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FUNDAMENTALS FOR DESIGNING OF WORKHOLDING DEVICES

Tutorial

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K64

Викладено теоретичні основи і методику проектування верстатних пристроїв. Наведено теоретичні схеми базування і конструкційних елементів пристроїв. Описано методи розрахунків пристроїв на зусилля затискання і точність установки заготовки. Подано приклади проведення розрахунків і конструкцій пристроїв для оброблення на токарних, свердлильних, фрезерувальних і шліфувальних верстатах.

Для студентів механічних спеціальностей.

Reviewers: Doctor of Engineering Science, Prof. O. A. Permiakov,
Candidate of Engineering Science, Assoc. Prof. V. M. Dolia

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K64 Fundamentals for Designing of Workholding Devices [Electronic resource] : tutorial / M. K. Knyazyev. – Kharkiv : National Aerospace University “Kharkiv Aviation Institute”, 2020. – 104 p.

Theoretical fundamentals and method for designing of workholding devices are set out. Theoretical locating diagrams and design elements of devices are shown. Methods for calculations of workholding devices by clamping force and accuracy of a workpiece mounting are described. Examples of calculations procedures and devices designs for processing in turning, drilling, milling and grinding machines are given.

This book is meant for students whose major subject is mechanics.

Fig. 74. Tables 7. Bibliogr.: 4 titles.

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INTRODUCTION

Improvements in designs of aircraft engines, purposed to increase of their operation life, reliability, economical indexes and other parameters, in a great degree influence manufacturing technologies for production of engine parts. Characteristic peculiarities of modern engines are complexity of design configurations of parts, wide application of hard-to-machine materials, high requirements for accuracy and condition of surface layer. Most of engine parts are produced by metal-cutting processing (machining) and so, a large quantity of workholding devices are used in various metal-cutting machines.

Workholding devices usually increase rigidity of flexible workpieces and rigidity of the system “machine-device-workpiece-tool” as a whole. Enlargement of rigidity, in its turn, reduces vibrations during cutting processes, facilitates rises of cutting conditions and, hence, productivity of machining.

Reduction of direct manufacturing time is provided by application of multi-place devices, in which two or more workpieces are mounted and machined simultaneously. Auxiliary time at small-batch and middle-batch production conditions covers 40 to 60 % total time per piece that is one of the directions for productivity improvements. Therefore proper selection of mechanisms and drives for clamping-unclamping motions can significantly reduce auxiliary time.

Tooling for manufacturing processes plays a very important role in intensification of production of parts; therefore each industrial enterprise pays large attention to the problems of designing, production and application of workholding devices.

In designing of workholding devices the main problems are improvements of devices designs. The optimal design of a device allows ensuring the specified accuracy of a workpiece machining, high productivity of process, safety of its application, high ergonomics properties. Design optimisation is related to analysis of various typical designs of device units and parts, application of modern methods for designing.

Basic elements of workholding devices and characteristic typical designs with different levels of mechanisation are submitted in this book. These designs proved high production properties for manufacture of aircraft engine parts.

These lectures are based on the book written by V. A. Shmanev, A. P. Shulepov and L. A. Anipchenko [1], while other sources [2-4] are used.

1 GENERAL INFORMATION ABOUT WORKHOLDING DEVICES

1.1 Purpose of workholding devices

Improvements of designs, quality and reliability of aircraft and space engines are directly connected with wide application of advanced technologies and means of automation and mechanization. In production of engines various manufacturing processes are used, which provide production of workpieces, machining of parts, assembly, testing, painting, packing of items and others. Among all the manufacturing processes the most complicated and labour-intensive are machining processes. This situation is explained by high complexity, low rigidity of aircraft engine parts, as well as, by wide usage of intractable materials. Besides that, engine components should meet the rigid requirements of geometric accuracy and quality of the machined surfaces. All the above mentioned lead to the necessity of wide application of production tooling.

Production tooling includes workholding devices, cutting, measuring and accessory tools, inspection tools, measuring instruments and devices, and others. Labour-intensiveness of production of workholding devices constitutes 60 percent of total production tooling volume.

Workholding devices are special additional (accessory) equipment for machine-tools. They are designed for:

1) mounting the workpiece to be machined during operations according to the requirements for the manufacturing process;

2) increasing the accuracy and quality of part surfaces;

3) increase of labour productivity;

4) enhancement of manufacturing capabilities of versatile and specialised machine tools;

5) labour-saving, improvements of work conditions and industrial safety.

1.2 Classification of workholding devices

All machine workholding devices are classified according to degree of specialisation, number of workpieces to be set, level of mechanization and automation, and type of machine tools.

By *degree of specialisation* according to the GOST 31.010.01-84 (national standard) the workholding devices are divided into versatile, specialised and special-purpose (Figure 1.1).

Versatile devices are those designed for mounting of workpieces of various designs in the range of mounting dimensions. Usually these devices are produced by machine-tool plants. They are accessories and attachments of machine tools and supplied together with them. They are widely used in individual, small-batch and partially in batch production.

These devices are divided into two groups. The first group includes those devices, which provide mounting of workpieces of various dimensions without any adjustment or regulation: chucks of various types, vices, rotating tables, etc. Another group includes those devices, which require adjustment to use all the range of possible dimensions: turning chucks with lever or wedge mechanisms, vices with cam clamp, etc.

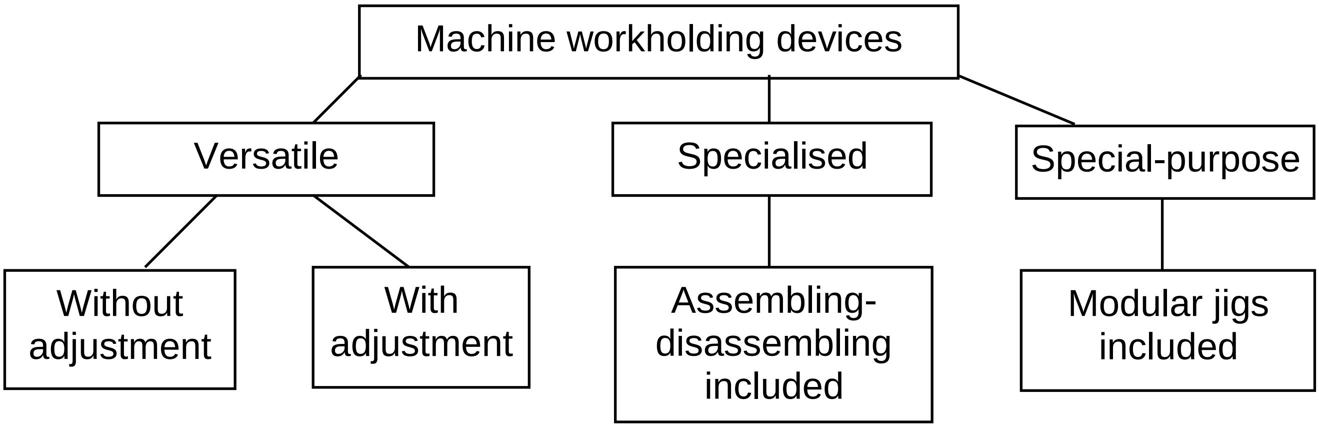


Figure 1.1 – Classification of machine workholding devices by specialization degree

Specialised devices are those, which are used for mounting of workpieces of the same type, that is, of workpieces with similar design and manufacturing characteristics.

These devices have restricted application – they are used in small-batch and medium-size lot production. Such devices are readjusted ones. They include assembling-disassembling devices and group devices.

Composition of *assembling-disassembling device* is formed from basic standardised assembly unit and set of replaceable adjusting parts. Set of replaceable adjusting parts includes normalised mounting, clamping and guide elements, necessary for individual workpiece. The additional machining of these elements and even making of new special parts are permitted.

For example, in order to assemble the assembling-disassembling jig it is necessary to produce and attach mounting, guiding and clamping elements to basic assembling unit (Figure 1.2). Mounting elements are fixed on the surface A of housing 1, drill bushings are installed in the cover 2 and clamping element is attached on the lower surface of cover. Clamping of workpiece is performed by clamping element, when jig plate 2 goes down by means of crankshaft mechanism 4 controlled by handle 3. Jig plate 2 is guided by plungers 5.

Group devices are designed for machining of selected predetermined group of workpieces in certain operation. They consist of basic device and set of replaceable adjusting parts. Basic device is versatile in respect of predetermined group of workpieces, and replaceable adjusting parts are special, they are connected with certain workpiece. When machining of each name of workpiece occurs, it is necessary to perform readjustment, that is, to install corresponding replaceable adjusting parts.

Special are those devices that are used for mounting of workpieces of one dimension-type. They are applied in batch and large-scale manufacture for mounting of certain workpiece in the given operation. These devices are specially developed and produced in the aircraft engine plants.

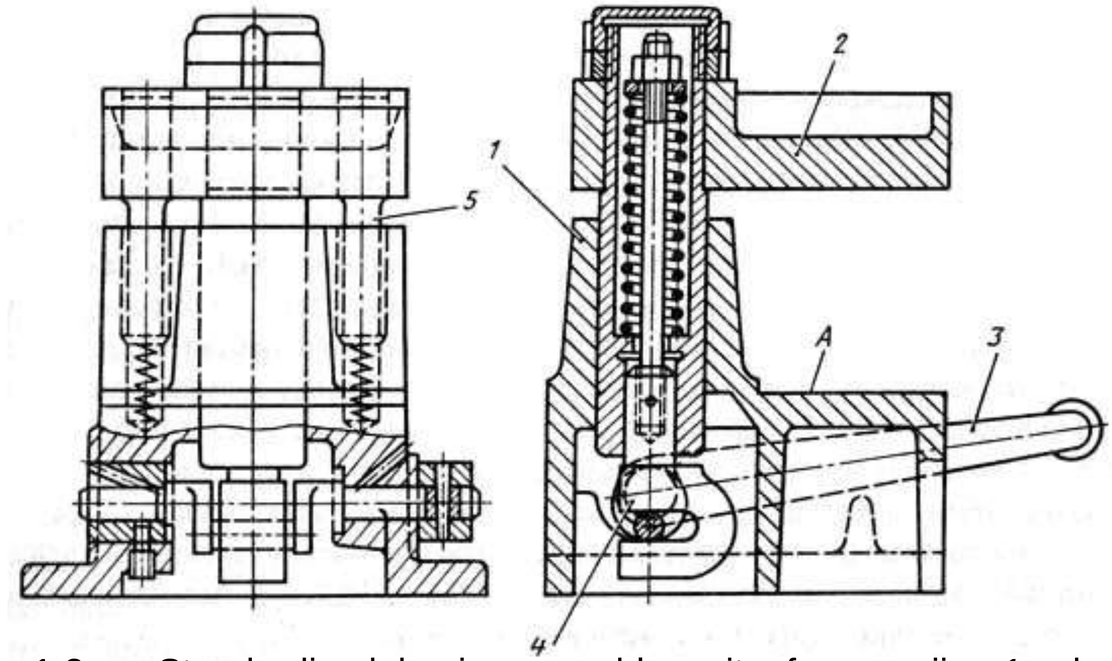


Figure 1.2 – Standardised basic assembly unit of pump jig: *1* – housing; *2* – cover; *3* – handle; *4* – crankshaft mechanism; *5* – plunger

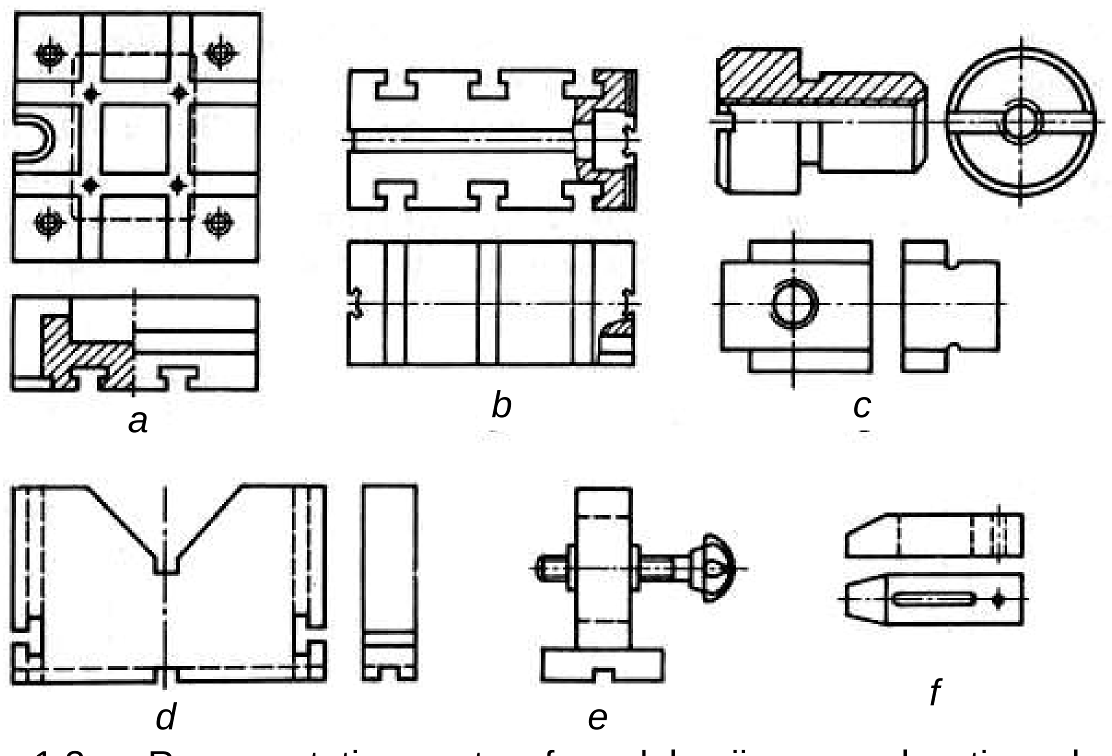


Figure 1.3 – Representative parts of modular jigs: *a* – locating elements; *b* – housing elements; *c* – mounting elements; *d* – guide elements; *e*, *f* – clamping elements

Modular jigs are assembled from the set of standardised elements (parts, units, mechanisms). Modular jig elements (Figure 1.3) are versatile, and assembled device is special, since it is designed for mounting of a certain workpiece in operation to be performed. After machining of predetermined number of workpieces the jig is disassembled and its elements are used for assembling of other devices.

One of modular jig design is shown in Figure 1.4. The device consists of plate 1, in which many high-accuracy slots and holes are made, locating and fastening elements 2…12, clamps 13…15. Fixation of workpiece 16 is performed by clamps.

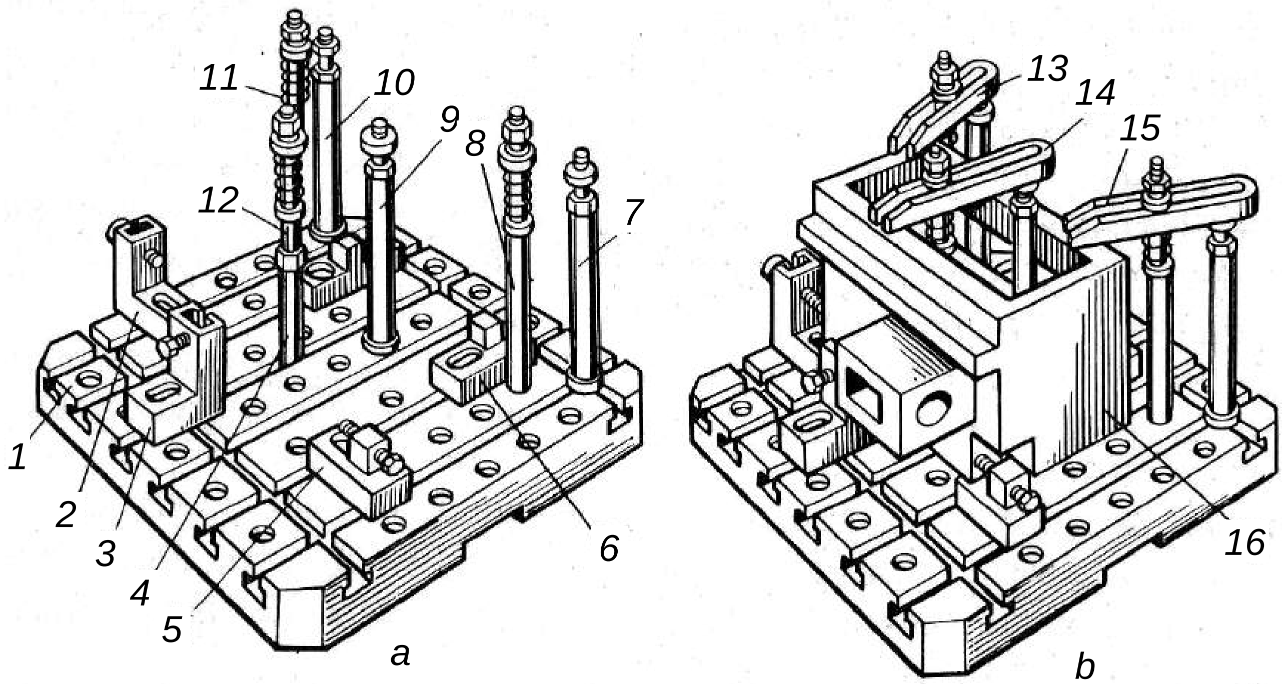


Figure 1.4 – Workholding device assembled from modular jig elements: *a* – plate with locating and fastening elements; *b* – workpiece mounted in device

Thus modular jigs elements are used many times for assembling of various jigs. These type of devices are widely used in individual, small-batch and sometime in batch production.

By number of workpieces being machined simultaneously the devices are divided into: *one-place* – for mounting of one workpiece and *multi-place* – for simultaneous mounting of some workpieces.

By degree of mechanisation and automation according to the GOST 23004-78 the devices are divided into:

– *manual* – those, which are manual engineering devices;

– *mechanised* – those, in which clamping and unclamping of workpieces is produced by means of energy of abiocoen, and the rest of motions – by people;

– *semi-automatic* – those, which are automatic engineering devices fulfilling predetermined algorithm of functioning partially with participation of people;

– *automatic* – those, which are automatic engineering devices.

1.3 Requirements applied to workholding devices

Workholding devices should meet the following requirements.

1. Providing of predetermined accuracy of workpiece mounting in operation.
2. High productivity and cost efficiency of the device application.
3. Performance of all service conditions: observation of rules of labour protection, ease of mounting and removal of workpiece, ease of the device maintenance, etc.

QUESTIONS

1. What is the purpose of workholding devices?
2. Describe classification of workholding devices
3. What are the requirements applied to workholding devices?

2 DIAGRAMS OF WORKPIECE MOUNTING

2.1 General

A workpiece should be correctly oriented relative to operational units of machine. Mounting is locating and clamping of workpiece in a device. Orientation of workpiece is provided by locating.

Locating is providing to workpiece or some item the required position relative to chosen system of coordinates. Respect to machining the locating is providing to workpiece the required position relative to machine elements that determine mechanical trajectory of cutting tool. Locating is realised on the datums of workpiece. A datum is any surface, line or point of workpiece, which is used for locating.

Mounting elements are designed for locating. They are rigidly connected to the body of workholding device. Mounting elements are made in the shape of mounting pins, plates, rings, bushings, fingers, prisms, mechanisms, etc.

To perform an operation it is necessary not only to provide locating, but also to ensure unmovable position of workpiece relative to workholding device. So when produce mounting of workpiece in workholding device the two tasks are solved: orientation of workpiece provided by locating, and making it unmovable (clamping).

To provide full immobility of solid body in a space it is necessary to eliminate 6 degrees of freedom: three linear motions along the axes and three rotations around those axes. Hence, it is necessary to put on the workpiece 6 rigid bilateral constraints, applied in support points.

Depending on machining conditions the orientation can be complete, when the workpiece is located by 6 support points, or incomplete, when the number of datum points is less than 6. Number of support points should not be more than 6. To provide a steady position of a workpiece the distance between points should be as large as possible. The larger the distance between points, the smaller the influence of errors of the datum surface shape on the workpiece position in a workholding device.

2.2 Mounting elements

Main rests are rigidly connected with device housing. Despite errors of shape and dimensions of datum surfaces, they always have contact with datum points in the same places.

Locating of workpieces in a workholding device is provided by main mounting elements. Additional (accessory) elements (points) do not take part in locating, but provide the higher steadiness and rigidity for workpieces.

Additional rests are made adjustable or self-placed. When mounting of workpiece the additional rests are individually adjusted to the surface of workpiece, and then are stopped. Additional rests during the operation serve as rigid rests. The number of additional rests can be one or more. But to simplify the design of a workholding device the number of additional rests should be minimal.

Mounting elements should meet the following requirements:

– number and location of the elements should provide orientation of workpiece with the required accuracy and sufficient steadiness in a workholding device;

– when using the datums with the roughness parameter ***Ra*** > 20 micrometer, mounting elements should be made with smaller contact surface to reduce influence of surface irregularities on the workpiece steadiness;

– mounting elements should not damage datum surfaces, especially those, which will not be machined;

– mounting elements should be rigid.

2.3 Locating of workpiece on datum plane and two side planes

Theoretical schematic diagram is presented in Figure 2.1. To realise locating of the plane datum it is necessary to align it with some predetermined plane of workholding device. Since the position of any plane is determined by three points, in order to perform locating the workholding device should possess three support points, which are located in one plane, but not on the one line.

Rigid rests are fulfilled in the shape of pins (Figure 2.2). Pins shown in Figure 2.2,*b* and Figure 2.2,*c* serve only for orientation of unmachined datums. Pins for machined datums should have plain head (Figure 2.2,*a*). Their diameter should be chosen according to the datum area. *Rest pins should be located from each other as far as possible to improve locating accuracy*.

Designs of rest pins are standardised – according to the standards they are called permanent rests. The pins are made with flat heads, spherical heads, and knurled heads. Holes for pins in the device housing are drilled through; mating of pins and holes – by the fit of H7/n6 or H7/p6. On device housing at the places of pins installation the small flat area elements (usually on the bosses) are provided (see Figure 2.2), which are machined simultaneously. These features provide high accuracy of location of rest surfaces of pins in one plane. Sometimes the dimension *H* includes allowance for machining of their rest surfaces after pressing pins into the housing holes.

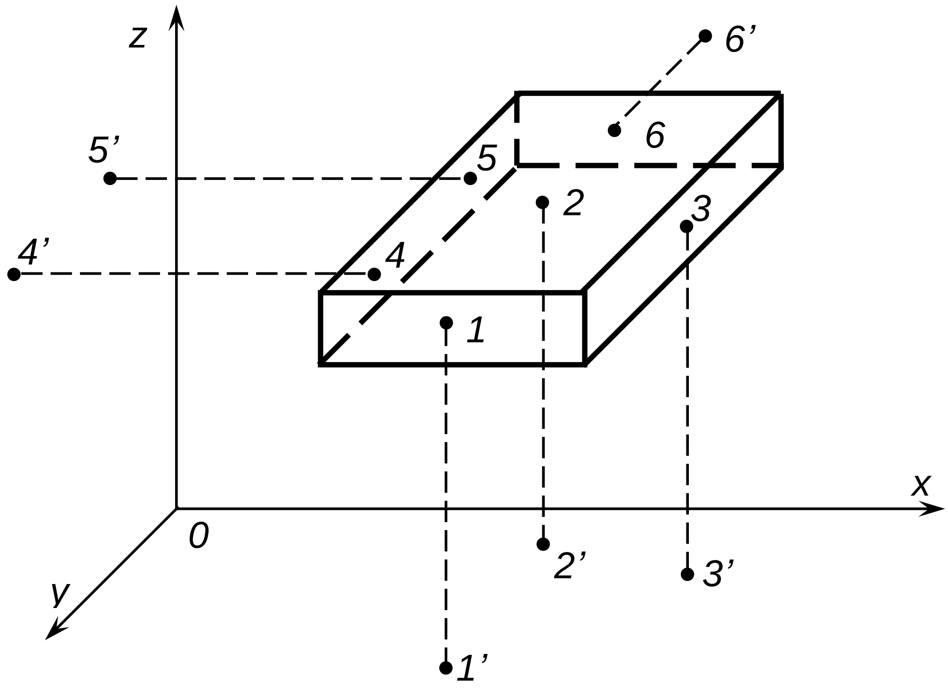


Figure 2.1 – Schematic diagram of locating on the datum plane and two side planes

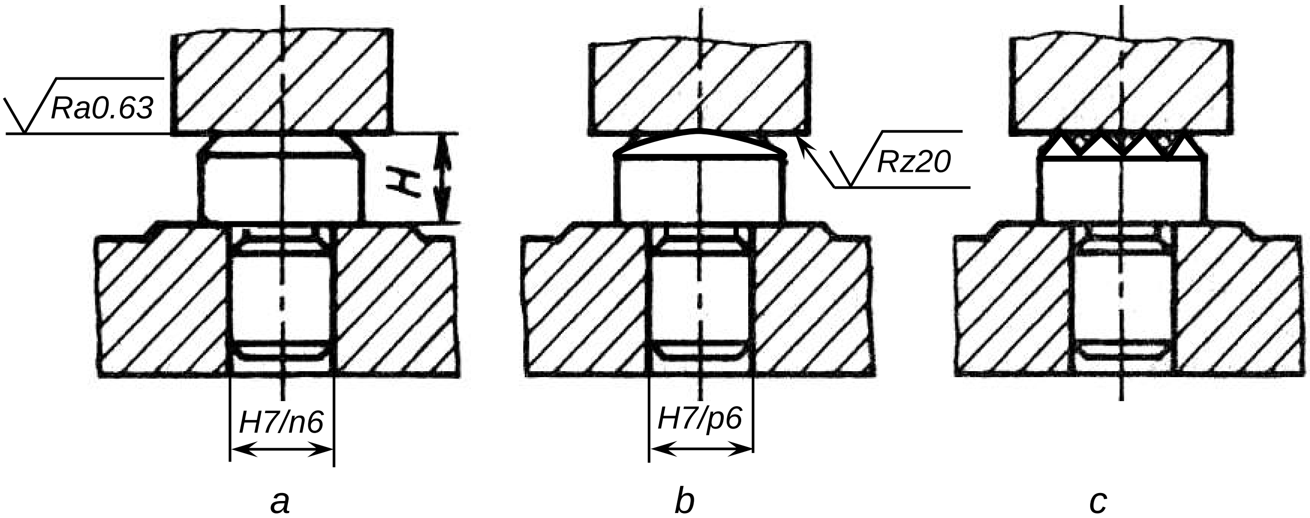


Figure 2.2 – Designs of rigid rest pins: *a* – with flat head; *b* – with spherical head; *c* – with knurled head

Sometimes ***adjustable rests*** (Figure 2.3) are used for locating of workpieces with unmachined plain datum instead of solid rest pins. Adjustable rests permit to change height of rests according to the value of machining allowance of workpieces of different batches. Adjustment is produced before machining of each batch of workpieces with another allowance. Designs of adjustable rests are normalised by the standards.

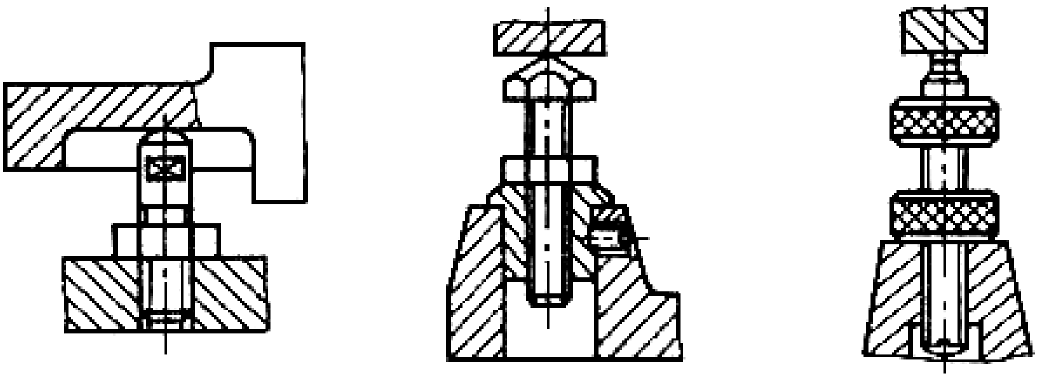
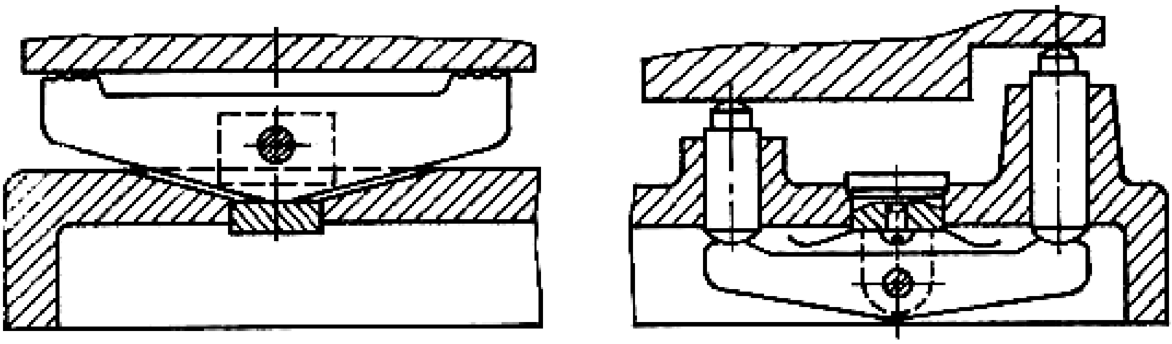


Figure 2.3 – Examples of workpiece mounting on adjustable rests

When mounting of non-rigid (flexible) workpieces, their deformation is possible under the action clamping force and cutting forces. To increase stiffness the contact area of a workpiece and device should be enlarged without violation of requirements of engineering mechanics – to define plane position three points are necessary and sufficient. It is reached by application of ***double*** (Figure 2.4,*a*) and ***floating*** (Figure 2.4,*b*) ***rests***, each of them substitutes one support pin in spite of contacts in two or three points on datum surface. Design of such rests provides coordinated movement of support surfaces and keeps practically constant position of support point (it is in the determined plane of device).

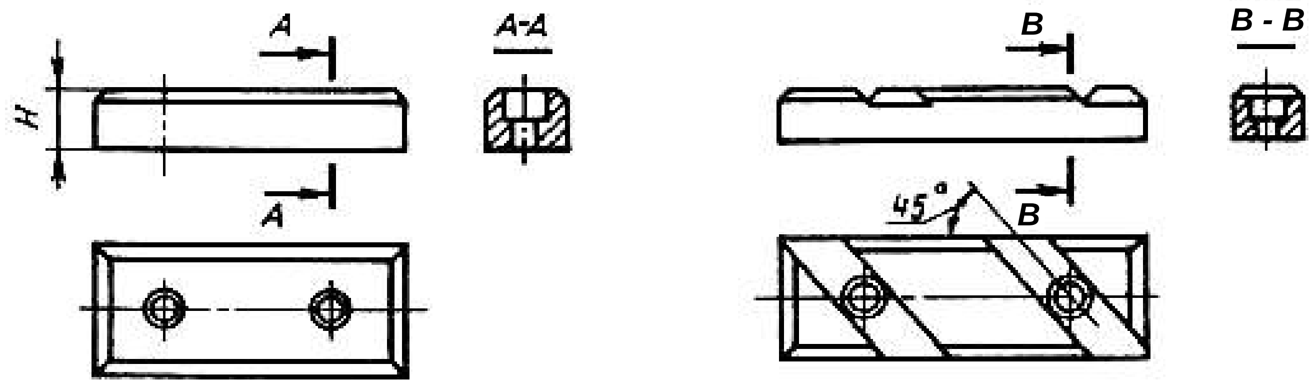


a *b*

Figure 2.4 – Double (*a*) and floating (*b*) rests

Locating with application of ***rest plates*** is the most commonly used method for orientation of machined datums. According to the standard the rest plates are produced of two types: flat (Figure 2.5,*a*) and with skewed slots (Figure 2.5,*b*). The latter provide better remove of chip from surface, therefore they should be used for mounting in horizontal plane, and flat plates – on side surfaces. The length of plates is chosen depend on length of datum. Rest plates are usually located on the bosses of device body. When the body is manufactured the plain areas of bosses are machined simultaneously. The height ***H*** of plates is machined with the *h6* accuracy grade. If necessary support surfaces of plates are fitted with the use of paint method.

If the workpiece does not acquire sufficient stability and stiffness when locating by above-considered methods, then necessary number of ***auxiliary rests*** is added to the main rests. Auxiliary rests differ by that *they are put in contact with workpiece after the locating is performed on main rests*. When apply auxiliary rests the attention should be paid to prevent violation of the locating provided.



a *b*

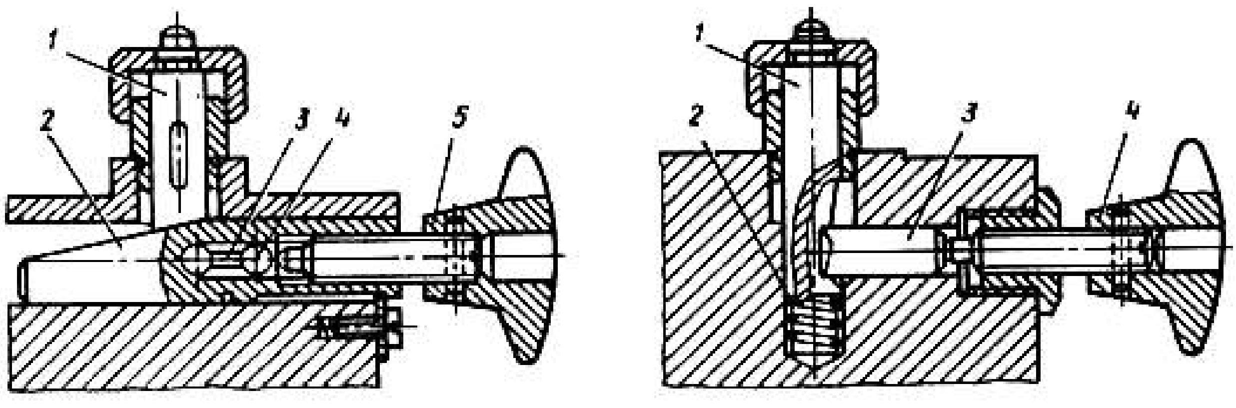
Figure 2.5 – Rest plates: *a* – flat; *b* – with skewed slots

Auxiliary rests are used to increase number of contact points of workpiece and workholding device to provide higher rigidity of a system. They prevent partially or completely workpiece deformations under the action of cutting and clamping forces.

By design auxiliary rests (mechanisms of rests) can be adjusting (screw-type), input (wedge-type) and self-adjusting (spring-type).

An adjusting rest is produced in a shape of screw jack. It is used when mounting rigid parts and under heavy conditions of machining (see Figure 2.3).

The diagram of input rest is depicted in Figure 2.6,*a*. Such rests are put in touch with datum surface of workpiece after the locating and clamping completed on the main rests. When linear movement of components 2, 3, 4, 5 occurs, supporting pin 1 comes into contact with datum of workpiece. Then rotating the knob 5, one reduces distance between balls 4, which move semicircular keys 3 apart, press them to the wall of hole in the body and thus fix the rest.



a *b*

Figure 2.6 – Auxiliary rests: *a* – wedge-type, *b* – self-adjusting

Self-adjusting auxiliary rest is shown in Figure 2.6,*b*. Before workpiece mounting supporting pin 1 slightly projects over main rests, and when mounting it sinks pressing the spring 2 and keeping in contact with datum surface of the workpiece. Rest fixing is produced by block 3 when rotating knob 4. Note that before every workpiece mounting on the main rests the supporting pins of auxiliary rests should be loosened.

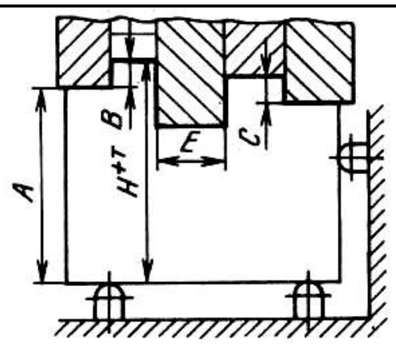
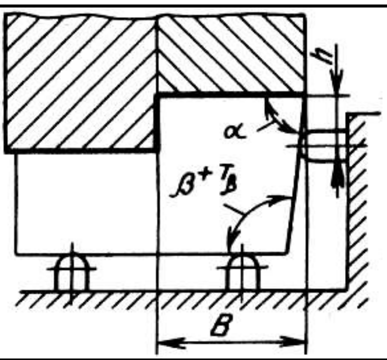
To provide high productivity of workholding devices the auxiliary rests should be equipped with drive mechanisms.

Errors should be determined in the direction perpendicular to the datum plane for all above-considered methods of locating. Locating error value depends on datum condition. For machined datums it can be assumed as equal to zero. It is permissible if machined datum has small non-flatness. In this case datum plane of all workpieces will coincide with predetermined plane of device practically without any error.

When locating unmachined datums an error can appear due to irregularities of datum surface and datum plane will be oblique relative to the predetermined plane of device. The value of obliquity (of angle between datum plane and given plane of device) will depend on height of irregularities and distance between supporting points. Knowing the value of datum irregularities and distance between rests, it is possible to determine a locating error for any point of datum.

Locating errors of workpieces for various typical schemes of mounting on datum plane are shown in Table 2.1. The relationships between normal force and depression of workpiece on various rests are given in the book [1]. They can be used for calculations of clamping errors.

Table 2.1 – Locating errors of workpiece when mounting on planes

Scheme of mounting	Dimension	Locating error
	***A*** ***B*** ***C*** ***E***	$\varepsilon_A = 0$ $\varepsilon_B = T$ $\varepsilon_C = 0$ $\varepsilon_E = 0$
	***B*** Angle ***α***	$\varepsilon_B = h\ \mathrm{tg} T_\beta$ $\varepsilon_\alpha = T_\beta$

2.4 Locating of workpiece on datum hole and plane

During machining of aircraft parts cylindrical holes are frequently used as a datum. To perform locating of workpiece on a hole means to align its axis with some given line of a device. Scheme of locating of workpiece on a cylindrical hole is depicted in Figure 2.7. Workpiece face is accepted as a mounting datum with three support points 1, 2, 3, and internal cylindrical surface brings two support points 4, 5. Point 6 eliminates the last degree of freedom – rotation relative to the axis $\boldsymbol{x}$.

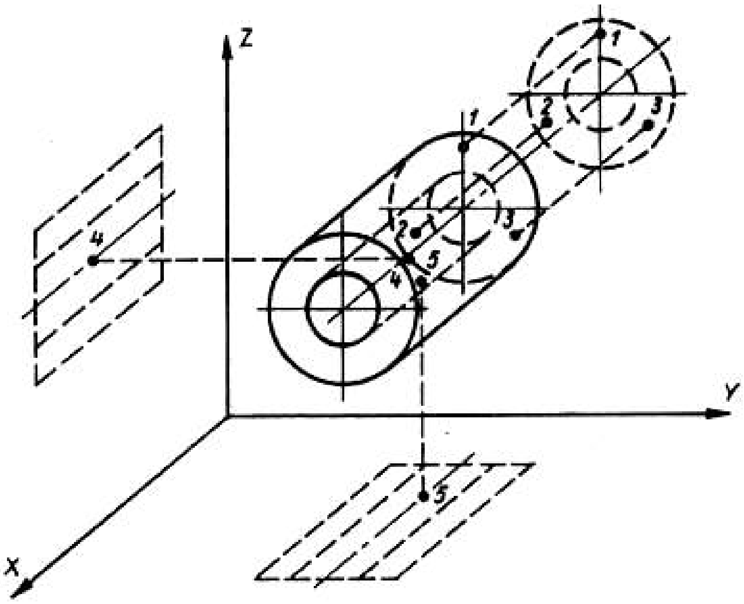


Figure 2.7 – Diagram for locating of workpiece on cylindrical hole

This locating diagram is provided by application of fingers and mandrels.

Locating on internal cylindrical surface (on finger) is shown in Figure 2.8. Workpiece is mounted on a cylindrical finger made with such limits that clearance fit is provided in the joint “workpiece-finger”.

