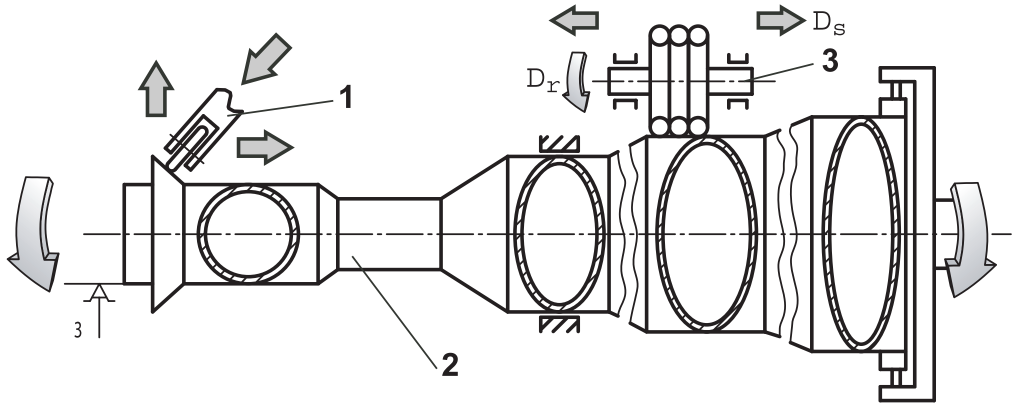


Figure 13.16 – Scheme of spinning of the pipe spar workpiece

The fillets are hardened with the single-row roller 1. The tool pressure on the spinned surface is provided with calibrated springs within 50…60 N. For connecting the steel tip (butt) and pipe spar, one uses argon arc welding. The circular seam is welded on the special installation of model УСМК-2 in the argon environment.

After this, the joint of the tip with the spar is processed thermally in order to relieve the welding stress.

After priming the internal surface with the atmosphere resistant coating, the ready spar is delivered to the stocks for manufacturing the nose part of the blade.

Test questions

1. Name the typical assembly types of milling NC machines that are used in the manufactures of the branch of industry.
2. What modifications of standard end milling cutters are used for milling?
3. What types of form end milling cutters are used for milling of spatially difficult surfaces?
4. Provide the schemes of bed-type and transversal three-axis milling of the sloped zone of the surface, part or equipment.
5. What technological peculiarities does the software of pressed stringer parts have?
6. Name the factors that determine the machining sequence of the fuselage bearing frames.
7. What types of five-axis milling are used for manufacturing the aircraft parts and technological equipment?
8. Provide the milling scheme of the end surfaces of the honeycomb filling of the lift devices' joints.
9. Name the route technology of manufacturing the aluminum pressed spar of the helicopter blade.
10. Give the schemes of external and internal grinding of steel pipe spar of the helicopter blade.
11. According to what scheme is the rolling of steel pipe spar performed?

14 MAIN DIRECTION OF INTENSIFICATION OF MACHINING PROCESSES WITH ALLOWANCE REMOVAL

Due to the necessity of reducing the laboriousness of machining, the following areas of increasing the efficiency of machining processes with removal of extra material are the most important:

– intensification of existing cutting processes mainly due to using new types of tooling materials, improving the design of cutting tool, optimization of cutting parameters and technological schemes of machining;

– using of new processes and methods of machining that are based on the additional influence of different types of energy (e.g. local heating of the workpiece, application of vibrations and ultrasonic frequency fluctuations) on the machined workpieces.

The machining of difficultly machined materials with different types of electrophysical, electrochemical and chemical machining has special interest.

14.1 Improvement of tooling material

Development of tooling material of increased hardness, strength heat- and red-hardness, high wear resistance is conditioned by ever higher usage of the parts of high-strength, stainless and heatproof steels and alloys in the aircraft airframe [3, 10, 11, 21].

To machine them, at first, one used fast-cutting steels of P18, P9, P12, P6M3 grades that differed from the tool material used earlier by significantly larger content of the alloying elements (vanadium, molybdenum, chromium, and wolfram). These fast-cutting steels keep their properties under the conditions of the temperature rise in the machined zone up to 600°C that allows to increase the cutting speed 2-3 times.

After this, new grades of fast-cutting steels of increased productivity were introduced to the legal standards; according to their composition they may be divided into three groups:

– *cobalt* (P9K5, P9K10, P10K5Ф5, P12Ф4K5) that are of high hardness and red-hardness and that are used for rough and semi-finishing machining of high-strength materials;

– *vanadium* (P9Ф5, P14Ф4, P12Ф5M) that have increased wear-resistance under the conditions of operating in the zone of low temperatures and did well for finishing machining;

– *cobalt-molybdenum* (P6M5K5, P9M4K8, P12Ф2K8M3) that have high hardness and red-hardness and provide good results during machining of heatproof and titanium alloys.

Fast-cutting steels of new grades, having the best results in hardness, red-hardness and heat conductivity, have provided the increase in tooling durability 2-3 times compared to the fact-cutting steel of P18 grade.

In order to increase the quality of fast-cutting steels, one has used the method of powder metallurgy in their production. Production tests showed that the tooling of fast-cutting steels of P6M5K5 and P9M4K8 grades manufactured by powder metallurgy has increased by 30…70% durability compared to the tooling manufactured by conventional method.

Many aircraft building plants have successfully introduced the *age-hardened* tooling alloys of ЕП634, ЕП-723 and ЕП831 grades that provide sevenfold increase of the tool durability by machining of parts of titanium alloys and high-strength steels compared to the fast-cutting steel of P18 grade.

Further intensification of cutting deals with using the tooling material of both hard alloys and cemented-oxide superstrong materials.

Nowadays the following groups of hard alloys are widely used in aircraft manufacturing:

- *wolfram* of ВК8 and ВК8В grades – for peeling and rough machining of high-strength materials, similar hard alloys of fine-grained structure of ВК6М and ВК10М grades and particularly fine-grained structure of ВК60М and ВК100М grades – for semi-finishing and finishing machining;
- *titanium-wolfram* – both for rough (alloy of Т5К10 grade) and finishing (alloy of grade Т15К6) machining of parts manufactured of heatproof and stainless steels;
- *titanium-tantalum-wolfram* – of ТТ10К8А and ТТ10К8Б grades – instead of the ВК8 alloy for machining of steel parts.

There is an effective way of increasing the productivity of cutting during machining of the parts of high-strength materials – it is the usage of cemented-oxide and superstrong tooling materials manufactured on the basis of polycrystal synthetic materials. *Cemented-oxide tooling materials* for cutting tools are produced as plates of aluminum oxide by pressing under high pressure with further sintering. They have high hardness and wear-resistance, strength, temperature stability up to 1200°C.

Cemented-oxide inserts of alloys of В-3, ВОК-60 and ВОК-63 grades are used for finishing machining of high-strength thermally treated steels. They may be fixed to the milling cutter body or cutter holder mechanically, by soldering or by gluing.

Production of large polycrystalline structures on the basis of boron nitride almost as hard as diamonds *opened* ample opportunities for equipping the cutting tooling with synthetic *superstrong materials (SSM).*

Cutters and milling cutters manufactured of this material – cubic boron nitride-P and geksanit borazon material-P – are usually used for finishing operations of machining the workpieces of hardened steels and titanium alloys.

As the result of fine turning, boring and milling with the tooling equipped with these materials, the same parameters of machining accuracy and surface roughness are provided as by grinding, but in this case one gets the surface layer of better quality, as it doesn't have the defects typical for grinding – burns, structure transformations, impregnation with abrasives.

14.1.1 Improvement of tooling design

The processes of dimensional machining may be significantly intensified by changing design of the cutting tooling, and the tooling with mechanical fixation of reversible cutting inserts (RCI) of hard alloy, of cemented oxide, and polycrystalline SSM are in the first place.

The variety of inserts allows, for example, to gather the set of specialized turning cutters of RCI for machining or wide range of the parts on the turning NC machines (Fig. 14.1).