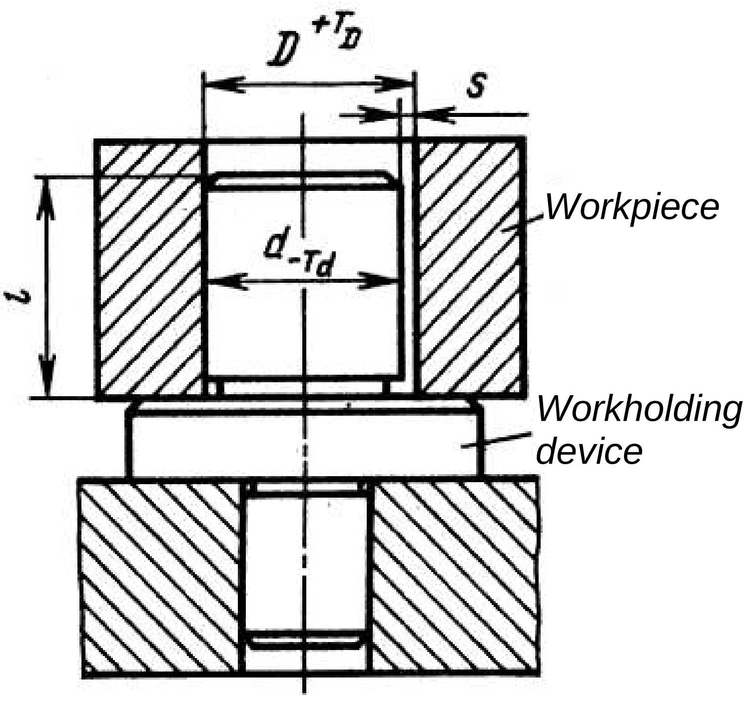


Figure 2.8 – Scheme for mounting of workpiece on cylindrical finger

Since a workpiece is mounted on a finger with clearance fit, then

$$\boldsymbol{d} = \boldsymbol{D} - \boldsymbol{S_g},$$

where $\boldsymbol{d}$ – maximum finger diameter; $\boldsymbol{D}$ – minimum hole diameter; $\boldsymbol{S_g}$ – clearance, guaranteed by fit (minimum guaranteed clearance).

Maximum clearance in joint will form

$$\boldsymbol{S_{max}} = \boldsymbol{S_g} + \boldsymbol{T_d} + \boldsymbol{T_D},$$

where $\boldsymbol{T_d}$, $\boldsymbol{T_D}$ – tolerances of finger and hole diameters.

For this method the locating error (runout) will be equal to maximum clearance

$$\boldsymbol{\varepsilon_L} = \boldsymbol{S_{max}},$$

and obliquity of datum axis will be defined by the formula

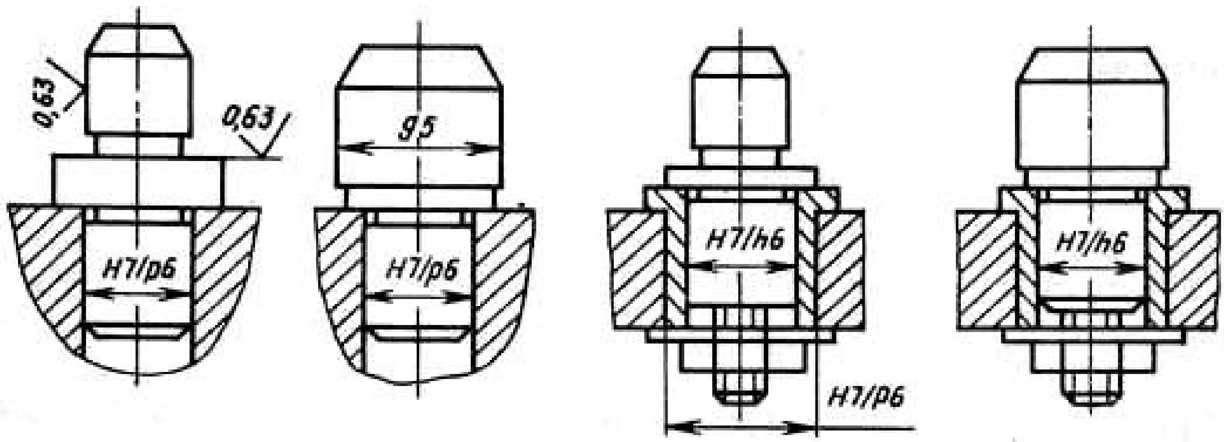
$$\boldsymbol{\alpha} = \mathrm{arctg}\frac{\boldsymbol{S_{max}}}{\boldsymbol{l}},$$

where *α* – angle of inclination of datum axis; ***l*** – finger length.

To avoid obliquity value of datum axis more than permissible limit, the finger length ***l*** is specified approximately 1.5***D***, where ***D*** – nominal diameter of datum hole.

Considered method of locating is used only for workpieces with datum holes machined by 6...9 accuracy grades. Sometimes in order to increase accuracy a workpiece is mounted on finger not by clearance fit, but by transition or even by interference fit (it is pressed on). In this case the locating error of the hole axis equals zero. This method is usually used for machining of workpieces on the mandrels installed in the centres of machine tools.

Design types of fingers are depicted in Figure 2.9. Finger designs are standardised. Fingers with shoulders are shown in Figure 2.9,*a*,*c*, without shoulders – in Figure 2.9,*b*,*d*. Fingers with diameter up to 16 mm are made of Y7A steel, and ones with diameter more than 16 mm – 20X(20Cr) steel with cementation (carbonisation) depth of 0.8...1.2 mm and hardening of HRC 49..54. Work surface of fingers is machined for fits H7/g6 or H9/g8 and ground to a roughness of ***Ra*** = 0.63...0.32 μm.



a *b* *c* *d*

Figure 2.9 – Mounting fingers: *a*, *b* – permanent; *c*, *d* – changeable

Locating error is characterised by displacement of workpiece at the value of diameter clearance between mating surfaces. If a datum face of workpiece is not perpendicular to the hole axis, the deviation of hole axis relative finger axis is possible. The book [1] contains formulas for calculations of locating errors for typical cases of mounting of workpieces on fingers and mandrels (Table 2.2).

In aircraft propulsion engineering the mandrels are widely used for workpieces mounting. By design they can be divided into solid and expendable.

Types of solid mandrels are depicted in Figure 2.10. Tapered mandrel (Figure 2.10,*a*) has a conicity of 1/2000...1/4000. Workpiece is mounted on it by cylindrical hole machined with accuracy grade of H6...H7. Due to the wedging effect it is reliably prevented from turning when machining is performed. Accuracy of centring is equal to 0.005...0.01 mm. The disadvantage of this mandrel is the absence of accurate fixation of workpiece along the mandrel length.

Solid mandrel shown in Figure 2.10,*b* is used for mounting of workpiece by interference fit. Workpiece is exactly oriented along the mandrel length by using backing rings. Groove 1 allows the workpiece faces to machine, neck 2 serves for guiding the workpiece. Accuracy of alignment is equal to 0.005...0.01 mm.

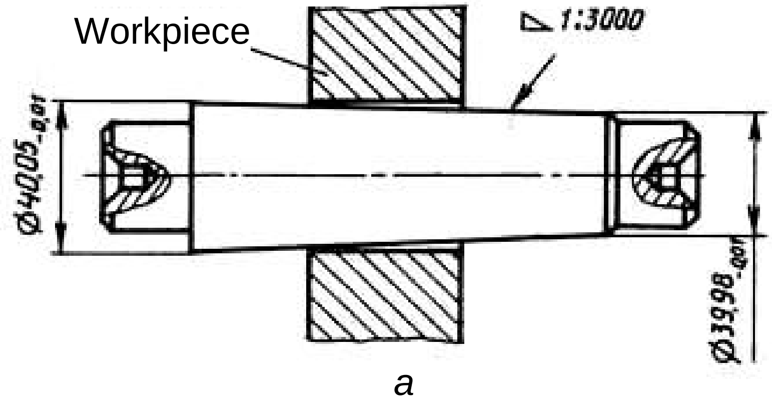


Figure 2.10 – Solid mandrels: *a* – tapered; *b* – for pressing the workpiece on; *c* – with guaranteed clearance (gang mandrels)

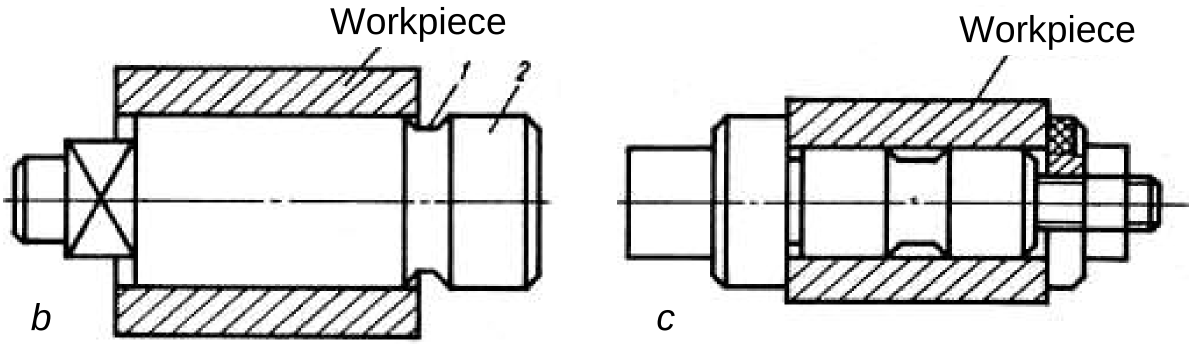
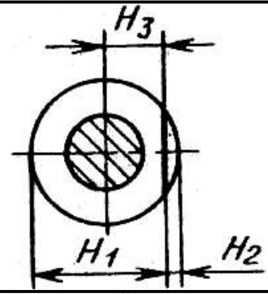
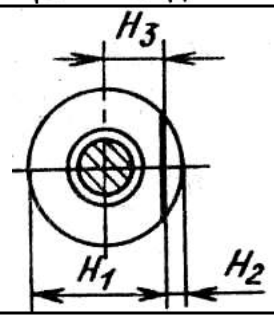


Table 2.2 – Locating errors for typical mounting schemes of workpieces on fingers and mandrels

Mounting	Mounting scheme	Dimension	Locating error ε_L
Interference fit		H_1 H_2 H_3 H_4	$0.5T_D + 2e$ $0.5T_D + 2e$ $2e$ 0
Clearance fit		H_1 H_2 H_3 H_4	$0.5T_D + 2e + T_d + T_{wd} + 2S$ $0.5T_D + 2e + T_d + T_{wd} + 2S$ $2e + T_d + T_{wd} + 2S$ $T_d + T_{wd} + 2S$

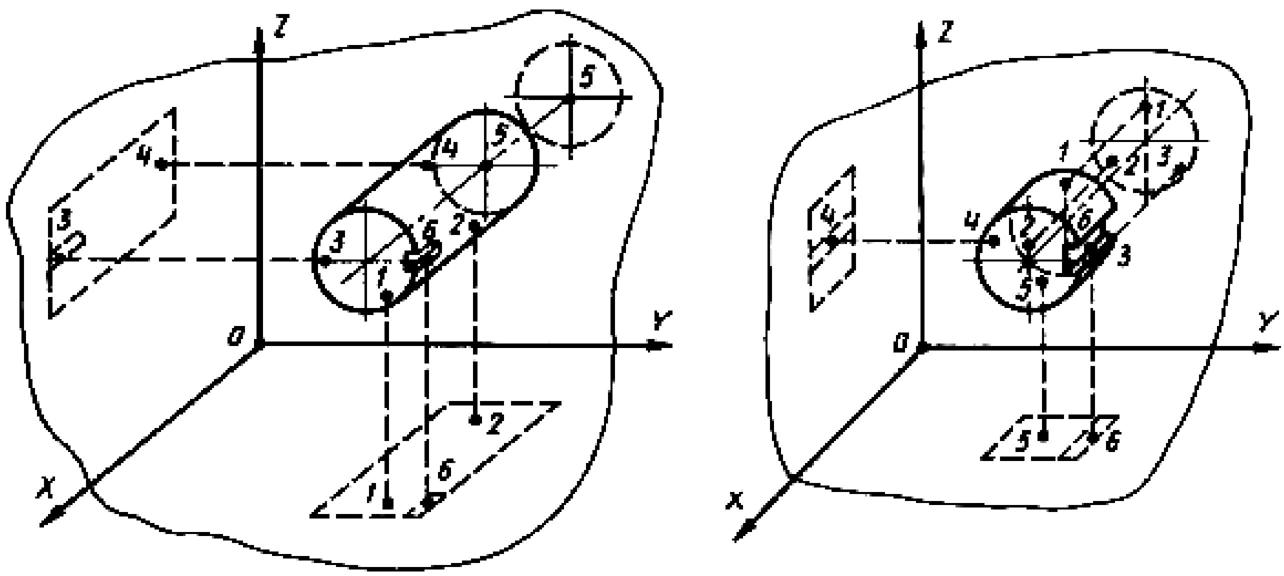
Note. e – eccentricity of outside surface relative to hole; H_3 – dimension from the axis of outside surface, mm; H_4 – dimension from the hole axis, mm; T_d and T_{wd} – tolerances of hole and finger diameters, mm; S – minimal radial clearance, mm; T_D – tolerance of workpiece outside diameter, mm.

Mandrel, on which the workpiece is mounted with clearance, is shown in Figure 2.10,*c*. Position of workpiece is determined by shoulder location, its rotation is prevented by tightening of nut. For this mandrel type the datum holes of workpiece is recommended to machine to the 7th accuracy grade. Accuracy of alignment depends on clearance and usually equals 0.02...0.03 mm.

Mandrels are made of 20X(20Cr) steel, carbonized to depth of 1.2...1.5 mm and hardened to a hardness of HRC 54...59. Work surfaces of journals are ground up to a roughness of ***Ra*** = 0.63...0.32 μm. Usually mandrels have centre holes, and for torque transfer a square shape, flat spot or driving bolt is provided at the end of the mandrel. Mandrels of more than 80 mm in diameter are produced hollow to lighten them. Expendable (self-centring) mandrels and mechanisms provide locating error of datum hole equal near to zero.

2.5 Locating of workpiece on outside cylindrical surface and face

Outside cylindrical surface is widely used for locating of workpieces of types: shafts, bushings, sleeves, etc. To realise locating of cylindrical surface means to align its axis with some given line of workholding device. Theoretical schemes of locating on a cylindrical surface and a plane perpendicular to its axis are shown in Figure 2.11. Depends on ratio of length ***l*** and diameter ***d*** two schemes are classified. They are distinguished by distribution of support points between cylinder and plane.



a *b*

Figure 2.11 – Diagrams for locating of cylindrical workpieces with ratios ***l/d*** ≥ 1 (*a*) and ***l/d*** < 1 (*b*)

Locating scheme of cylindrical workpiece with ratio of ***l/d*** ≥ 1 (“long cylinder”) is shown in Figure 2.11,*a*. Datum surface has four support points: two of them are located on the generatrix (generating line) 1–2 and the other two – on the generatrix 3–4. Locating on such cylindrical surface eliminates four degrees of freedom from a workpiece. Face brings support point 5, eliminating capability of workpiece movement along the axis *x*. Support point 6 eliminating capability of workpiece rotation around the axis *x* can be put on the surface of key slot.

Locating scheme of cylindrical workpiece with ratio of $\boldsymbol{l/d}$ < 1 ("short cylinder") is shown in Figure 2.11,*b*. For this ratio the support points located on the generatrices of cylinder do not provide stable position of workpiece. Therefore the workpiece face is assumed as mounting datum brining three support points 1, 2, 3. Cylindrical surface has two support points 4 and 5. Position of support point 6 is similar to the previous locating scheme.

In aircraft propulsion engineering the following locating schemes are used: on hole, with prism and by means of self-centring device. They are distinguished by accuracy, ease of use and application fields.

When locating on a hole (Figure 2.12) rest element is ***bushing*** 1, into the hole of which a workpiece is inserted. It is necessary to provide a guaranteed clearance in the join of workpiece and bushing to make mounting of workpiece into the bushing hole possible. The diameters of datum and hole are connected by relationship

$$\boldsymbol{D} = \boldsymbol{d} + \boldsymbol{S_g},$$

where $\boldsymbol{D}$ – minimum hole diameter; $\boldsymbol{d}$ – maximum finger diameter; $\boldsymbol{S_g}$ – guaranteed clearance (minimum guaranteed clearance).

Taking into account the guaranteed clearance, as well as machining errors of workpiece and bushing hole the maximum clearance in joint will be

$$\boldsymbol{S_{max}} = \boldsymbol{T_D} + \boldsymbol{T_d} + \boldsymbol{S_g}.$$

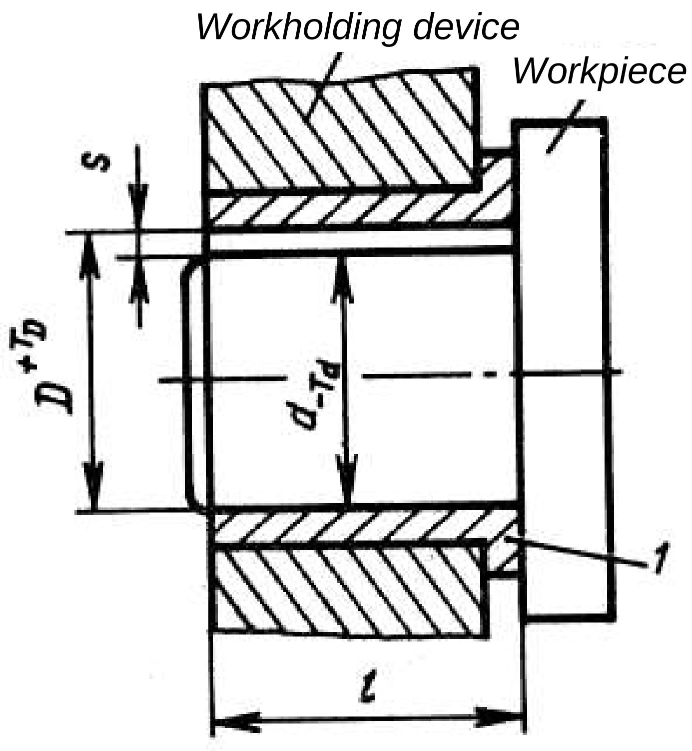


Figure 2.12 – Scheme for mounting of workpiece in cylindrical hole

In the limits of this clearance displacement of datum axis relative to the bushing hole axis is possible on the value equal to half of clearance $\boldsymbol{S_{max}}/2$. The maximum distance between extremely displaced positions of datum axis is a locating error that equals $\boldsymbol{\varepsilon_L} = \boldsymbol{S_{max}}$.

Thus error $\boldsymbol{\varepsilon_L}$ of datum axis for this locating method is equal to

$$\boldsymbol{\varepsilon_L} = \boldsymbol{T_D} + \boldsymbol{T_d} + \boldsymbol{S_g}.$$

Moreover, in the $\boldsymbol{S_{max}}$ limits the obliquity of datum axis is possible that is calculated from formula

$$\boldsymbol{\alpha} = \mathrm{arctg}\frac{\boldsymbol{S_{max}}}{\boldsymbol{l}}.$$

This locating method is applied for workpieces with datums machined up to the 7...9 accuracy grades. To provide ease of workpiece mounting the guaranteed clearance should be obtained by clearance fit.

When designing a workholding device, the length ***l*** of bushing is assumed not less than 1.5 datum diameters, otherwise significant obliquity of workpiece axis will appear.

Locating of outside cylindrical surfaces by means of ***prisms*** (***V-blocks***) gained wide application. Prism is called mounting element with working surface in the shape of slot created by two planes inclined at angle of ***α*** (Figure 2.13). Prisms for mounting of short workpieces are standardised. Prism determines position of workpiece axis perpendicular prism base by its alignment with axis of angle slot. Axis of angle slot is considered to be an axis drawn through the point *A* of work planes concurrence at right angle to prism base. For proper use of this property of prism it is necessary to provide exact symmetry of work planes relative to the axis of angle slot, that is, exactly observe half of prism angle ***α/***2.

Prism determines position of longitudinal workpiece axis *x*. In this connection the necessity of its accurate fixing on the device body appears. Therefore in addition to fastening screws 1 the prism position is determined by means of pins 2.

Prisms with angles ***α*** of 60, 90 and 120° are used in devices. Prisms with ***α*** = 90° gained the most wide spreading. Prisms with ***α*** = 120° are applied, when workpiece has no complete cylindrical surface and position of workpiece axis is to be determined by small arc of circle. Workpiece placed on such prisms has low stability. Prisms with angle ***α*** = 60° are used to increase stability of workpiece when significant cutting forces are applied parallel to the prism base.

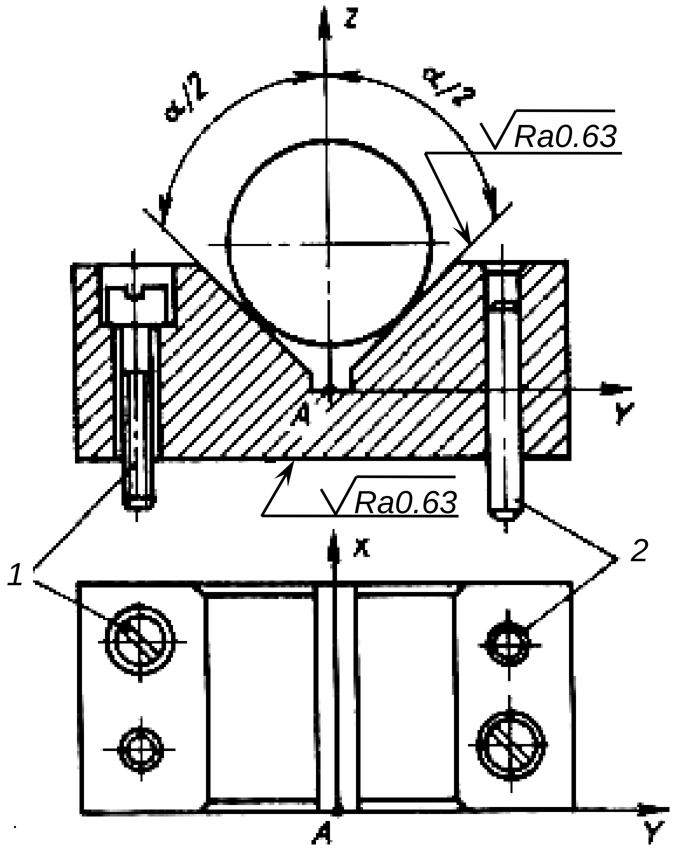
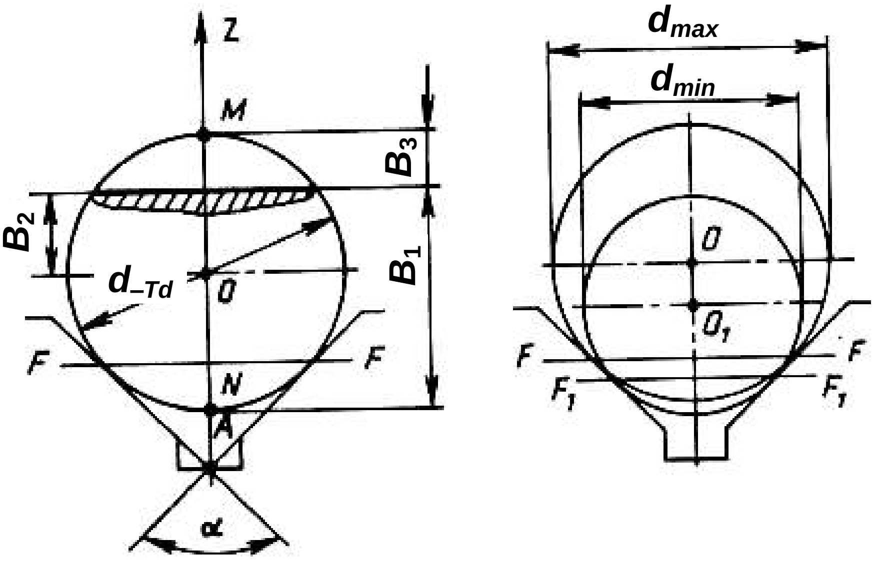


Figure 2.13 – Prism (V-block) design

For mounting of workpieces with carefully machined datums the prisms with wide support surfaces are used, and for rough datums – with narrow support surfaces. Long workpieces are mounted on two aligned prisms, which are ground simultaneously after installation on working surfaces to provide coincidence of axes and equality of heights. If the machining conditions require application several prisms, two of them are made rigid (main rests), and others – adjustable (auxiliary rests).



a b

Figure 2.14 – Scheme of workpiece mounting on prism

Figure 2.14 shows the scheme of shaft mounting on prism for machining a flat spot. The position of flat in the direction of *z* axis relative to the shaft cylindrical surface may be specified by a designer by one of three dimensions $\boldsymbol{B_1}$, $\boldsymbol{B_2}$, $\boldsymbol{B_3}$. For each of these dimensions the same datum is used – touching generatrices of the cylinder with prism work surfaces and crossing the points *F* and F_1. In all cases locating error takes place, which relates to the misalignment of datums – mounting and measuring.

When shaft diameter in the workpieces batch changes in the range of tolerance limits $\boldsymbol{T_d}$ the mounting datum – touching generatrices of shaft and prism – changes its position, displacement of datum occurs. When mounting a cylindrical workpiece on the maximum diameter $\boldsymbol{d_{max}}$ (Figure 2.14,*b*), mounting datum crosses the points *F–F*, when mounting workpiece on the minimum diameter ($\boldsymbol{d_{min}} = \boldsymbol{d_{max}} - \boldsymbol{T_d}$), it is displaced to the position F_1–F_1.

According to Figure 2.14 locating error:

for the $\boldsymbol{B_1}$ dimension

$$\boldsymbol{\varepsilon_L} = \frac{\boldsymbol{T_d}}{2}\left[\frac{1}{\sin(\boldsymbol{\alpha}/2)} - 1\right],$$

for the $\boldsymbol{B_2}$ dimension

$$\boldsymbol{\varepsilon_L} = \frac{\boldsymbol{T_d}}{2}\left[\frac{1}{\sin(\boldsymbol{\alpha}/2)}\right],$$

for the $\boldsymbol{B_3}$ dimension

$$\boldsymbol{\varepsilon_L} = \frac{\boldsymbol{T_d}}{2}\left[\frac{1}{\sin(\boldsymbol{\alpha}/2)} + 1\right].$$

Production engineer can gain an accuracy increase of operation dimension without changing mounting datum, but changing prism position relative to workpiece. The book [1] contains typical schemes of mounting of cylindrical workpieces on the prism and corresponding errors of dimensions depend on tolerance for diameter of datum surface.

To reduce locating errors the various self-centring devices are used. Self-centring devices are those, in which support surfaces are movable and connected in such a manner that can simultaneously and with equal displacement move to the axis of the device or move off it. Support surfaces of self-centring devices can be made either in the shape of jaws or in the shape of whole cylindrical surface of thin-walled bushing being elastically deformed by clamping forces.

The main advantage of self-centring devices is that their locating error equals zero. These devices can be applied for locating workpieces with both machined and unmachined datum. They include various self-centring chucks: three-jaw, collet, hydroplastic. Their designs will be described later.

2.6 Locating of workpieces on two holes and plane

Locating on two holes and plane is used for machining of workpieces, such as bodies, casings, plates. This scheme of locating provides simplicity of workholding device and constancy of datums at most of the operations in the manufacturing process with application of CNC machine tools.

Theoretical locating scheme is shown in Figure 2.15. Three support points 1, 2, 3 are located on the plane A, two points 5, 6 – in the hole B, one point 4 – in the hole C. Distribution of support points among the surfaces belonging to the set of datums may be changed, if depth of at least one hole is more than its diameter. Then in this hole four support points can be located, and in the second hole and on the plane – per one support point.

Plane and two holes are always accurate datums. Plane is machined to final or near-to-final condition at one of the first operations. Holes, generally, are reamed up to the 7th accuracy grade. Rest plates and two rigid or retractable fingers are used as mounting elements. Retractable fingers are used for mounting of large and heavy workpieces, as well as for fixing of position of machine pallets.

By design two schemes are defined: mounting on two cylindrical fingers, and mounting on one cylindrical finger and one diamond finger. Applications of these combinations are determined by accuracy of diameters and relative position of datum

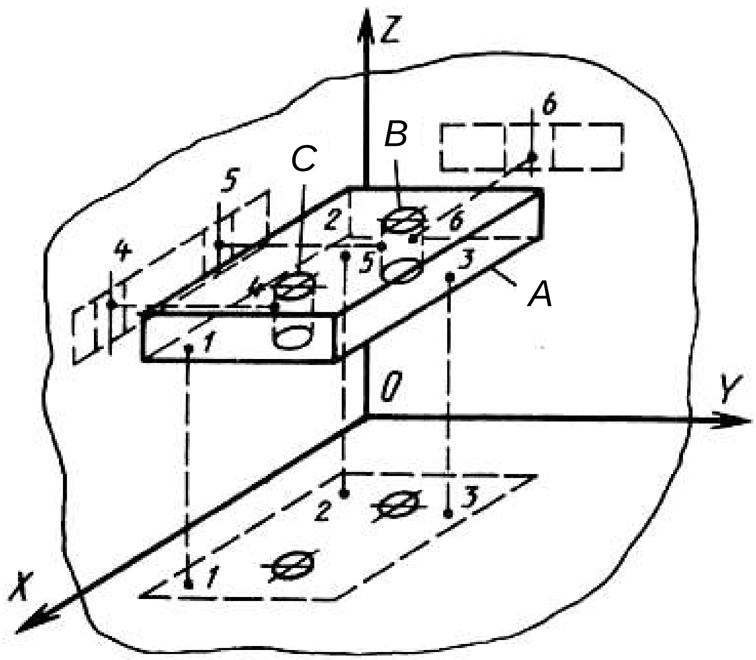


Figure 2.15 – Theoretical diagram of workpiece locating on two holes and plane

holes and by required accuracy of relative distances and rotations of work surfaces.

When developing the workholding fixtures with two pins a designer has to solve a problem of determining pins diameters, their tolerances for manufacturing and wear, tolerance for centre-to-centre pins distance. The initial conditions for solving this problem are: providing of mounting on two fingers of any workpiece with centre-to-centre distance and holes diameters in the limits of tolerances, providing of specified tolerances of dimensions and surface position performed in manufacturing operation.

Usually diameter of one finger is specified as equal to the nominal diameter of datum hole, and tolerance is specified by *f6*, *f7*, *e9* depend on hole accuracy.

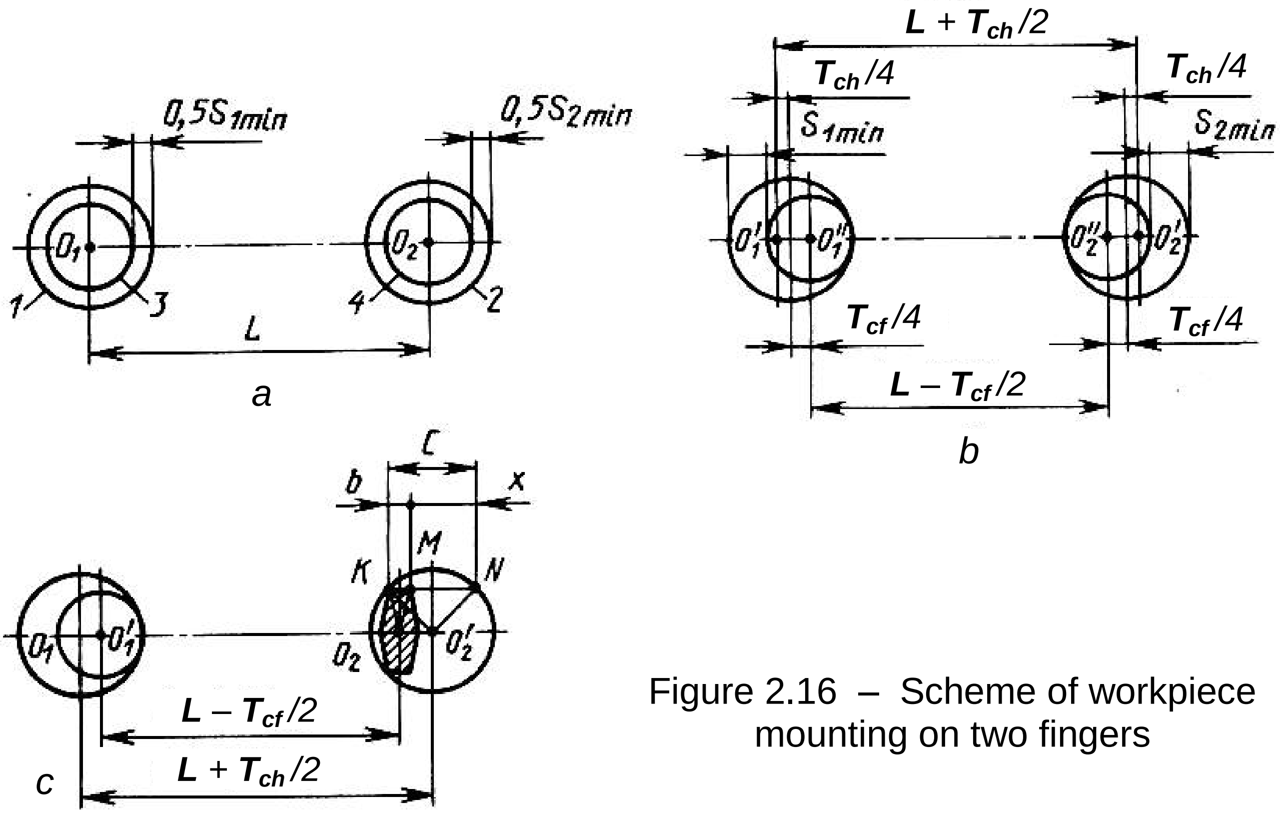


Figure 2.16 – Scheme of workpiece mounting on two fingers

There are conditions, which define the possibility of workpiece mounting on two cylindrical fingers. In Figure 2.16,*a* the positions of holes 1 and 2 and fingers 3 and 4 for nominal centre-to-centre distance $\boldsymbol{L}$ between them. To provide the mounting condition let us consider the worst-case (Figure 2.16,*b*), when holes centre-to-centre distance is produced according to the upper limit of size ($\boldsymbol{L} + \boldsymbol{T_{ch}}/2$), fingers centre-to-centre distance – according to the lower limit of size ($\boldsymbol{L} - \boldsymbol{T_{cf}}/2$), and clearances in matings of holes with fingers are made minimal – $\boldsymbol{S_{1min}}$ and $\boldsymbol{S_{2min}}$. For this position axis of each finger will be displaced in the direction of middle of centre-to-centre distance by the $\boldsymbol{T_{cf}}/4$ value, axis of each hole will shift in the direction opposite to the middle of centre-to-centre distance by the $\boldsymbol{T_{ch}}/4$ value relative to nominal positions of axes O_1 and O_2. Hence, distances $O_1'O_1''$ and $O_2'O_2''$ and are equal to ($\boldsymbol{T_{ch}}/4 + \boldsymbol{T_{cf}}/4$). It is clear from Figure 2.16,*b* that holes axes can shift relative to fingers axes by the

$S_{1min}/2$ and $S_{2min}/2$ values. From this consideration the condition of workpiece mounting on two cylindrical fingers follows

$$S_{1min} + S_{2min} \geq T_{ch} + T_{cf}\ .$$

If it is necessary to specify minimal clearance between finger and the second hole the same like for the first hole (by *f6 ... e9*), then tolerances for centre-to-centre distances will be very small. It is clear from the workpiece mounting condition. It makes machining of datum holes more expensive. Usually tolerances for centre-to-centre distances of fingers and holes are specified much more than tolerances of their diameters. Therefore, in order to provide the condition of workpiece mounting on two cylindrical fingers, the diameter of the second finger has to be reduced.

Let us determine the diameter of the second finger from the condition that clearance S_{2min} value is equal to the difference of minimal diameter of hole d_{h2min} and maximal diameter of finger d_{f2max}, that is

$$S_{2min} = d_{h2min} - d_{f2max}.$$

Substituting S_{2min} with this expression in the condition of workpiece mounting on two cylindrical fingers we will get

$$S_{1min} + d_{h2min} - d_{f2max} = T_{ch} + T_{cf}\ ,$$

then

$$d_{f2max} = d_{h2min} + S_{1min} - T_{ch} - T_{cf}$$

and

$$d_{f2} = (d_{h2min} + S_{1min} - T_{ch} - T_{cf})_{-Tf2},$$

where T_{f2} – tolerance of the second finger diameter.

Hence, in order to provide capability of workpiece mounting on two cylindrical fingers, it is necessary to increase minimal clearances in fits of fingers and holes, but this frequently results in impermissible reduction of mounting accuracy. It is managed to significantly increase this accuracy under the condition of guaranteed mounting of any workpiece from a batch with holes centre-to-centre distances being in the range of size limits, if the second finger will be cut (diamond), but not cylindrical.

Scheme of such workpiece mounting on one cylindrical finger and one diamond finger is shown in Figure 2.16,*c*. As one can see, flat spots increase gap X in the direction of a common axis of two datum holes O_1O_2 that allows mounting workpieces with wider tolerances. The condition of workpiece mounting can be written similar to the previous condition

$$S_{1min} + X \geq T_{ch} + T_{cf}.$$

The X value is determined from consideration of two triangles O_2KM and $O_2'KN$, which have a common height h. This height can be defined from each triangle:

$$h^2 = \left(O_2'K\right)^2 - \left(\frac{KN}{2}\right)^2 = \left(O_2K\right)^2 - \left(\frac{KM}{2}\right)^2;$$

$$\frac{d_{h2}^2}{4} - \frac{C^2}{4} = \frac{d_{f2}^2}{4} - \frac{b^2}{4},$$

it follows $C = \sqrt{d_{h2}^2 - d_{f2}^2 + w^2}$.

As $C = X + b$, then

$$X = \sqrt{d_{h2}^2 - d_{f2}^2 + b^2} - b .$$

Then the condition of workpiece mounting can be written

$$S_{1min} + \sqrt{d_{h2}^2 - d_{f2}^2 + b^2} - b \geq T_{ch} + T_{cf}$$

and diameter of diamond pin

$$d_{f2} = \sqrt{d_{h2}^2 + b^2 - \left(b + T_{ch} + T_{cf} - S_{1min}\right)^2} .$$

Displacements of the workpiece relative to its medium position in the directions perpendicular to the axis of a cylindrical finger are determined by minimal radial clearance S_{1min}, tolerance of datum hole diameter T_{dh1}, tolerance of finger diameter T_{df1}, and tolerance for its wear T_{wf1} (Figure 2.17). The smallest displacement equals $0.5S_{1min}$, and the largest – ($0.5S_{1min} + 0.5T_{dh1} + 0.5T_{df1} + 0.5T_{wf1}$).

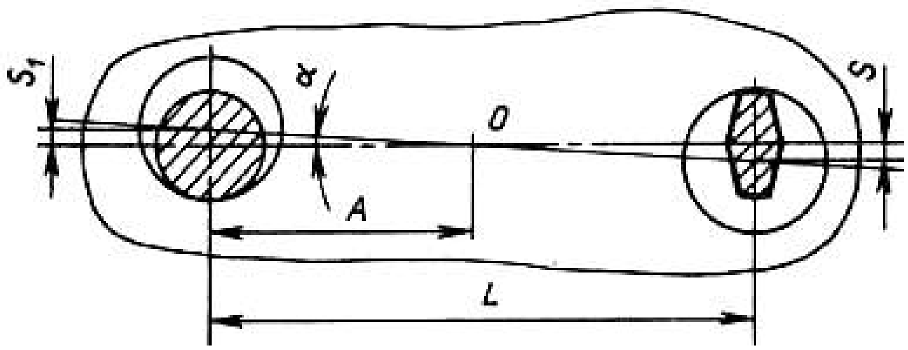


Figure 2.17 – Diagram for calculation of error of workpiece mounting on fingers

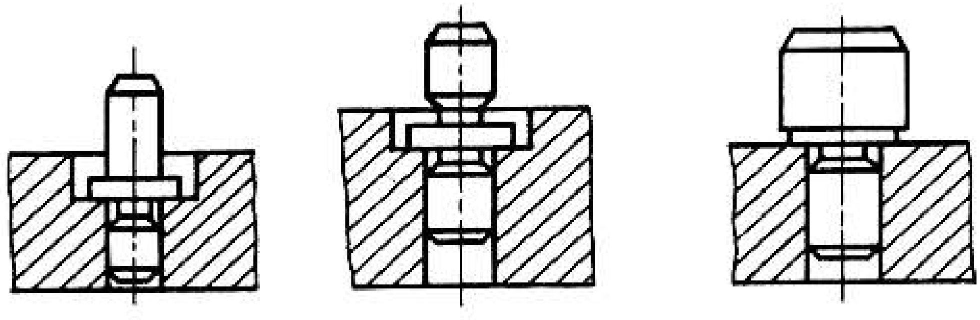
Mounting error for dimensions to be obtained is calculated from the values of displacements. The largest angular displacement of workpiece α from its nominal position is calculated from formula

$$\sin\alpha \approx (0.5S_{1min} + 0.5T_{dh1} + 0.5T_{df1} + 0.5S_{2min} + 0.5T_{dh2} + 0.5T_{df2} + 0.5T_{wf1} + 0.5T_{wf2})/L,$$

where S_{2min} – minimal radial clearance when mounting on diamond pin (determined on land diameter); T_{dh2} – tolerance of hole diameter for diamond pin; T_{df2} – tolerance of land diameter of diamond pin; T_{wf2} – wear tolerance of diamond pin.

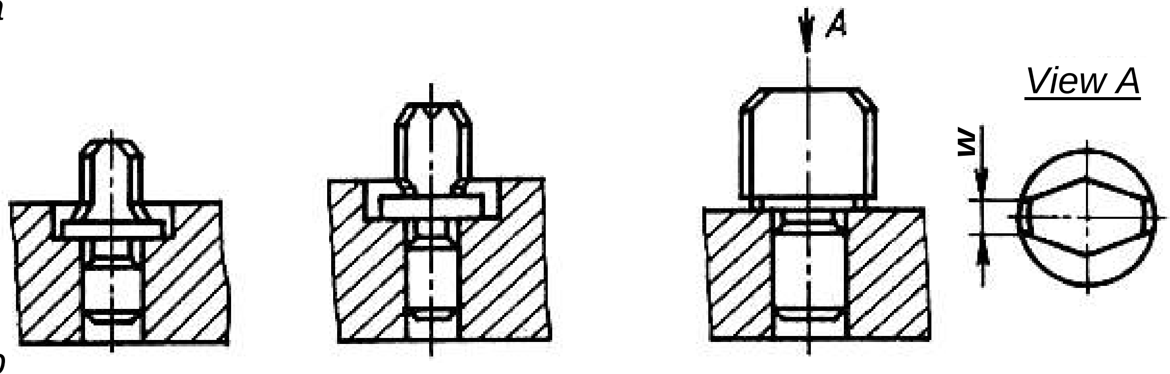
In order to reduce the α angle value, the L distance should be specified as the largest.

Mounting fingers used for workpiece mounting on two holes and plane are standardised (Figure 2.18). The standard specifies the width of cylindrical land ***w***. It depends on cylindrical pin diameter and is specified for diameters of 4...6 mm equal to 1 mm, diameters of 6...8 mm – 2 mm, diameters of 8...12 mm – 3 mm, diameters of 12...32 mm – 4 mm, etc. Dimensions of cylindrical finger depend on workpiece mass. If workpiece mass is up to 5 kg, the finger diameter does not exceed 6 mm, up to 15 kg – 10 mm, up to 45 kg – 12 mm, up to 120 kg – 16 mm, and for greater mass – 20 mm.



For ***D*** ≤ 10 mm   For ***D*** = 10…16 mm   For ***D*** ≤ 16 mm

a



b

Figure 2.18 – Mounting fingers: *a* – cylindrical; *b* – diamond

2.7 Locating of workpieces on centre holes

When machining shafts, rods, and other similar they are frequently mounted on conical surfaces of centre holes. Shaft mounting on two centre holes allows aligning axis of workpiece and axis of centres, that is, reduce to zero error caused by misalignment of manufacturing datum and own coordinate system for all dimensions originated from shaft axis (ε_L = 0). Such a scheme of mounting has got wide application due to the following advantages: simplicity of workholding device design; absence of error caused by misalignment of datums for diameter dimensions; providing of the principle of datums constancy for various machining operations.

The disadvantage of this scheme is a necessity of machining additional surfaces – centre holes.

Theoretical scheme of locating (Figure 2.19) is realised according to the above-considered rule of 6 points.

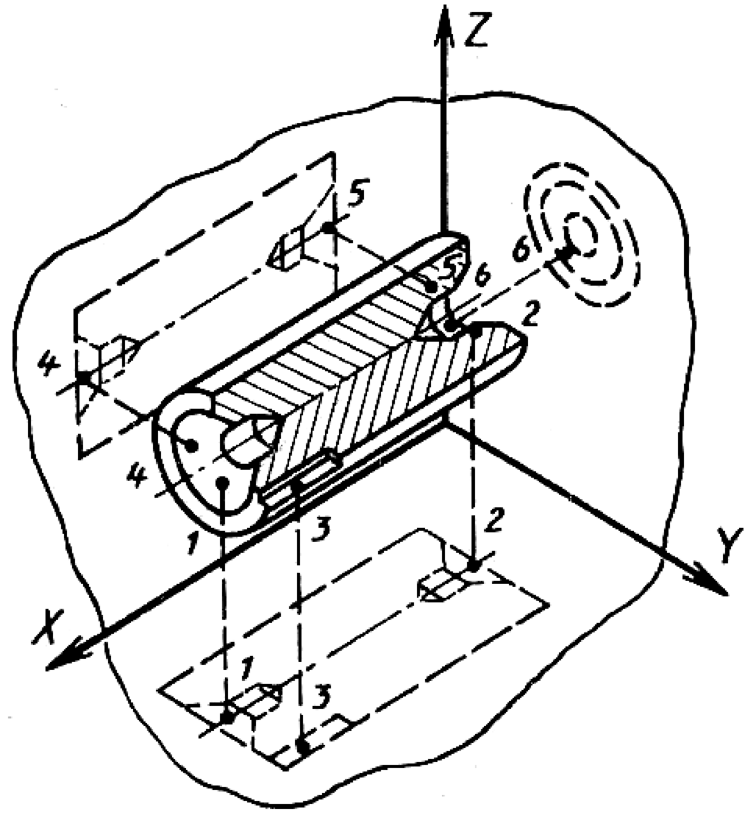


Figure 2.19 – Theoretical diagram of shaft locating on centre holes

Dead and live centres with the 60° angle are used as mounting elements. Their design modifications are depicted in Figure 2.20. The following mounting schemes are applied: on ordinary dead centres (Figure 2.20,*a*), on half-centres (Figure 2.20,*b*), on special centres with three narrow lands 1 (Figure 2.20,*c*). Drive centre (Figure 2.20,*d*) transmits torque by its toothed surface to the shaft, when an axial force is applied to the centre. This centre provides torque transmittance, which is necessary to finish cuts, but it worsens the surface condition of datum chamfer.

Centres are made of Y7A, Y10A steels and heat treated to obtain hardness number of HRC 54...60, wear resistance is improved by welding deposition of cemented carbides.

Error of mounting on a dead centre depends on accuracy of centre holes machined.

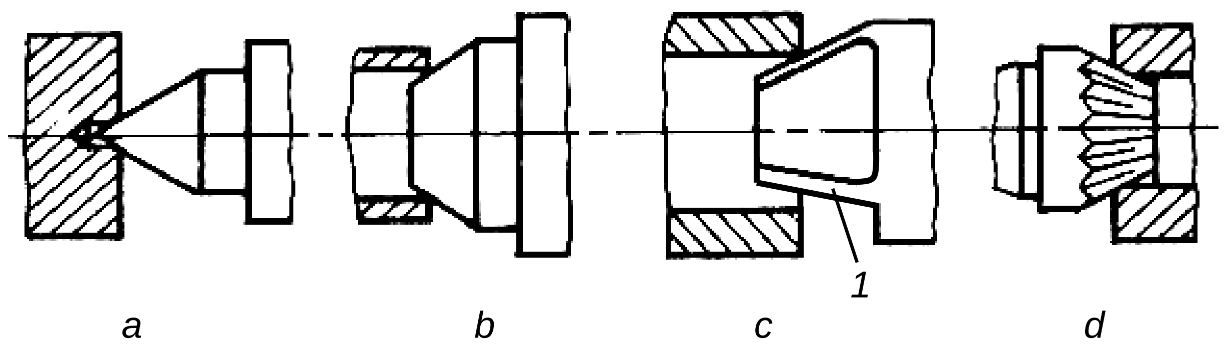


Figure 2.20 – Dead centres

QUESTIONS

1. What is locating? Explain the rule of six points.
2. Describe locating diagram of workpiece on datum plane and two side planes and locating errors.
3. Describe mounting elements for locating of workpiece on datum plane and two side planes.

4. Describe locating diagram of workpiece on datum hole and plane and locating errors.

5. Describe mounting elements for locating of workpiece on datum hole and plane.

6. Describe locating diagram of workpiece on outside cylindrical surface and face and locating errors.

7. Describe mounting elements for locating of workpiece on outside cylindrical surface and face and locating errors.

8. Describe locating diagram of workpieces on two holes and plane. What are the conditions of mounting a workpiece on two cylindrical fingers and mounting on cylindrical and diamond fingers?

9. What is the error of the angular position of workpiece at mounting on two holes and plane?

10. Describe mounting elements for locating of workpiece on two holes and plane.

11. Describe locating diagram of workpieces on centre holes and locating errors.

12. Describe mounting elements for locating of workpiece centre holes.

3 CLAMPING MECHANISMS OF WORKHOLDING DEVICES

3.1 Purpose of clamping mechanisms and requirements for them

Clamping mechanisms (clamps) are designed for providing contact between workpiece and mounting elements and creating reliable fixture of workpiece during machining. In addition a workpiece is provided with higher stiffness and vibrostability that, in its turn, allows obtaining a specified accuracy and productivity.

All clamping devices can be divided into three groups.

The ***first group*** (Figure 3.1,*a*) includes those clamping devices, which have power mechanism (PM) and power drive (PD) that creates initial force $\boldsymbol{F_i}$ transformed by power mechanism into clamping force $\boldsymbol{Q}$, and provides motion of contact element (CE) directly clamping a workpiece (WP) to mounting (ME) of workholding device. Applied drives are various: pneumatic, hydraulic, air hydraulic, mechanical, etc.

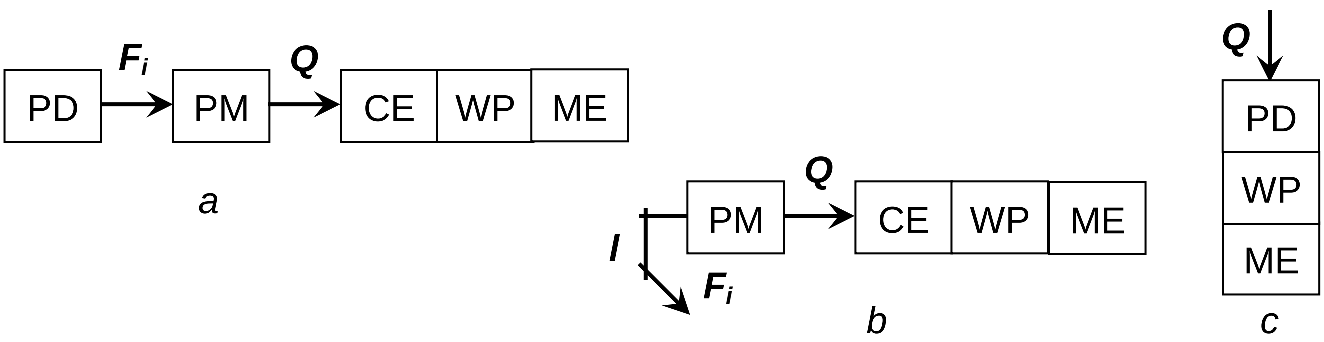


Figure 3.1 – Principal diagrams of clamping devices

The ***second group*** includes those clamping devices, which are composed of only power mechanism actuated by a worker (machine operator), who applies initial force $\boldsymbol{F_i}$ on the lever ***l***. These devices are called manually actuated clamping devices.

The ***third group*** includes those clamping devices, which have no power mechanism, and drives used can be called by convention, since they do not cause motion of clamping elements and only create clamping force ***Q***. Force ***Q*** in these devices is a net force of uniformly distributed load acting directly on a workpiece and resulting either from atmospheric pressure (when vacuuming the opposite side of a workpiece) or from an action of magnetic flux.

Clamping devices should meet the following requirements:

a) workpiece position provided by locating must not change when clamping;
b) clamping should be reliable to avoid workpiece displacement during machining;
c) workpiece surface deformation, as well as workpiece distortion should be minimal and in the permissible range;
d) should provide uniform clamping of workpieces, especially in multi-piece devices;
e) clamping and unclamping of workpieces should be done with minimal force and time consumption;
f) should be reliable in operation, simple by design, easy and safety in maintenance.

Non-observance of these requirements can cause machining errors, and change of workpiece position during cutting process – failure of cutting tools and occupational (professional, factory) accidents.

Compliance with these requirements is provided by proper selection of clamping scheme and magnitude of clamping force ***Q***. Selection of workpiece clamping scheme is fulfilled simultaneously with the development of locating scheme that results in determining location and direction of clamping force.

3.2 Calculations of clamping forces for different schemes of workpiece mounting

When machining, the workpiece is subjected to the action of cutting forces, bulk forces, as well as forces of secondary and random nature, creating possibilities for workpiece displacement. Cutting forces are variable values by magnitude, direction and origin of force. For transient regime (tool cutting-in) cutting force increases from zero up to maximum and decreases from maximum to zero (tool coming-out). Under steady-state condition cutting force is also inconstant and changes in some range. The amplitude of cutting force oscillations reaches 10 % of its nominal value. Origin of cutting force continuously travels longwise surface to be machined, and so cutting force has not static, but dynamic nature. When machining discontinuous surfaces, cutting force oscillations increase greatly. When machining by dull tool cutting forces rise by

10...30 % and more.

Bulk forces are gravity, centrifugal and inertia forces that appear under some definite condition of machining.

Gravity forces act and are to be considered, when a workpiece is mounted on vertical or inclined elements. During machining a workpiece mass continuously reduces and position of its centre of gravity changes.

Centrifugal forces appear during machining, if the workpiece centre of gravity is shifted relative to its axis of revolution. Magnitudes of centrifugal forces and moments of forces under dynamic disbalance conditions are compatible with values of cutting forces and forces moments for finishing machining.

Inertia forces (moments) appear only when a workpiece is reciprocating or rotates with large angular acceleration (for instance, when spindle brakes). Usually these forces and moments of forces are small in comparison with cutting forces and moments of cutting forces.

Direction and origin of cutting force change due to travel of cutting tool along the work surface and variations of cutting conditions. Cutting forces and moments influence on a workpiece: they tend to turn a workpiece relative to mounting elements, to shift a workpiece from the mounted position in a workpiece device, to pull out a workpiece from a clamping device. In spite of these factors, a workpiece should keep constant position relative to device mounting elements during machining.

Forces and moments acting on a workpiece are determined according to the norms and formulas of theory of metal cutting as applied to a certain type of machining.

During machining real cutting forces can significantly differ from calculated values due to variation of mechanical properties of work material, work hardening and defective skin of workpieces, dulling of cutting tool, unevenness of removing allowance, etc. Furthermore, accepted scheme of calculation of clamping force does not take into account various contact conditions (surface deformation, presence of lubricant, various roughness, etc.) between device mounting surfaces and workpiece, workpiece and clamp interface.

All these variations of cutting forces and contact conditions cannot be considered by calculation method. Therefore in practical calculations the value of cutting force, determined from calculation method, is to be multiplied by clamping reliability coefficient ***K***.

Values of clamping reliability coefficient ***K*** should be chosen depending on certain conditions of operation performance and method of workpiece clamping. The GOST 12.2.029-77 specifies the coefficient as ***K*** = 2.0...2.5 for rough machining and ***K*** = 1.3...1.5 for finishing machining and for machining of workpieces from non-ferrous alloys.

The magnitude of the required clamping force is calculated from statics relationships by considering the workpiece equilibrium state under the action of applied forces. For that it is necessary to develop a loading diagram, that is, to draw all acting forces on the workpiece locating scheme: cutting forces and moments, clamping forces, reactions of the supports and friction forces on the interfaces of workpiece and mounting elements, workpiece and clamping elements. Loading diagram should be drawn for the most unfavourable position of cutting tool on the work surface.

Direction of probable displacement or turning of a workpiece under the action of cutting forces and moments is determined from the loading diagram, values of projections of all forces onto direction of displacement are calculated and equations of forces and moments are formulated.

Formulas for calculation of clamping force ***Q*** providing reliable workpiece fixing are derived from statics equations. Let us consider two examples.

Example 1. In operation of milling the flat (Figure 3.2) for a selected locating scheme the workpiece of ***l*** length under the action of cutting forces can turn relative to the point *O* and displace in axial (horizontal) direction.

From the equilibrium condition ($\Sigma M_i = 0$) the equation of moments has the following form

$$Qa + Fl = P_z b + P_r l,$$

where P_z, P_r – cutting forces; F – friction force, $F = f\,Q$.

After application of the clamping reliability coefficient ***K*** the equation will get the form

$$Qa + f\,Ql = K\,(P_z b + P_r l),$$

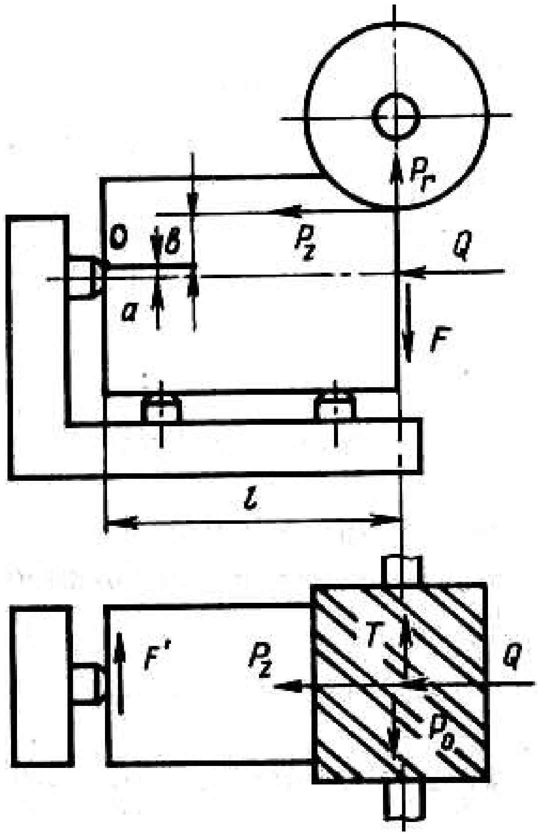


Figure 3.2 – Diagram for calculation of clamping force value holding a workpiece at milling

followed by

$$Q = \frac{K\left(P_z b + P_r l\right)}{a + fl},$$

where f – coefficient of friction between workpiece and clamping elements.

Axial force P_o tries to displace a workpiece. Friction forces between workpiece and mounting elements (F') and between workpiece and clamping elements (F) will hold it in a device ($\Sigma F_i = 0$). An equation of forces with application of the clamping reliability coefficient ***K*** has the following form

$$Qf + Q\,f' = K\,P_o,$$

followed by

$$Q = \frac{KP_o}{f + f'},$$

where f' – coefficient of friction between workpiece and mounting elements of device.

The maximal clamping force ***Q*** should be chosen from two values and used for further development of clamping device.

Example 2. In operation of drilling hole in a round workpiece (Figure 3.3) is clamped in three-jaw chuck. It can displace axially relative to jaws under the action of cutting force $\boldsymbol{P_o}$ and rotate in jaws under the action of cutting moment $\boldsymbol{M}$. Applied clamping force should be of such magnitude that prevents both displacement and rotation of workpiece relative to jaws. Depends on the shape of toothing on jaws the resistance to displacement and rotational sliding can differ, because of different coefficients of friction.

Supposing that for workpiece displacement in jaws along the axis coefficient of friction will be $\boldsymbol{f_1}$, and for rotational sliding – $\boldsymbol{f_2}$.

Frictional forces between jaw and workpiece will be for axial displacement equal to $\boldsymbol{F_1} = \boldsymbol{f_1 Q}$, for rotational sliding – $\boldsymbol{F_2} = \boldsymbol{f_2 Q}$.

Let us determine the value of clamping force under the condition of the absence of any workpiece displacement in jaws. The balance of forces:

$$3\boldsymbol{F_1} = \boldsymbol{P_o}.$$

After substitution of $\boldsymbol{F_1}$ value application of clamping reliability coefficient K the equation will get a form

$$3\,\boldsymbol{f_1 Q} = \boldsymbol{P_o},$$

followed by

$$\boldsymbol{Q} = \frac{\boldsymbol{KP_o}}{3\boldsymbol{f}_1}.$$

The value of clamping force under the condition of absence of any workpiece rotational sliding in jaws is determined. Since the workpiece is clamped in three jaws, the balance of moments of forces will have a form

$$3\boldsymbol{F_2}\,\boldsymbol{r} = \boldsymbol{M},$$

where $\boldsymbol{r}$ – radius of the outside cylindrical surface of workpiece on the section of its clamping in jaws.

After substitution of $\boldsymbol{F_2}$ value and application of clamping reliability coefficient $\boldsymbol{K}$ the equation will get a form

$$3\,\boldsymbol{f_2}\,\boldsymbol{Qr} = \boldsymbol{K}\,\boldsymbol{M},$$

followed by

$$\boldsymbol{Q} = \frac{\boldsymbol{KM}}{3\boldsymbol{f}_2\boldsymbol{r}}.$$

The maximal value of clamping force should be chosen from two calculated values.

In devices frictional forces appear on surfaces of contact of workpiece and mounting elements, as well as in places of contact of clamping devices and workpiece surfaces. The value of the friction coefficient depends on many

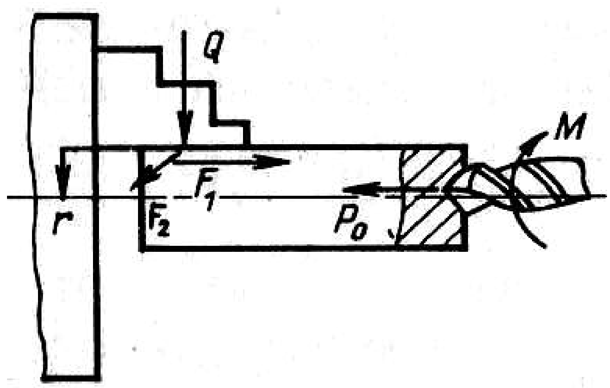


Figure 3.3 – Diagram for calculation of clamping force when drilling hole in a round workpiece on a turning machine

factors. Its determination is connected with additional difficulties. In many devices toothings of various shapes and directions are made on contact surfaces. When clamping teeth are pressed into the body of workpiece, and depth of impression depends on the value of normal reaction force in the places of contact. Forces appeared on such surfaces, which resist rotation or shift of workpiece, cannot be named by frictional forces. It would be more exact to call them forces of resistance to displacement. But in order to simplify calculations and to shorten expressions, the term "coefficient of friction" and symbol "***f*** " are used.

In devices there are a lot of various combinations of contact surfaces different by shape, surface condition, hardness, etc. The values of coefficient of friction for several combinations of contact surfaces are given in the Table 3.1.

Having determined the value of clamping force ***Q***, a designer selects the type of clamping device. Doing that he considers the following parameters: value of clamping force, sizes and shape of a workpiece, type of operation to be performed, and production run. For selected power mechanism the initial force F_i should be determined, which will provide the required clamping force ***Q***.

Table 3.1 – Values of friction coefficient

Characteristic of contact surface	Value ***f***
Machined surface of a workpiece contacts with a plane of rest elements (plates, magnetic plate, etc.)	0.10…0.15
Machined surface of a workpiece contacts with a rest element on line (locating on prism) or on sphere surface (locating on rest pin with spherical head)	0.18…0.30
Unmachined surface of a workpiece contacts with a hardened rest element	0.50…0.80
Contact element rests on cylindrical surface of a workpiece (when mounting in jaws, collets, etc.) and has:	
smooth surface	0.25
ring grooves	0.35
X-shaped grooves	0.45
Contact element rests on unmachined surface and has:	
ring grooves	0.40…0.50
toothing (knurling)	0.50…0.80

When specifying power mechanism with manual drive, it is necessary to consider that a worker should not apply a force not more than F_i = 150 N to handle of the key.

A lot of schemes and designs of power mechanisms are tested in practice. Many of them are standardised and a designer has an opportunity to select such a design scheme, which in the most measure corresponds to the conditions of operation of a designed device.

3.3 Designs of simple clamping devices

Clamping mechanisms of workholding devices are divided into simple and combined. The simple mechanisms are those, in which the force generated by a certain power source is transferred to a workpiece through one part. They are: screw pair, wedge, cam (eccentric), and spring. Combined mechanisms consist of some simple clamps mounted in series connection.

By number of origins of clamping force the clamping devices are divided into single and multipoint. Multipoint devices clamp one workpiece in several points or several workpiece simultaneously and with equal forces.

Screw clamps have wide application, they are simple by design and allow creating large clamping force. The significant disadvantage is that the clamping operation takes relatively long auxiliary time. Clamping is produced by bolt or nut.

Diagrams of screw clamps are depicted in Figure 3.4. Direct action of bolt butt-end on a workpiece causes rumpling of surface and so it is permitted for clamping of unmachined or rough-machined workpieces (Figure 3.4,*a*). Clamping bolts are made of the 45 steel with heat hardening of head and work end up to HRC 35…40 according to the GOSTs 13434-68 and 13435-68. Application of auxiliary thread bushing enhances repair after wear-out of a joint. Bolt work end turned to diameter d_1 is used to make easier unscrewing of the bolt, if necessary.

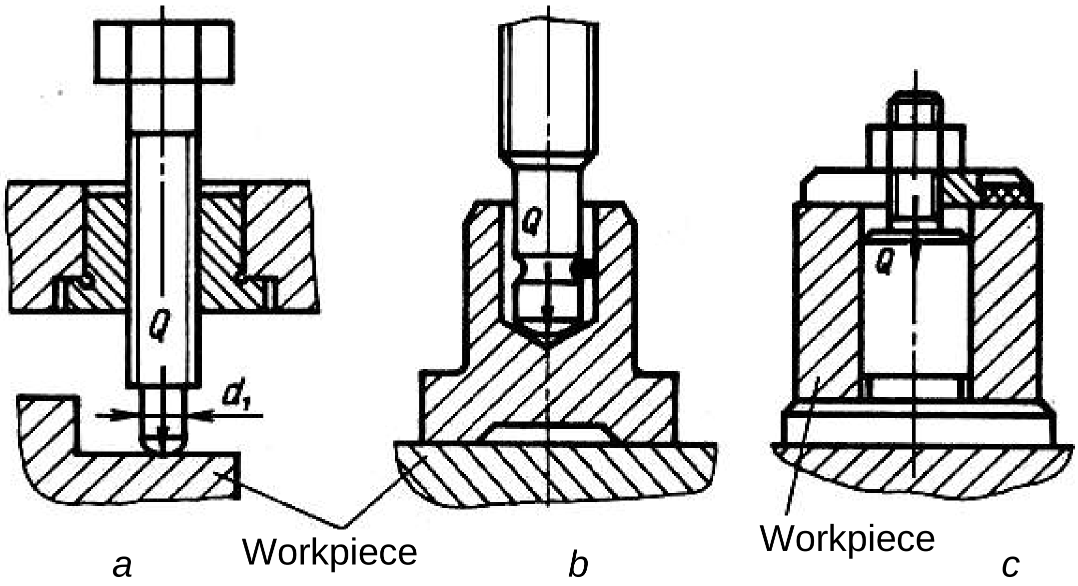


Figure 3.4 – Diagrams of screw clamps: *a* – clamping by a bolt butt; *b* – clamp with a rest plate; *c* – clamping by a nut with quick-detachable washer

When impressions on the clamped surface of a workpiece are not permitted, rest plates are used (Figure 3.4,*b*). Rest plate is hingedly fixed to a work end of clamping bolt and provides transferring of clamping force on the larger area, thus reducing the contact pressure. Hinged fixing of the plate protects clamping bolt from bending, even when clamped surface of a workpiece is inclined.

Nuts used for clamping workpieces in workholding devices are applied, when a workpiece is based on a hole (Figure 3.4,*c*). Clamping nuts of devices operate in conjunction with slotted (quick-detachable) washers, which provide the capability of workpiece mounting and removal with a small unscrewing of nut.

Wedge clamps. Clamping of workpieces by direct action of a wedge is used rarely. But wedge in conjunction with other parts of a clamping mechanism has got wide application due to simplicity and compactness of design, performance reliability. The use of wedge in the clamping mechanism provides increase of initial force of power drive, change of direction of initial force, self-braking of the mechanism. If a wedge mechanism is used for change of direction of clamping force, the wedge angle is usually equal to 45°, and, if for increase of clamping force or clamping reliability, then the wedge angle is specified as 6…15°.

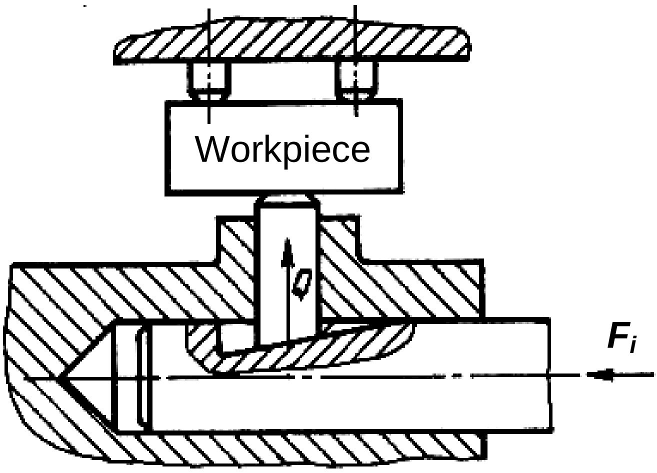


Figure 3.5 – Diagram of wedge-plunger mechanism

The direct action of a wedge on a workpiece surface is not recommended to avoid damage of a workpiece. For this purpose an intermediate component of clamping mechanism is applied (Figure 3.5). Movement of wedge occurs under action of pneumatic, hydraulic equipment, or manually – with a screw pair.

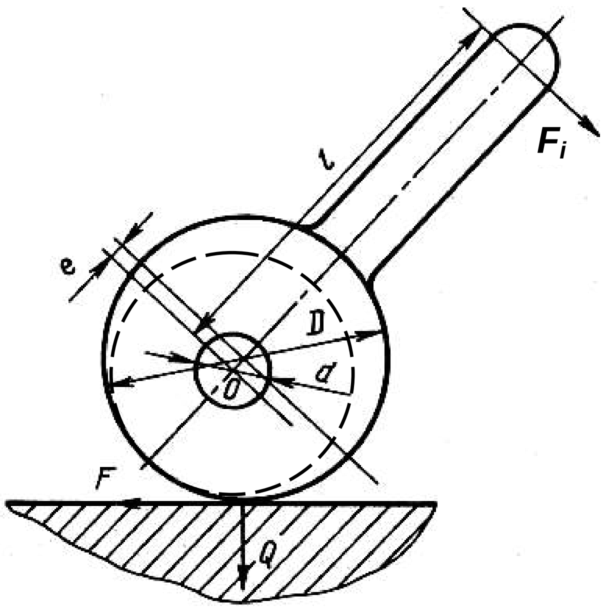


Figure 3.6 – Diagram of forces distribution in circular cam: ***D*** – outside cam diameter; ***d*** – inside cam diameter; ***e*** – eccentricity; ***l*** – lever; F_i – initial force

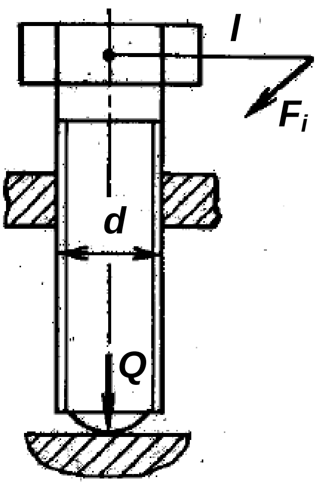
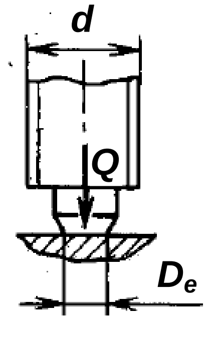
Cam clamps are widely applied means for workpiece clamping in fixtures. Their distinctive features are simplicity of production, ease of usage and high speed of operation. But they have lower clamping force, clamping reliability, and versatility, in comparison with a screw clamp. Cam clamps are better suited for such machining conditions that occur without significant knocks and vibrations.

Cam (eccentric) is a joint of two elements – round disk of the (***D***/2 – ***e***) radius and flat single-side wedge (Figure 3.6). When the cam rotates around the disk axis *O*, a wedge is inserted into the gap between disk and workpiece that generates forces of clamping ***Q*** and friction ***F***.

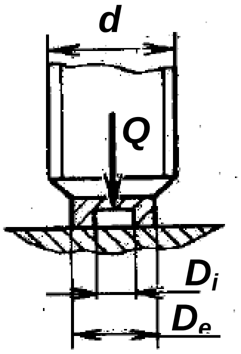
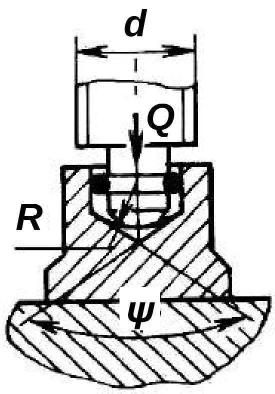
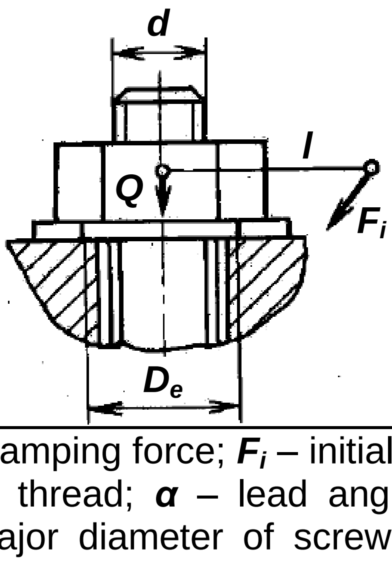
Work surface of cams can be circle (circular cams) or spiral (curved cams). The difference is that in the evolvement of circular cams a flat wedge transforms into the curvilinear with variable angle $\boldsymbol{\alpha}$ depending on the rotational angle $\boldsymbol{\beta}$, and for curved cams the angle $\boldsymbol{\alpha}$ does not depend on the angle $\boldsymbol{\beta}$. This means that curved cams create stable constant clamping force for batch of workpieces, and circular cams – do not. When clamping by circular cams, the working rotational angle $\boldsymbol{\beta}$ changes depend on the variation of workpiece dimension in the batch, and, hence, the angle $\boldsymbol{\alpha}$ and clamping force $\boldsymbol{Q}$ also change. Meanwhile technology of making circular cams is much easier, than of curved cams. Steels 20 and Y7A are used for producing cams. The 20 steel is subjected to cementation and hardening up to hardness number HRC 55…60. The Y7A steel is subjected to hardening up to hardness number HRC 48…52.

Design formulas for the determination of the clamping force of power mechanisms (Table 3.2) are given in the book [1].

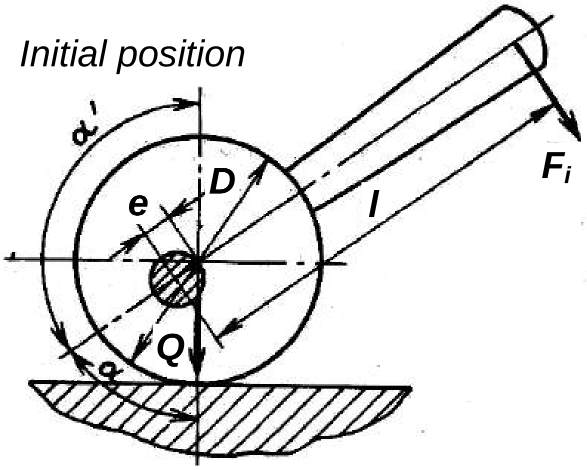
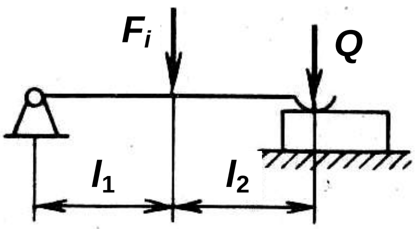
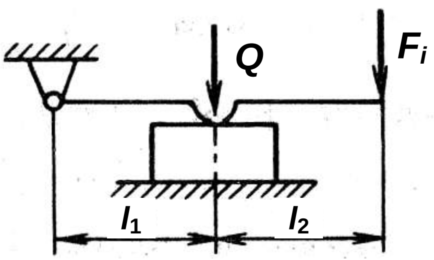
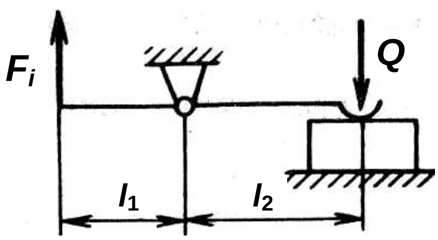
Table 3.2 – Formulas for calculations of clamping force

Clamping mechanism	Formulas
Screw mechanisms	
Bolt with spherical work end 	$F_i = \frac{r_p \mathrm{tg}(\alpha + \varphi_n)}{l} Q$ Approximate value for threads M8…M52 $F_i = \frac{d}{10l} Q$
Bolt with flat work end 	$F_i = \frac{r_p \mathrm{tg}(\alpha + \varphi_n) + \frac{1}{3} f D_e}{l} Q$ Approximate value for threads M8…M52 $F_i = \frac{0.1d + 0.05D_e}{l} Q$

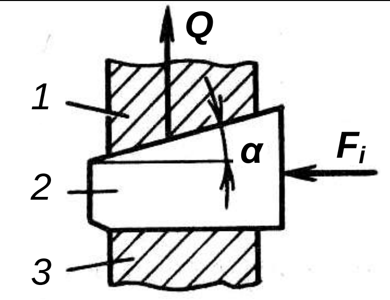
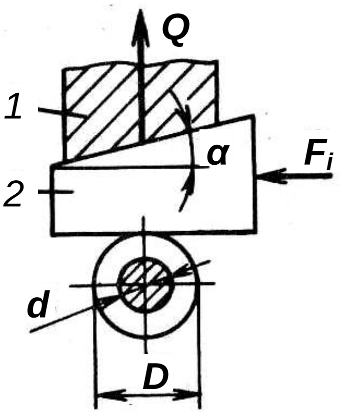
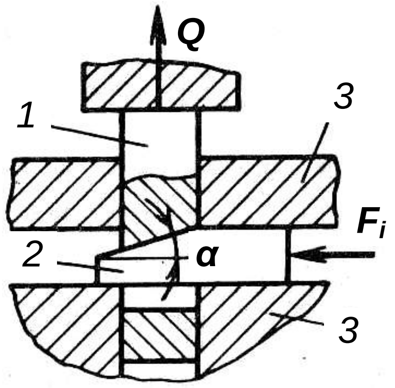
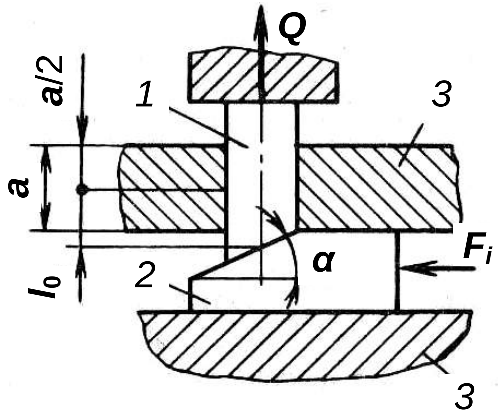
Continuation of Table 3.2

Clamping mechanism	Formulas
Screw mechanisms	
Bolt with ring surface of work end 	$F_i = \dfrac{r_p \operatorname{tg}(\alpha + \varphi_n) + \frac{1}{3} f \frac{D_e^3 - D_i^3}{D_e^2 - D_i^2}}{l} Q$ Approximate value for threads M8…M52 $F_i = \dfrac{0.1d + 0.05 \frac{D_e^3 - D_i^3}{D_e^2 - D_i^2}}{l} Q$
Bolt with rest plate 	$F_i = \dfrac{r_p \operatorname{tg}(\alpha + \varphi_n) + f \cdot R \cdot \operatorname{ctg}\frac{\psi}{2}}{l} Q$ Approximate value for threads M8…M52 $F_i = \dfrac{0.1d + 0.05R \cdot \operatorname{ctg}\frac{\psi}{2}}{l} Q$
At nut application 	$F_i = \dfrac{r_p \operatorname{tg}(\alpha + \varphi_n) + \frac{1}{3} f \frac{D_e^3 - d^3}{D_e^2 - d^2}}{l} Q$ Approximate value for threads M8…M52 $F_i = \dfrac{0.1d + 0.05 \frac{D_e^3 - d^3}{D_e^2 - d^2}}{l} Q$
Q – clamping force; F_i – initial force; l – arm of initial force; $2r_p$ – pitch diameter of screw thread; α – lead angle of screw thread (α = 2°30’ for metric thread); d – major diameter of screw thread; φ_n – normalised friction angle of thread (φ_n = 10°30’); f – friction coefficient of between rest butt end of crew and work-piece; D_e – external diameter of rest butt end of crew or nut; D_i – internal diameter of rest butt end of crew or nut; R – radius of rest butt end of crew; ψ – angle of bearing surface of rest plate	

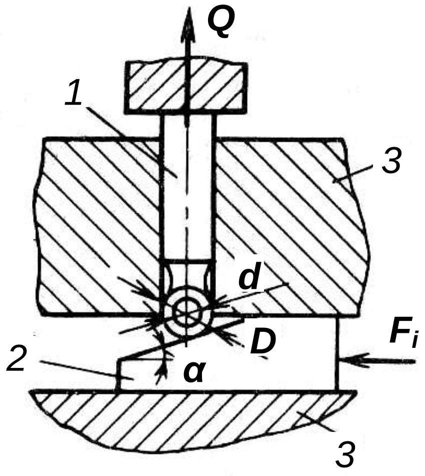
Continuation of Table 3.2

Clamping mechanism	Formulas
Eccentric mechanisms	
	$F_i = \frac{e\left[1+\sin(\alpha' + \varphi)\right]}{l}Q$ Approximately at φ = 8°and α' = 82° $F_i = \frac{2e}{l}Q$
e – eccentricity; ***α'*** = (180° – ***α***); ***α*** – rotation angle from initial position; ***φ*** – friction angle in the place of clamping force application (tg***φ*** = ***f*** = 0.12…015)	
Lever mechanisms	
	$F_i = \frac{l_1 + l_2}{l_1 \cdot \eta}Q$
	$F_i = \frac{l_1}{(l_1 + l_2) \cdot \eta}Q$
	$F_i = \frac{l_2}{l_1 \cdot \eta}Q$
Q – clamping force; F_i – initial force; l_1 , l_2 – arms of levers; ***η*** – coefficient of losses for friction in the seat of lever (***η*** = 0.85)	

Continuation of Table 3.2

Clamping mechanism	Formulas
Wedge and wedge-plunger mechanisms	
	$\boldsymbol{F_i} = \left[\mathrm{tg}(\boldsymbol{\alpha} + \boldsymbol{\varphi}) + \mathrm{tg}\boldsymbol{\varphi}_1\right]\boldsymbol{Q}$
	$\boldsymbol{F_i} = \left[\mathrm{tg}(\boldsymbol{\alpha} + \boldsymbol{\varphi}) + \mathrm{tg}\boldsymbol{\varphi}_{1\boldsymbol{n}}\right]\boldsymbol{Q}$
	$\boldsymbol{F_i} = \dfrac{\mathrm{tg}(\boldsymbol{\alpha} + \boldsymbol{\varphi}) + \mathrm{tg}\boldsymbol{\varphi}_1}{1 - \mathrm{tg}\boldsymbol{\varphi}_2\mathrm{tg}(\boldsymbol{\alpha} + \boldsymbol{\varphi})}\boldsymbol{Q}$
	$\boldsymbol{F_i} = \dfrac{\mathrm{tg}(\boldsymbol{\alpha} + \boldsymbol{\varphi}) + \mathrm{tg}\boldsymbol{\varphi}_1}{1 - \dfrac{3\boldsymbol{l}_0}{\boldsymbol{a}}\mathrm{tg}\boldsymbol{\varphi}_2\mathrm{tg}(\boldsymbol{\alpha} + \boldsymbol{\varphi})}\boldsymbol{Q}$

Continuation of Table 3.2

<table>
<tr><th>Clamping mechanism</th><th>Formulas</th></tr>
<tr><td>
</td><td>$$F_i = \frac{\mathrm{tg}(\alpha + \varphi_n) + \mathrm{tg}\varphi_1}{1 - \mathrm{tg}\varphi_2 \mathrm{tg}(\alpha + \varphi_n)} Q$$</td></tr>
<tr><td colspan="2">*1* – plunger; *2* – wedge; *3* – body; ***Q*** – clamping force; F_i – initial force; α – wedge angle; φ – friction angle between plunger and wedge ($\mathrm{tg}\varphi = f$ = 0.10…0.15); φ_1 – friction angle between wedge and body ($\mathrm{tg}\varphi_1 = f_1$ = 0.10…0.15); φ_n – normalised friction angle between wedge and roller ($\mathrm{tg}\varphi_n = f\, d / D$); φ_2 – friction angle between plunger and body ($\mathrm{tg}\varphi_2 = f_2$ = 0.10…0.15); φ_{1n} – normalised friction angle between wedge and roller ($\mathrm{tg}\varphi_{1n} = f_1\, d / D$); ***a***, l_0 – dimensions of mechanism</td></tr>
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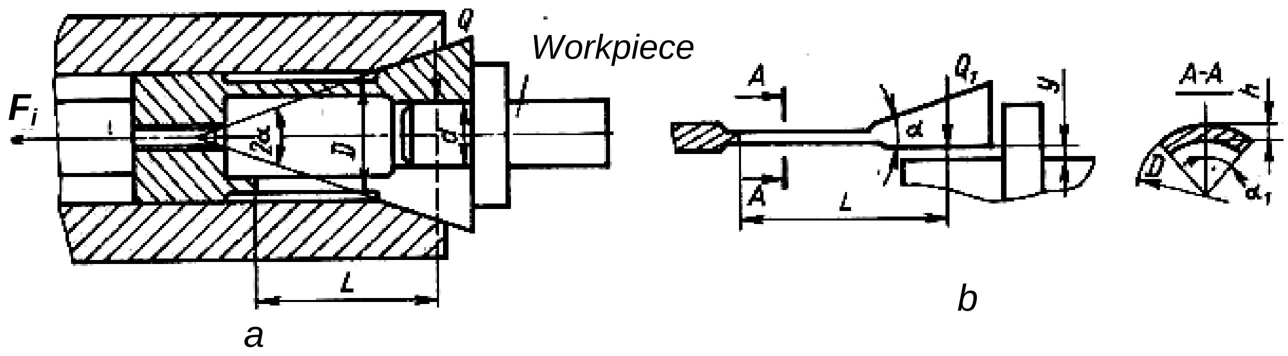
3.4 Mechanisms with elastodeformed elements

3.4.1 Collet mechanisms

Collets are longitudinally split spring bushings, which can align and clamp workpieces by outside and inside diameters. Collet mechanisms are widely applied for holding bar stocks, as well as short piece blanks.