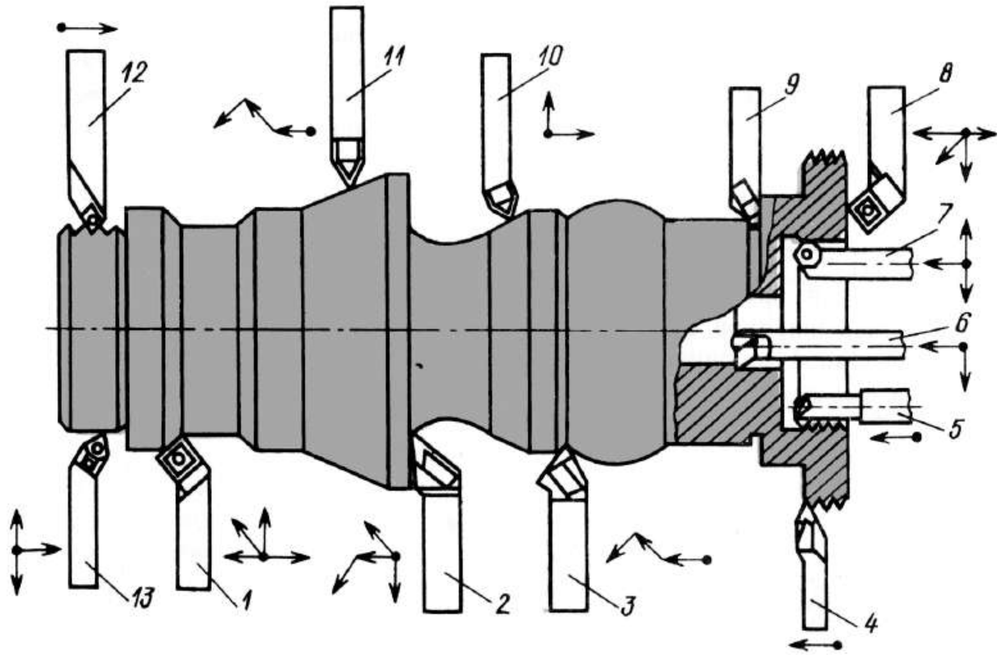


Figure 14.1 – Machining scheme of main typical surfaces with turning cutters with RCI

The tooling set for turning NC machines usually includes the following cutters (see Fig. 14.1):

– 1 – straight-turning offset cutters with φ = 45° for chuck machining of the parts like flanges: external turning, facing, chamfering ;

– 2 – profiling cutters with φ = 93...95° that allow to turn the parts along the cylinder and reverse cone with the angle up to 30°, machine the radial, end surfaces and fillets;

– 3 – profiling cutters with φ = 63° for machining of half-spherical surfaces and cones with the angle up to 60°;

– 4 – threaded ones with rhombus inserts that allow to produce thread with the pitch 2…6 mm (profile angle is provided by the insert shape);

– 5 – threading ones for internal threading that allow to produce thread with the pitch up to 2 mm with access to the hole end surface;

– 6 – boring ones with φ = 95° for boring of through holes;

– 7 – boring ones with φ = 92° for boring of the holes with the diameter 22 mm and greater;

– 8 – straight cutter ones with φ = 45° and square inserts for external turning, facing, chamfering;

– 9 – groove ones for external grooving 1…6 mm wide with the depth equaling to width (the cutters are developed using the two-sided RCI for internal and external angular grooves);

– 10 – straight-turning ones with triangular-shaped RCI and φ = 93° that allow turning cylindrical and profiled surfaces;

– 11 – straight-turning ones with triangular-shaped RCI and φ = 63°;

– 12 – threading ones for external cutting with the pitch up to 2 mm; cutter point profile is provided by sharpening of the inserts with the angle equaling to the cutting profile angle;

– 13 – straight side-facing ones with triangular-shaped RCI with φ = 92...95° for turning of stepper surfaces, chamfering, facing by moving from the external diameter to the part center.

Main advantages of using the tooling with mechanical fixation of RCI are the following:

– there is no soldering of cutting inserts, and therefore, of thermal stress caused by soldering, and this eliminates cracks and increases the safety factor of the tooling during operation;

– the cutting tool geometry is stable during cutting inserts' replacement, and constant roughness of the cutting edges is provided;

– hard alloys and other tooling materials may be used more efficiently.

Holders of turning cutters are manufactured in different sizes: full-size, shortened, and tool cartridges. Tool cartridges allow to create various types of single- and multi-cutter controlled tools.

The tooling is installed into the tooling head (cutter block) slot or toolholder, and after that machining accuracy is specified.

Among the RCI tooling, the group of turning cutters is the most significant. There is an integrated coding system of certain symbols of RCI turning cutters.

The example of designations of boring cutters according to the *ISO* recommendations is given in the Fig. 14.2. Other types of turning cutters are encoded according to this scheme.

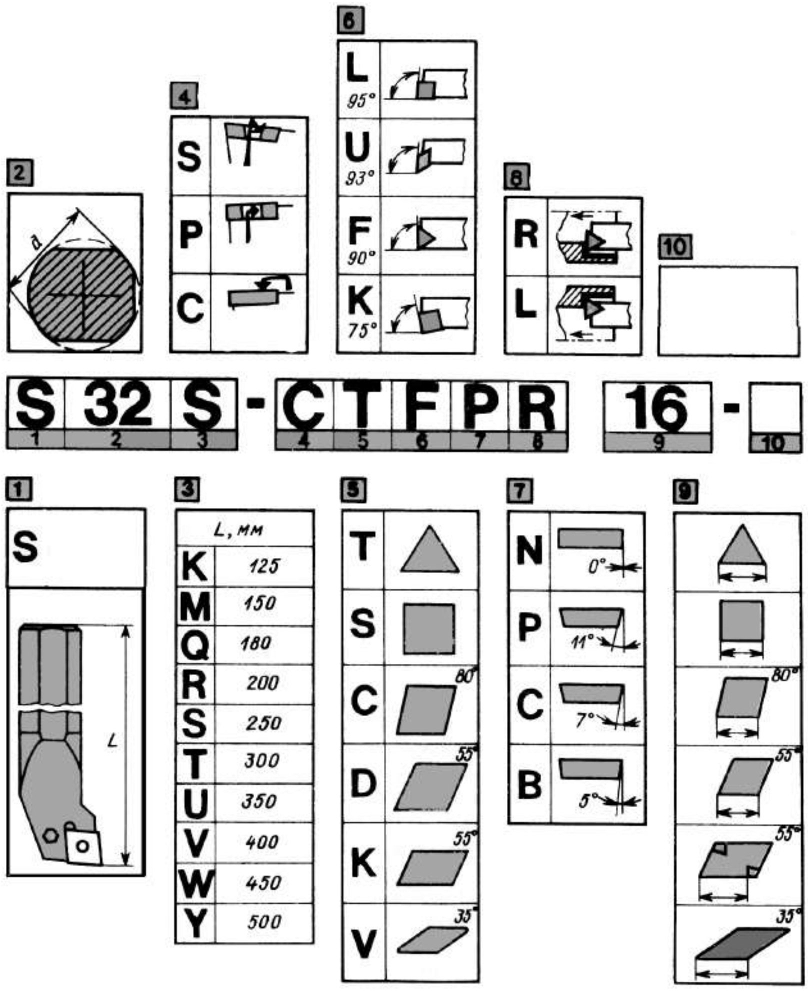


Figure 14.2 – Scheme for giving the designations of boring cutters
The scheme for giving the designations of boring cutters (see Fig. 14.2) includes the following elements: 1 – type of the mandrel (S – solid steel one); 2 – diameter; 3 – length; 4 –mechanism of fixation (S – with the bolt, P – by hole, C – with the catcher); 5 – insert shape; 6 – type of the mandrel; 7 – insert clearance angle; 8 – version of the mandrel; 9 – cutting edge length; 10 – marking of the plant-manufacturer

14.1.2. Methods of increasing the tool durability

Wear of cutting tooling is the process of breaking of the surface layers which leads to progressive changing of the shape and condition of the tooling cutting surfaces. In case of cutting, friction and wear-out of tooling related to it differs from the friction wear-out of structure elements. During cutting, there occurs friction of newly formed surfaces of the chip removed with front and clearance surfaces of the tooling.

Oil-cooling technological environments (OCTE) provide the most favourable conditions for machining (maximum tool durability, optimal workpiece temperature, etc.). Oil-cooling liquids (OCL), compressed air, and inert gases for blowing-off belong to OCTE. OCL make up about 97% of all OCTE used in production and are used mostly for heat abstraction from cutting area in order to reduce temperature, and therefore, increase the cutting tool durability.

During finishing machining, due to OCL, one produces the surfaces with minimal roughness. OCL also prevent corrosion of cutting tooling and machined surfaces of the workpiece. There are different methods of supply the OCL to the cutting area: flowing, supplying under pressure from the clearance surface of the tool, spraying (aerosol or mist).