Figure 3.7 illustrates designs of collet mechanisms for alignment by outside diameter: with a draw-in collet used for clamping of piece blanks (Figure 3.7,*a*,*b*); with push-out collet (Figure 3.7,*c*) used mainly for clamping of a bar stock (a stop is mounted before collet for positioning of a bar stock in the axial direction). Longitudinal slots transform each collet segment into a cantilever beam that performs radial elastic motions at the expense of interaction of collet and casing tapers, when a collet moves longitudinally. Since radial motions of all collet segments occur simultaneously and with equal speed, the mechanism acquires self-centring feature.

The number of collet segments depends on its work diameter ***d*** and profile of clamped workpieces. If $d \le 30$ mm, a collet has three segments, if $30 < d < 80$ mm, then it has six. In order to provide operability of collet, the deformation of its segments must not exceed elasticity limit. This determines the increased requirements for accuracy of datum diameter of a workpiece that should be no worse than the 9th accuracy grade.



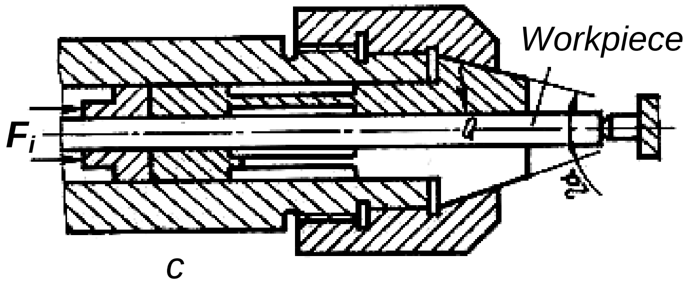


Figure 3.7 – Diagrams of collet mechanisms: *a* – clamping of a short workpiece with a pull-type collet; *b* – design of collet segments; *c* – clamping of a bar with a push-type collet

Collets are made of the Y8A or 65Г(65Mn) steel, large collets – of the 15XA(15Cr) or 12XH3A(12CrNi3A) steel. A work part of collet is hardened up to HRC 55…62, and a tail part is subjected to tempering to hardness of HRC 30…40.

Centring error originates from production inaccuracy of the collet chucks and equals 0.05…0.10 mm.

When determining the value of initial force $\boldsymbol{F_i}$, special consideration should be made in respect that some portion of drive power is consumed by deformation of collet segments. Force $\boldsymbol{Q'}$, required for deformation of a segment, can be determined, when collet segment is considered as a cantilever beam (Figure 3.7,*b*) with $\boldsymbol{L}$ overhang. Deformation is calculated from

$$y = \frac{Q'L^3}{3EJ},$$

then for all segments

$$Q' = \frac{3EJ}{L^3} yn,$$

where $\boldsymbol{E}$ – elasticity modulus of collet material; $\boldsymbol{J}$ – moment of inertia of cross section of collet sector in the place of collet segment connection: $J = \frac{D^3 h}{8}\left(\alpha + \sin\alpha_1 \cos\alpha_1 - \frac{2\sin^2\alpha}{\alpha_1}\right)$; $\boldsymbol{D}$ – outside diameter of segment surface; $\boldsymbol{h}$ – segment thickness; $\boldsymbol{\alpha_1}$ – half-angle of sector of collet segment; $\boldsymbol{L}$ – length of collet segment from place of connection to middle section of collet taper; $\boldsymbol{n}$ – number of segments in collet; $\boldsymbol{y}$ – bending deflection of a segment, that is, radial clearance between collet and workpiece.

Thus, the value of initial force $\boldsymbol{F_i}$ is calculated from the formula

$$\boldsymbol{F_i} = (\boldsymbol{Q} + \boldsymbol{Q'})\left[\text{tg}(\boldsymbol{\alpha} + \boldsymbol{\varphi}_1) + \text{tg}\boldsymbol{\varphi}_2\right],$$

where $\boldsymbol{\alpha}$ – half-angle of collet taper; $\boldsymbol{\varphi_1}$ – angle of friction between collet and sleeve; $\boldsymbol{\varphi_2}$ – angle of friction between collet and workpiece.

3.4.2 Mechanisms with diaphragms

Mechanisms with diaphragms are used for alignment and clamping by outside and inside cylindrical surfaces of workpieces: rings, bushings, etc. During the deformation of diaphragm its dimensions increases by small value. Therefore datum workpiece surfaces should be machined not worse than 7…8 accuracy grade. The basic component of such a mechanism is diaphragm. Clamping of a workpiece in the diaphragm is performed by action of elastic force. First, before mounting a workpiece the diaphragm is deformed by initial force $\boldsymbol{F_i}$ to create clearance and insert a workpiece. Then, after mounting a workpiece the force $\boldsymbol{F_i}$ is removed and the diaphragm clamps a workpiece (Figure 3.8,*b*).

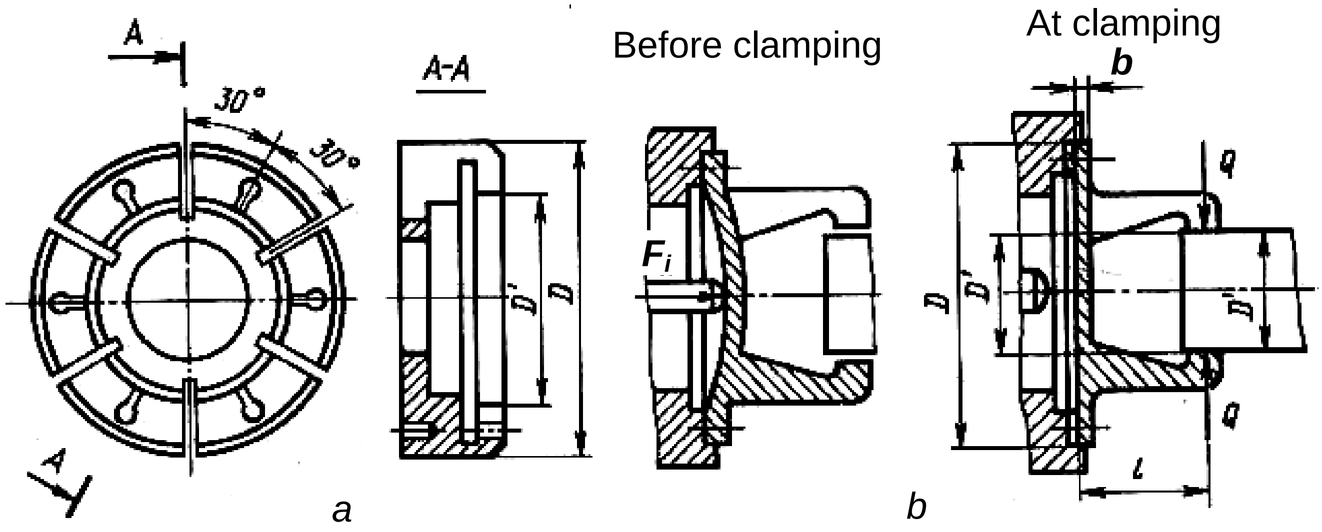


Figure 3.8 – Diaphragms: *a* – cup-shaped; *b* – horn-type

In the devices cup-shaped and horn diaphragms are used (see Figure 3.8). They are normalized.

Cup-shaped and horn diaphragms are made of 65Г(65Mn), 30ХГС (35CrMnSi) steels and are subjected to a heat treatment to obtain hardness of HRC 40…45.

Chucks with cup-shaped and horn diaphragms can provide alignment accuracy of 0.003…0.010 mm.

The algorithm for the development of a horn-type diaphragm (see Figure 3.8,*b*) is given in the book [1]. Clamping force $\boldsymbol{Q}$ at one jaw (horn) is

$$\boldsymbol{Q} = 10^3 \frac{\boldsymbol{KM_C}}{\boldsymbol{nfr}},$$

where $\boldsymbol{M_C}$ – moment of cutting forces, Nm; $\boldsymbol{n}$ – number of jaws at diaphragm ($\boldsymbol{n}$ = 6…12); $\boldsymbol{f}$ – friction coefficient between workpiece and jaw; $\boldsymbol{r}$ – radius of workpiece datum ($\boldsymbol{r} = 0.5\boldsymbol{D'}$); $\boldsymbol{K}$ – coefficient of clamping reliability.

Moment necessary for deformation of diaphragm disk

$$\boldsymbol{M_D} = \frac{\boldsymbol{Qnl}}{2\boldsymbol{\pi r}},$$

where $\boldsymbol{M_D}$ – moment distributed along disk of the $\boldsymbol{r}$ radius, which causes diaphragm deformation; $\boldsymbol{l}$ – distance between middle of jaws and middle plane of diaphragm.

Diaphragm external diameter is assigned according to

$$\boldsymbol{D} = (1.3\ldots3.0)\,\boldsymbol{D'},$$

where $\boldsymbol{D'}$ – diameter of workpiece datum.

Diaphragm disk thickness is assigned

$$\boldsymbol{b} = 0.25\,\boldsymbol{D}.$$

Using ratio $\boldsymbol{D}/2\boldsymbol{r}$ the fixation moment of diaphragm $\boldsymbol{M_F}$ in the $\boldsymbol{M_D}$ portions is determined from Table 3.3.

Table 3.3 – The $\boldsymbol{M_F}$ values depending on ratio $\boldsymbol{D}/2\boldsymbol{r}$

$\boldsymbol{D}/2\boldsymbol{r}$	1.25	1.50	1.75	2.0	2.25	2.50	2.75	3.0
$\boldsymbol{M_F}$	0.825	0.675	0.590	0.565	0.555	0.565	0.575	0.585

Cylindrical rigidity of diaphragm deformation is

$$\boldsymbol{B} = \frac{\boldsymbol{Eb}^3}{10^3 \cdot 12\left(1-\boldsymbol{\mu}^2\right)},$$

where $\boldsymbol{E}$ – elasticity modulus ($\boldsymbol{E} = 2.1\cdot10^5$ MPa); $\boldsymbol{\mu}$ – coefficient ($\boldsymbol{\mu}$ = 0.3).

The angle of jaws (horns) turn $\boldsymbol{\varphi}$ at minimum limit diameter of workpiece datum surface

$$\boldsymbol{\varphi} = \frac{\boldsymbol{M_D r}}{10^3 \cdot \boldsymbol{B}(1+\boldsymbol{\mu})}.$$

Maximum angle of jaws (horns) turn $\boldsymbol{\varphi'}$ is

$$\boldsymbol{\varphi}' = \boldsymbol{\varphi} + \frac{\boldsymbol{T_{D'}}}{2\boldsymbol{l}} + \frac{\boldsymbol{H}}{2\boldsymbol{l}},$$

where $\boldsymbol{T_{D'}}$ – tolerance of workpiece datum diameter $\boldsymbol{D'}$; $\boldsymbol{H}$ – clearance between workpiece datum and jaws before mounting the workpiece with the largest datum diameter ($\boldsymbol{H}$ = 0.01…0.03 mm).

Initial force for jaws (horns) turn before workpiece clamping

$$\boldsymbol{F_i} = \frac{4\cdot10^3\boldsymbol{\pi B\varphi'}}{2\cdot\ln\left(\boldsymbol{D}/2\boldsymbol{r}\right)}.$$

3.4.3. Mechanisms with disk springs

Mechanisms with leaf springs are used in those cases, when significant clamping forces and small overall dimensions of clamping devices are required. Disk (Belleville) springs (Figure 3.9,*a*) are applied in devices for locating and clamping of workpieces for finish machining. Disk spring is a concave washer of the shape of truncated cone with blind slots. When the axial force $\boldsymbol{F_i}$ is applied, the increment of outside (mounting) spring diameter occurs.

Diagram of the mechanism with two packs of springs is shown in Figure 3.9,*b*. When the force $\boldsymbol{F_i}$ is applied, the packs constrict in axial direction, increase in diameter, and a workpiece is aligned and clamped. Depend on the size of springs the increment of diameter may be 0.1…0.4 mm. Therefore, datum surfaces of workpieces may be produced by the 7…10 accuracy grades, and alignment accuracy reaches 0.01…0.03 mm.

The algorithm for calculations of the spring clamps is recommended in the book [1]. Initial (axial) force for one spring is calculated from

$$F_{i1} = 1.33 \cdot tg(\beta - 2°)\, Q_1,$$

where $\boldsymbol{Q_1}$ – clamping force created by one spring; $\boldsymbol{\beta}$ – spring angle at unloaded condition (β = 10…12°).

The required quantity of springs to withstand the cutting moment with reliability coefficient $\boldsymbol{KM_C}$ is

$$n = \frac{KM_C}{M_f},$$

where $\boldsymbol{M_f}$ – friction moment created by one spring on the workpiece surface at the application of initial force $\boldsymbol{F_{i1}}$.

The $\boldsymbol{M_f}$ friction moment value for the selected disk spring can be found from the handbook [3].

Initial force for a set of springs in mechanism is calculated from

$$F_i = F_{i1} \cdot n = 1.33 \cdot tg(\beta - 2°)\, Q_1 \cdot n.$$

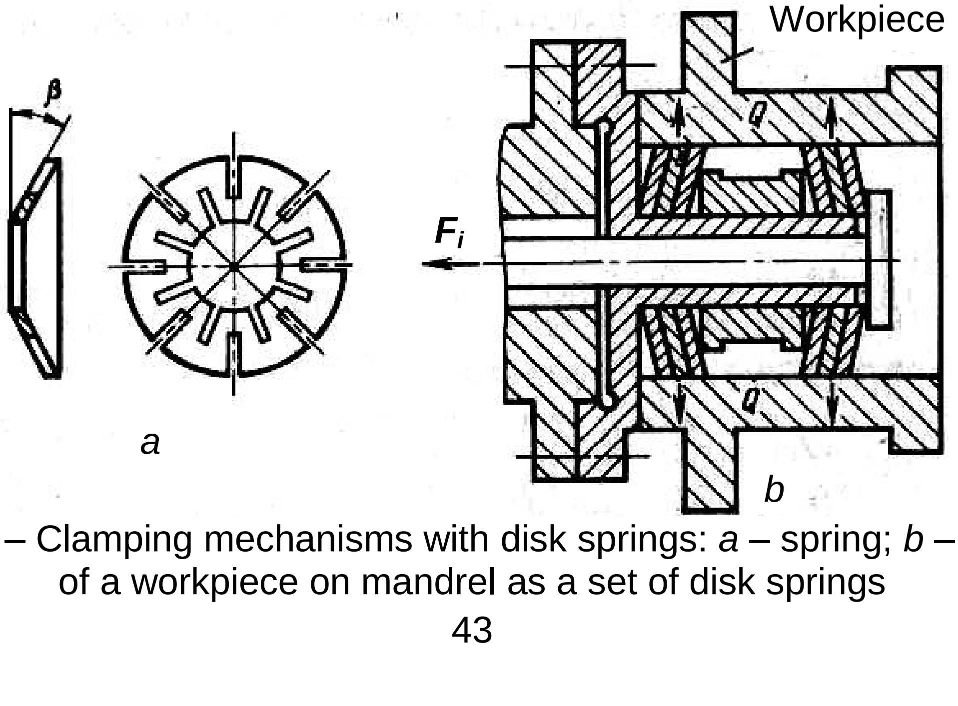


Figure 3.9 – Clamping mechanisms with disk springs: *a* – spring; *b* – mounting of a workpiece on mandrel as a set of disk springs

3.4.4 Mechanisms with hydroplast

In these power mechanisms a working media, through which a hydrostatic pressure is created in a closed volume, is hydroplast. Diagrams of power mechanisms with hydroplast are depicted in Figure 3.10. Thin-walled bushing 2 is pressed onto the body 1. The ring-shaped closed cavity is produced between the body and thin-walled section of bushing. The cavity is filled with hydroplast 3, which consists of polyvinylchloride resin, dibutyl phthalate, vacuum oil, calcium stearate. A pressure is created in hydroplast by means of plunger 4. Thin-walled section of bushing is deformed under the pressure. It centres and clamps a workpiece.

Devices with hydroplast are used for centring and clamping of workpieces both on internal (Figure 3.10,*a*), and on external diameter (Figure 3.10,*b*). Accuracy of datum surfaces should not be lower than the 7…9 accuracy grade. The devices provide high accuracy of centring of 0.03…0.01 mm. Tool carbon Y7A and alloy chromium 30ХГС(30CrMnSi) steels are used for thin-wall bushings. They are heat-treated to obtain hardness HRC 35…40.

The algorithm for calculations of hydroplast clamps is recommended in the book [1]. First the fit of workpiece and bushing is selected. The fit should be with clearance to mount workpiece on bushing easily (see Figure 3.10,*a*). If the hole diameter of workpiece $\boldsymbol{D_W}$ is performed with basic deviation *H* of basic hole, the tolerance band for bushing diameter is selected from *f7*…*g9*.

The length of thin-wall segment of bushing is assigned

$$\boldsymbol{l} = (1.0 \ldots 1.3)\, \boldsymbol{l_W},$$

where $\boldsymbol{l_W}$ – workpiece length.

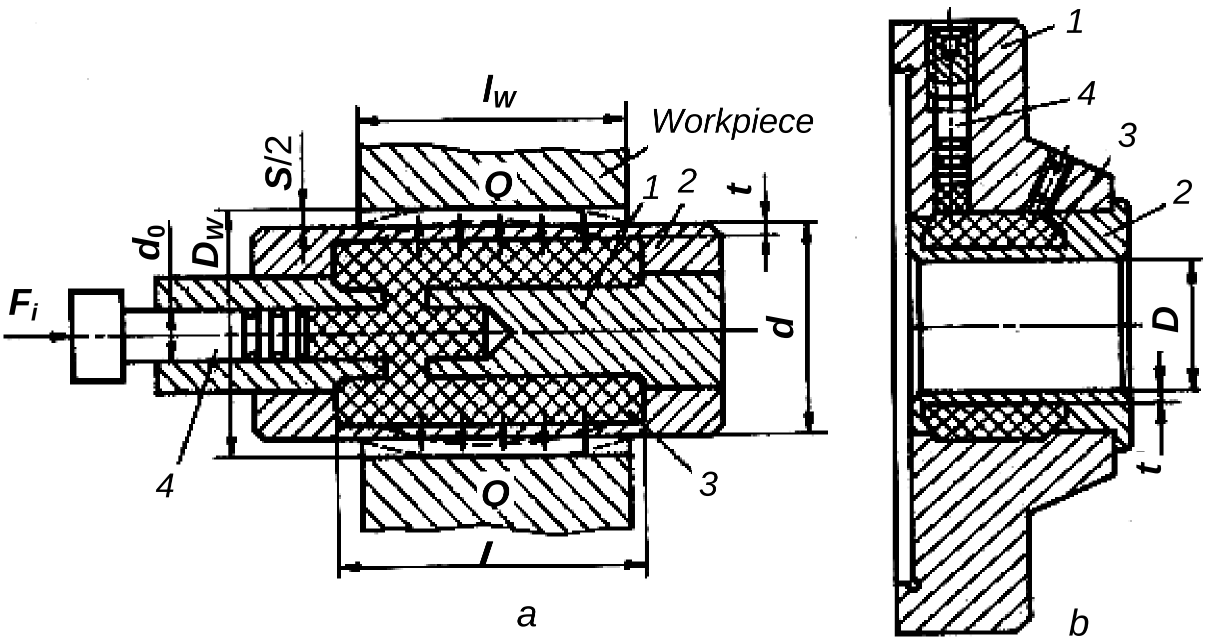


Figure 3.10 – Power mechanisms with hydroplast: *a* – loading diagram for mounting on workpiece hole; *b* – chuck for mounting on external surface of workpiece

The thickness of thin-wall segment of bushing is determined from the following dependencies: t = (0.01d + 0.25) mm at $l \le 0.5d$ and $d \le 50$ mm, $t = 0.002d$ mm at $d > 50$ mm; t = (0.015d + 0.5) mm at $l > 0.5d$ and $d \le 50$ mm, $t = 0.025$ mm at $d > 50$ mm.

Maximum clearance between workpiece and bushing at the unloaded condition

$$S_{max} = D_{Wmax} - d_{min}.$$

Permissible elastic deformation of bushing is determined from the following dependencies: for bushings from chromium steels $\Delta D = 0.003D$ mm; for bushings from structural steels $\Delta D = 0.002D$ mm.

Interference value at clamping equals

$$N = \Delta D - S_{max}.$$

Hydrostatic pressure is calculated from the formulas:

- $p = \dfrac{2\Delta D \cdot E \cdot t}{d^2}$ for bushings with $l > 0.3d$;
- $p = \dfrac{1.25\Delta D \cdot E \cdot t}{d \cdot l}$ for bushings with $l \le 0.3d$,

where p and E are in MPa; ΔD and t are in mm.

Clamping force is calculated from

$$Q = 5 \cdot 10^5 \frac{(2t)^{3/2}}{\sqrt{d}} N,$$

where Q is in N; t, d and N are in mm.

The force that prevents displacement of workpiece in axial direction and rotational sliding

$$F = fQ = 5 \cdot 10^5 \frac{(2t)^{3/2}}{\sqrt{d}} Nf,$$

where f – friction coefficient.

The maximum transmitting moment

$$M_{max} = F\frac{d}{2} = 2.5 \cdot 10^5 \frac{(2t)^{3/2}}{\sqrt{d}} Ndf, \text{ [N·m]}.$$

The calculated M_{max} value is compared with moment of cutting forces M_C. Workpiece will not slide, if the condition is performed

$$M_{max} > K\, M_C.$$

Initial force that is applied to plunger to create clamping force Q

$$F_i = \frac{\pi d_0^2}{4} p,$$

where d_0 – plunger diameter.

3.5 Diagrams of combined clamping devices

Combined clamping devices consist of two or more simple clamping mechanisms. Clamps, including lever in combination with screw, cam (eccentric) or wedge mechanism, are called strap clamps.

Designs of strap clamps are shown in Figure 3.11. Movable screw strap (Figure 3.11,*a*) finds wide application in fixture designs. At the initial position a clamping strap 1 (lever) with screw 2 is in the left-side position, which provide free access for mounting of a workpiece. Spring, through the conical washer, transfers a force to clamping strap and holds it at the upper position. After a workpiece has been mounted on the mounting elements of a fixture, lever with a screw is moved into the right-side extreme position. By rotation of the screw 2 by means of a spanner the clamping of a workpiece is performed by the strap 1. To prevent slipping rotation of the strap during clamping of a workpiece the screw 2 is placed into the slot of support plate 3 fastened to the body.

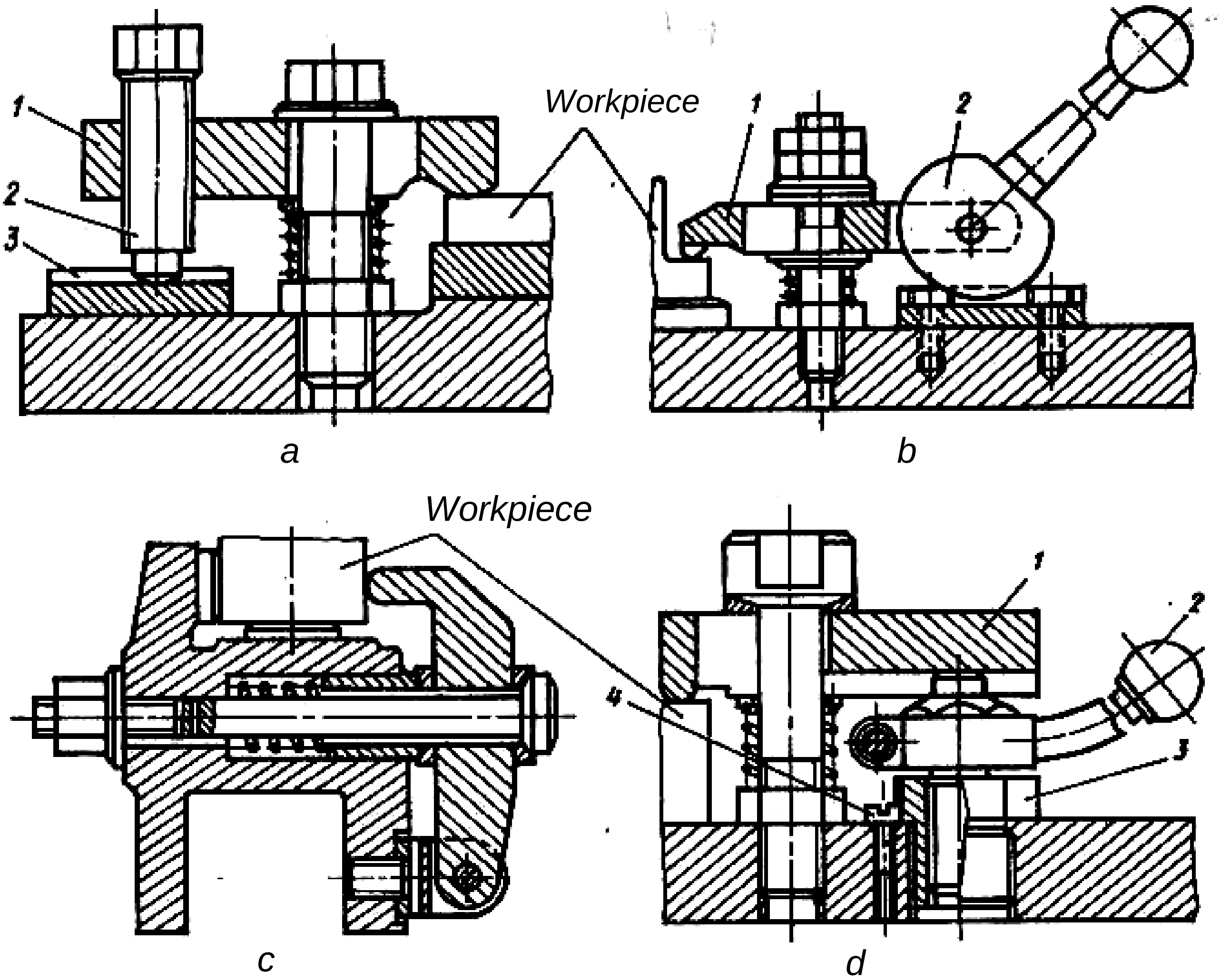


Figure 3.11 – Types of strap clamps: *a* – screw; *b* – cam; c – lateral; *d* – with a screw-jack

One of designs of the cam strap clamps is depicted in Figure 3.11,*b*. In the initial position the clamping strap 1 with cam 2 is located in the right-side extreme position. After a workpiece has been mounted, they are moved to the left-side extreme position. Rotating a cam handle clockwise a workpiece clamping is produced. Application of strap clamps with cam mechanism permits to shorten auxiliary time for workpiece clamping.

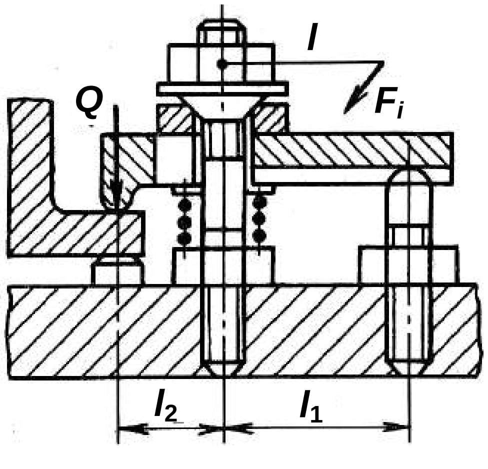
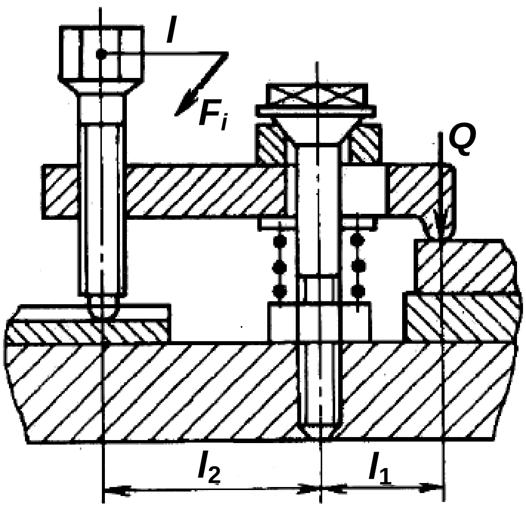
Design of lateral strap clamp is depicted in Figure 3.11,*c*. Clamping is realized in horizontal and vertical directions due to mounting of lever on the axle.

Design of strap clamp with a screw-jack is depicted in Figure 3.11,*d*. Transfer of a force to a workpiece is realized via lever 1 by rotation of handle 2. To prevent wear of fixture body an intermediate thread bushing 3 is installed. It is locked by screw 4.

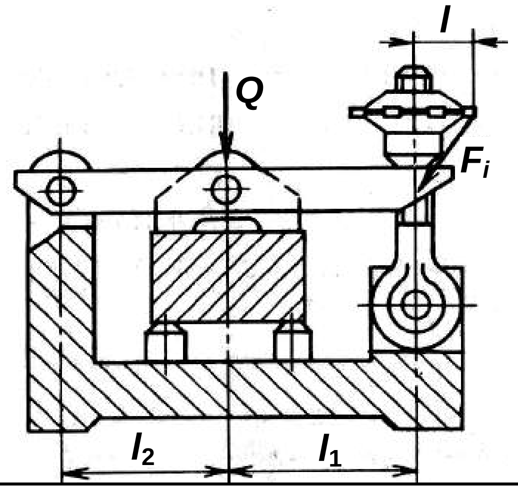
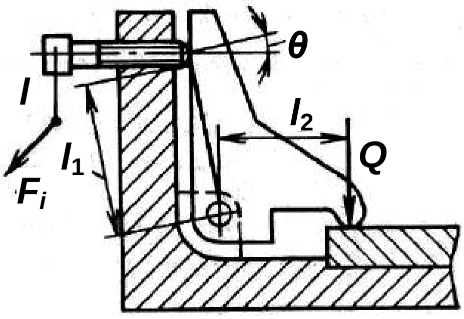
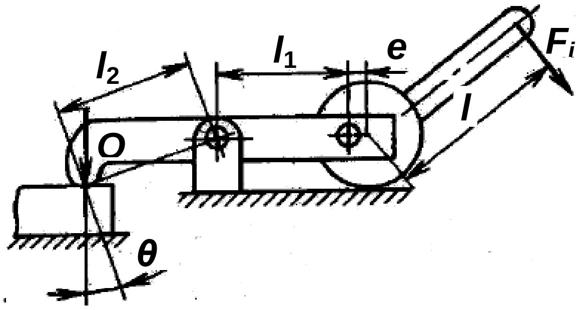
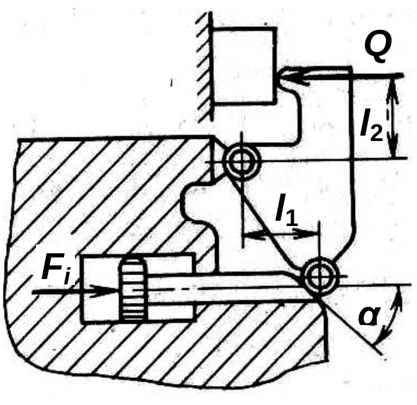
Strap clamps are combined clamping fixtures, which are used for increase of clamping force, change of the travel value of clamping element, change of direction of clamping force, decrease of overall dimensions of clamping fixtures, as well as for convenient control of fixtures.

Design formulas for determination of clamping force of the most widely applied fixtures are given in Table 3.4 from the book [1].

Table 3.4 – Formulas for calculations of initial force

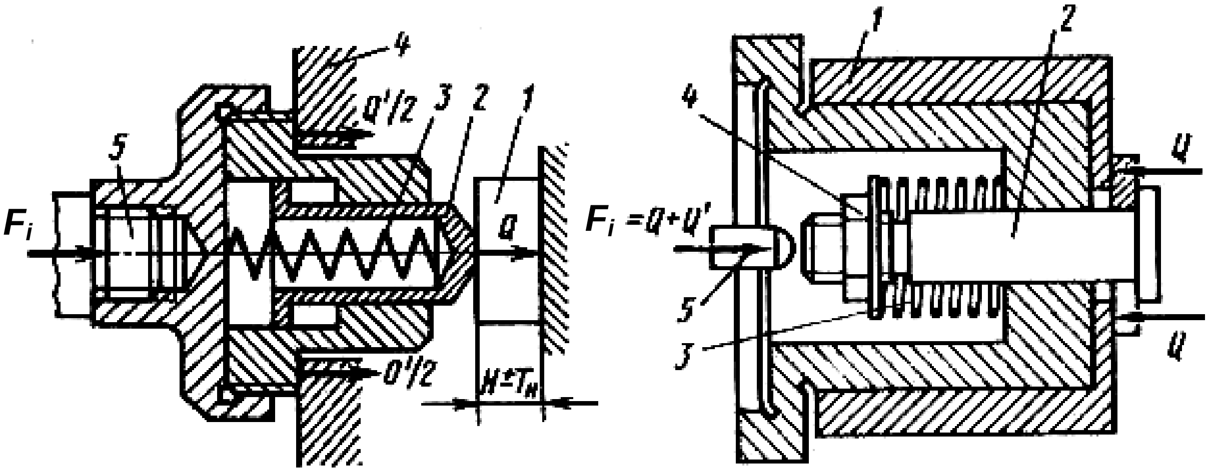
Clamping mechanism	Formulas
	$F_i = \dfrac{r_p \operatorname{tg}(\alpha + \varphi_n) + \dfrac{1}{3} f \dfrac{D_e^3 - d^3}{D_e^2 - d^2}}{l} \dfrac{l_1 + l_2}{l_1 \eta} Q$
	$F_i = \dfrac{r_p \operatorname{tg}(\alpha + \varphi_n)}{l} \dfrac{l_2}{l_1 \eta} Q$

Continuation of Table 3.4

<table>
<tr><th>Clamping mechanism</th><th>Formulas</th></tr>
<tr><td>
</td><td>$$F_i = \frac{r_p \mathrm{tg}(\alpha+\varphi_n) + \frac{1}{3} f \frac{D_e^3 - d^3}{D_e^2 - d^2}}{l} \frac{l_1}{(l_1+l_2)\eta} Q$$</td></tr>
<tr><td>
</td><td>$$F_i = \frac{r_p \mathrm{tg}(\alpha+\varphi_n)}{l}\frac{l_2}{l\cdot\eta\cdot\cos\theta}Q$$</td></tr>
<tr><td>
</td><td>$$F_i = \frac{e\left[1+\sin(\alpha+\varphi)\right]}{l}\frac{l_2\cos\theta}{l_1\eta}Q$$</td></tr>
<tr><td>
</td><td>$$F_i = \frac{\mathrm{tg}(\alpha+\varphi_n)+\mathrm{tg}\varphi_1}{1-\mathrm{tg}(\alpha+\varphi_n)}\frac{l_2}{l_1\eta}Q$$</td></tr>
<tr><td colspan="2">$\boldsymbol{\theta}$ – angle between lever arms and force direction; for other symbols – see Table 3.2</td></tr>
</table>

3.6 Spring and spring-hydraulic clamping devices

In ***spring clamping mechanisms*** a spring is an element that converts initial force F_i of drive into clamping force Q. The Q force in generated by compression of the spring. There are two principal diagrams of spring clamping mechanisms. In the diagram shown in Figure 3.12,*a*, the required compression of spring 3 is performed by motion of drive rod 5. The plunger 2 transmits the force Q to a workpiece 1. The clamping force Q is limited by rest 4 that carries the excessive drive force Q'.



a *b*

Figure 3.12 – Typical designs of spring clamping devices

In the diagram shown in Figure 3.12,*b*, the required compression of spring 3 is regulated by the nut 4 at adjustment of the device. The Q force is transmitted to the workpiece 1 via the rod 2. For unclamping of the workpiece the drive rod 5 moves the rod 2 in right-hand direction that additionally compresses the spring 3.

In ***spring-hydraulic clamping devices*** the clamping is usually performed by disk springs (Bellevibic springs), and hydraulic drive is used only for unclamping the workpiece.

The hydraulic cylinders are divided into pull type and push type depending on the direction of clamping force in mechanism.

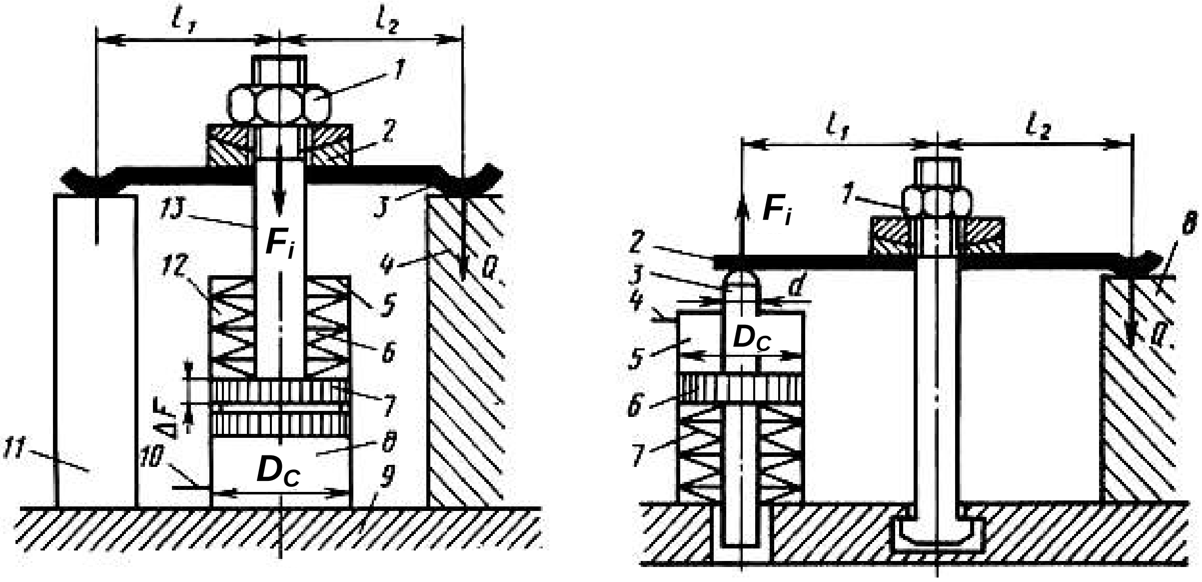
Pull spring-hydraulic cylinder (Figure 3.13,*a*) consists of two main units: spring chamber 12 and hydraulic chamber 8. Spring pack consists of disk springs 6 and other joined parts. Hydraulic chamber 8 receives pressure from external source (pump) through pipeline 10.

Initial force F_i is generated in cylinder 5 by spring pack 6, when pressure is absent in hydraulic chamber 8 between bottom of cylinder 5 and piston 7.

The device generates clamping force

$$Q = P_i \frac{l_1}{l_1 + l_2}.$$

Cylinder 5 is attached to the table of machine-tool. The operation of clamping mechanism occurs in the following manner. In order to unclamp a workpiece 4, liquid is supplied at pressure to hydraulic chamber 8. Under the pressure the piston 7 moves upwards and compresses spring pack 6. The rod 13 with nut 1 also moves upwards and releases clamp 3 pressed to spacer 11 and workpiece 4.



a b

Figure 3.13 – Diagrams of spring-hydraulic clamping devices with pull (*a*) and push (*b*) cylinders

After mounting of the next workpiece, hydraulic chamber 8 is connected with exhaust hydraulic line 10, and pressure decreases in this chamber so piston 7 with rod 13 moves down under the action of disk springs 6. These springs generate initial force $\boldsymbol{F_i}$. It is transmitted to the clamp 3 through the nut 1 and spherical washer 2.

In the push spring-hydraulic cylinder (Figure 3.13,*b*) at supply of liquid through hydraulic line 4 into hydraulic chamber 5 the piston 6 moves down and thus compressing disk springs 7 and releasing a workpiece 8. At connection of hydraulic chamber 5 with exhaust hydraulic line the disk springs 7 move piston 6 with rod 3 upwards. The springs generate initial force $\boldsymbol{F_i}$, which is transmitted to a workpiece 8 through the clamp 2. Clamping force is calculated from the formula

$$\boldsymbol{Q} = \boldsymbol{P_i}\frac{\boldsymbol{l}_1}{\boldsymbol{l}_2}.$$

Pull hydraulic cylinder depicted in Figure 3.14 is produced in two designs. Main performance (Figure 3.14,*a*) is used for clamping of two blanks 14 of small height. In this case the clamp 11 is mounted directly on the cylinder body 1. The piston 3 and rod 12 with pack of disk springs 9 are installed into body 1. The washer 6 serves for compensation of the spring pack 9 changes. The cylinder body 1 is closed by threaded cover 10 on the bottom. The cover is also used for preliminary compression of disk springs. The lower threaded end of rod 12 is screwed into the block nut 13 mounted in the T-slot of the table.

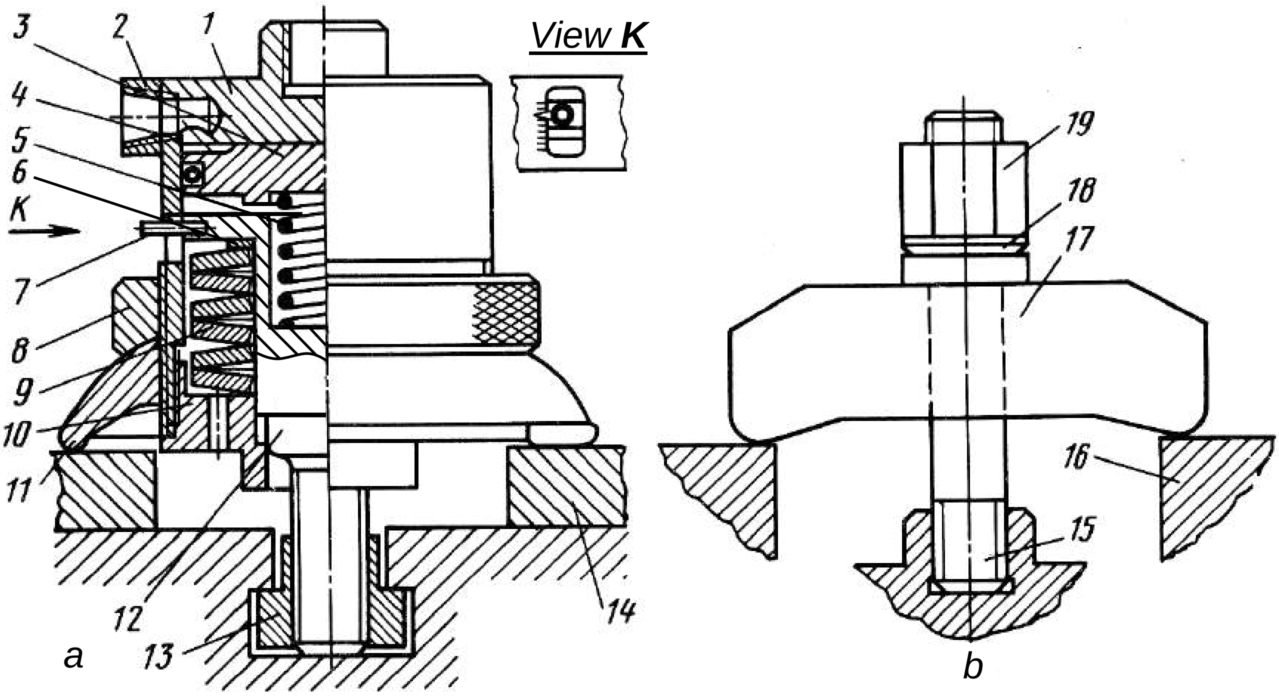


Figure 3.14 – Diagrams of clamping device with pull hydraulic cylinder for small height (*a*) and large height (*b*) workpieces

When work liquid is supplied under pressure through the hole 2 into hydraulic chamber 4 between bottom of body 1 and piston 3, the body 1 moves upward. The force of a pressurised liquid is transmitted from the body 1 through the cover 10 to the spring pack 9 and thus compressing it. Together with body 1 the nut 8 and strap 11 move upward and release workpieces 14.

At mounting of the next workpieces under strap 11 some tuning is performed by nut 8 in order to eliminate gaps in the joints of clamping mechanism. After that the hole 2 is connected to exhaust hydraulic line. Under force of compressed springs 9 the body 1 together with nut 8 moves down. The nut 8 by its spherical surface presses spherical surface of strap 11 and realises clamping of two workpieces 14. Deformation of spring pack is detected by indicator 7.

When applying the cylinder (Figure 3.14,*b*) for clamping of workpieces 16 of large height the nut 8 and strap 11 are removed and stud 15 is screwed into the upper hole of body 1. Clamping is performed by strap 17. Elimination of gaps in joints is realised by nut 19 pressing the spherical washer 18.

3.7 Power drives for clamping mechanisms

Main purpose of a power drive is creation of initial force $\boldsymbol{F_i}$. Various types of drives are used in workholding devices: pneumatic, hydraulic, pneumohydraulic, electric, electromagnetic, magnetic, vacuum, and centrifugal-inertial.

Pneumatic drives have the widest application. Therefore all machining shops of aircraft engine enterprises are equipped with compressed-air pipe lines with the pressure of 0.4…0.6 MPa. Pneumatic drives have high operating speed (response time 0.5…2 s), simple design, convenience in control, reliability and stability in operation. There are also disadvantages: non-uniform motion of rod, large dimensions because of air low pressure and noise from exhaust air.

Pneumatic drives usually include pneumatic motor transforming energy of compressed air into initial force $\boldsymbol{F_i}$ on a rod, pneumoapparatus – control and measuring devices, valves, pipes, etc. As a rule, pneumatic motor is built into design of a workholding device. The rest of pneumatic elements are mounted outside of workholding device.

Pneumatic motors and devices are standardised and normalised and so pneumatic drive is usually composed of standardised components.

Pneumatic motors are divided into piston and chamber types. Piston motors are usually applied in workholding devices for turning machines, the chamber ones – for milling and drilling devices. Main components of piston motors are cylinder and piston (Figure 3.15,*a*). Pneumatic chambers (Figure 3.15,*b*) consist of two cast or stamped cups and flexible diaphragm from special rubber or rubber cloth. Stroke of chamber rod d is limited by possible diaphragm deformation. Piston motors have no such limitations, and so they are used for large strokes.

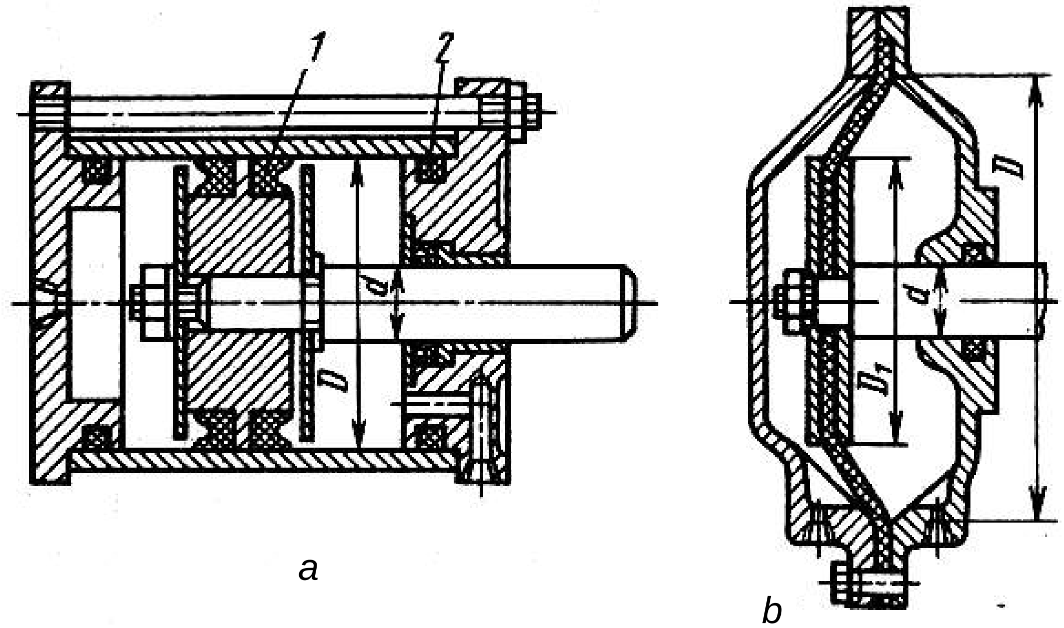


Figure 3.15 – Types of pneumatic motors of double action: *a* – piston; *b* – chamber; 1 – lip-type seal; 2 – O-ring

Pneumatic motors can be of single and double action. In single-action motors work stroke is performed by compressed air, and reversed (opposite) stroke – by spring force.

Figure 3.16 depicts the design of three-jaw lever versatile chuck with pneumatic drive. Pneumatic cylinder 10 of double action is mounted on the back end of spindle 8 of turning machine. Chuck body 5 is attached to the conical surface of spindle 8 via adaptor 6. Such joint provides higher accuracy of chuck alignment. Jaws 3 with lips 1 and fixing elements 2 are moved by levers 4 from sliding sleeve 7.

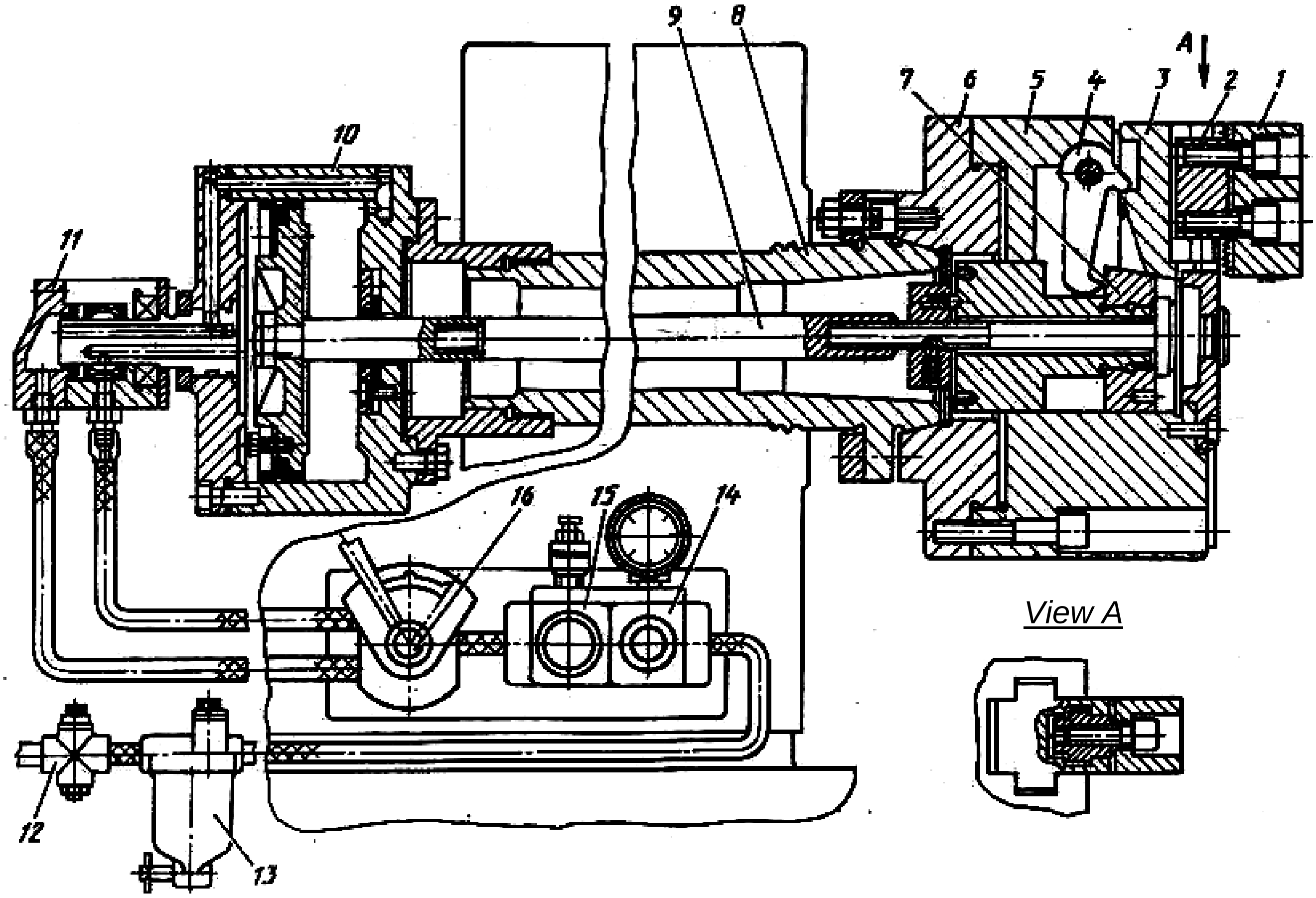


Figure 3.16 – Three-jaw chuck with pneumatic drive

The sleeve is joined by screw with rod 9 of pneumatic cylinder 10. Compressed air from pipeline is supplied to air coupling 11 of pneumatic cylinder through intake valve 12, water trap with filter 13, return valve 14, pressure regulator 15 and distributing valve 16. Under the pressure piston of pneumatic motor moves to the left, and, hence, jaws – to the centre of chuck, thus clamping a workpiece. When feeding the compressed air to the left cavity of cylinder, the piston moves to the right and jaws move outside sliding along inclined flats of sleeve 7, thus, unclamping a workpiece.

In ***hydraulic drives*** the initial energy is energy of compressed work liquids (usually oil). Figure 3.17 shows principal diagram of workholding device for clamping of workpiece 6 by lever 5. Hydraulic drive consists of oil tank 1, hydraulic pump 2, control valves 3 (hydrodistributor), hydraulic motor of piston type 4 (hydrocylinder), check and regulation equipment 7 (safety valve, return valve, hydraulic accumulator, reducing valve, throttle, manometer) and pipes 8.

Designs of hydraulic cylinders and their combinations with workholding devices are the same like in pneumatic drives.

In comparison with pneumatic drives hydraulic drives have the following advantages:

- significant reduction of dimensions of hydraulic motors and, hence, a workholding device in the whole due 10…30 times oil pressure higher than

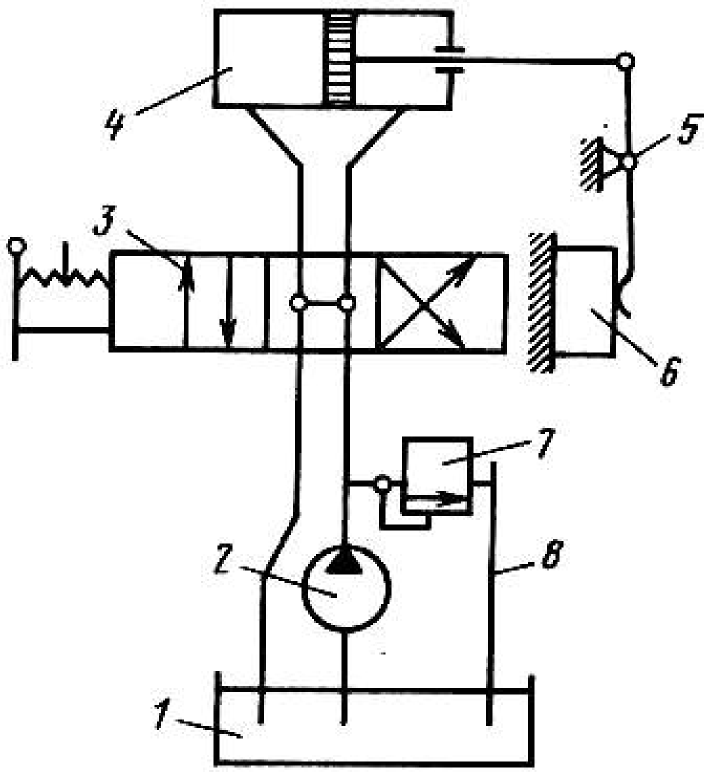


Figure 3.17 – Principal diagram of hydraulic drive

pressure of compressed air;

- large forces from rods of hydrocylinders can be delivered directly to a workpiece without power mechanisms – boosters;
- multi-position clamping without boosters by many hydrocylinders controlled by one control valve;
- hydrocylinders operate smoothly and noiselessly;
- work liquid (oil) performs also the function of lubricant as well.

At the same time the main disadvantages of hydraulic drives are their high initial cost as well as increasing requirements for service to avoid oil leakages.

In ***pneumohydraulic drives*** the initial energy is energy of compressed air that is first transformed into energy of compressed liquid, and then into force on the piston rod. Creation of pneumohydraulic drive is an attempt to combine advantages of pneumatic and hydraulic drives.

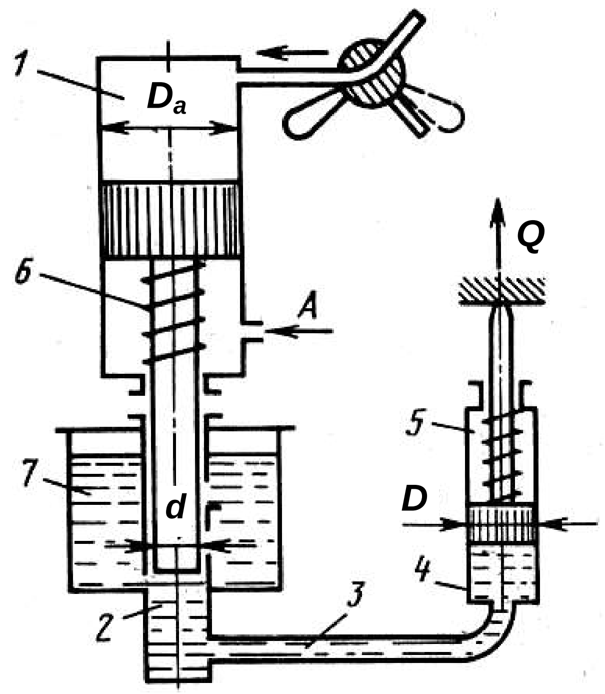


Figure 3.18 – Principal diagram of pneumohydraulic drive

Principal diagram of pneumohydraulic drive is depicted in Figure 3.18. Compressed air is supplied into cylinder 1 of diameter D_a, rod of which has diameter d_h and which is a piston of hydrocylinder 2. Oil from cylinder 2 goes through pipe 3 into work cylinder 4 of diameter D, rod of which generates clamping force Q. Reverse stroke of cylinders 1 and 4 are provided by springs 6 and 5. Reservoir 7 serves for feeding the hydraulic segment of system.

Pneumohydraulic drive multiplies initial force by coefficient $K = (D_a / d_h)^2$, so the force Q increases several tens times in comparison with initial force F_i generated by pneumatic cylinder 1, so as $D_a >> d_h$.

Design of pneumohydraulic drive depicted in Figure 3.19 provides fast motion of rod to a workpiece and generation of large force ***Q*** at the end of work stroke. Piston 3 in the cylinder 2 moves to the right under the pressure of compressed air delivered through nipple 1. The piston motion creates increased pressure in the cavity 16 of cylinder 2 filled with oil. This pressure is kept by compression of spring 7 by movable washer 6. Oil going through the window 15 and passage 14 in the rod 4 is pressed into cavity 13 of hydraulic cylinder 9. At that the piston 8 moves fast to the right till the moment of contact of rod 11 and workpiece 12. Significant increase of oil pressure occurs at the end of piston 3 stroke, when window 15 will sink entirely into bushing 5, thus closing cavity 13. Reverse stroke of drive is realised by compressed air supply into cylinder 9 via nipple 10.

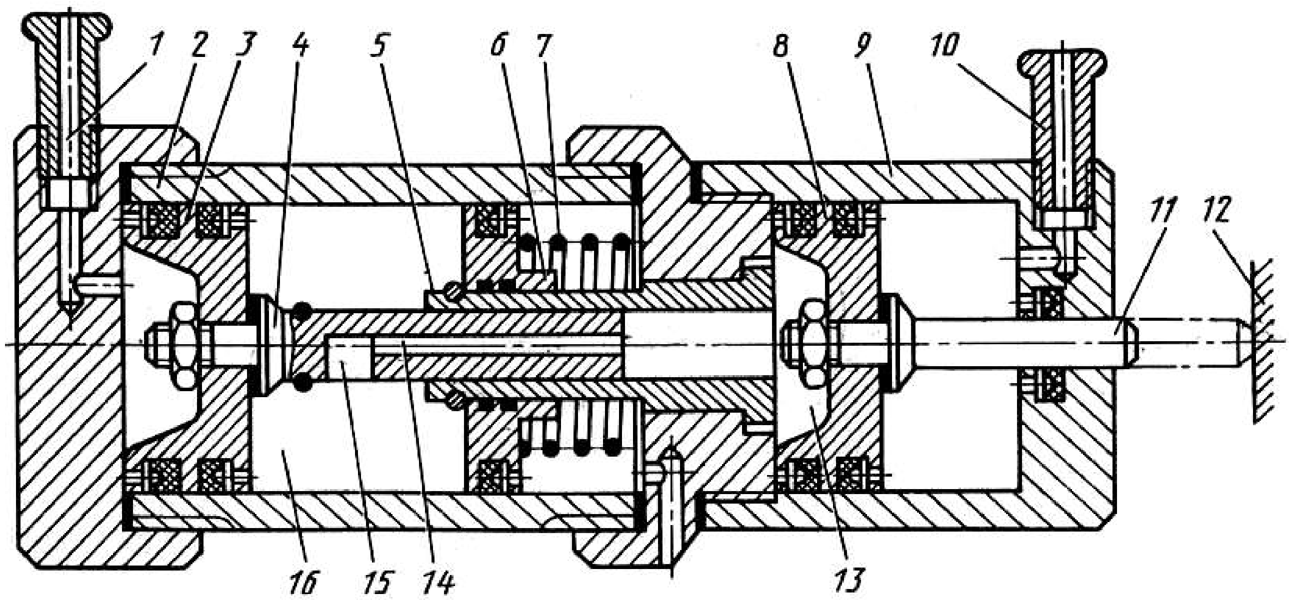


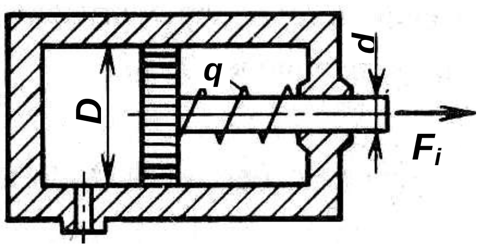
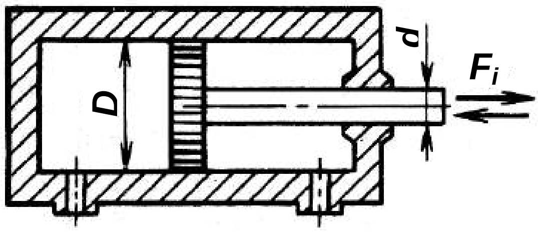
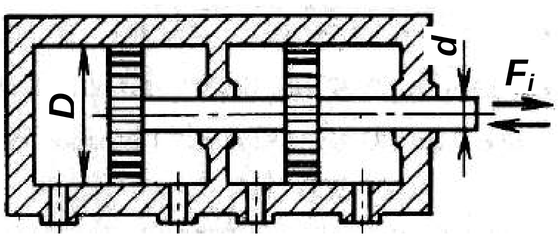
Figure 3.19 – Pneumohydraulic drive of improved design

Calculation formulas for initial force $\boldsymbol{F_i}$ of pneumatic and hydraulic motors are submitted in Table 3.5 from the book [1].

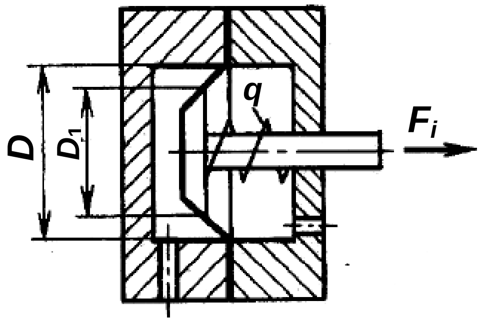
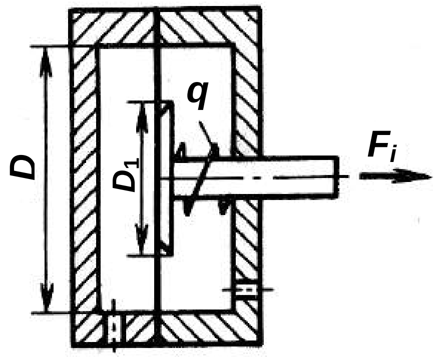
Vacuum drive is based on direct action of atmospheric pressure on a clamped workpiece. In order to create excessive atmospheric pressure between the rest surfaces of workpiece and workholding device the internal vacuumized cavity is arranged (Figure 3.20). For better pressure tightness usually various gaskets are applied: rubber O-rings (Figure 3.20,*a*), rubber strips (Figure 3.20,*b*), etc. These seals allow creating vacuum in internal cavity 0.015…0.030 MPa. Vacuum pumps are applied for creation of vacuum.

When mounting a thin-wall workpiece with datum surface machined by grinding, the device without seal can be applied (Figure 3.20,*c*). In this case many holes of small diameter are drilled for vacuuming, air is sucked through them and multi-point clamping occurs.

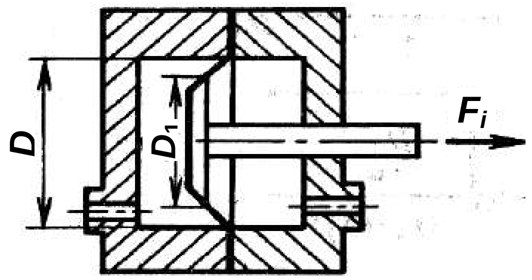
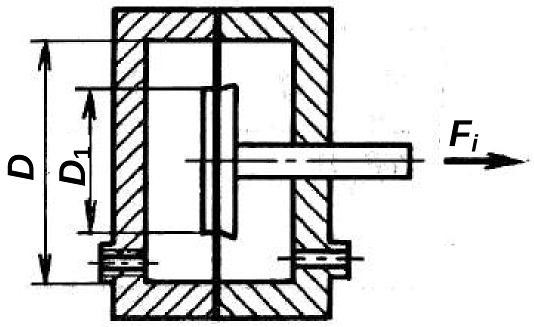
Table 3.5 – Formulas for calculations of initial force generated by power drives

Clamping mechanism	Formulas
Single-acting pneumatic cylinders	
Single-piston 	$F_i = \frac{\pi}{4} D^2 p\eta - q$ $D = 2 \cdot \sqrt{\frac{P_i - q}{\pi p\eta}}$
Double-acting pneumatic cylinders	
Single-piston 	Push force $F_i = \frac{\pi}{4} D^2 p\eta$ Pull force $F_i = \frac{\pi}{4}\left(D^2 - d^2\right) p\eta$ $D = \sqrt{\frac{4P_i}{\pi p \eta} + d^2}$
Double-piston 	Push force $F_i = \frac{\pi}{4}\left(2D^2 - d^2\right) p\eta$ Pull force $F_i = \frac{\pi}{2}\left(D^2 - d^2\right) p\eta$ $D = \sqrt{\frac{2P_i}{\pi p\eta} + d^2}$
$\boldsymbol{F_i}$ – initial force; ***D*** – piston diameter; ***d*** – rod diameter; ***p*** – compressed air pressure (***p*** = 0.40…0.63 MPa); ***η*** – efficiency factor (***η*** = 0.85); ***q*** – resistance force of spring in the extreme work position of piston	

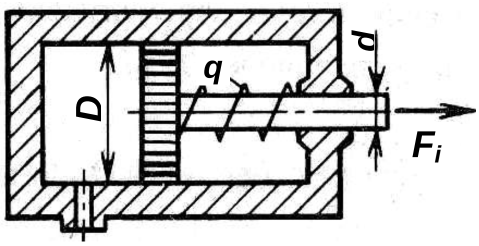
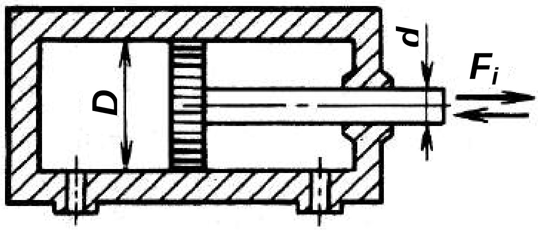
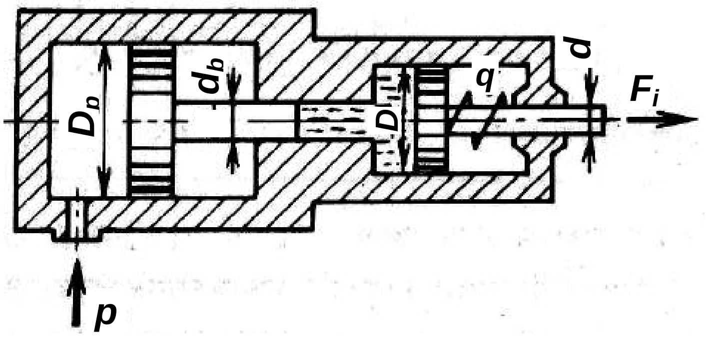
Continuation of Table 3.5

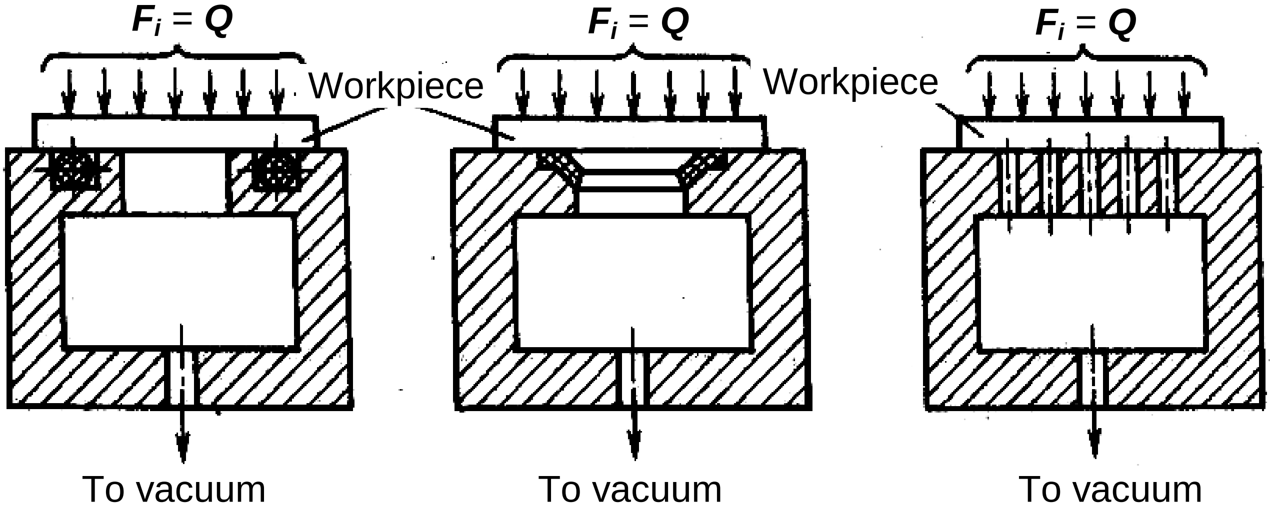
Clamping mechanism	Formulas
Single-acting diaphragm actuators	
Plate diaphragm  	For plate rubber-fabric diaphragms at initial position of rod $F_i = \frac{\pi}{16}(D - D_1)^2 p - q$, at position of rod at motion 0.3*D* $F_i = \frac{0.75\pi}{16}(D - D_1)^2 p - q$, $D = 4 \cdot \sqrt{\frac{P_i + q}{0.75\pi p}} - D_1$
Flat diaphragm  	For flat rubber-fabric diaphragms at initial position of rod $F_i = \frac{\pi}{16}(D - D_1)^2 p - q$, at position of rod at motion 0.07*D* $F_i = \frac{0.75\pi}{16}(D - D_1)^2 p - q$, $D = 4 \cdot \sqrt{\frac{P_i + q}{0.75\pi p}} - D_1$. For flat rubber diaphragms at initial position of rod $F_i = \frac{\pi}{4} D_1^2 p - q$, at position of rod at motion 0.22*D* $F_i = \frac{0.9\pi}{4} D_1^2 p - q$, $D_1 = 2 \cdot \sqrt{\frac{P_i + q}{0.9\pi p}}$

Continuation of Table 3.5

Clamping mechanism	Formulas
Double-acting diaphragm actuators	
Plate diaphragm 	For plate rubber-fabric diaphragms at initial position of rod $F_i = \frac{\pi}{16}(D - D_1)^2 p$, at position of rod at motion 0.3***D*** $F_i = \frac{0.75\pi}{16}(D - D_1)^2 p$, $D = 4 \cdot \sqrt{\frac{P_i}{0.75\pi p}} - D_1$
Flat diaphragm 	For flat rubber-fabric diaphragms at initial position of rod $F_i = \frac{\pi}{16}(D - D_1)^2 p$, at position of rod at motion 0.07***D*** $F_i = \frac{0.75\pi}{16}(D - D_1)^2 p$, $D = 4 \cdot \sqrt{\frac{P_i}{0.75\pi p}} - D_1$. For flat rubber diaphragms at initial position of rod $F_i = \frac{\pi}{4} D_1^2 p$, at position of rod at motion 0.22***D*** $F_i = \frac{0.9\pi}{4} D_1^2 p$, $D_1 = 2 \cdot \sqrt{\frac{P_i}{0.9\pi p}}$
F_i – initial force generated by actuator; ***D*** – actuator chamber diameter; D_1 – plate diameter; ***p*** – compressed air pressure (***p*** = 0.40…0.063 MPa); ***q*** – resistance force of spring in the extreme work position of piston	

Continuation of Table 3.5

Single-acting hydraulic cylinders	
Single-piston 	$F_i = \frac{\pi}{4} D^2 p_h \eta - q$ $D = 2 \cdot \sqrt{\frac{P_i - q}{\pi p_h \eta}}$
Double-acting hydraulic cylinders	
Single-piston 	Push force $F_i = \frac{\pi}{4} D^2 p_h \eta$ Pull force $F_i = \frac{\pi}{4}\left(D^2 - d^2\right) p_h \eta$ $D = \sqrt{\frac{4P_i}{\pi p_h \eta} + d^2}$
F_i – initial force; D – piston diameter; d – rod diameter; p_h – oil pressure in cylinder; η – efficiency factor (η = 0.9 at use of lip-type seals, η = 0.97 at use of O-rings); q – resistance force of spring in the extreme work position of piston	
Pneumohydrodrive	
	$F_i = \frac{\pi D^2}{4} p \left(\frac{D_p}{d_b}\right)^2 \eta_V \eta_M \eta'_M - q$
F_i – initial force generated by hydraulic cylinder rod; D – hydraulic cylinder piston diameter; d – hydraulic cylinder rod diameter; D_p – pneumatic cylinder piston diameter; d_b – booster rod diameter; p – compressed air pressure (p = 0.40…0.63 MPa); η_V – volumetric efficiency factor of drive (η = 0.95); η_M – mechanical efficiency factor of booster (η_M = 0.95); η'_M – mechanical efficiency factor of hydraulic cylinder (η'_M = 0.95); q – resistance force of spring in the extreme work position of piston	



a *b* *c*

Figure 3.20 – Schematic diagrams of vacuum drive: *a* – with rubber ring; *b* – with rubber strip; *c* – without seal

Value of initial force $\boldsymbol{F_i}$ (clamping force $\boldsymbol{Q}$) is calculated from the formula

$$F_i = Q = A_u p_e Q, \text{ [N]},$$

where $\boldsymbol{A_u}$ – area of workpiece used and limited by seal, m^2; $\boldsymbol{p_e}$ – excessive pressure that equals difference between atmospheric pressure and vacuum in internal cavity of device, MPa; $\boldsymbol{\lambda}$ – coefficient of pressure tightness of vacuum system ($\boldsymbol{\lambda}$ = 0.80…0.85).

Vacuum drives are very effective for clamping of workpieces with flat datum surfaces at fine-finish operations.

Electromagnetic and magnetic drives are based on creation of clamping force by magnetic flux going through a workpiece. The clamping force is created by electromagnets in electromagnetic devices and by permanent magnets – in magnetic devices.