Coating of wear-resistant layer is especially effective for the tooling that are sharpened only on the front surface (e.g. for profiled milling cutters). In this case, even after further re-shapenings wear-resistant coatings keep their positive influence on the tool workability.

Cutting tool durability increases up to six times if a 5…15 mkm thick wear-resistant layer of titanium carbide, niobium, boride or nitride are coated on its surface. Wear-resistance of the tooling of fast-cutting steel with the coating of titanium nitride increases 2 – 5 times.

Further increase of tool durability was reached by separating the mentioned above coating thickness on separate layers. Each layer performs a certain function as to different types of wear-out, strength of cohesion and thermal expansion. The coating is deposited on the inserts of hard alloys using gas-cycle and thermal diffusion methods.

The company “Sandvik” (Germany), for example, recommends the following three-layer coating with the thickness of each layer 1…3 mkm:

– internal layer of titanium carbide provides high wear-resistance and good adhesion of the coating with the hard alloy;

– intermediate layer of aluminum oxide provides necessary heat resistance;

– external layer of titanium nitride reduces friction of the cutting tool front surface.

Preliminary heating of the workpiece material is one of the ways of intensifying the cutting of difficultly processes materials. Here, one uses the methods of inductive, electric arc, electric contact, and plasma heating of the workpieces.

Workpiece heating results in increasing the article machinability due to the change of material mechanical structure in the chip-formation area, increase of its plasticity and reduction of strength and hardness.

Change of mechanical characteristics M_2 of machined material due to the temperature increase from T_1 to T_2 is determined with the formula

$$M_2 = M_1 exp\left[-\alpha_T\left(T_2 - T_1\right)\right], \qquad (14.1)$$

wherein M_1 are mechanical characteristics of the material by the temperature T_1; α_T is the temperature coefficient that depends on the material properties and conditions of plastic deformation.

As mechanical characteristics of the workpiece material are changed, there is reduction of the cutting force, lowering of the wear intensity of cutting tooling, increase of the cutting speed.

Despite this, heating of the workpiece is expedient only when softening of the workpiece prevails over softening of the tool working surfaces. This is why for cutting with heating one uses mostly hard-alloyed and cemented-oxide cutters.

Cutting with preliminary plastic deformation of the workpiece (Fig. 14.3.) provides changing of physical and mechanical properties of the material of the cut layer. Preliminary plastic deformation of the machined surface with the force ***P*** is performed with the knurl roll (see Fig. 14.3, a) placed in front of the cutter. The roll and the turning cutter are moved along the workpiece axis with constant longitudinal feed.

The cutter that moves after the roller removes previously weakened layer of the material, which results in eliminating the plasticity reserve of machined material, and its cutting machinability increases. Turning with preliminary plastic deformation significantly increases cutting machinability of ductile high-strength steels like Х18Н9Т, ЕІ437Б, ЕІ811, etc.

Penetration into the workpiece body of wedge-like roll (see Fig. 14.3, b) allows to create the net of microcracks in the material surface layer, which significantly increases machinability and durability of hard-alloyed tooling.

Cutting with vibration is one of the ways of intensifying the processes of machining of high-strength materials. The essence of this process is in the fact that additional oscillating movement is added to the machining kinematic scheme in the direction of the feed movement of perpendicularly to the workpiece surface. Most frequently, these vibrations are of sinusoidal shape.

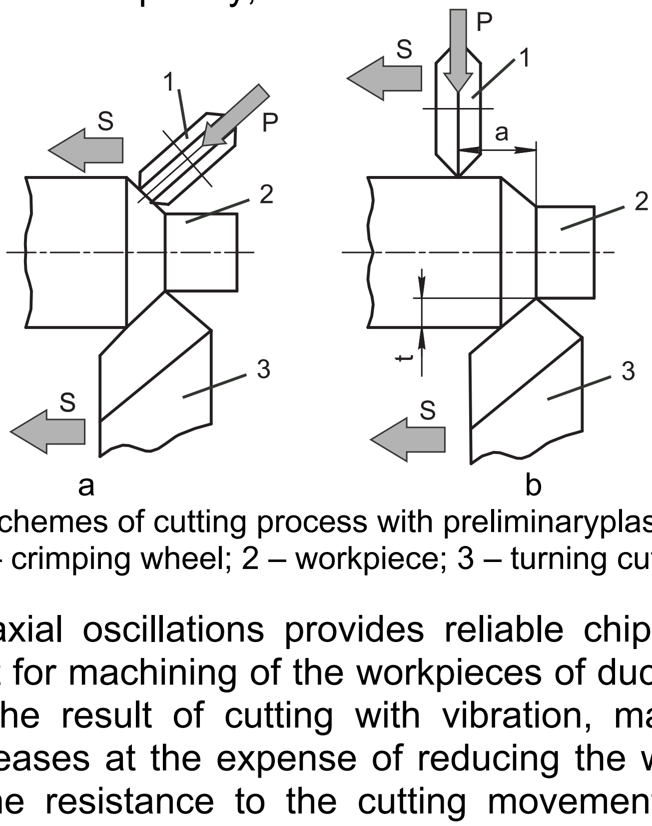


Figure 14.3 – Schemes of cutting process with preliminaryplastic deformation:
1 – crimping wheel; 2 – workpiece; 3 – turning cutter

Cutting with axial oscillations provides reliable chip breaking, which is especially important for machining of the workpieces of ductile materials on the NC machines. As the result of cutting with vibration, machinability of high-strength steels increases at the expense of reducing the wear intensity of the tooling, reducing the resistance to the cutting movement, and lowering the temperature in the cutting area. The process of cutting with vibration increases the efficiency of OCL influence on the tool cutting blade.

14.2 High-speed cutting

The method of high speed cutting (HSC) provides the following fundamental changes, first of all, during milling:

- increasing the feed speed of the milling cutter up to 20 m/min (maximum speed for usual machining is 0,5 m/min);
- increasing the specific volume of the chip up to 100 cm^3/(min·kilowatt) (maximum volume for usual machining is 40 cm^3/(min·kilowatt));
- increasing the spindle rotational speed up to 20000 min^{-1} (maximum rotational speed in serial milling machining equipment nowadays doesn't exceed 5000 min^{-1});
- cutting of main (machining) time of milling 3 – 5 times.

This method is especially effective for machining of thin-walled ribs and walls due to reducing the cutting forces 3 – 4 times and practically full absence of heating of the workpiece during cutting.

The company "Forest-liné" (France) has created the machine of H1.1600UTGV model for fast-cutting machining of the workpieces of aluminum alloys with the dimensions 4000×1600×400 mm [12].

The machine is a movable portal that moves along the guide elements of the vertical base column. The machined workpiece is fixed on the vacuum table of machine (Fig. 14.4). Such structural configuration is typical for machining equipment that implements the *HSC* technology.

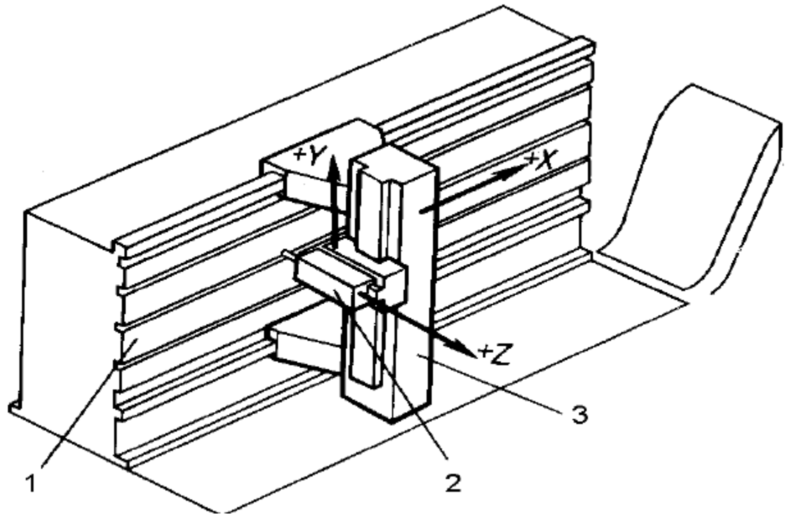


Figure 14.4 – Structural configuratiof the fast-cutting machine

For natural removing of chip from the cutting area, table of the machine 1 is placed vertically; spindle head 2 with horizontal spindle is located on portal 3 that includes the machine table. The spindle head is equipped with the high-speed electric engine, the rotor of which is installed on the active magnetic bearings. The spindle has two directions of rotation, the rotational speed is controlled from 3000 to 30000 min^{-1} with the electronic frequency transformer at constant angular momentum.

There is automatic change of the tooling in the spindle on machine with the tooling from the immovable magazine that has 14 tools by means of additional moves of the milling cutter head.

The portal and the vertical carriage (axes X and Y) have aerostatic guide elements, by means of which the high values of accuracy and speed of coordinate moves are provided. The milling cutter head (Z-axis) moves along the guide elements made of plastic.

The feed drives are equipped with high-torque electric engines of direct current with electronic controllers. Special servodrive traces high dynamics of the machine of this type and implements acceleration up to 10 m/sec^2. For chip removal the conveyer placed in the front part of the machine foreseen is used.

The drives of longitudinal (X-axis) and horizontal transversal (Z-axis) movements of the milling cutter head are two-sided, synchronized with the electronic system and manufactured in the form of gears and rods with the device for gap removal. The drive of vertical movement of the carriage (Y-axis) is manufactured in the form of pre-loaded ball screw with a very large pitch in order to provide high feed speeds. Unloading of the vertical carriage is carried out with the help of pneumatic cylinder.

The machine is equipped with the NC device with simultaneous control of the movements along the three coordinate axes, which provides the feed speed of the machining stroke up to 20 m/min in the plane XY and up to 10 m/min in the planes XZ and YZ. The feed speed of the auxiliary movement is equal to 30 m/min.

Development of NC machining equipment for high-speed cutting machining using the *HSC* method requires solution of the following complex of technical and technological problems:

1. Manufacturing of the cutting tooling of guaranteed durability. For high-speed cutting tooling of hard alloy with multi-layer coating is the most suitable.

2. Manufacturing of spindle assemblies of machining equipment with rotational speed 10000…60000 min^{-1} with the capacity up to 100 kilowatt.

3. Development of methods and tooling for active automatic control of the workpiece geometrical parameters and condition of the cutting tooling during machining. Under the condition of controlling the parts outside the machine the result of machining is determined only and the active influence of the control stage on providing the necessary machining accuracy is excluded.

4. High fly-off speed of the cutting tooling fragments in case of its breaking and large volume of chip require special solutions as to structural configuration for ensuring the safety requirements in the zone of machining. The solution of this problem may be in the typical structural configuration of the machine (see Fig. 14.4) – reliable removing of chip from the zone of cutting due to the vertical placement of the table, protection of the cutting area with the casing, and remote control of the machining process.

5. Elimination of dynamic inaccuracies in case of maintenance of the set given feed speed. This requires additional reduction of the length of the trajectory linear segments, which causes the corresponding increase of the CP volume. For high-speed cutting, it is required that the angles in the places of

rapid change of the tool moving direction were rounded, and the tool advance and withdrawal movements were performed along to the tangent arc.

6. Development of software and technical means of combining computers with the NC devices, which provides loading of the CP of large volume to the extent of their maintenance that goes parallel with machining (segmented feed mode).

14.2.1 Upgrading of machining equipment

Today the enterprises of aerospace branch of industry use such models of NC milling machines as MA655, ФП7, ФП17 of all modifications, bed-type milling five-axis machine ВФ5Н, bed-type milling machine ФП241С with movable portal, etc.

The machine-building enterprise Savelov’ska public corporation “SAVMA” (“САВМА”) (former title – production association “Progress”) has manufactured over 30 thousand high-accuracy NC machines for aerospace industry.

Machines that are available today on these enterprises may be reingeneered in order to implement wide usage of high-speed cutting technology *HSC*.

One upgraded milling machine, due to higher quality of machining and new technological possibilities may substitute from two to four machines of the same model.

Vertical-milling multicenter machine of ФП7/17ВС3 model was created by upgrading the machine of ФП7 model, about 15 thousand items of various modifications of which were manufactured for the aerospace industry.

The machine of ФП7/17ВС3 model has enhanced parameters: spindle rotational speed – 12000 min^{-1}; speed of working movements along the axes – 16000 mm/min; spindle rated power increased up to 45 kilowatt. This machine with full protection of the cutting area has new mechanism of tool change for 12 positions, and the size of its working zone is 3000×1600×500 mm.

The machine has speed dynamic digital drives of alternate current with real-time interface (*SERCOS-interface*). The machine **is** equipped with the NC system of MTC200 model of *CNC/SPS* class. Machining accuracy is 0,03 mm, surface roughness is less than $\boldsymbol{R_a}$ 0,8 mkm.

Modifications of ФП7ВС2 and ФП17ВС2 are used for machining of the workpieces of non-ferrous alloys, ФП7ВС3 and ФП17ВС3 – of heavily machined materials, titanium alloys in particular.

The company ”SAVMA” prepares for production the new five-axis multicenter machine of МЦ-1 model for machining of parts of single and double curvature of high machining efficiency.

Machining equipment of new generation allows the following:

− 2 – 10 times increase the productivity, significantly increase machining accuracy;

− reduce roughness of machined surface up to $\boldsymbol{R_a}$ 0,3, eliminate expensive finishing and fine finishing operations of machining.

To conduct adaptive control of the cutting parameters, machines of new generation are equipped with the sensors of the cutting force and angular momentum and specialized computing machinery. Adaptation system controls the tool feed speed, distributes allowance, protects the machine from overloading, detects tool breaking, and interrupts the machining cycle.

14.3 Computerization of machining processes

Computerization of engineering tasks is one of the main ways of increasing the competitive ability of the products of any machine-building enterprise independently of the type of production.

The key point of the modern stage of production is the transformation from discrete to electronic description (EID) of the item of manufacturing.

The basis of EID is paperless application of the item information model that includes all data of the item with respect to the international standards.

Basic components of the EID are the following:

– complex of software for automated design of the item *CAD (CAD – Computer Aided Design)*;

– system of automating the work preparation *CAM (CAM – Computer Aided Manufacturing);*

– engineering analysis system *CAE (CAE – Computer Aided Engineering);*

– system for controlling the information about the machine PDM *(PDM – Product Data Management).*

As basic means of computer integrated technologies, the enterprises of aerospace industry use the following high-level systems: *Unigraphics, CATIA, CADDS-5, EUCLID*, etc.

These systems include programs for creation of the mathematical model of the surface manufactured part, designing the internal layout of the compartments, assemblies and aircraft in general, maintaining the project database, engineering preparation, planning and production control of the works.

Design of the parts, workpieces, and facility of technological equipment based on solid modeling, development of drawing documentation, preparation of CP for the NC equipment – all these tasks are solved by using the whole set of computer integrated *CAD/CAM-systems*.

Turning. With the help of the *CAM*-module of computer integrated systems, one solves the tasks of generation of the CP of two-axis machining for the following types and engineering steps of turning: rough and finishing, longitudinal and transversal turning, facing, grooving, machining of fillets, boring, threading and performing the cycles for hole machining.

For each operation or for each operation step, there is a possibility to control such parameters as cutting depth, directions and angles of working and auxiliary movements, workpiece shape and geometry, number and step of working and auxiliary passes. All turning operations or operation steps are determined with respect to the geometrical parameters of the tooling – lead and auxiliary side cut angles.

Milling. CAM-module provides performing of the following types and steps of milling:

– contour plane machining with various types of trajectories of tool advance to the contour and withdrawing it and the possibility of their tool radius correction, machining of cavities of various depth, drilling and other types of hole machining;

– rough, semi-finishing or finishing machining with parallel machining passes along the given direction (the step between the passes may be constant or it may be calculated according to the machining quality criterion – crest height);

– multi-axis solid machining using special software for controlling the angle between the tool vector and the normal to the machined surface considering the tool movement path.

For computer modeling of milling, trajectories of working and auxiliary tool movements are especially important, possibility to apply various types of tools radius and length correction, to specify the workpiece shape and geometry, select the zones of machining or tracking path of borders of holding elements of machining equipment.

Electric erosion machining. CAM-module allows to specify various types of contour correction and path of machining and auxiliary passes of the electrode-tool along the external or internal contour machined.

Four-axis electric erosion machining with wire electrode-tool is modeled with two part contours (upper and lower) or directly with the linear surface built according to these contours.