Magnetic devices have more advantages in comparison with electromagnetic devices as electric current is not used, and so the magnetic devices are safe in operation. Magnetic and electromagnetic devices are produced in the form of rectangular plates and round faceplates.

Figure 3.21 depicts the magnetic V-block for clamping of cylindrical workpieces is depicted. At horizontal position of magnet 1 magnetic flux goes through both side elements 2 and 3 of the prism and presses workpiece 5 to prism. Side elements are divided by non-magnetic plate 4. At vertical position of magnet the magnetic flux closes the loop in a body and workpiece is released.

Value of initial force $\boldsymbol{F_i}$ (clamping force $\boldsymbol{Q}$) is calculated from the formula

$$F_i = Q = A_u p_e Q, \text{ [N]},$$

where $\boldsymbol{A_u}$ – area of workpiece used in contact with device surface, mm^2; $\boldsymbol{p_S}$ – specific force generated by electromagnetic or vacuum magnetic device, MPa (**p_S** = 0.35 MPa); **λ** – coefficient that takes into account losses because of imperfectness of contact surfaces of the workpiece and the device (**λ** = 0.9).

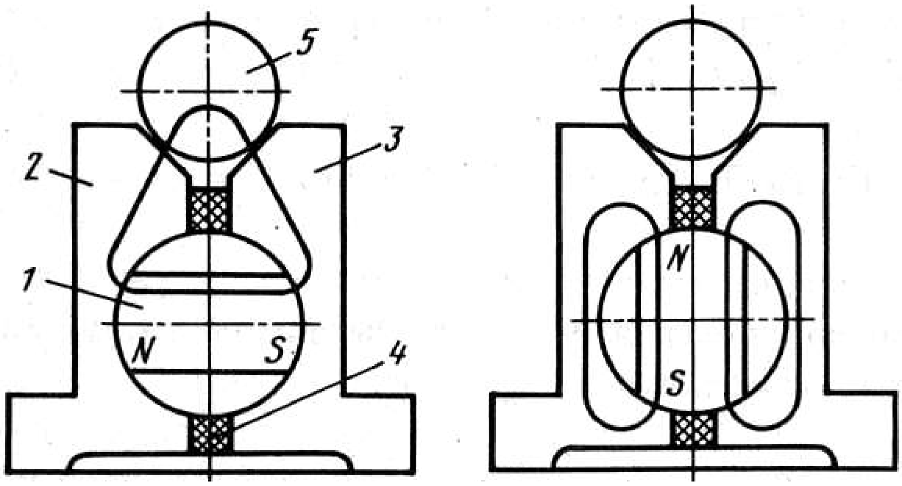


Figure 3.21 – Diagram of magnetic drive

QUESTIONS

1. What are the purpose, classification and requirements for clamping mechanisms?
2. What are the general principles for calculations of clamping forces for different schemes of workpiece mounting?
3. Describe designs and operation principle of screw clamping mechanism.
4. Describe designs and operation of wedge clamping mechanism.
5. Describe designs and operation principle of cam (eccentric) clamping mechanism.
6. Describe designs and operation principle of lever clamping mechanism.
7. Describe designs and operation principle of collet mechanisms.
8. Describe designs and operation principle of clamping mechanisms with diaphragms.
9. Describe designs and operation principle of clamping mechanisms with disk springs.
10. Describe designs and operation principle of clamping mechanisms with hydroplast.
11. Describe designs and operation principles of combined clamping devices.
12. Describe designs and operation principle of spring and spring-hydraulic clamping devices.
13. Describe designs and operation principle of pneumatic drives.
14. Describe designs and operation principle of hydraulic drives.
15. Describe designs and operation principle of pneumohydraulic drives.
16. Describe designs and operation principle of electromagnetic and magnetic drives.
17. Describe designs and operation principle of vacuum drives.

4. GUIDE ELEMENTS AND INDEXING DEVICES

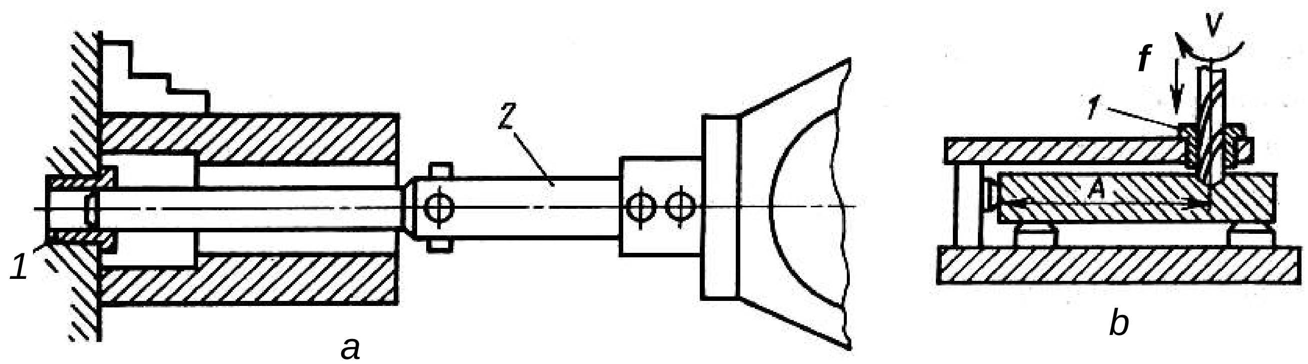
4.1. Purpose of guide elements

Guide elements of fixtures serve for directing and coordinating of a cutting tool and perform various functions.

The ***first group*** of elements allows preventing the run-off (push-off) of a cutting tool during machining. For this purpose the guide bushings are used when boring deep holes with a long holder. Guide bushing 1 (Figure 4.1,*a*) is installed into workholding device for guiding the front end of cantilever holder 2 when machining in a turret-lathe.

The ***second group*** of elements performs two functions simultaneously: guides a tool along the specified path (that is, prevents run-off of a tool) and provides to him the required position relative to the device. This group includes drill (jig) bushings, which are used in drilling and boring devices. For example, drill bushing 1 (Figure 4.1,*b*) provides fulfilment of the ***A*** dimension.

The ***third group*** of guide elements serves for providing accurate position of tool relative to the device. For instance, setting element 2 (Figure 4.1,*c*) is carefully installed in the device. When adjusting, the setting element is moved to a milling cutter and with aid of feeler gauge the mill position is determined. Due to this procedure the position of mill relative to the setting element and the rest elements 3 is provided and adjusting of machine-tool for the specified ***A*** dimension is obtained. Adjusting of machines with application of setting elements takes less time than method of trial cuts, and thus increases accuracy. Therefore, it is widely used in aircraft propulsion engineering.



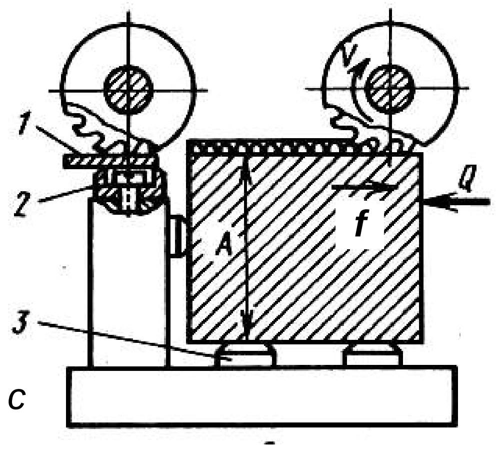


Figure 4.1 – Devices with elements for guiding the cutting tools: *a* – with guide bushing; *b* – with drill bushing; *c* – with setting element for milling cutter

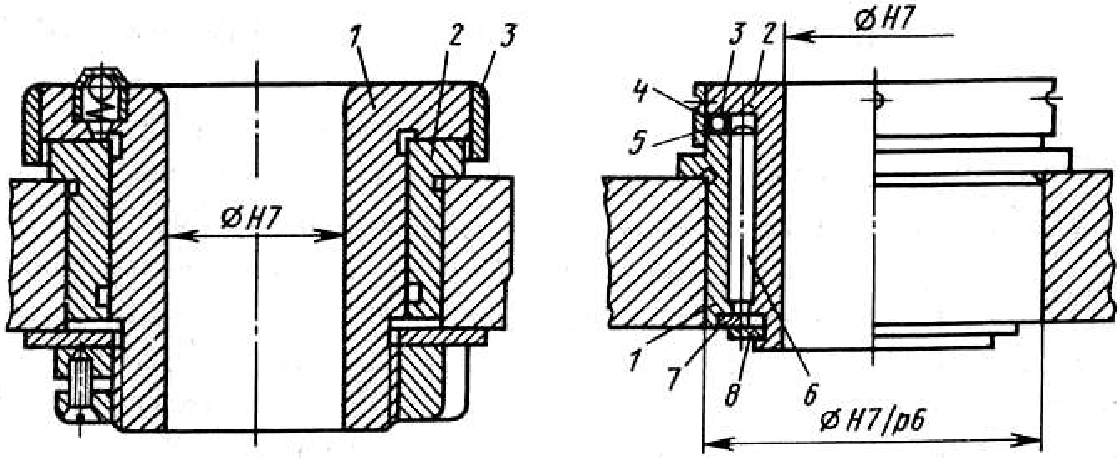
4.2 Designs of guide bushings

Stationary bushings are simpler by design, but they are heated to impermissible high temperatures when rotate. Therefore, the rotating bushings are always applied at high rotational speeds.

In Figure 4.2,*a* the rotating bushing is depicted. It is installed in a slide bearing. In this case intermediate bushing 2 is pressed into the body of the device. The rotating bushing 1 is installed by slide fit. It is held from axial displacement by shoulder from one end, and by nut and washer – from another end. Tool is inserted into the hole of bushing. The bushing 1 rotates together with a tool. Attrition surfaces are protected from chip by shield 3. The bushing hole diameter is machined to the *H7* accuracy grade, and tool diameter – by the *g6*.

The rotating bushing of normalized design is shown in Figure 4.2,*b*. It is installed in a needle bearing. The bushing 1 is pressed into the device body by the *H7*/*p6* fit. The rotating bushing 2 is installed in the bushing 1 on roll-needles 6, and from the face side – on the balls 4, placed into bearing cage 3. Washer 7 and locking ring 8 hold the rotating bushing from axial displacement. Ring 5 protects bearings from chip.

Designs of bushings applied in the boring devices are shown in the book [1]. They are mounted on a slide and roll bearings. Key slot is performed on the surface of bushing hole to provide its constrained rotation.



a *b*

Figure 4.2 – Guide rotating bushings mounted on a slide bearing (*a*) and frictionless bearing (*b*)

4.3 Designs of drill bushings

Drill bushings are applied for determination of position and guiding of various tools for holemaking operations: drills, core drills, reamers, etc. They determine the position of a tool axis relative to mounting elements of device and increase its radial stiffness. They provide magnifying of positioning accuracy of holes and labour productivity, and thus it is unnecessary to mark a workpiece with scratches. Increase of tool stiffness improves accuracy of a hole diameter, decreases its deflection, allows machining at higher cutting speeds. In average the hole accuracy is increased by 50 % as compared with hole accuracy made without drill bushing.

Devices equipped with drill bushings for machining of holes in drilling machines are called drill jigs.

The most of applied designs of bushings are standardised. There are three ***standard bushing designs***: permanent, changeable and quick-change.

Permanent bushings are made without shoulder according to the GOST 18429-73 (Figure 4.3,*a*) and with shoulder according to the GOST 18430-73 (Figure 4.3,*b*). They are used if a hole is machined only by one tool (drill or core drill). Permanent bushings are pressed into jig plate by the *H7/n6* fit.

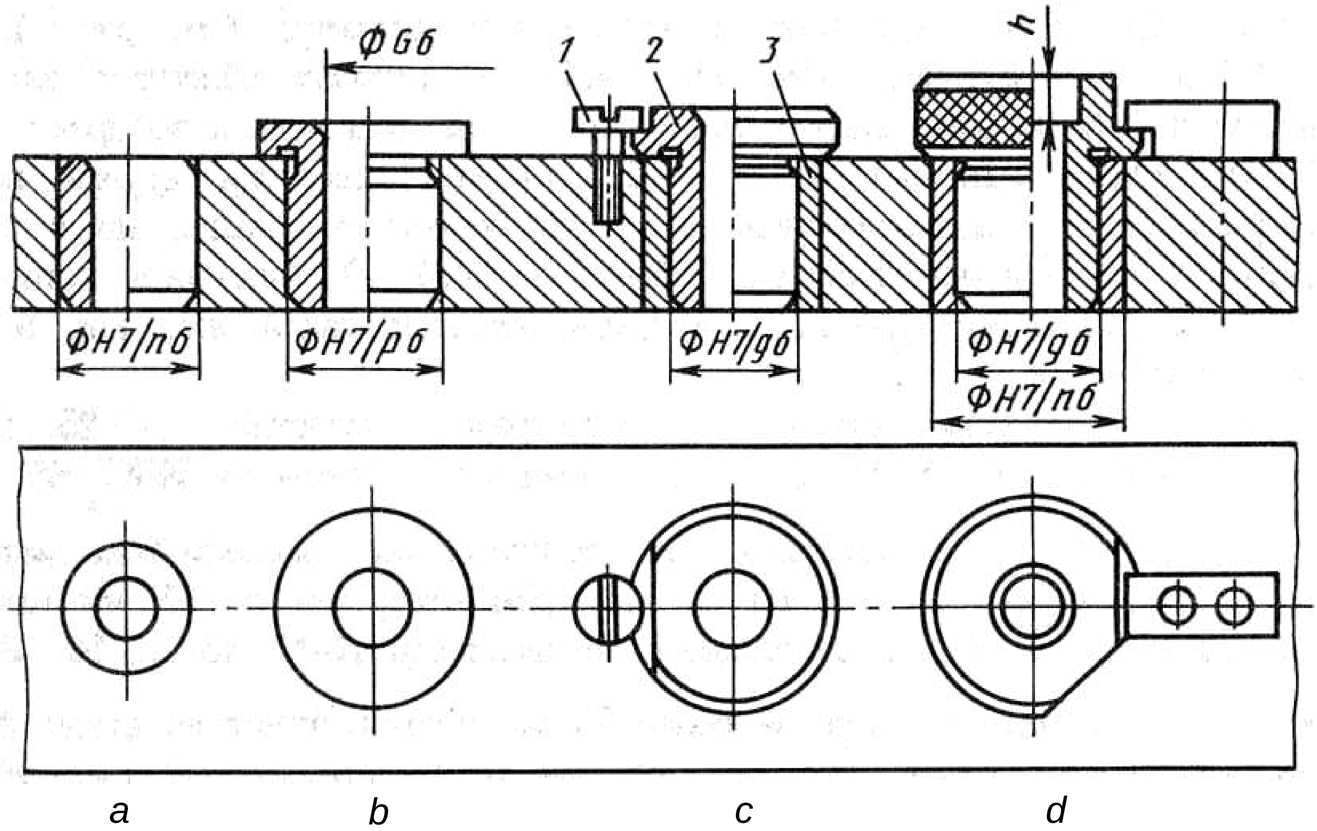


Figure 4.3 – Standardised drill bushings: *a* – permanent without shoulder; *b* – permanent with shoulder; *c* – changeable; *d* – quick-change

Changeable bushings are made according to the GOST 18431-73 (Figure 4.3,*c*). Like permanent bushing they are used for machining of holes with one tool, but they require relatively frequent change due to their wear. Under the normal machining conditions, the bushings withstand approximately 10,000…15,000 drillings, but for increased accuracy of holes machined in high-strength materials tool life shortens abruptly. Changeable bushings 2 are installed into intermediate bushings 3 by the *H6/g5* or *H7/g6* fit. To avoid their slide turning and lifting during machining they are fixed by screws 1. The intermediate bushings 3 are pressed into jig plate by the *H7/n6* fit.

Quick-change bushings are made according to the GOST 18432-73 (Figure 4.3,*d*). Like changeable bushing they are installed into intermediate bushings by the *H6*/*g5* or *H7*/*g6* fit. They are applied when a hole is machined by several tools: drill, core drill, reamer, etc. For guiding of each tool, its quick-change bushing is provided. All bushings have the same outside diameter, and inside diameter are equal to the diameter of a corresponding tool. Shoulder is performed high and with a knurled surface to make the bushing removal and installation more convenient. Bushing has through flat spot, which make it easier to change the bushing, and side step, which is used for clamping it with a strap to prevent pushing-out of bushing by a chip.

Cutting tool is inserted into holes of drill bushings by slide fit with guaranteed clearance. Diameter of tool is considered as a basic shaft, bushing hole is produced in the system of shaft, and bushing hole diameter provides necessary fit. The fits *G7* or *F8* are used for guiding the drills and core drills, and *G7* – for the reamers.

Permanent, changeable and quick-change bushings are produced in two modifications: without recess on internal diameter (see Figure 4.3,*a*, *b*, *c*) and with recess (see Figure 4.3,*d*), which facilitates entering a tool into a bushing. Height of permanent and changeable bushings is selected according to the GOST. It equals to 1.5…2 diameters of bushing hole for tool. The height of quick-change bushings is a little bigger, but recess of the *h* height is provided (see Figure 4.3,*d*). Due to this recess length of contact of a tool with bushing is the same as in permanent bushings.

All drill bushings with hole diameters of up to 25 mm are made of steels У10А (U10A), У10А (U12A) and heat-treated to the hardness number HRC 62…65. Frequently bushings are made of wear-resistant alloy steels. Intermediate bushings with hole diameters of up to 25 mm are made of steel У7А (U7A) and hardened to the hardness number HRC 45…50. All bushings with hole diameters of more than 25 mm are made of steel 20, carbonized to depth of 0.8…1.2 mm and heat-treated to the hardness number HRC 62…65.

Distance between the lower end of bushing and workpiece surface is selected equal to 0.3…1.0 hole diameter.

Special bushings have the design, which corresponds to the peculiarities of a workpiece and operation. But general considerations of selection of fit “tool-bushing”, its height, distance between bushing and workpiece are the same as for standard bushings.

Special bushing of elongated shape (Figure 4.4,*a*) serves for making it nearer to a workpiece having a step. Special bushing for drilling hole on a curved surface of workpiece is shown in Figure 4.4,*b*. If holes to be machined are located at very short distance, it is impossible to mount two bushings near each other. In these cases single special bushing 1 is used. It has two guide holes and its position is fixed by pin 2 (Figure 4.4,*c*).

Rotating jig bushings are used for guiding the reamers (Figure 4.5,*a*) and limitation of axial movement of tool (Figure 4.5,*b*). In this case jig bushing is called stop bushing, and axial bearing is installed into the jig body.

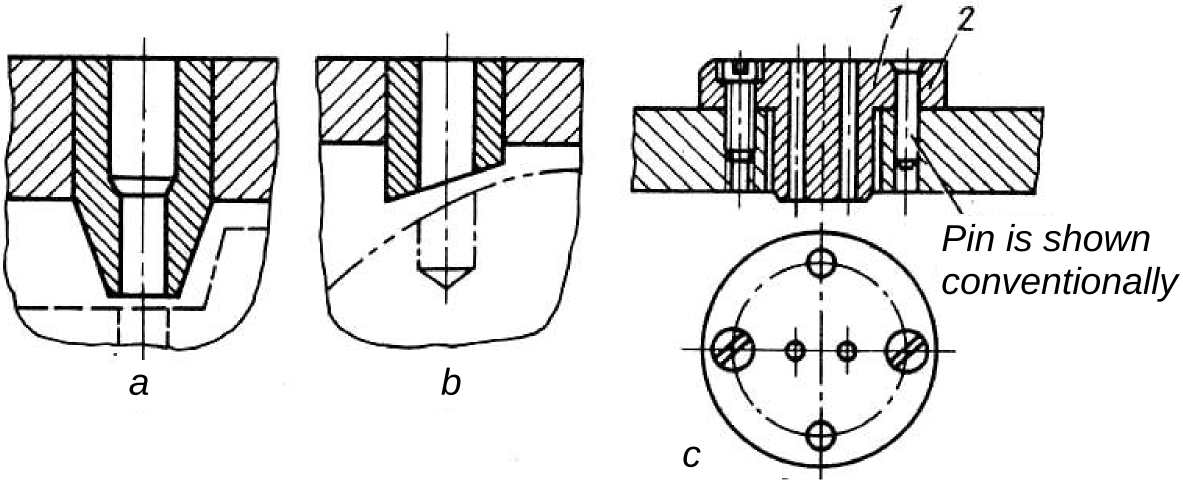


Figure 4.4 – Special jig bushings for drilling: *a* – on a step; *b* – on a curved surface; *c* – of two holes located at small distance

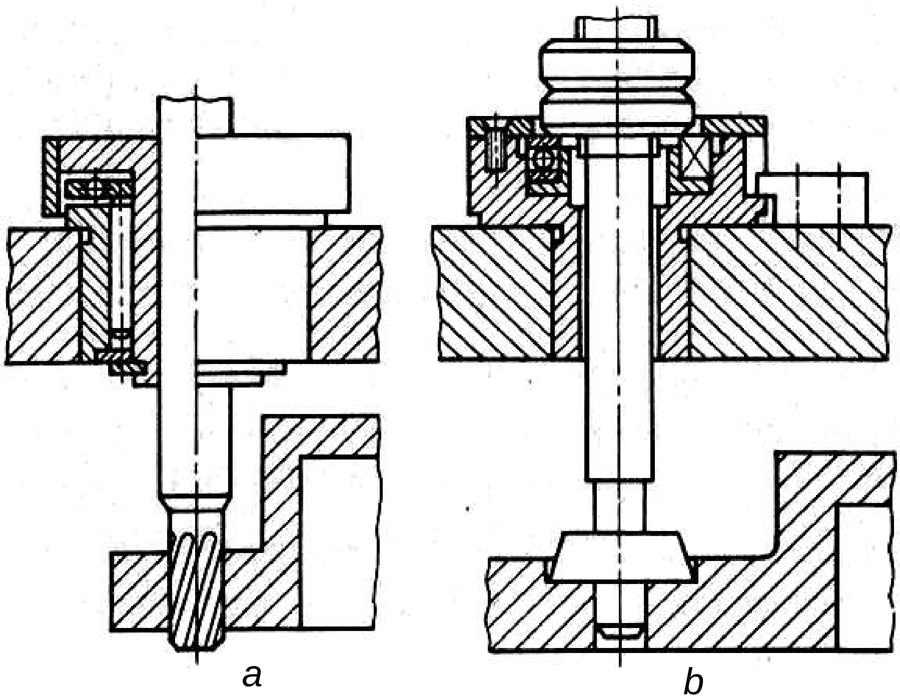


Figure 4.5 – Rotating bushings: *a* – for guiding a tool (reamer); *b* – jig stop

4.4 Purpose and Designs of Indexing Devices

Indexing devices provide a capability to set work piece into various positions. It is possible to turn workpiece through the given angle or to move it for the necessary distance relative to the device body. In practice indexing devices for rotation of a workpiece are used more often. Therefore, such devices are usually called rotary devices.

Rotary devices are widely used in drilling and milling machines. Main elements of such devices are indexing plate (disk) and retainer, which determines plate position. Retainer is located in a device body, which is clamped to the machine table, and indexing plate together with a workpiece – in a rotating part of device. Indexing plate has as many sockets as many positions a work piece should occupy. Rotary devices can be with horizontal, inclined or vertical axle of indexing plate.

Accuracy of workpiece setting into the given position depends on a device operation: accuracy of sockets positions in an indexing plate; design, position, machining accuracy and wear of retainer; presence of clearance between retainer and socket, trunnion (journal) of rotating part and bushing of device body.

By shape of sockets indexing plates are divided into two groups: with holes and with slots. Indexing plates with holes are shown in Figure 4.6,*a*. Bushings 2 are pressed into plate 1. To reduce wear bushings are heat-treated to high hardness and ground with high accuracy. Holes in bushings for retainer are made cylindrical or conical. Conical holes provide higher accuracy of indexing.

Indexing plates with slots are shown in Figure 4.6,*b*. Disks with asymmetric slots (type I) are more effective as compared with symmetric slots (type II), because dirt on any surface of symmetric slot definitely would cause indexing error. When dirt appears in asymmetric slot, retainer would remove it from radial surface, and dirt on the inclined surface does not influence the indexing error.

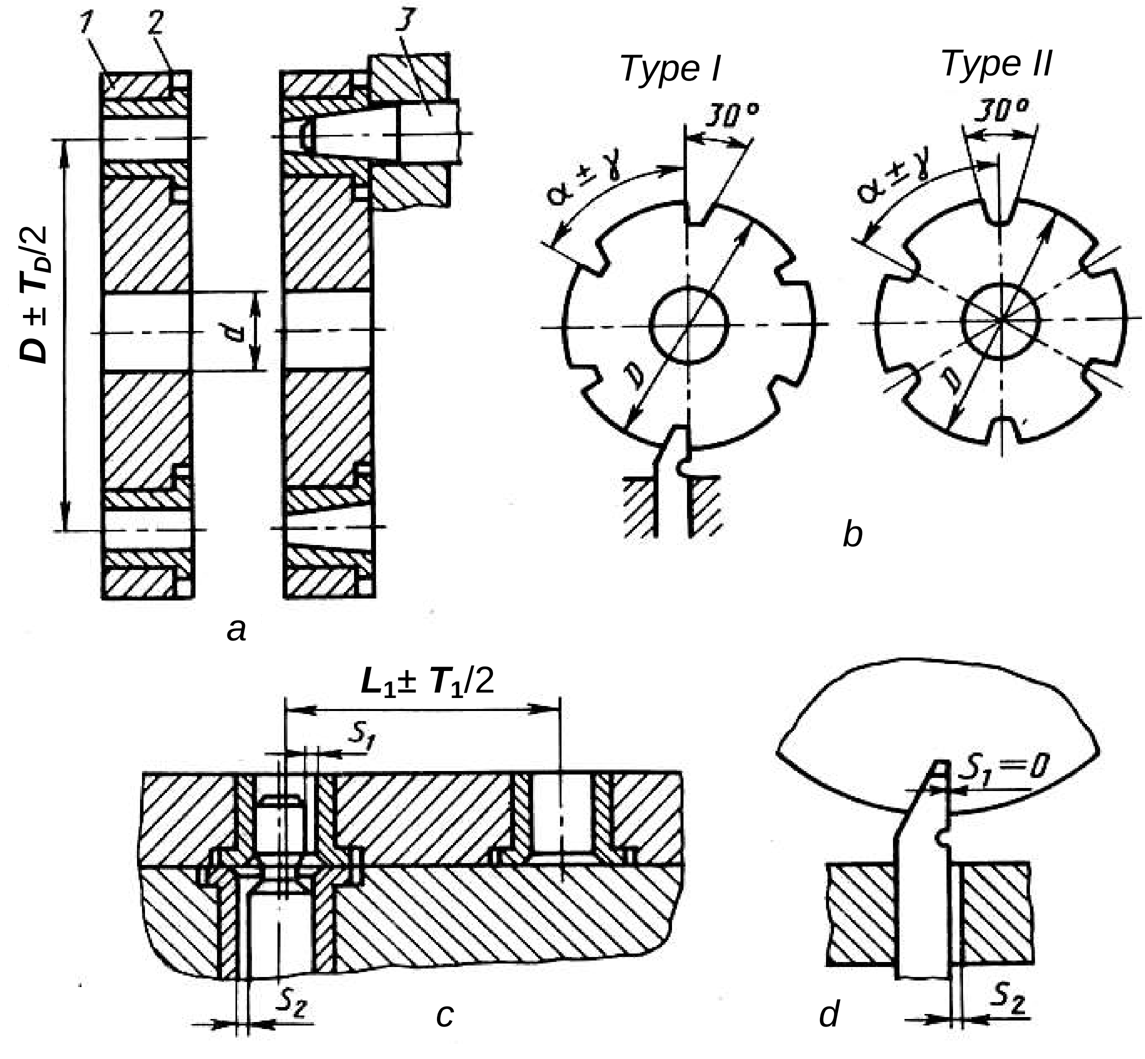


Figure 4.6 – Indexing disks with holes (*a*) and slots (*b*) and operation diagrams of retainers: cylindrical (*c*) and prismatic (*d*)

For equal accuracy of angle pitches (**$\alpha \pm \gamma$**) the disks with slots provide higher accuracy of indexing as compared to disks with holes. But disks with slots are more complicated for manufacturing.

Retainers are designed for exact fixation of position of indexing disk. Working profile of retainer is determined by profile of a socket of indexing disk. Retainers differ by mechanisms used for their movement.

Pitch error for cylindrical retainer (Figure 4.6,*c*)

$$\Delta S = S_1/2 + S_2/2 + T_1 + e,$$

where S_1 and S_2 – clearances in joints of retainer with retainer bushing and guide bushing, respectively; T_1 – tolerance of centre-to-centre distance of nearby bushings for retainer; e – eccentricity of bushings.

Usually $T_1 \le 0.03$ mm, and joint of retainer with bushings are produced by the *H7*/*g6* fit. In precise indexing devices $T_1 \le 0.02$ mm, and joint – *H6*/*h5* fit; in the especially important cases $T_1 \le 0.015$ mm, the lapping of retainer against bushings is produced with clearances S_1 and S_2 of not more than 0.01 mm. When conical or prismatic retainers are used, then $S_1 = 0$ (see Figure 4.6,*d*).

Figure 4.7 presents two designs of retainer. Pull-type cylindrical retainers (Figure 4.7,*a*) are widely used in simple indexing devices. Design of retainer with toothed rack (Figure 4.7,*b*) can provide higher accuracy of position. It is ensured by conical work end of retainer (joint without clearance) and elastic bushing 1 with hydroplast. At screwing-in the screw 3 the pressure from plunger 2 is transmitted by hydroplast to thin wall of bushing 1. The latter is deformed with reduction of hole diameter and, thus, it decreases or entirely eliminates clearance between bushing and retainer rod.

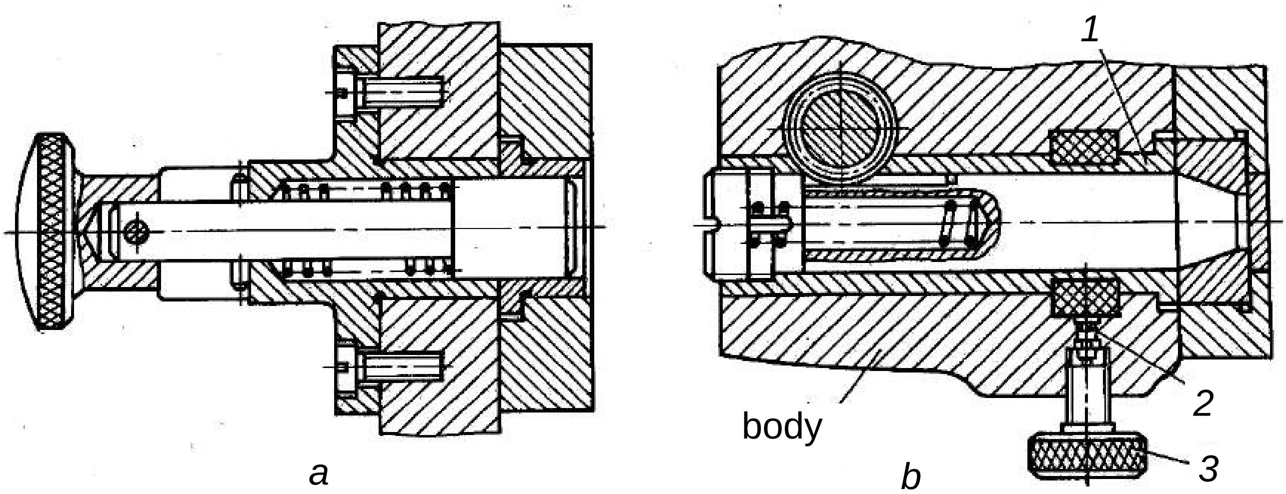


Figure 4.7 – Designs of retainers: *a* – cylindrical pull-type; *b* – conical toothed

The rotary part of indexing device is reliably fixed to body in order to improve stiffness of device and reduce cutting force transmitted to retainer. For this purpose, the clamps of special designs are used.

At designing of indexing devices, the normalised basic units and other elements are used.

Normalised rotary table (semi-product) is depicted in Figure 4.8. It consists of body 1, indexing plate with journal 2. The plate has holes with permanent bushings to do fixation in proper angular position with toothed retainer rod 3. Such retainers are convenient for simultaneous control of retainer rod 3 and tightening the indexing plate with aid of clamp 4 from one handle 5. At designing of indexing device, the rotary table with required quantity of positions (holes) is selected, as well as, other elements for locating and clamping of workpiece. If needed, the guide element is located on L-shaped bracket, which is fastened to the device body. At rotation of axle by handle 5 the clamp 4 is loosened, and pin 6 rotates gear 7 and pulls retainer rod 3 out of indexing plate hole. After this the indexing plate is turned to the next position. Under the action of spring the retainer rod 3 comes into the hole of plate 2. Then the clamp 4 is tightened by rotation of handle 5. By its conical surface the clamp 4 presses conical ring 8. the ring moves down journal of rotary plate 2 via nut and, thus, presses the plate 2 to body 1.

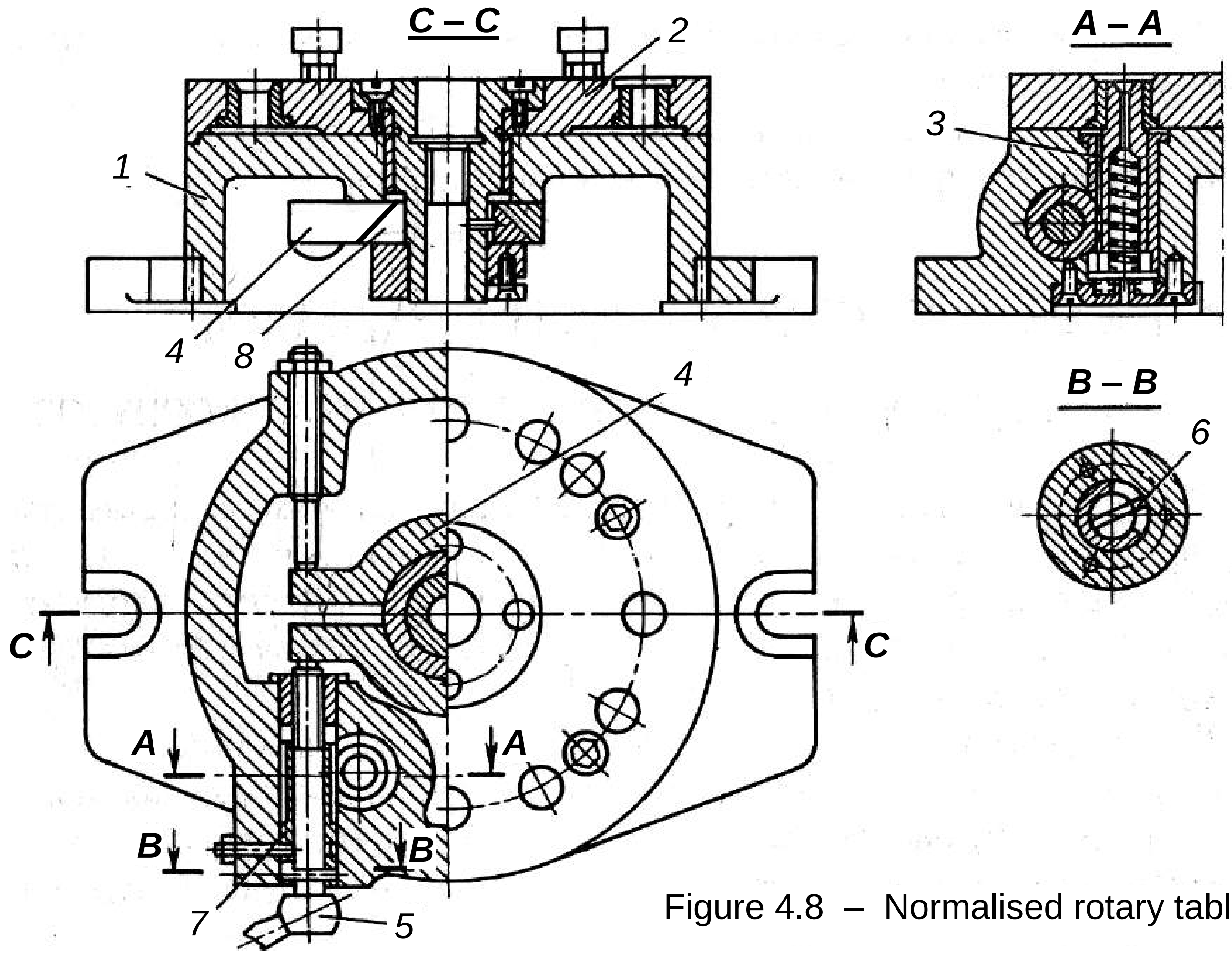


Figure 4.8 – Normalised rotary table

QUESTIONS

1. What are the purpose and classification of guide elements?
2. Describe designs of guide bushings.

3. Describe designs of drill bushings.
4. Describe purpose and designs of indexing devices.
5. Describe designs of main elements of indexing devices.

5. BODIES OF WORKHOLDING DEVICES

5.1 Purpose, designs, materials

Body (casing) is a main part of a device, on which all other elements are placed and exactly located, creating the whole mechanism. Datum surfaces are provided on the casing, by which the casing is positioned and fastened to machine tool.

Device casing bears all forces applied to a workpiece during its clamping and machining. Therefore, it should possess sufficient strength, rigidity, and vibrostability (damping capacity). These properties are provided by selection of rational structure of casing and addition of stiffening ribs.

Casing of complicated shapes are made of blanks produced by casting (Figure 5.1,*a*) from cast irons СЧ15-32 (SCh15-32), СЧ18-36 (SCh18-36), casings of higher strength – of steels 35Л (35L) or 45Л (45L), lightened casings – of aluminium alloys АЛ4 (AL4), АЛ9 (AL9). Production terms of casings are relatively long.

In the considered example of drill jig body the plane 1 serves as datum surface. Surfaces 2 and 3 are designed for accommodation of mounting and clamping elements, and hole 4 – for drill bushing. Stiffening ribs are designed for strength improvement and rigidity upgrade of the device body.

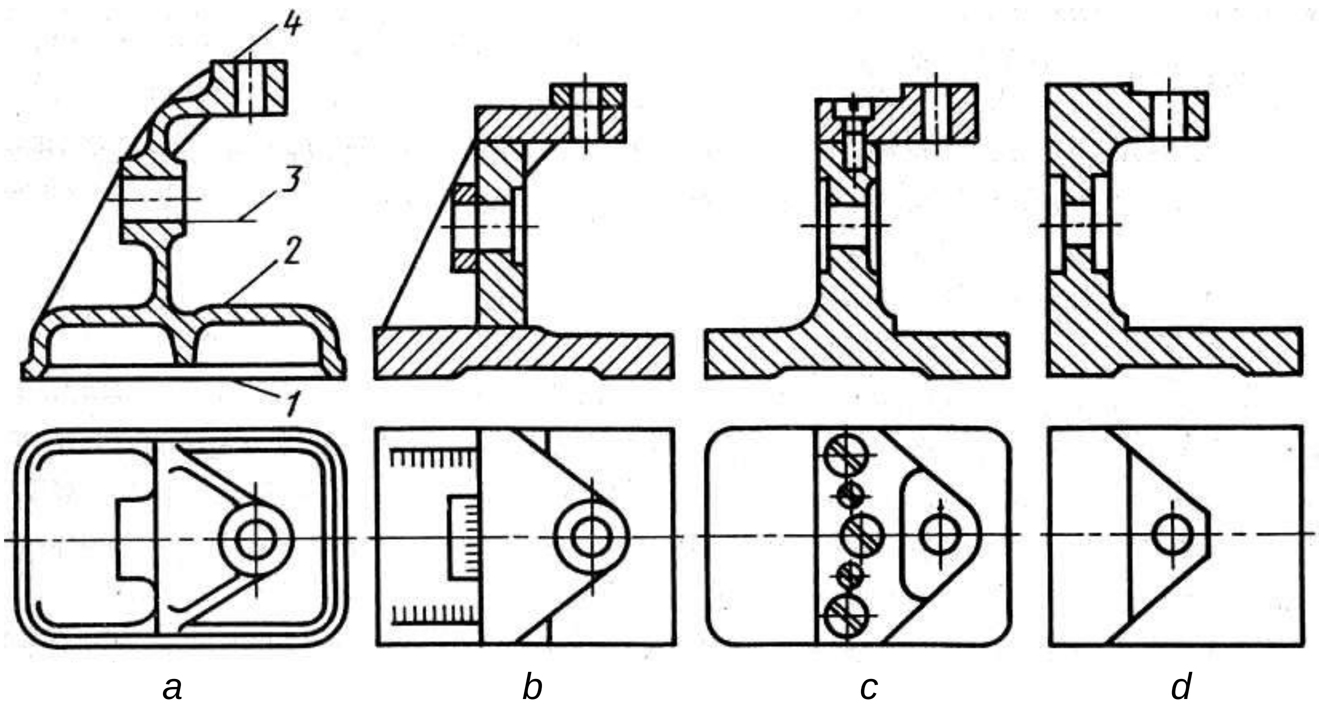


Figure 5.1 – Typical designs of workholding device bodies: *a* – cast design; *b* – weld design; *c* – forged design

Bodies of middle and even complicated shapes are produced by welding from rolled blanks (Figure 5.1,*b*). Here the stiffening ribs are also included. In this case production time is shortened; their mass and cost are lower as compared with a cast casing.

Assembled bodies (Figure 5.1,*c*) are produced from rolled, cast or forged blanks. Before assembling the blanks are machined with apt accuracy, holes for fastening elements are produced. The considered design includes two parts: T-shape element and special bracket. These parts are fixed by two pins for higher accuracy and fastened by screws.

Bodies of less complicated shapes and increased strength and hardness are made of forgings (Figure 5.1,*d*).

Casings produced from cast, forged and weld blanks should be heat-treated (tempered) for release of residual stresses.

Selection of a body design and method for its production depends on the certain conditions of an enterprise. In practice the cast and assembled bodies are applicable the most widely.

5.2 Methods for mounting of device bodies in machines

Workholding device with aid of datum surfaces of body is installed on work element of machine (spindle, table) that has apt locating surface. Form, dimensions and tolerances for locating surface are standardised for all machines. This data is provided in catalogues, handbooks and manual of machine.

Bodies of devices for turning machines are frequently attached to spindle via auxiliary element – intermediate flange. The following methods of device installation are used in practice: in centres, in taper hole of spindle, on outside spindle surfaces and on intermediate flange.

When installing in centres (Figure 5.2,*a*) the body (mandrel) is mounted on cones (dead or live centres) 2 and 4, which are fixed in spindle 1 and tailstock quill 5. Rotation of mandrel 3 is provided by driver chuck connected to spindle 1. This method gives an opportunity to use the device in any turning machine.

If installation of device body 3 is performed into spindle hole (Figure 5.2,*b*), the body should have special locating surface in the form of taper shank *B* that corresponds to taper hole *A* in spindle 2.The body is fixed by pull stud 1. This method is multi-operated as spindle taper hole in different machines has the same Morse taper number. But stiffness decreases, because the body is fixed as a cantilever beam.

When mounting the device body 2 on spindle 1 (Figure 5.2,*c*), the alignment surface *A* is machined carefully to suit the spindle locating surface *C*. Also a threaded hole in the body 2 is machined for its fixation on spindle 1. This method ensures big stiffness of joint. The disadvantages are: lower alignment accuracy because of position deviation of hole *A* and clearance in the joint with the spindle surface *C*; difficulties at machining of high-accuracy hole *A*; lower universality because of different forms and dimensions of locating surfaces of spindles in different turning machines.

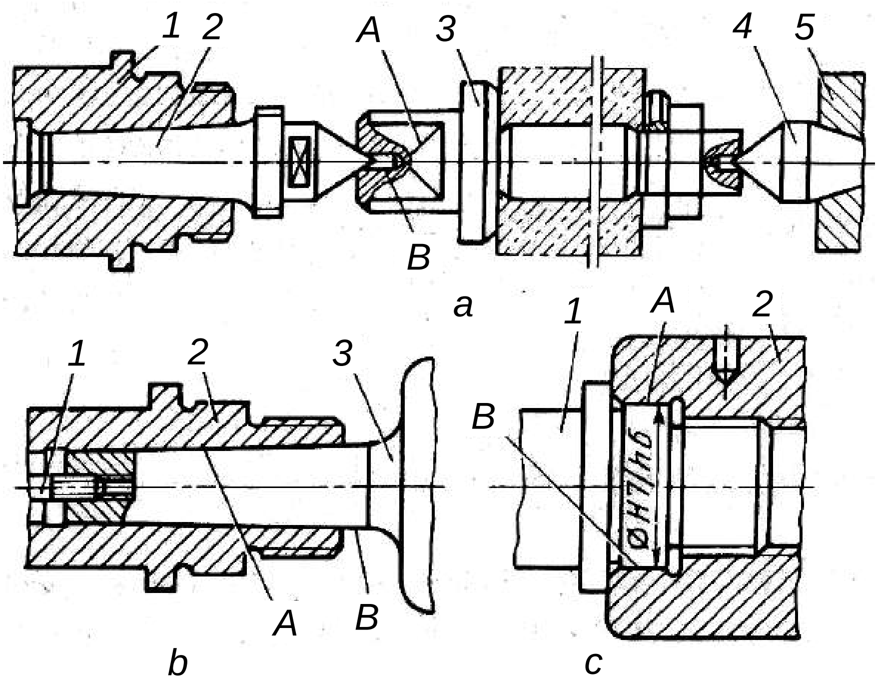


Figure 5.2 – Methods of installation of workholding devices in turning machines: *a* – in centres; *b* – in spindle hole; *c* – on spindle external surfaces

In Figure 5.3,*a* the workholding device is attached to spindle 1 with the aid of intermediate flange 2 in a turning machine with alignment on cylindrical surfaces. Joint of the device body with intermediate flange is made by screws 3. Intermediate flange is fixed on spindle end by metric thread. Intermediate flange (Figure 5.3,*a*) on the left side has alignment cylindrical surface *A* performed according to the alignment surface of spindle, and on the right side – the alignment collar *B* of height ***h*** = 2...4 mm. It is recommended to perform the collar diameter with tolerance band *k6* or *h6*. Respective recess is made in the body part of device with diameter tolerance band *H7* or *H6*.

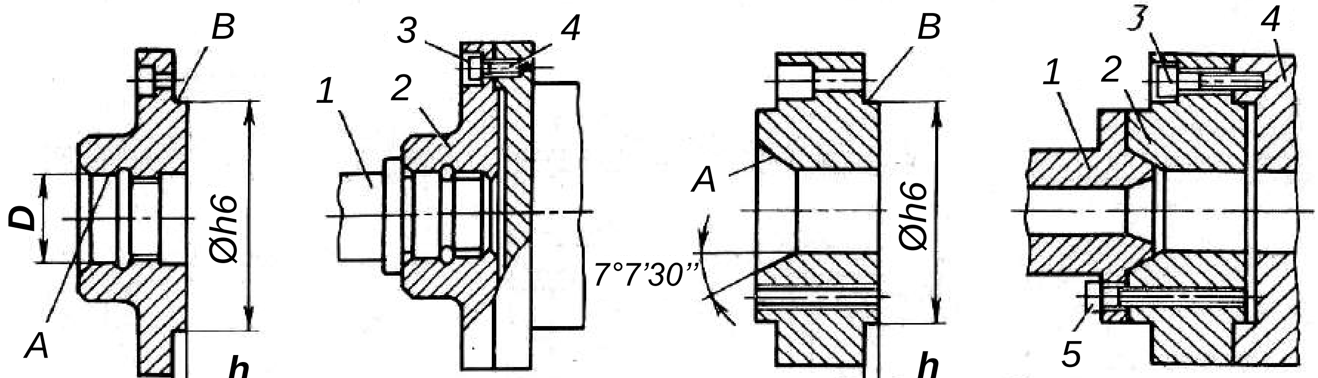


Figure 5.4 – Installation of workholding devices on intermediate flange in turning machines

Figure 5.3,*b* illustrates similar joint for machine spindle with conical alignment surface. Intermediate flange 2 is fastened to spindle flange 1 by bolts 5, and body to Intermediate flange – by screws 3.

Installation of devices in grinding machines is performed mainly in centres like in turning machines, though there are some differences in designs of grinding and turning machines. Modern machines for external grinding have non-rotating spindle that excludes run-out of spindle and improves machining accuracy. Rotation is transmitted to the device by driver plate being not connected to spindle.

The spindle usually rotates in universal external grinding machines. In this case the workholding device is located in the taper hole of spindle or on intermediate faceplate. Usually self-centring chucks or mandrels are attached to faceplate to accommodate workpiece.

In milling, boring, drilling, multi-operation and other machines the device body is installed by its locating surfaces on a table, which has standardised T-slots. Locating surfaces are machined on the bottom side of device body (Figure 5.5); they contact with the table plane. In small devices locating surface *A* is continuous (Figure 5.5,*a*). For middle and large size devices a shallow recess *B* (Figure 5.5,*b*) or cavity *C* (Figure 5.5,*c*) is made in the centre of locating plane *A*. Due to these cavities central segment of locating plane *A* does not contact with table that improves stability of body locating.

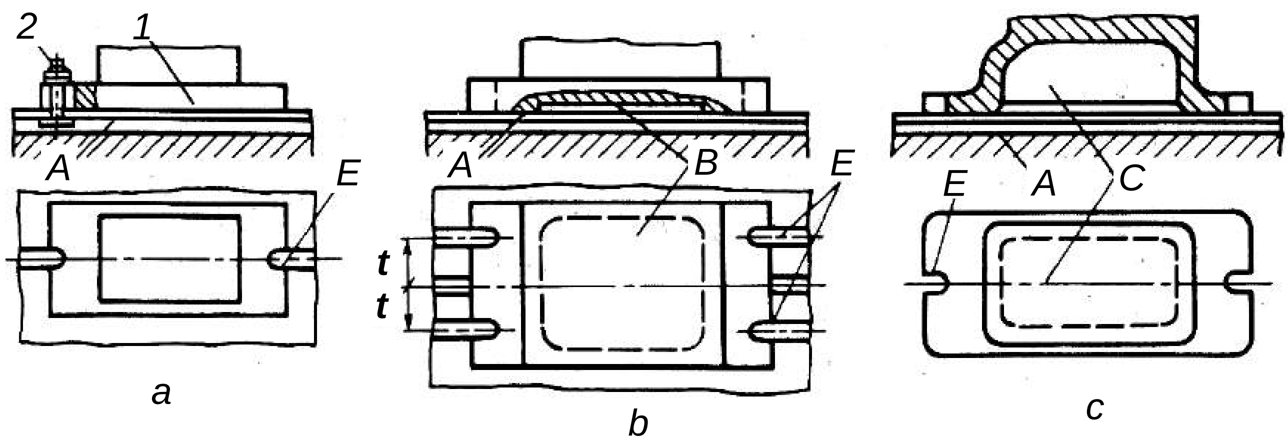


Figure 5.5 – Locating surfaces of bodies of milling devices

In order to fix a device the slots *E* are made in the body plate 1 (Figure 5.5,*a*). Fasten bolts 2 are inserted into these slots, and their heads – into T-slots of machine table. Number of bolts and body slots is determined by actual cutting forces. In most cases two slots are enough, but at large loads four slots and bolts are applied – per two fasten elements on each side. Positions of body slots correspond with T-slots coordinating dimensions ***t***.

Orientation of workholding device relative to the direction of table T-slots is performed with aid of prismatic keys. Standardised prismatic keys (Figure 5.6,*a*) are widely used for this purpose. The key main dimension is width ***B*** that should be equal to width of the table T-slot. Dimension ***B*** is performed by tolerance band *h8*. In keys with groove the dimension B_1 is made 0.5…1.0 mm larger than width ***B*** that is necessary for fitting (filing) the key to actual dimension of T-slot.

Two keys are fixed by screws 3 in body plate 1 on the bottom side of device in special key slots (Figure 5.6,*b*). Keys are located in such a manner that they are in the same T-slot (Figure 5.6,*c*).

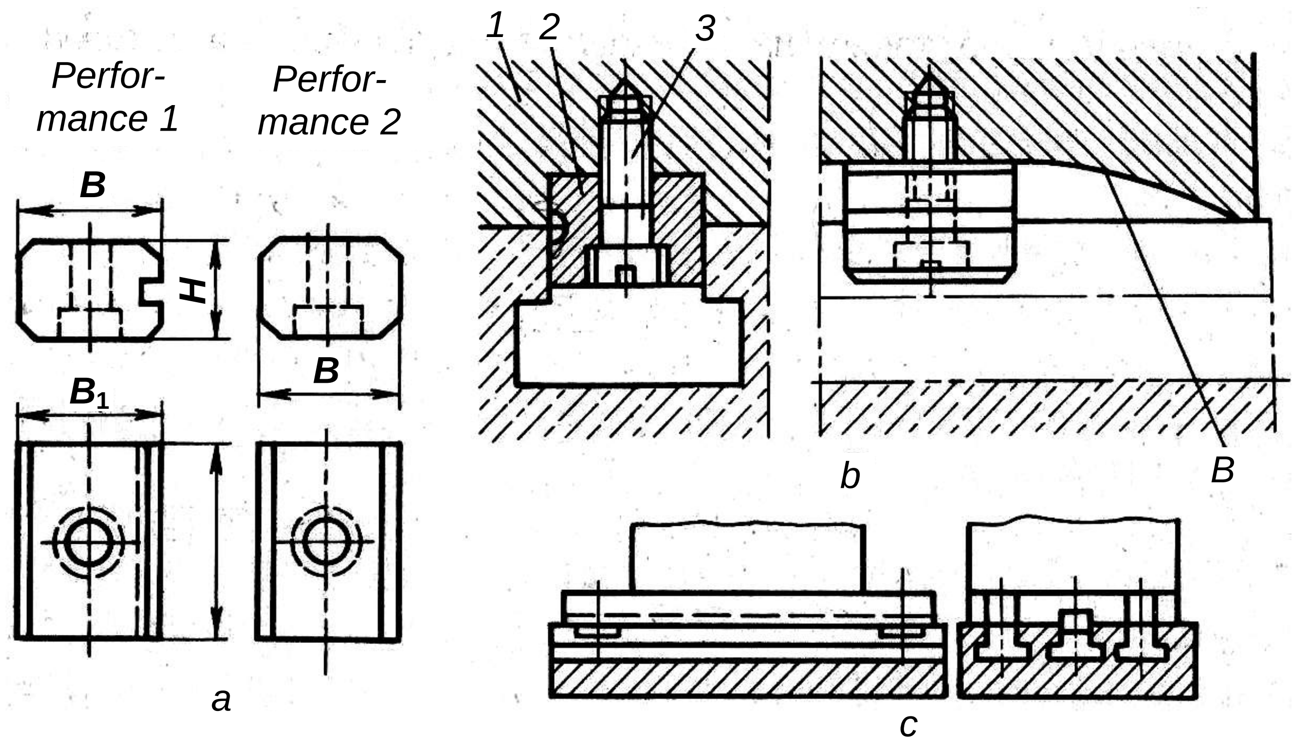


Figure 5.6 – Installation of workholding devices with aid of keys in milling machines: *a* – designs of standard keys; *b* – method for key fastening; *c* – installation diagram

QUESTIONS

1. What are the requirements applied to bodies of workholding devices?
2. What types of initial blanks are used for production of bodies of workholding devices?
3. What methods are used for installation of workholding devices in turning machines?
4. What methods are used for installation of workholding devices in milling machines?

6 DESIGNS OF WORKHOLDING DEVICES FOR VERSATILE MACHINES

6.1 Workholding devices for turning machines

Workholding devices for turning machines are designed for mounting of mainly round workpieces with machining of round surfaces. Therefore these devices should possess *capability of simultaneous locating and clamping*, which means that these devices should be *self-centring*. By design of self-centring mechanism (element) the chuck and mandrels are divided into several types: jaw, collet, membrane, with leaf springs, with hydroplast, etc. Depending on type and accuracy of machining, chucks and mandrels with respective self-centring mechanism are selected. Devices can be with hand or mechanised power drive.

Chucks are those devices, which locate and clamp workpieces mainly along outer datum surface. Chucks are connected to spindle via special adaptor – flange (see Figure 3.16).

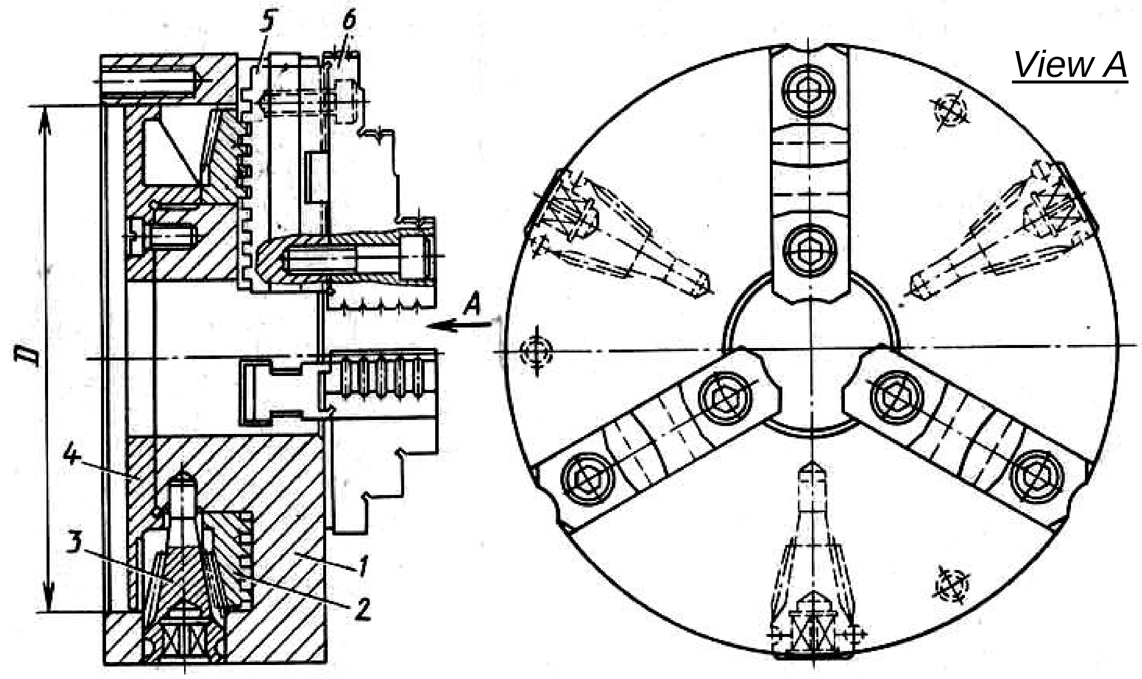


Figure 6.1 – Self-centring three-jaw chuck with spiral-rack drive mechanism

Design of versatile three-jaw chuck (Figure 6.1) provides capability to locate and clamp a workpiece by three assembly jaws. They consist of main 5 and replaceable 6 jaws located in radial T-shape slots of body 1. Segments of Archimedes spiral are performed on the surfaces of main jaws 5 faced to the body. Proper positions of spiral segments on jaws 5 provide their equal distances from the axis of rotation. They are engaged with the spiral of disk 2. Spiral disk are centred by the body hub. On the opposite side of disk the conical gear (bevel) ring is performed. Disk is engaged with three bevel gears 3 mounted in the body. Shield 4 serves for axial fixation of spiral disk 2 and protection from chip. Drive of jaws is performed by rotation of bevel gear 3 that gives rotational motion to spiral disk 2 that transforms into linear motion of jaws 5. Finally locating and clamping of a workpiece is performed by replaceable jaws 6 attached to main jaws 5.

These chucks do not ensure high accuracy of mounting (centring) of workpieces because significant machining error of the spiral surfaces with variable curvature radius. Small contact areas of jaws teeth with the spiral disk facilitate fast wear that reduces accuracy of locating and stiffness of clamping. Hand drive increases clamping-unclamping cycle. Therefore these chucks are usually used for rough and semi-finish machining in individual and small-batch production.

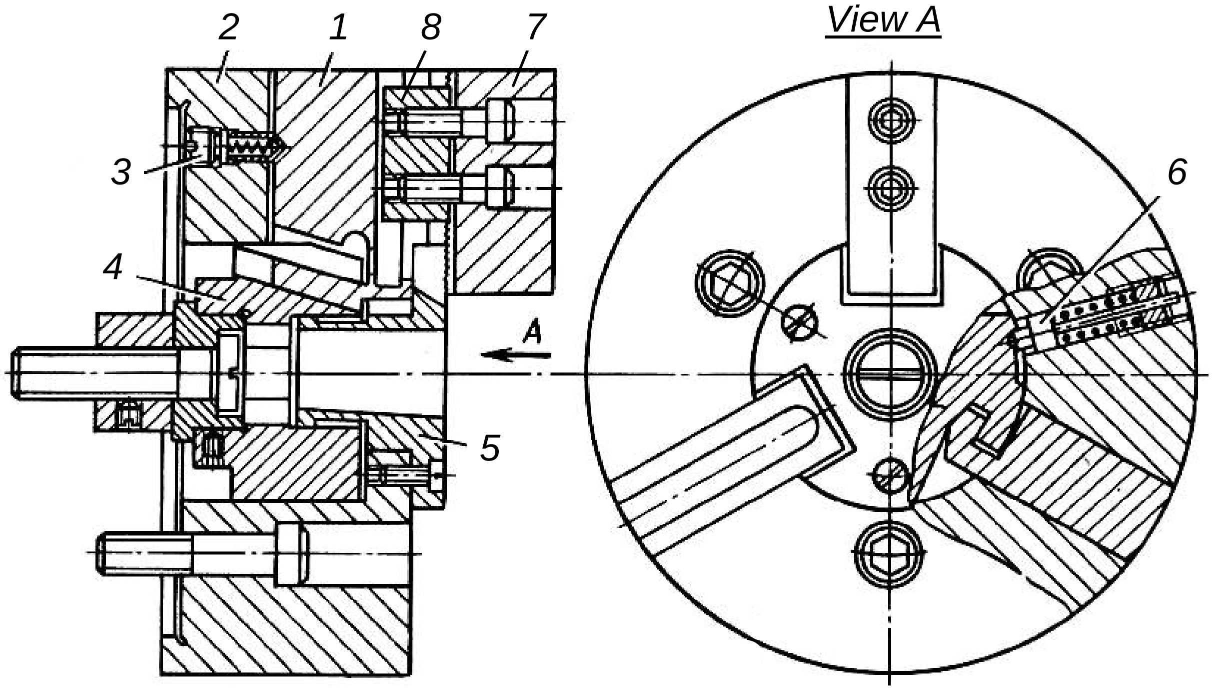


Figure 6.2 – Self-centring three-jaw chuck with wedge drive mechanism

Design of *wedge-type* three-jaw chuck with pneumatic drive (GOST 24351-80) has the advantages of upgraded accuracy, rigidity and wear resistance (Figure 6.2). Main jaws 1 are placed in radial slots of body 2. Jaws ledges are inclined and they are in contact with inclined slots of sliding coupling 4, thus creating three wedge pairs. Sliding coupling is moved by pneumatic motor (not shown). Bushing 5 protects wedge pairs from chip and bushing hole is used for mounting of centres and stops. Retention lock 3 determines work position of wedge pairs. When changing main jaws 1, the bushing 5 should be removed, sliding coupling 4 is rotated counterclockwise at the angle of 15º till the stop by pin 6 and jaws 1 are pulled out the body slots. Replaceable jaws 7 are fastened by two screws to main jaws 1 with aid of inserts 8 placed into T-shape slots of main jaws. Face teeth (splines) with pitch 1.5 mm are performed on the flat surfaces of main and replaceable jaws for setting replaceable jaws for the applicable diameter of workpiece at the same distance from axis of rotation. Angles of wedge pairs are 15º that provide strokes of jaws approximately 8 mm. Therefore the chuck is adjusted for another dimension at changing of workpiece with another diameter. At adjustment the screws are loosened, replaceable jaws 7 together with inserts 8 are displaced relatively main jaws 1 at the needed number of pitches, and then the screws are tightened.

Clamping of a workpiece is performed by motion of sliding coupling 4 to the left. It makes jaws 1 to move along wedges inclined surface to the axis of rotation, thus clamping a workpiece (not shown). Initial force $\boldsymbol{F_i}$ is generated by pneumatic drive and transmitted to the coupling 4 via axial screw attached to the coupling. Then initial force is transformed into clamping force $\boldsymbol{Q}$ by drive mechanisms of jaws – wedge pairs. For unclamping a workpiece it is necessary to apply reversed initial force to the coupling 4 to make it to move to the right. The jaws 1 sliding along inclined surfaces of coupling will go outwards, thus unclamping a workpiece.

In industry the chucks with built-in pneumatic drive are widely applied (Figure 6.3). Here the pneumatic drive of chamber type with ring diaphragm 4 is placed into body 5 (Figure 6.3,*a*). Three rods 8 are inserted into T-shape slot of the ring attached to the diaphragm 4. The rods 8 have slots (Figure 6.3,*b*, sectional view *A–A*) for engagement with levers of threaded shafts 2. The shafts 2 have both threaded ends with right-hand (lower end) and left-hand (upper end) threads. This feature allows increasing twice axial motion of the shafts at their rotation. One threaded end of shaft is engaged with steady threaded bushing 3 and another one – with movable threaded bushing 6. The bushings 6 are connected with jaws 7 through adjustment screws 1.

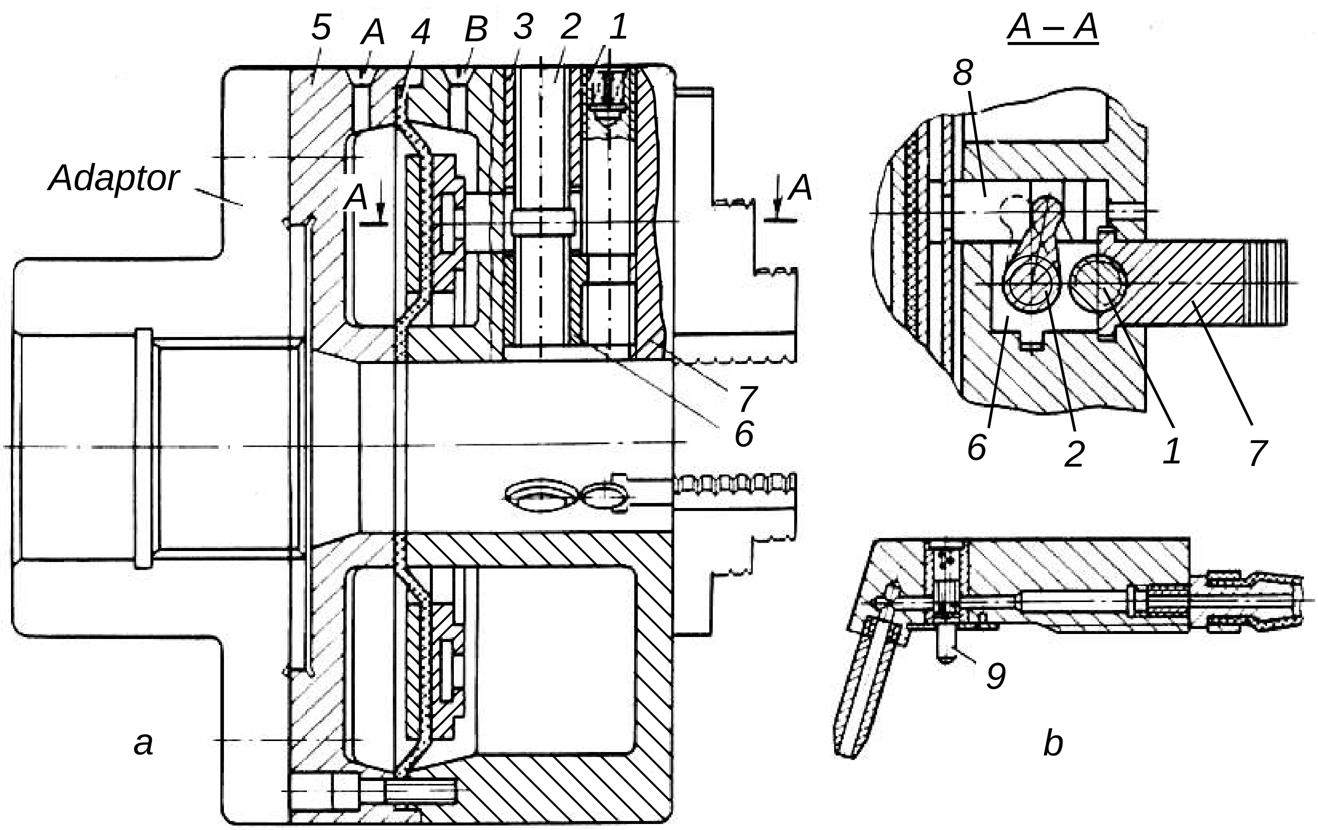


Figure 6.3 – Self-centring three-jaw chuck with pneumatic chamber built-in body: *a* – diagram of chuck; *b* – air tap of gun type

At compressed air feed to the left cavity of pneumatic actuator through hole *A* the diaphragm 4 deforms and moves the rods 8 to the right. The threaded shafts 2 are rotated by the rods 8 with aid of levers (see Figure 6.3,*a*, sectional view *A*–*A*). At that, the shafts move axially in the steady bushing 3 at the value determined by thread pitch and angle of shaft rotation. At the same time the movable bushing 6 pushed by the shaft 2 moves axially inside at the double value due to right-hand and left-hand threads. In its turn the bushing 6 pushes the screw 1 and jaw 7 inside, thus clamping a workpiece. Stability of clamping is ensured by self-friction in the threaded pair of shaft 2 and bushing 6.

For unclamping a workpiece compressed air is injected into the right cavity of pneumatic actuator through the hole *B*. The diaphragm 4 deforms and moves the rods 8 to the left. The shafts 2 rotate in opposite direction and pull the bushings 6, screws 1 and jaws 7 outside.

Compressed air feed is performed by gun-type tap (Figure 6.3,*b*) at pressing the button 9.

Design of this chuck provides motion of jaw at the value 1.1…1.5 mm. Therefore range of workpiece diameter deviations should not exceed 2.2…3.0 mm. The adjustment of chuck for new dimension is performed by rotation of the screws 1, and jaws positions are located on a special ring produced with mean diameter of workpiece.

6.2 Workholding devices (drill jigs) for drilling machines

Drill jigs are workholding devices for drilling machines that serve for locating and clamping of a workpiece and guiding of cutting tools by drill bushings. Drill bushings determine position of cutting tools (drills, core drills, reamers, etc.) relative to datum surfaces of jig.

According to the brunch standards OST 1.51558-84 and OST 1.51574-84 in aircraft engines industry the following types of drill jigs are applied: lay-on jigs (template jigs), cover jigs, jigs with hinged clamping plate, turning-over jigs, rotary jigs.

Lay-on jigs are applied for machining of one or several holes with parallel axes in large workpieces. They have simple design that includes jig plate with drill bushings, locating and clamping elements. Jig is mounted (laid) on a workpiece and fixed to it.

Cover jigs in comparison with lay-on jigs have mounting elements to install jig on a machine table. They have also mounting elements for a workpiece. Jig plate (cover) is performed removable or hinged. It accommodates drill bushings. Jig plate is located precisely relatively the mounting elements.

Example of cover jig design is depicted in Figure 6.4. Jig plate (cover) 2 with pressed drill bushing 3 is hingedly joined with body 1. Jig plate is opened before workpiece mounting. Workpiece is located by finger 5 and rest plate (ring) 4. Angular position of a workpiece is fixed by prism 8. Jig plate is closed after workpiece mounting and the plate 2 is fixed to the body by pin 7. Clamping of workpiece is performed by clamping screw 6.

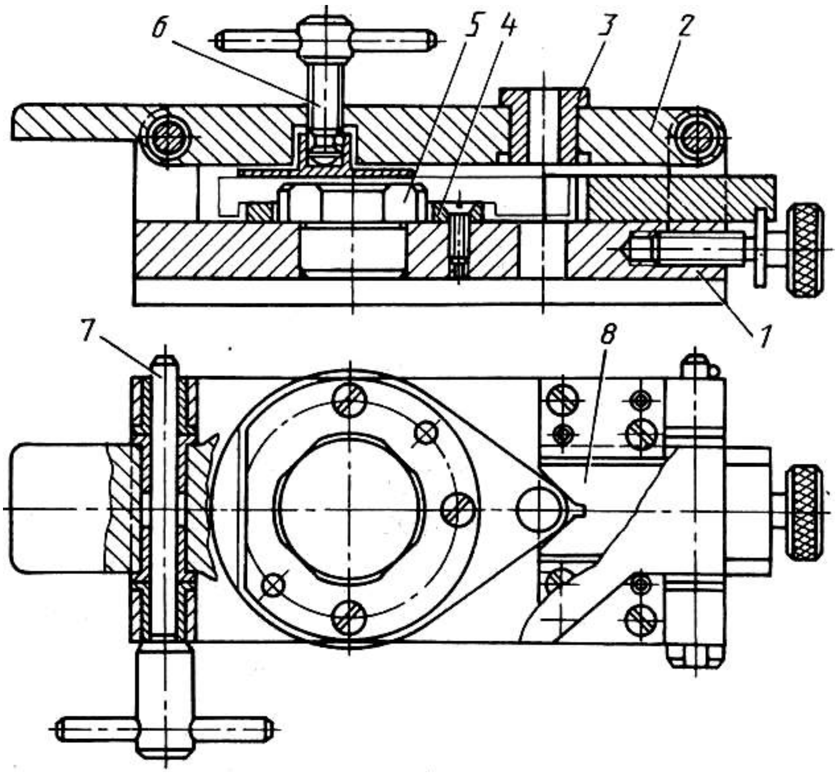


Figure 6.4 – Design of drill jig with hinged jig plate

Jigs with hinged clamping plate have open or closed bodies. Drill bushings are mounted directly in the jig body. It allows improving accuracy due to absence of jig plate, that is, reduction of quantity of joints errors.

Example of jig with hinged clamping plate is depicted in Figure 6.5. The jig is designed for drilling of two holes in a workpiece.

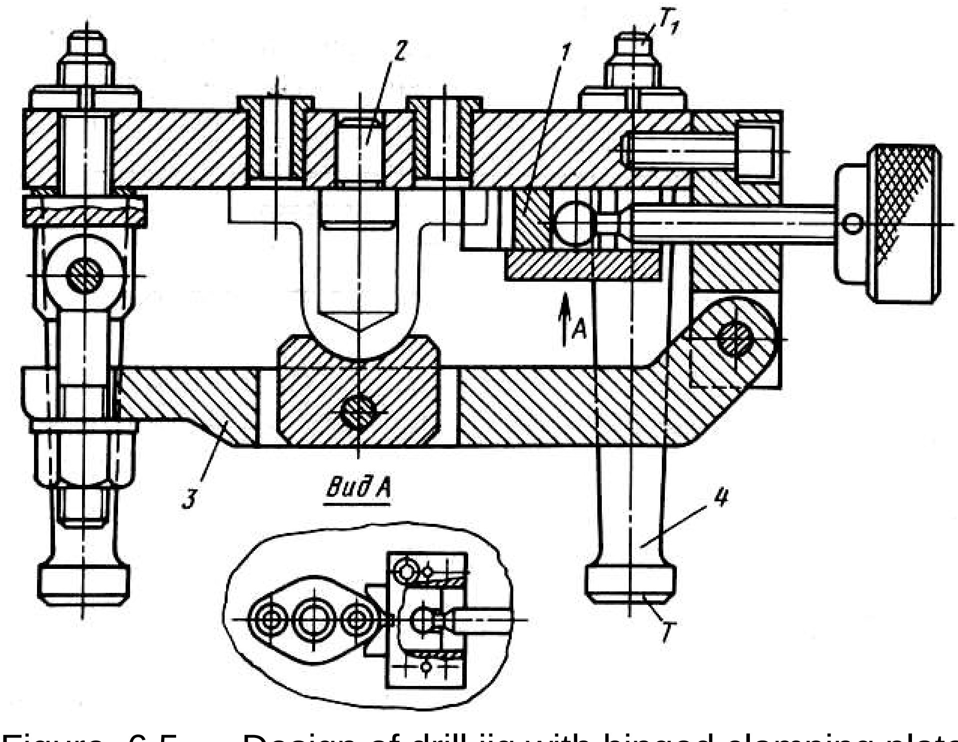


Figure 6.5 – Design of drill jig with hinged clamping plate

For mounting of a workpiece the jig is attached to the faces T_1 of columns 4. Clamping plate 3 is opened. Workpiece is mounted on finger 2 and angularly fixed by prism 1. Then workpiece is clamped by plate 3 and fastened by dog-bolt. After this the jig is turned over and put in work position on the faces *T* of columns 4 on a machine table.

Turning-over jigs are applied for machining of holes in small workpieces, whose axes are located in radial directions or on the face of workpiece. Body of jig has quantity of rest (datum) planes equal to quantity of workpiece positions during operation on the machine table. When performing the operation, the jig is turned from one rest plane (position) to another.

Rotary jigs are applied for machining of holes located along circle on the butt surface of workpiece or in radial directions in the same section. They differ from turning-over jigs by presence of dividing device that allows rotating and fixing a workpiece in the next position relative to drill bushing mounted in a jig body. Rotary jigs have no limitations by workpiece dimensions and number of machined holes.

Rotary jigs can be with horizontal, vertical and inclined axis of rotation.

Figure 6.6 shows the device with vertical axis of rotation for drilling of holes in compressor disk of aviation engine. The device consists of two main units: drill jig and indexing device. Machined workpiece 1 is mounted on face plate 2 and aligned (centred) by bead *Øh6*.

Face plate has holes for a drill going through. Before workpiece mounting compressed air is fed to pneumatic chamber 10, rod 11 goes up; quick-changeable washer 18 and cover 17 are released. Workpiece is mounted, cover is put on the workpiece with alignment along the hole in the workpiece; quick-changeable washer is inserted into groove of rod 11. Clamping of workpiece is performed by force of spring elastic deformation installed in the pneumatic chamber 10 after exhaust of compressed air. Face plate 2 is fastened to disk 16 by bolts 3. Thrust ball bearing 4 is placed between disk 16 and device body 15, thus, creating a capability of rotation of the upper device unit with workpiece relative to the body.

Drill bushing 20 is mounted in jig plate 21 through intermediate (permanent) bushing 19. The plate is aligned on the rest 22 by two pins 25 and fastened by bolt 24 via quick-changeable washer 23. Before mounting and removal of a workpiece the bolt 24 is loosed, washer 23 and plate 21 are removed.

Mechanism of dividing and fixation of angular position includes indexing disk 6 with pins 7 uniformly distributed along circle, slide plate 9 with wedges 8, guides 5 and pneumatic cylinder 14. Indexing disk 6 is attached to rotary unit of device by central bushing 13 and nut 12.

When exhausting a compressed air from pneumatic cylinder 14 the piston goes to the right driven by spring and moves slide plate 9 and wedges 8. Thereby the right wedge goes out the engagement with pins 7, and the left wedge goes to the right and rotates the indexing disk 6 counterclockwise at the half-angle. Then compressed air is fed into pneumatic cylinder 14, slide plate 9 with wedges 8 goes to the left and the right wedge completes rotation of indexing disk with another half-angle and fixes indexing disk 6 in a proper angular position. After the hole machining the compressed air is exhausted and indexing process is repeated again.

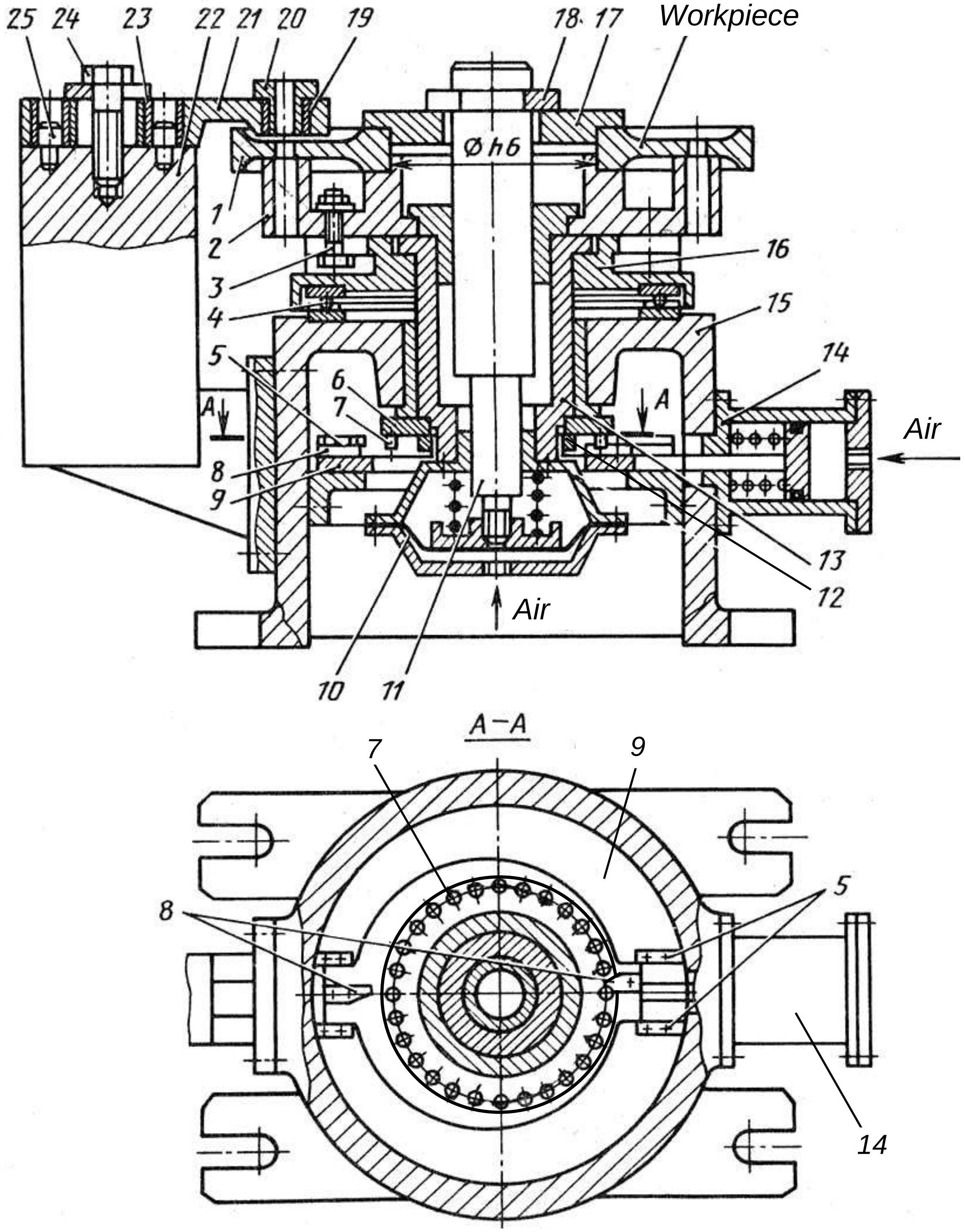


Figure 6.6 – Design of drill jig with mechanised indexing device

This device significantly improves productivity of labour and ensures high accuracy of relative position of compressor disk holes.