14.3.1 Stages of developing of the CP of machining process

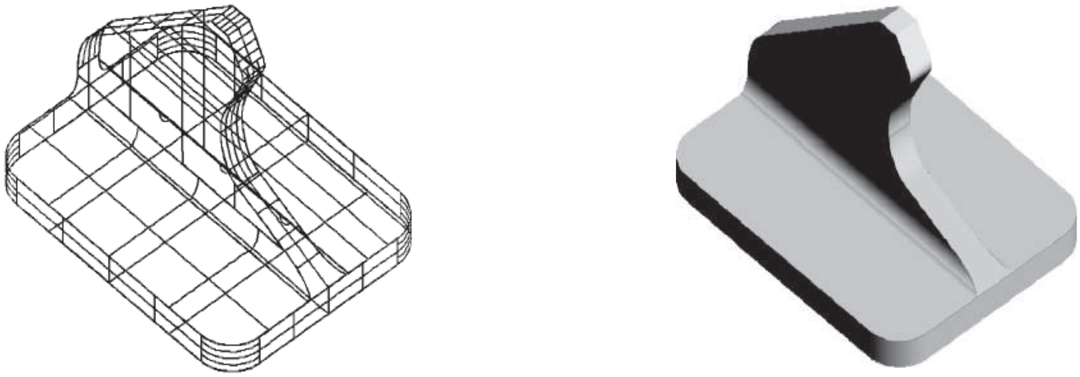
Machining CP as the combination of commands written in programming language from the point of view of engineer is the description of the operation plan in the language of the NC machine device.

The NC subsystem, being one of the components of computer system, uses the necessary information from the integrated system database. The external initial information for the NC subsystem is the geometrical model of the machined part of the wire (Fig. 14.5, a) or surface (Fig. 14.5, b) drawing.

It is known from the experience of introducing computer integrated systems in aircraft production that about 80% of the tasks on CP formation doesn't require usage of solid models.

Practically all tasks of deck contour milling, drilling and turning may be solved at the level of frame and surface models. Here, the amount of information required for solving these tasks is significantly smaller than in case of solid parametrical modeling.

The stages of creating of machining CP based upon computer integrated systems are shown in the Fig. 14.6.



a b

Figure 14.5 – Computer geometrical model of the part:
a – wire; b – surface

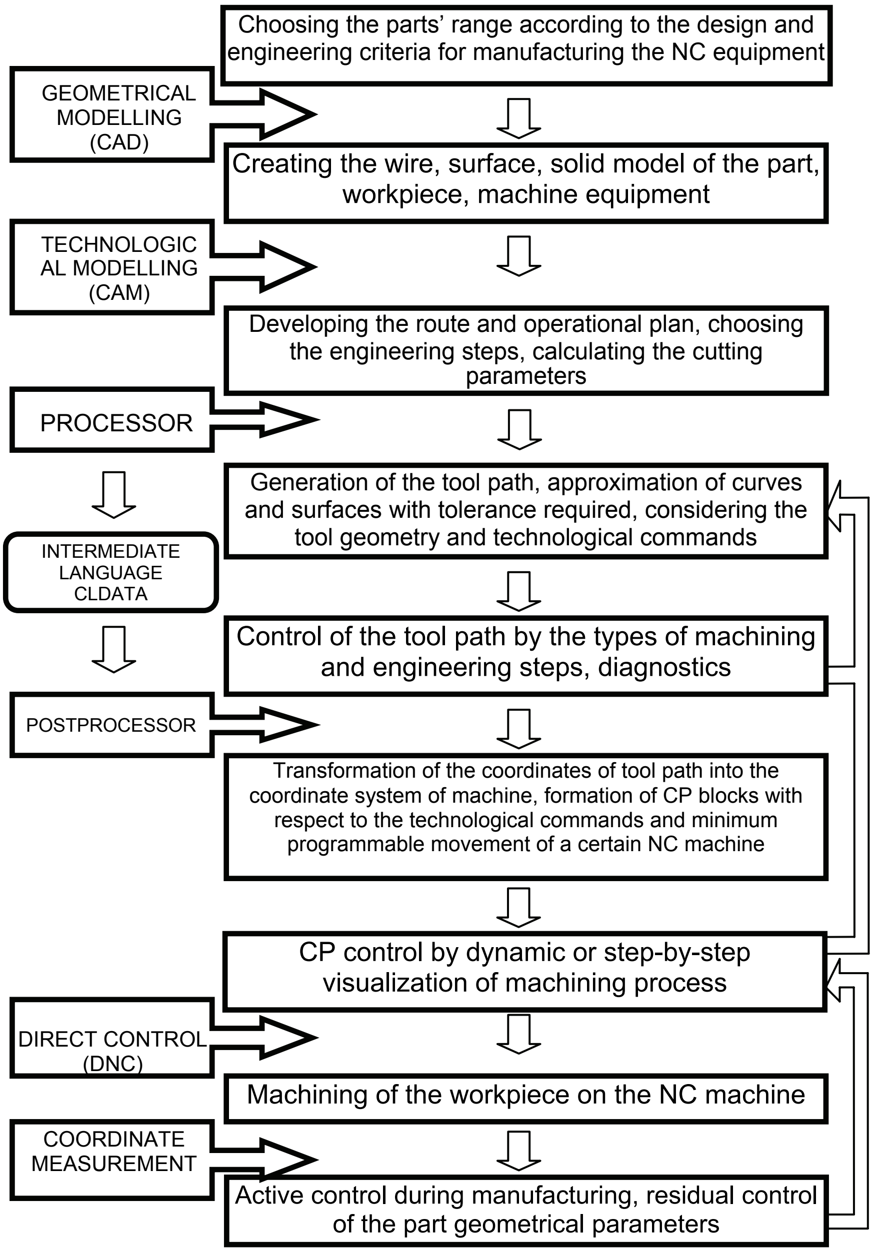


Figure 14.6 – Stages of creating the machining CP
on the basis of computer integrated systems

Manufacturing route includes the sequence of manufacturing operations that provide the necessary machining of the part.

Depending upon the equipment used for program machining, the manufacturing operation may be turning, milling, welding, control, etc. The operation consists of a sequence of engineering steps.

Step is a parameterized description of the tool path and cutting parameters of machining – feed, spindle rotational speed, and tool geometry.

The concept of the manufacturing step may be generalized if by machining one understands performing the necessary movements independently of the process type. Then, for example, the process of automatic measurement of the part with measuring heads may be also classified as the manufacturing step.

Generation of the CP is carried out in two stages (see Fig. 14.6). At the first stage, processing of the initial information is performed with the processor.

Processor is the program for initial processing of the information that forms the data on machining independently of the type of machine.

Processor performs the following set of tasks of calculating the tool path:

- representation of all geometrical objects as canonical forms;
- finding the points and lines of intersection of various geometrical elements;
- approximation of different curves and surfaces with set tolerance; approximation or interpolation of tabulated functions;
- considering the geometrical parameters of the tool during generation of tool path.

The result of processor operation is fully calculated tool path (Fig. 14.7).

During the second stage of CP formation, information reprocessing is realized with the postprocessor that, unlike the processor, is focused on a certain model of the NC technological equipment.

Postprocessor is a matching program that considers the peculiarities of the NC system of a certain machine and forms the CP blocks in the programming language in the *ISO* codes.

Postprocessor performs the following typical functions:

- transforming the coordinates of the tool path into the coordinate system of the technological equipment;
- determining the feed values of working and auxiliary moves, commands for coordinate moves, with respect to the value of minimum programmable movement (impulse price) of the NC device;
- coding of the values of feed and spindle rotational speed;
- generation of the commands for tool change, and also correcting its length and radius, turning on and off of the OCL supply;
- performing a number of service functions (calculation of the CP volume, time of the part processing on the machine, etc.).

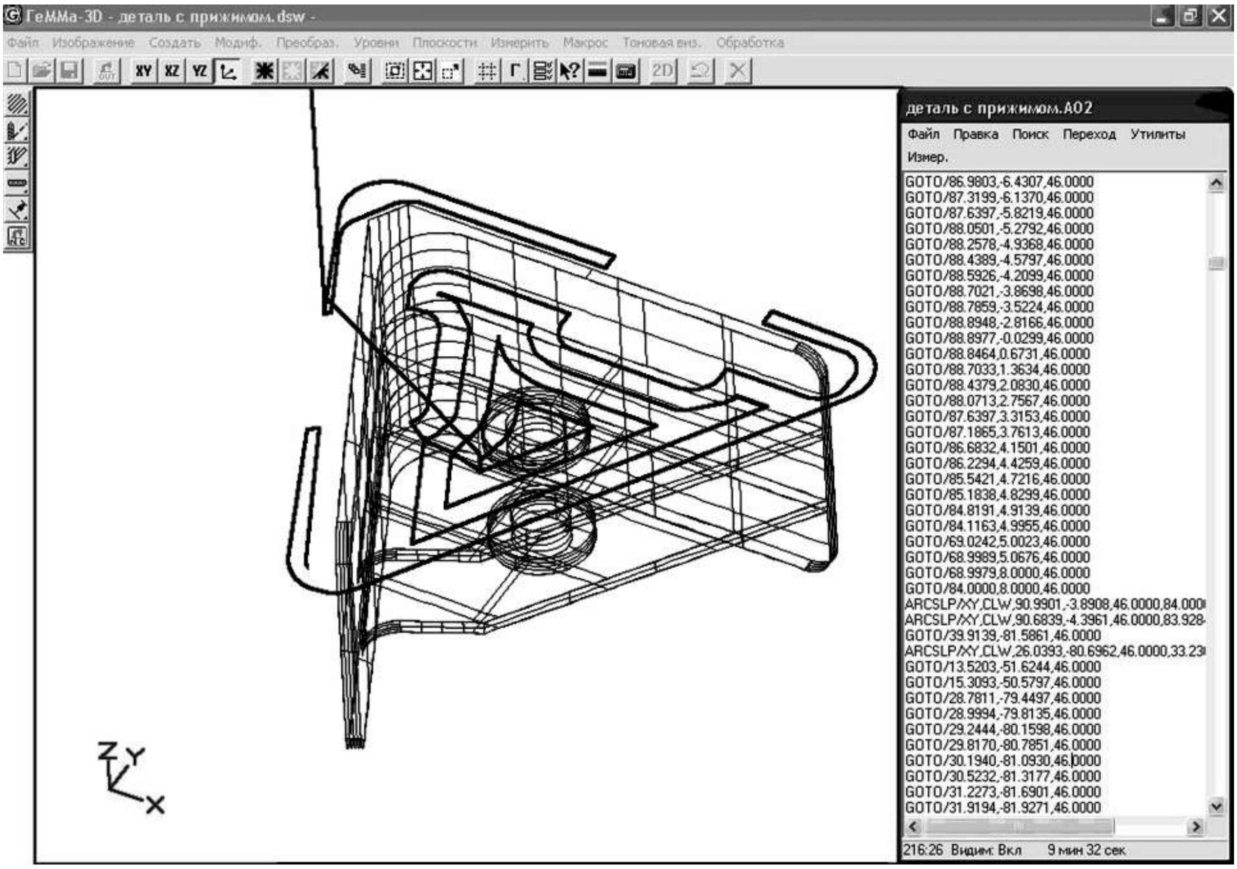


Figure 14.7 – Control of the tool path on the stage of processing

When forming the commands generating tool path, the postprocessor considers the type of interpolation (linear, circular), way of generating of the path (in the absolute coordinate, in the incremental one). The most important function of the postprocessor is considering the limitations of NC technological equipment, to which belong the boundaries of moving of the equipment executive devices and changing of the feed speed and spindle rotational speed, maximum permissible speeds and velocity steps of the equipment executive devices, limitations of changing the circle arc radius during the circular interpolation, etc.

The result of considering the boundaries may be postprocessor automatic correction of the values and feed parameters, changing the spindle speed and tool path, sending of the diagnostic message.

The tool path may be changed, for example, during assigning the path at the high feed along more than one axis at a time, which is inadmissible for most machines. In this situation, the postprocessor may arrange the coordinatewise movement to the set point, keeping the values of quick-action feed constant. Initialization of one or another postprocessor is done automatically on the basis of the instruction given by the technologist-programmer in the text of the initial program.

Enhancing the abilities of the NC technological equipment, and also the need in unification of the data structure, have conditioned the creation of the standard intermediate language "processor – postprocessor" according to the *ISO* recommendations. This form of presenting of the intermediate data is called *CLDATA* (abbreviation of *Cutter Location Data* – data on the tool location).

14.3.2. Visualization of the sequence of machining process

Visualization of the sequence of machining process allows to detect the mistakes that may appear, in particular, due to the fault of *CAD/CAM*-system postprocessor.

The CP control is carried out visually on the computer screen by means of dynamic or staged visualization of the sequence of machining process (Fig. 14.8). Here, one doesn't need to check the CP on the machine without the workpiece or test machining of the workpiece.

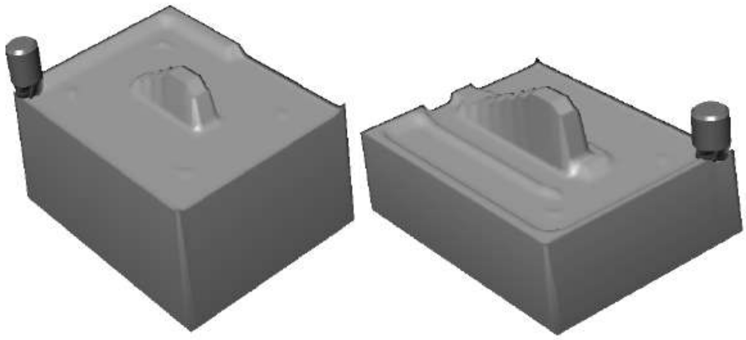


Figure 14.8 – Step-by-step visualization of machining process

The program of visualization of machining process allows the following:

- non-stop control of the CP or by separate blocks, showing the tool path and highlighting the machining zone with different colours if needed;
- calculation of the workpiece dimensions and machining time;
- change the perspective and scale of the image, show the machined surfaces.

Visualization of machining process significantly machining time for checking the CP and increases its probability.

14.3.3 Coordinate measuring of workpieces and parts

Coordinate measuring is determining of geometrical parameters of an object by sequential finding the values of coordinates of the object points in the chosen reference system and further processing of this information.

Coordinate measuring of workpieces and parts in the zone of machining is carried out with measuring heads (MH). Using the MH on processing NC machines allows to determine the dimensions of the part without its removing from the machine, i.e. to make the operations of control and machining as close as possible (Fig. 14.9).

The stimulus to industrial exploration of coordinate measuring on the machine was the creation of MH that transmit the signals of measuring distantly (by means of radio channel, infrared emission).

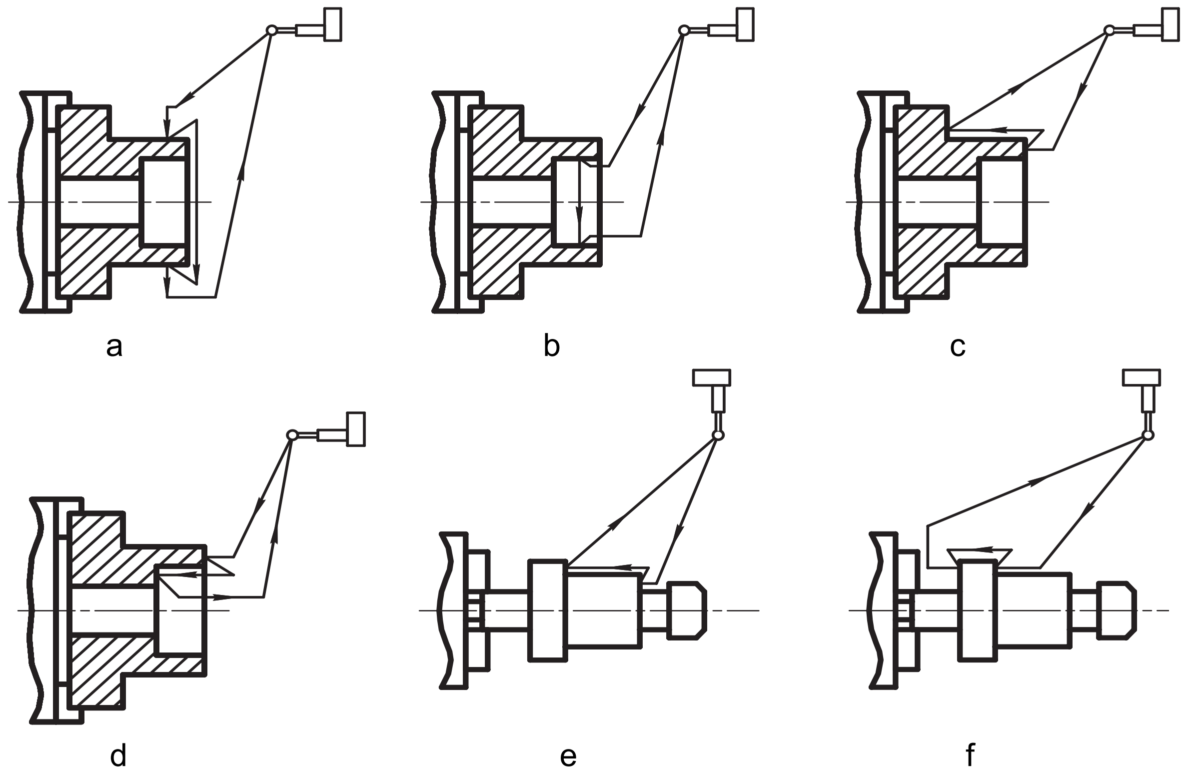
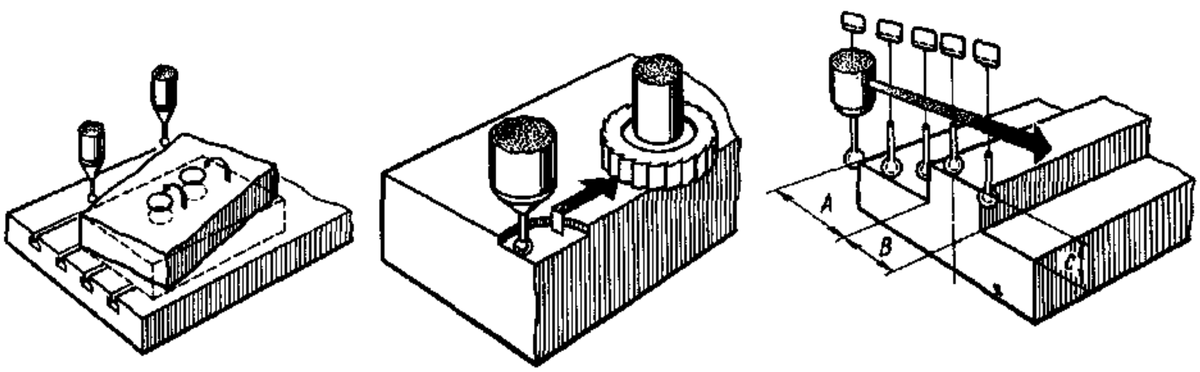


Figure 14.9 – Typical schemes of using the MH for measuring:
a, b – correspondingly of external and internal diameters;
c, d, e – of machined surface length; f – of flange thickness

For example, on the turning machine, the MH allows to check the accuracy of the workpiece installation in the chuck, namely, to find the values of its radial and end face runout, specify the distribution of allowance between the machining passes.

Measuring the part geometrical parameters allows to correct the initial coordinates during the tool setup.

The schemes of using the MH with the probe on the multicenter NC machine are shown in the Fig. 14.10.



a b c

Figure 14.10 – Schemes of using the MH for measuring the following:
a – inaccuracies of the workpiece installation; b – value of allowance
for finishing machining; c – part dimensions

Coordinate measuring performed directly on the machine provides high responsiveness during controlling the geometrical parameters of the manufactured parts, and implementation of adaptive control of machining accuracy.

The results of measurements are processed statistically in order to determine the tendency of changing the value of systematic inaccuracy, and also to eliminate the influence of random error. The results of the measurements are also used for correcting the control or measurement programs.

For final control of the geometrical parameters of large-size parts and equipment, the enterprises of aerospace industry use *monitoring machines* (MM) equipped with personal computers for controlling the process of verification and processing the results of measurement.

By the possibilities of high-precision coordinate measurements, the MM of bridge-type assembling (Fig. 14.11) are the most suitable for the enterprises of the industry.

The dimensions of the bridge-type MM measuring space are 8000×2500×1500 mm, and the systematic inaccuracy of measurement doesn't exceed ± 40 mkm.

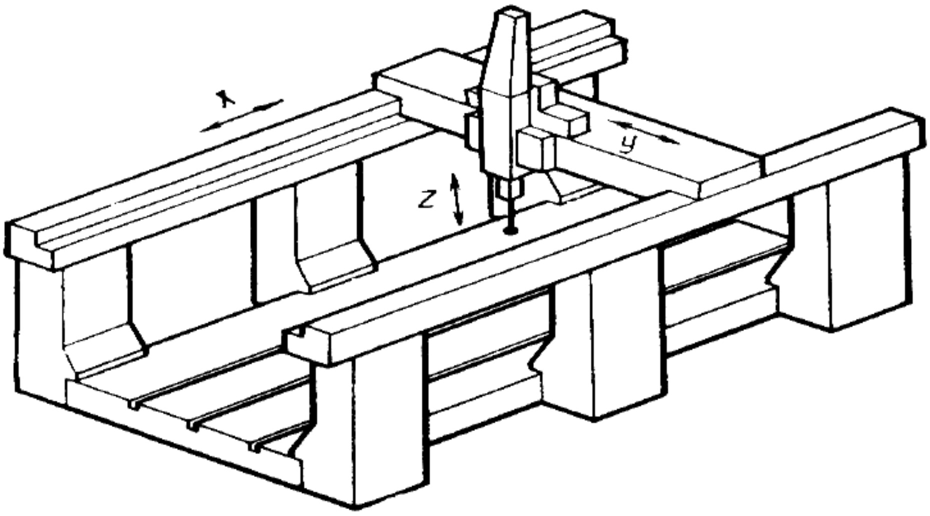


Figure 14.11 – Bridge-type MM

MM are used for solving the typical measuring tasks:

– controlling the complex geometrical surface by its comparing with the mathematical model;

– scanning of the cross-sections of the part in order to create the mathematical model of the surface on their basis;

– scanning of complex geometrical surfaces in order to create the processing CP on the NC machines.

MM significantly simplify the metrological preparation of new articles manufacturing, as there is no need in creating the special measuring and sample equipment. The protocol of verification results given out by MM is an official document. Operational and dialogue programming allows efficient use of MM in single-type and short-run production.

Test questions

1. Name the areas of increasing the efficiency of machining process with extra material removal.
2. Name the groups of tooling fast-cutting materials of increased efficiency.
3. What groups of tooling of hard alloys are used for machining of high-strength materials?
4. Name the spheres of using cemented-oxide and superstrong materials and describe the method of their manufacturing.
5. What are the advantages of using the tooling with mechanical mounting of RCP ?
6. What elements are included in the scheme of denomination of boring cutters according to the *ISO* recommendations?
7. What functions are performed by OCTE and OCL in the methods of increasing the durability of the tooling?
8. Describe the mechanism of deposition of multilayer wear-resistant coatings on the tool working surfaces.
9. What occurs during preliminary heating of the workpiece material of difficultly machined materials?
10. Give the scheme of cutting process with preliminary plastic deformation.
11. Enlist main peculiarities of machine structural configuration for high-speed cutting (HSC).
12. What technical and technological problems occur during implementation of the HSC processes?
13. What new technological features are received by upgrading of milling NC machines?
14. Name the main features of integrated CAD/CAM-systems.
15. What functions are performed by the processor and postprocessor during generation of CP for machining?
16. What typical coordinate measurements are performed with MH and MM?

BIBLIOGRAPHIC LIST

1. Вайсбург, В.А. Автоматизация процессов подготовки авиационного производства на базе ЭВМ и оборудования с ЧПУ [Текст] / В.А. Вайсбург, Б.А. Медведев, А.Н. Бакумский. – М. : Машиностроение, 1985. – 216 с.

2. Барвинок, В.А. Основы технологии в производстве ЛА [Текст] / В.А. Барвинок, П.Я. Пытаев, Е.П. Корнев. – М. : Машиностроение, 1995. – 398 с.

3. Белянин, П.Н. Производство широкофюзеляжных самолетов [Текст] / П.Н. Белянин. – М. : Машиностроение, 1979. – 360 с.

4. Гжиров, Р.И. Программирование обработки на станках с ЧПУ [Текст] / Р.И. Гжиров, П.П. Серебреницкий. – Л. : Машиностроение, 1990. – 588 с.

5. ГПС в авиастроении [Текст]: учеб. пособие / В.С. Кривцов, С.Г. Васильченко, Ю.В. Дьяченко, В.Е. Зайцев. – Х. : Нац. аэрокосм. ун-т «Харьк. авиац. ин-т», 2001. – 98 с.

6. Дерябин, А.Л. Технология изготовления деталей на станках с ЧПУ и в ГПС [Текст] / А.Л. Дерябин, М.А. Эстерзон. – М. : Машиностроение, 1989. – 288 с.

7. Джур, Е.А. Технология производства космических ракет [Текст]: учебник / Е.А. Джур, С.И. Вдовин. – Дп.: Изд-во ДГУ, 1992. – 184 с.

8. Кривцов, В.С. Інженерні основи функціонування і загальна будова аерокосмічної техніки [Текст] / В.С. Кривцов, Я.С. Карпов, М.М. Федотов. – Х. : Нац. аерокосм. ун-т „Харк. авіац. ін-т”, 2002. – 486 с.

9. Дьяченко, Ю.В. Использование контрольно-измерительных систем в технологической подготовке производства [Текст]: учеб. пособие / Ю.В. Дьяченко, В.В. Коллеров. – Х. : Харьк. авиац. ин-т, 1988. – 58 с.

10. Камалов, В.С. Производство космических аппаратов [Текст] / В.С. Камалов. – М. : Машиностроение, 1982. – 280 с.

11. Кривов, Г.А. Технология самолетостроительного производства [Текст] / Г.А. Кривов. – К. : КВІЦ, 1997. – 459 с.

12. Компьютерные интегрированные технологии авиационного производства [Текст]: учеб. пособие: в 6 ч. / В.С. Кривцов, Ю.В. Дьяченко, В.Е. Зайцев и др. – Х. : Нац. аэрокосм. ун-т «Харьк. авиац. ин-т», 2002. – Ч. 3 : Автоматизирование технологической документации. – 71 с.

13. Лещенко, В.А. Станки с ЧПУ (специализированные) [Текст] / В.А. Лещенко, Н.А. Богданов. – М. : Машиностроение, 1988. – 568 с.

14. Маталин, А.А. Технология механической обработки [Текст] / А.А. Маталин. – Л. : Машиностроение, 1977. – 464 с.

15. Кушнаренко, С.Г. Методы и оснащение для упрочнения элементов самолетных конструкций ППД [Текст] / С.Г. Кушнаренко, В.П. Цыганов, В.Т. Сикульский. – Х. : Харьк. авиац. ин-т, 1988. – 55 с.

16. Обработка металлов резанием [Текст]: справочник / под общ. ред. А.А. Панова. – М. : Машиностроение, 1988. – 736 с.

17. Джур, Є.О. Полімерні композиційні матеріали в ракетно-космічній техніці [Текст]: підручник / Є.О. Джур, Л.Д. Кучма. – К. : Вища освіта, 2003. – 339 с.

18. Боборыкин, Ю.А. Программирование обработки на станках с ЧПУ [Текст]: учеб. пособие / Ю.А. Боборыкин, Ю.В. Дьяченко, А.В. Пьянков. – Х. : Гос. аэрокосм. ун-т "Харьк. авиац. ин-т", 2000. – 100 с.

19. Дьяченко, Ю.В. Проектирование постпроцессоров для оборудования ГПС [Текст]: учеб. пособие / Ю.В. Дьяченко, В.Е. Зайцев, А.В. Пьянков. – Х. : Нац. аэрокосм. ун-т "Харьк. авиац. ин-т", 2001. – 100 с.

20. Пуховский, Б.С. Обработка высокопрочных материалов [Текст]/ Б.С. Пуховский, А.П. Гавриш, Е.Ю. Грищенко. – К. : Техніка, 1983. – 134 с.

21. Руденко, П.А. Проектирование и производство заготовок в машиностроении [Текст]/ П.А. Руденко, Ю.А. Харламов. – К. : Вища шк., 1991. – 247 с.

22. Современные технологии авиастроения [Текст] / под ред. А.Г. Братухина. – М. : Машиностроение, 1999. – 832 с.

23. Справочник технолога-машиностроителя: в 2 т. [Текст] / под ред. А.Г. Косиловой. – М. : Машиностроение, 1986. – Т. 1. – 656 с.

24. Справочник технолога-машиностроителя: в 2 т. [Текст] / под ред. А.Г. Косиловой. – М. : Машиностроение, 1986. – Т. 2. – 496 с.

25. Степанов, А.А. Обработка резанием композиционных полимерных материалов [Текст] / А.А. Степанов. – Л. : Машиностроение, 1987. – 176 с.

26. Строганов, Г.Б. Технологическое обеспечение авиационного производства [Текст] / Г.Б. Строганов, Ю.Г. Роик. – М. : Машиностроение, 1991. – 368 с.

27. Дьяченко, Ю.В. Технология изготовления лопастей вертолетов [Текст]: учеб. пособие / Ю.В. Дьяченко, В.В. Коллеров, А.Н. Мещеряков. – Х. : Харьк. авиац. ин-т, 1992. – 54 с.

28. Технология обработки конструкционных материалов [Текст] / под ред. П.Г. Петрухи. – М. : Высш. шк., 1991. – 512 с.

29. Технология самолетостроения [Текст] / под ред. А.Л. Абибова. – М. : Машиностроение, 1982. – 551 с.

30. Технология производства летательных аппаратов из композиционных материалов [Текст]: учеб. пособие / В.Е. Гайдачук, В.Д. Гречка, В.Н. Кобрин, Г.А. Морозов. – Х. : Харьк. авиац. ин-т, 1989. – 322 с.

31. Технологія виробництва деталей літальних апаратів [Текст]: підручник / І.А. Грищенко, К.А. Животовська, В.М. Король та ін.; за ред. Ю.М. Терещенка. – К. : Вища освіта, 2004. – 448 с.

32. Богуслаев, В.А. Основы технологии машиностроения [Текст]: учеб. пособие / В.А. Богуслаев, В.И. Цыпак, В.К. Сценко. – Запорожье: ОАО «Мотор Сич», 2003. – 336 с.

33. ДСТУ 2232-93. Базування та бази в машинобудуванні. Терміни та визначення. – Введ. 01.07.94. – К. : Держстандарт України, 1994. – 35 с.

34. ДСТУ 2233-93. Інструменти різальні. Терміни та визначення. – Введ. 01.07.94. – К. : Держстандарт України, 1994. – 43 с.

35. ДСТУ 2249-93. Оброблення різанням. Терміни, визначення та позначення. – Введ. 01.01.95. – К. : Держстандарт України, 1994. – 63 с.

36. ДСТУ 2298-93. Верстати металорізальні. Терміни та визначення. – Введ. 01.01.95. – К. : Держстандарт України, 1994. – 32 с.

37. ДСТУ 2391-94. Система технологічної документації. Терміни та визначення. – Введ. 22.10.94. – К. : Держстандарт України, 1994. – 47 с.

38. ДСТУ 2579-94. Цифрова індикація та цифрове керування устат-куванням. Терміни та визначення. – Введ. 01.07.95. – К. : Держстандарт України, 1995. – 48 с.

CONTENTS

Навчальне видання

Сікульський Валерій Терентійович

Д'яченко Юрій Веніамінович

Борисевич Володимир Володимирович

Проскурін Сергій Дмитрович

Толмачов Микола Григорович

Смаль Станіслав Миколайович

Воронько Ірина Олексіївна

Гейштор Марія Костянтинівна

ТЕХНОЛОГІЯ ВИГОТОВЛЕННЯ ДЕТАЛЕЙ ЛІТАЛЬНИХ АПАРАТІВ З ВИДАЛЕННЯМ ПРИПУСКУ
(Англійською мовою)

Редактор Т.А. Григоренко
Технічний редактор Л.О. Кузьменко

Зв. план, 2012
Підписано до друку 07.11.2012
Формат 60×84 1/16. Папір офс. № 2. Офс. друк.
Ум. друк. арк. 10,8. Обл.-вид. арк. 12,25. Наклад 100 пр.
Замовлення 292. Ціна вільна

Національний аерокосмічний університет ім. М.Є. Жуковського
«Харківський авіаційний інститут»
61070, Харків-70, вул. Чкалова, 17
http://www.khai.edu
Видавничий центр «ХАІ»
61070, Харків-70, вул. Чкалова, 17
izdat@khai.edu

Свідоцтво про внесення суб'єкта видавничої справи
до Державного реєстру видавців, виготовлювачів і розповсюджувачів
видавничої продукції сер. ДК №391 від 30.03.2001