6.3 Workholding devices for milling machines

Usually large cutting forces and moments are generated at milling of workpiece surfaces. Therefore workholding devices should be strong and rigid, and workpieces should be reliably and rigidly clamped in order to prevent displacement of a workpiece from the position of locating.

One of the designs of versatile spring-hydraulic vices is depicted in Figure 6.7. Steady lip 8 is mounted together with spring-hydraulic cylinder built into the body 11 of rotary unit of vice. Screw 9 goes through the hole in vertical plate 16 of rotary body 11 mounted on steady unit 10 of vice. The screw 9 is engaged with the nut 15 fixed in the slide block 14. Another end of screw 9 is attached to bushing 4 with pack of leaf disk springs 5. Thrust ball bearing 6 is mounted between springs pack 5 and body 11 in order to reduce force for rotation of screw 9 at hydraulic pressure supply. O-rings 2 are mounted on the piston 3 for sealing.

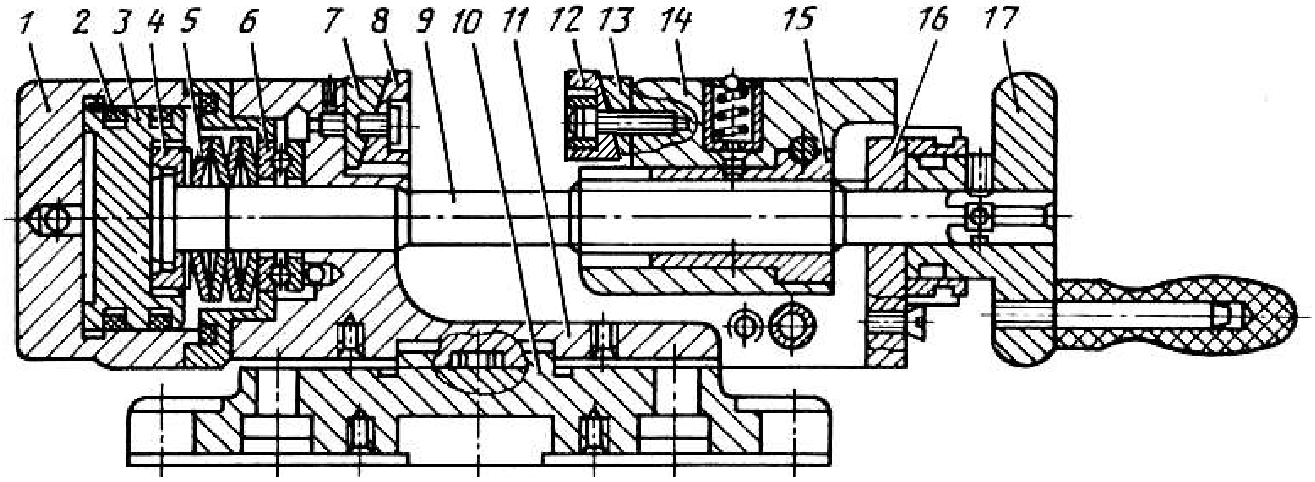


Figure 6.7 – Design of vice with spring-hydraulic mechanism

The device operates in the following manner. Work liquid is fed under the pressure into the hydraulic cavity between piston 3 and cover 1. The piston 3 goes to the right, thus, compressing pack of springs 5 by bushing 4 and moving the screw 9 together with slide block 14 and movable lip 12. A workpiece is mounted between steady 8 and movable 12 lips. Gaps between lips and workpiece are eliminated by rotation of flywheel 17 with screw 9 and motion of slide block 14 with movable lip 12. Then hydraulic cavity of the cylinder is connected with exhaust hydraulic line and springs 5 perform clamping of a workpiece by force of spring elastic deformation. At that springs pack 5 pulls screw 9 to the left together with slide block 14 and movable lip 12. Inclined surfaces of plates 7 and 13 improve reliability of workpiece clamping.

6.4 Workholding devices for grinding machines

The most of round datum surfaces of aircraft engine surfaces are produced with high accuracy of diameters (accuracy grades 5…8) and small tolerance for relative position of surfaces should be not more than 0.005…0.050 mm. Usually these surfaces are machined in grinding machines. In order to ensure such high accuracy the workholding devices for grinding operations should be produced with higher accuracy than tolerance for a part dimension: workpiece mounting error is not more than 30…40 % tolerance value. Workholding devices for grinding should include such high-precision self-centring elements that provide the needed level of locating and clamping accuracy. Therefore self-centring mandrels and chucks are the mainly devices for grinding.

Design of end mandrel with hydroplast is shown in Figure 6.8. The mandrel is used for mounting of bushing workpiece on internal cylindrical surface in internal grinding machine. Several passages 3 are performed in the body 1. They are filled with hydroplast. Elastically deforming thin-wall bushing 4 is used for centring and clamping of a workpiece. Pressure in hydroplast is created by plunger 2 with threaded end. Increase of pressure (workpiece clamping) and decrease of pressure (workpiece unclamping) is generated by rotation of plunger in two opposite directions. Axial locating of workpiece is performed by three rest pins 5. The mandrel is attached to spindle of grinding machine via flange 7 by screws 6.

These mandrels provide high accuracy of centring with mounting error 0.005…0.010 mm. They are the most suitable for workpiece of

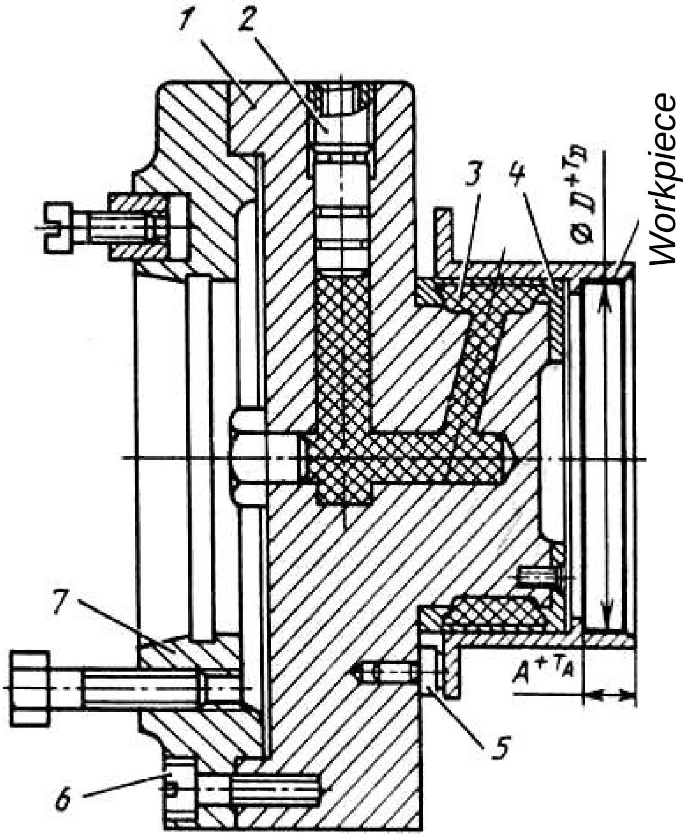


Figure 6.8 – Design of end mandrel with hydroplast

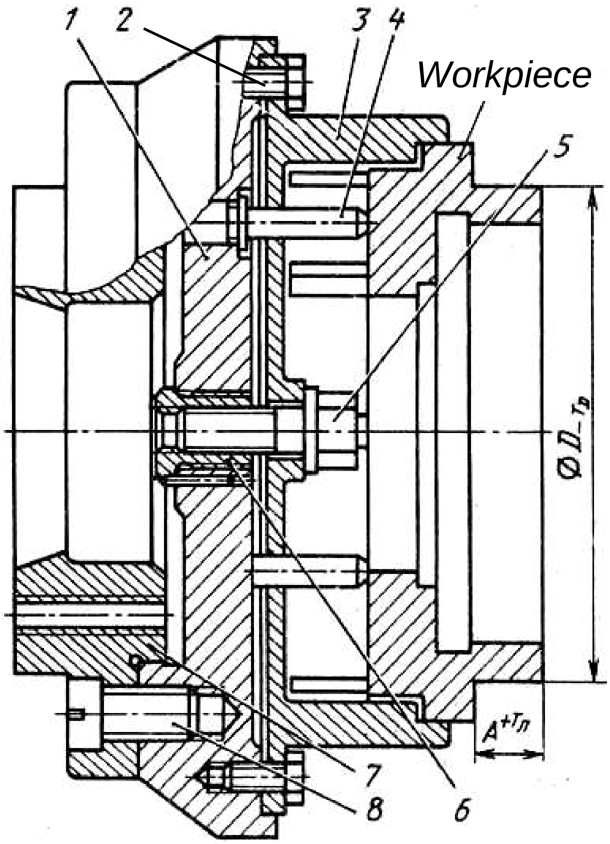


Figure 6.9 – Design of membrane chuck

low stiffness.

Membrane chucks (Figure 6.9) provide precise locating of a workpiece (0.005…0.020 mm) and high accuracy of machined surfaces. Membrane 3 of cup type is fastened to the body 1 by bolts 2. Three fingers 4 are used for workpiece locating in axial direction. Clamping of workpiece is performed manually by rotation clockwise of bolt 5 screwed into the nut 6. Unclamping of workpiece occurs at rotation of bolt 5 in opposite direction (counter-clockwise). The chuck is attached to the spindle via adaptor – flange 7 with conical hole. Flange 7 is fastened to body 1 by screws 8.

QUESTIONS

1. Describe designs of workholding devices for turning machines.
2. Describe designs of workholding devices (drill jigs) for drilling machines.
3. Describe designs of workholding devices for turning machines.
4. Describe designs of workholding devices for grinding machines.

7 DESIGNING PROCEDURE FOR WORKHOLDING DEVICES

7.1 Initial data for designing

The practice of aircraft engines manufacture shows that 60...65 % total quantity of workholding devices for metalcutting operations are of special-purpose design and only 35...40 % are universal and universal-assembling devices. Those special-purpose devices include 30...35 % specialised devices and modular jigs, which can be disassembled and readjusted for other configurations, and 65...70 % special-purpose devices of unique designs. These portions for each enterprise can vary in some ranges depending on type of products, production type, level of mechanisation and automation of manufacturing process, application of CNC machines. For example, CNC machines allow reducing significantly quantity of metal-cutting operations and, thus, decreasing quantity of workholding devices.

Special-purpose devices of unique designs are developed by designers. Designer's work is tightly connected with work of production engineer. Production engineer does planning of manufacturing processes, performs operation charts and sketch sheets and shows mounting diagrams for workpiece in different operations, that is, locating and clamping schemes along workpiece surfaces. Production engineer also specifies the sequence of manufacturing steps, accuracy of geometric parameters (dimensions and forms, surface roughness), machines to be applied, types of cutting tools and measuring instruments, cutting conditions for manufacturing steps. All these data allow determining principal configuration of special-purpose workholding device. Based on manufacturing operation chart a production engineer issues the request (task) for development of workholding device.

Designer of devices realises idea of production engineer. Usually designer develops and analyses several variants of workholding device, while keeping the same principal mounting diagram proposed by production engineer, and selects the best design of them. After that, designer agrees the configuration of workholding device with production engineer and performs necessary calculations and drawings.

For making the designing works a designer should have the following *initial data*:

- work drawings of part and initial blank;
- current manufacturing operation chart with sketch sheet and specified locating and clamping schemes;
- operation charts of previous operations, in which datum surfaces and surfaces used for clamping in current operation are machined;
- annual program for this part manufacture;
- technical data of machine used in current operation.

Designer of workholding devices also needs auxiliary materials: albums of typical designs of universal, specialised and special-purpose devices; standardised power drives, devices mechanisms and elements; information about structural materials for parts of devices; technical guide materials, handbooks, teaching books, etc.

Designing of special-purpose workholding devices is performed in the following *sequence*:

- Analyses of initial data and development of possible principal configurations of device;
- Engineering and economic calculations to ground the selection of device optimal variant;
- Performance of design calculations and design documentation for the selected variant.

7.2 Analyses of initial data and development of design variants for workholding device

Careful analysis of work drawings of part and initial blank, technological documentation gives complete picture of shape, dimensions, accuracy and other technical requirements for workpiece at the stage of considered manufacturing operation. All this information is necessary for selection of principal configuration of workholding device.

From the operation chart the designer understands the mounting diagram, reveals surfaces selected for locating and clamping, accuracy requirements for dimensions, position and form of workpiece, special requirements for machining, sequence of manufacturing steps, geometric configurations of cutting tools, cutting conditions including cutting velocity V_C, spindle rotational speed n_m, cutting force P_Z, cutting moment M_C, etc.

Designer also should understand form, area, dimensions, accuracy, stiffness and location of datum surfaces (locating elements, sets of datums) and places for clamping of workpiece in the considered manufacturing operation. All these characteristics influence on selection of apt mounting and clamping elements and whole configuration of workholding device. For example, mounting error is directly connected with accuracy of datum surfaces and accuracy of their relative position. Small stiffness and small area of a datum surface require special design solutions to ensure accuracy and reliability of workpiece mounting. Special calculations of workpiece deformation under cutting and clamping forces are carried out. If the calculation results are not satisfactory respect to accuracy and reliability, the special auxiliary elements should be created and fixed in the design of workholding device.

If the device is developed for the first metalcutting operation, designer should carefully investigate datum and clamping surfaces of initial blank in order to ensure high reliability of mounting.

Designer should know quantity of parts to be produced annually and machine time per piece to estimate productivity of machining process and preliminary propose design solutions for mechanisation and automation of developed workholding device.

When analysing the machine technical data, designer pays attention to shape and dimensions of machine’s surfaces to contact with workholding device (locating and clamping): shape and dimensions of spindle end in turning machine; T-slots in table of milling machine, etc. Form and dimensions of attachment surfaces of workholding device should correspond to the respective surfaces of machine and ensure proper accuracy of alignment.

Analysis of typical designs of workholding devices helps to determine the optimal design configuration of the device.

Based on the analysis of initial data and auxiliary materials designer develops several principal diagrams of device. He can do changes in prototype device related to several elements or create absolutely new versions of workholding device.

7.3 Engineering and economic calculations

Engineering and economic calculations allow analysing the developed principal variants of workholding device and selecting the optimal one from them. Engineering calculations include device accuracy calculations in relation to accuracy of workpiece geometric parameters and reliability of workpiece clamping. Economic calculations are connected with estimation of economic efficiency of the device application in manufacturing process and determination of its productivity.

First of all it is necessary to estimate the accuracy of workholding device to be sure that the selected variant will be useful for manufacturing process.

7.3.1 Workholding device accuracy calculations

Accuracy of parts is a result of functioning of technological system. Technological system includes separate elements (machine tool – workholding device – cutting tool – workpiece), each of which exerts influence on machining error. It is necessary to understand a mechanism of their influence on total error and be able to quantitatively estimate this influence in order to define accuracy requirements for constituent elements of technological system.

When performing any manufacturing operation, an expected error must not exceed specified tolerance of geometric parameter, that is

$$\boldsymbol{\varepsilon} \leq \boldsymbol{T},$$

where $\boldsymbol{\varepsilon}$ – expected total (summarised) error of machining of specified geometric parameter; $\boldsymbol{T}$ – tolerance specified for geometric parameter (dimension, shape or positional relationship of surfaces).

Total error includes some manufacturing errors, which are combined into two groups: ε_M is an error of workpiece mounting and ε_P is an error of processing method. Then

$$\varepsilon = (\varepsilon_M + \varepsilon_P) \leq T$$

and

$$\varepsilon_M = T - \varepsilon_P.$$

The last equation shows that admissible error connected with workpiece mounting in a workholding device is a part of total tolerance $\boldsymbol{T}$. Thus accuracy calculations of a workholding device consist in determination of expected mounting error that must not exceed admissible error ε_M.

The ε_P error appears in process of machining a workpiece. It is influenced by many random processing factors, which cannot be predicted and calculated because of absence of reliable initial data. Therefore mostly the ε_P error is determined from the statistical data, though this approach does not include all the real conditions of machining. But it allows determining the ε_P error value fast and with satisfactory level of accuracy for the production conditions.

Determination of ε_P error is performed in the following sequence: on the basis of analysis the production errors, which appear during machining and affect the given geometric parameter, are revealed; their values are determined from the statistical data [4], and then the ε_P error is calculated with the probabilistic method of summation.

The main problem for a designer of workholding devices is determination of expected mounting error ε_M. This error mainly depends on selection and accuracy of mounting datums, design of mounting elements, accuracy and wear of mounting and other elements, which affect the mounting error. Mounting error ε_M includes the following constituents: locating error ε_L, clamping error ε_C, and workholding device error of its production and wear ε_D (Figure 7.1).

Locating error ε_L is a shift of actual position obtained during locating relative to the required one. For some given locating scheme it is determined by projection of distance between limit positions of measuring datum (or initial datum for dimension) on the direction of dimension provided by machining. It can be different for the same locating scheme. When initial (dimension) datum and manufacturing (mounting) datums coincide, locating error is near to zero. Value of theoretical locating error depends on locating diagram. Typical locating schemes and accuracy calculations are considered in Chapter 2.

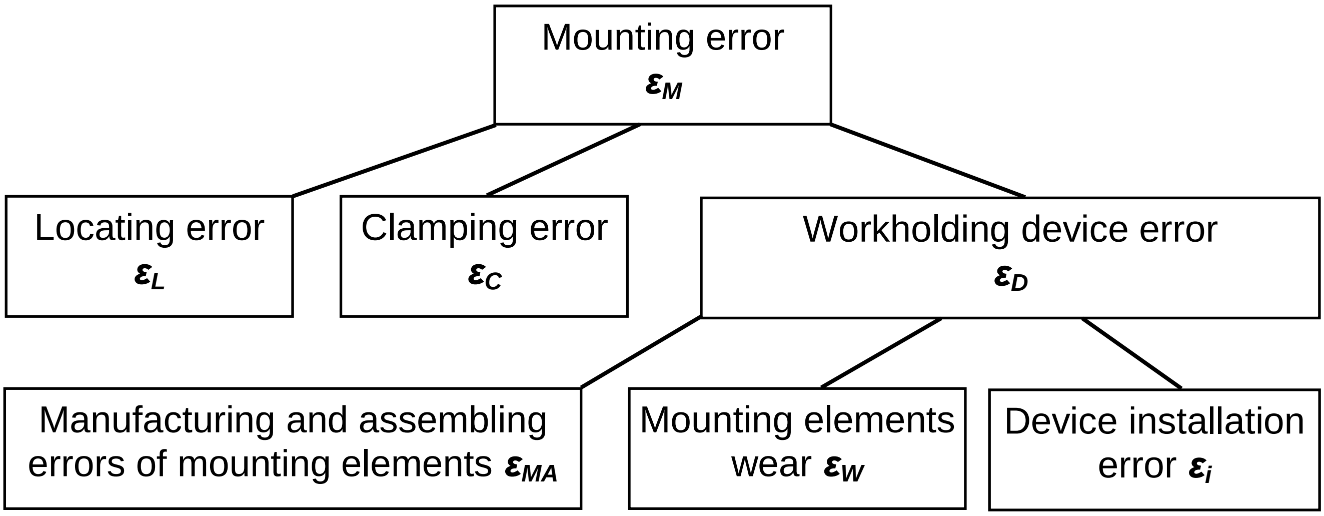


Figure 7.1 – Structure of mounting error

Clamping error ε_C is a difference of limit displacements of measuring (dimension) datum in the direction of obtained dimension caused by action of clamping forces. A workpiece shift results from elastic deformations of separate elements of chain, which provides force closure of a workpiece. When stiffness of a device body and workpiece is satisfactory, the clamping error depends mainly on displacement in the junction of a workpiece and mounting elements.

Clamping force should reliably press a workpiece to the rests of device. For incomplete clamping scheme, when this condition is not fulfilled, significant turn or shift of a workpiece may occur from its initial position.

The value of manufacturing datum shift is non-constant value for clamping of workpiece batch. It is explained by variations of clamping force, microgeometry (roughness) and physical-mechanical properties of surface layer of workpiece on the places of manufacturing datums.

Figure 7.2,*a* shows diagram illustrating a origin of the ω_C error at clamping a workpiece in operation of milling a slot of the ***A*** width. Mounting datum is displaced under the action of clamping force ***Q***. If clamping force changes in the range ***Qmin ... Qmax*** the mounting datum moves from the m'n' to m''n'' position with respective change of dimension from A_1 to A_2. Clamping error is calculated from the formula

$$\varepsilon_C = (y_{max} - y_{min})\cos\alpha,$$

where α is angle between direction of the ***S*** dimension to be obtained and direction of clamping force ***Q***.

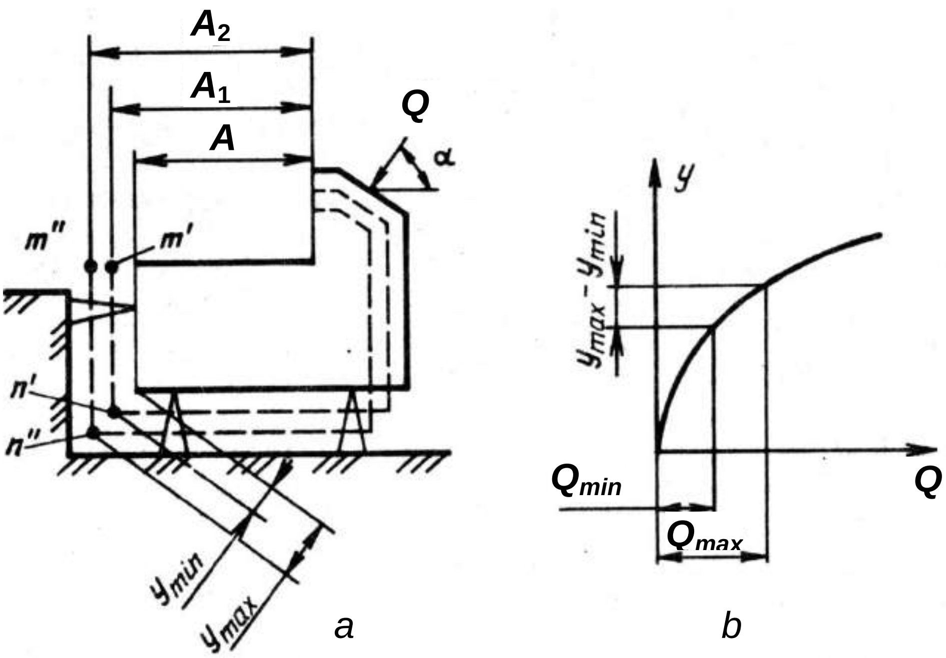


Figure 7.2 – Diagram of clamping error generation

Dependency of contact deformations at the interfaces between workpiece and device mounting element on clamping force is shown in Figure 7.2,*b*. In general it can be described the formula

$$\boldsymbol{y} = \boldsymbol{c}\boldsymbol{Q}^{n},$$

where ***Q*** is clamping force applied to mounting elements; ***c*** is coefficient characterising type of contact, workpiece material, roughness and structure of surface layer.

The ***c*** and ***n*** values are determined experimentally for each case.

In order to reduce the ε_C value it is necessary to provide constant value of clamping force ***Q***. Therefore workholding devices with manual drive are not recommended for performance of precise machining in aircraft technology.

Position error of a workpiece ε_D caused by workholding device error is defined by manufacturing and assembling errors of its mounting elements ε_{MA}, by their wear ε_W, and by errors of device installation in a machine ε_i.

Constituent ε_{MA} characterises inaccuracy of position of device mounting elements. In aircraft propulsion engineering the manufacturing capabilities of device production provide the value of this error in the range ε_{MA} = 0.010...0.015 mm.

Constituent ε_W characterises wear of device mounting elements. The wear value depends on operation time of workholding device, material and mass of workpiece, condition of its datum surfaces, as well as conditions of workpiece mounting and removal. Wear of rests (supports) is checked during scheduled inspection of workholding devices. If wear reaches limit value specified by technical conditions on a device assembly drawing, the replacement of rests is performed.

Constituent ε_i characterises error of device installation caused by displacement of its body relative to a spindle or table of machine. Device shift on a machine is reduced by application of guide elements (keys, centring shoulders, retainers), by lapping of mating surfaces of machine and device. For production of aircraft engine parts this constituent equals to ε_i = 0.005...0.020 mm.

The ε_{MA}, ε_W and ε_i values are distances between limiting projections of measuring datum of work piece in the direction of obtained dimension. They are dispersion fields of random variables. But action of the ε_D constituents occurs depending on conditions of a device application and production type.

For use of single-place device in small-batch and medium-batch production the ε_{MA} value is considered as systematic error and can be compensated during machine adjustment. And the ε_W and ε_i errors distributions obey the laws of equal probability and normal (Gaussian) distribution. Taking into account the above, one can write a general formula

$$\varepsilon_D = \sqrt{3\varepsilon_W{}^2 + \varepsilon_i{}^2} + \varepsilon_{MA}.$$

When applying the device as a workpiece carrier (accompanying fixture) the error is calculated from

$$\varepsilon_D = \sqrt{\varepsilon_W{}^2 + \varepsilon_i{}^2 + \varepsilon_{MA}{}^2}.$$

At mass production workholding device is used in one fixed work place (machine), errors ε_{MA} and ε_i are compensated by setting the machine for operation, and so

$$\varepsilon_D = \varepsilon_W.$$

When calculating ε_L, ε_C, ε_D a designer has no all reliable data, hence, it is rather impossible to calculate these errors with satisfactory accuracy. Therefore it is recommended to provide an accuracy margin of a workholding device equal to 10...20 %. Mounting error is determined according to the rule of addition of random variables from the formula

$$\varepsilon_M = 1.2\sqrt{\varepsilon_L{}^2 + \varepsilon_C{}^2 + \varepsilon_D{}^2}.$$

Calculated error ε_M is checked by means of formula $\varepsilon_M \le (T - \varepsilon_P)$. If this error exceeds admissible error, then the ε_M value should be reduced at the expense of increase of manufacturing accuracy of workholding device or by change of locating scheme. After that the calculations are performed again.

Usually in one operation several surfaces of workpiece are machined, hence, several geometric parameters should be ensured. Therefore calculations of workpiece mounting errors in workholding device are performed for each geometric parameter.

Example 1. Accuracy calculations are performed for mandrel for finish turning of workpiece outside surface (Figure 7.3). Analysis shows that perform-

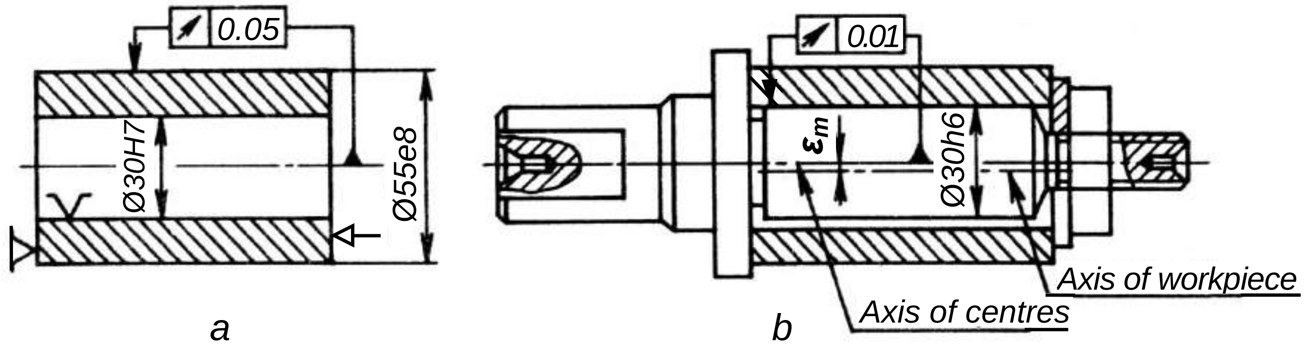


Figure 7.3 – Diagrams for calculations of accuracy at turning on mandrel: *a* – workpiece sketch; *b* – workholding device

ance of dimension *Ø55e8* does not depend on workholding device, but value of workpiece runout, which should not exceed 0.050 mm, depends on accuracy of workpiece mounting on the mandrel.

First the guarantee of tolerance for runout $\boldsymbol{T}$ = 0.050 mm is checked (see Figure 7.3,*a*).

Error of operation dimension consists of two components connected with machining method ε_P and mounting ε_M

$$\varepsilon = \varepsilon_P + \varepsilon_M.$$

Mounting error includes errors of locating ε_L, clamping ε_C and workholding device ε_D

$$\varepsilon_M = 1.2\sqrt{\varepsilon_L{}^2 + \varepsilon_C{}^2 + \varepsilon_D{}^2}\,.$$

In this case the workpiece is mounted along hole Ø30H7. Mandrel diameter is Ø30h6.

Processing error ε_P is determined by stiffness of technological system, thermal deformations, cutting tool wear. For the considered case ε_P = 0.010 mm [4].

Locating error equals the biggest clearance between diameters of workpiece and mandrel. According to the standards $Ø30H7 = Ø30^{+0.021}$, $Ø30h6 = Ø30_{-0.013}$, hence

$$\varepsilon_L = S_{max} = D_{max} - d_{min} = ES - ei = +0.021 - (-0.013) = 0.034 \text{ mm}.$$

For this method of clamping ε_C = 0 (no radial component of clamping force).

The device error ε_D includes manufacturing error ε_{MA}, wear ε_W and installation ε_i.

In this case ε_i = 0, because the mandrel is installed in centres without errors, that is, axis of centre holes in mandrel does not displace relative to surfaces of centres.

Manufacturing error ε_{MA} is runout of rest surface of mandrel relative to its datum surfaces (centre holes). For this case in aviation engine technology ε_{MA} = 0.010 mm.

Wear of mandrel is specified in technical requirements for the device and it should not exceed $\boldsymbol{\varepsilon_W}$ = 0.015 mm.

Thus, total error is calculated

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon_P} + 1.2\sqrt{\boldsymbol{\varepsilon_L}^2 + \boldsymbol{\varepsilon_{MA}}^2 + \boldsymbol{\varepsilon_W}^2} =$$

$$= 0.010 + 1.2\sqrt{0.034^2 + 0.010^2 + 0.015^2} \approx 0.048 \text{ mm.}$$

Hence $\boldsymbol{\varepsilon} \le \boldsymbol{T}$ and the mandrel ensures the specified accuracy:

0.048 mm < 0.050 mm.

Example 2. Accuracy calculations are performed for workholding device for boring of stepped hole in workpiece in turret lathe (Figure 7.4). Analysis shows that several dimensions $\boldsymbol{D}$, $\boldsymbol{D_1}$, $\boldsymbol{D_2}$, $\boldsymbol{A_1}$, $\boldsymbol{A_2}$, $\boldsymbol{A_3}$, $\boldsymbol{A_4}$, $\boldsymbol{B_1}$ are obtained. Designed device influences only on accuracy of dimension $\boldsymbol{B_1}$ = 50 ± 0.06 mm with tolerance $\boldsymbol{T}$ = 0.12 mm.

The processing error equals $\boldsymbol{\varepsilon_P}$ = 0.015 mm determined from the handbook [4].

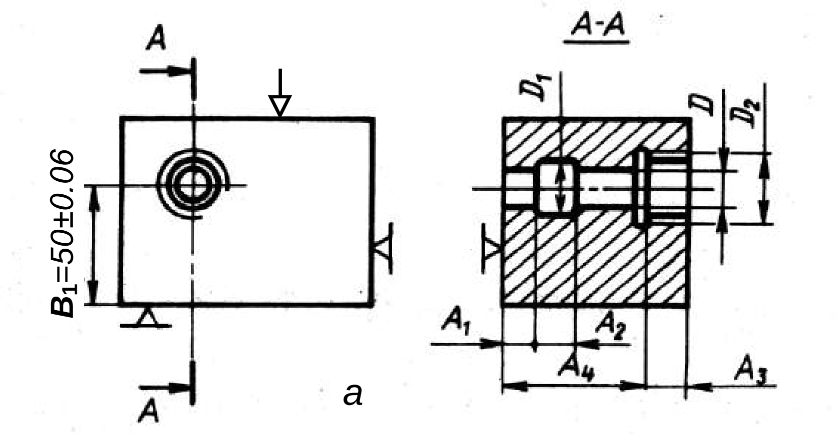
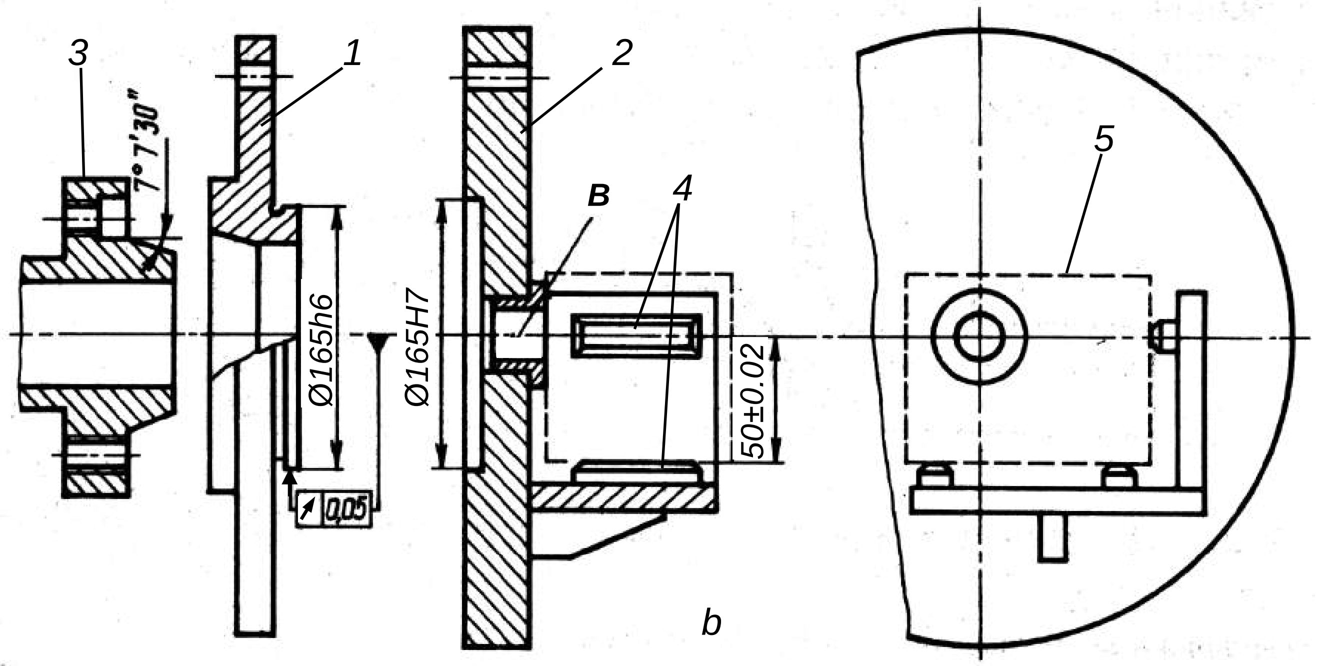


Figure 7.4 – Diagrams for calculations of accuracy at boring in a turret lathe: *a* – workpiece sketch; *b* – workholding device: *1* – flange; *2* – body plate; *3* – work end of spindle; *4* – rest plates; *5* – workpiece



In this case the locating error $\varepsilon_L = 0$, because initial datum of dimension B_1 coincide with mounting datum.

The clamping error $\varepsilon_C = 0$, because vector of force clamping does not coincide with direction of dimension B_1 and due to small deformation of workpiece surface on large areas of rest plates.

The device installation error ε_i is determined by clearance between collar of flange *Ø165h7* and recess of body plate *Ø165H7* relative to the axis.

According to the standards: $Ø165h6 = Ø165_{-0.025}$, $Ø165H7 = Ø165^{+0.040}$. Hence, the first installation error equals maximum clearance

$$\varepsilon_{1i} = S_{max} = D_{max} - d_{min} = ES - ei = +0.040 - (-0.025) = 0.065 \text{ mm}.$$

The maximum permissible displacement (the second installation error) of the flange collar relative to the axis equals half-tolerance for radial runout

$$\varepsilon_{2i} = TCR / 2 = 0.05 / 2 = 0.025 \text{ mm}.$$

The device manufacturing and assembling error ε_{MA} is a tolerance of distance (*50±0.02*) between rest plate and axis ***B*** of recess, which equals $\varepsilon_{MA} = T = \Delta s - \Delta i = +0.02 - (-0.02) = 0.04$ mm.

The device wear error is negligible and so assumed $\varepsilon_W = 0$.

The result total error is

$$\varepsilon = \varepsilon_P + 1.2\sqrt{\varepsilon_{1i}^{\,2} + \varepsilon_{2i}^{\,2} + \varepsilon_{MA}^{\,2}} =$$

$$= 0.015 + 1.2\sqrt{0.065^2 + 0.025^2 + 0.040^2} \approx 0.111 \text{ mm}.$$

Hence, the designed device ensures the specified accuracy as

$$(\varepsilon = 0.111 \text{ mm}) < (T = 0.120 \text{ mm}).$$

Example 3. Accuracy calculations are performed for workholding device for milling of flat spot in round workpiece, which is fixed in the V-block of angle $\alpha = 90°$ (Figure 7.5). Tolerance of operation dimension 20js11(± 0.065) is $T = 0.130$ mm.

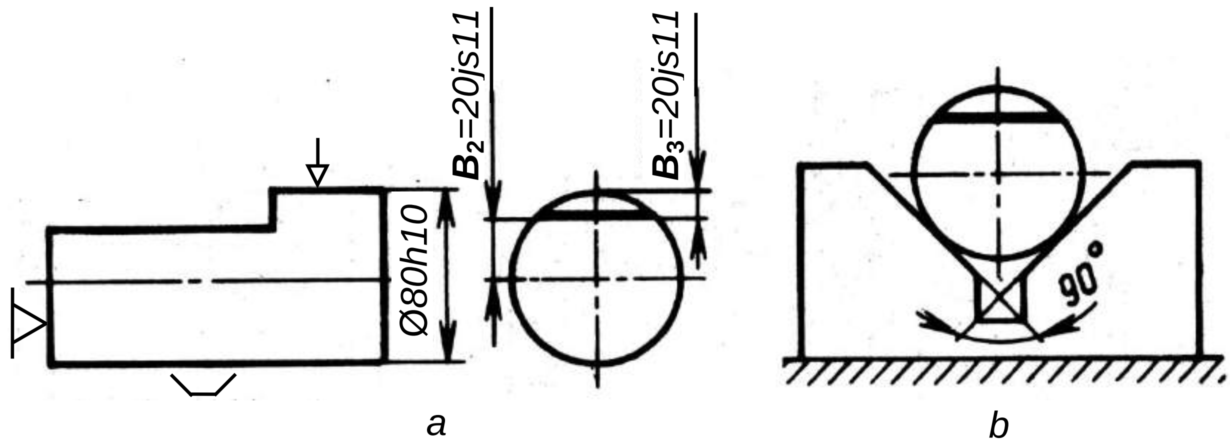


Figure 7.5 – Diagrams for calculations of the device accuracy at milling in V-block: *a* – workpiece sketch; *b* – workholding device

Processing error ε_P is determined by stiffness and deformation of technological system under the actions of cutting forces, temperature in the cutting zone. At milling under the specified conditions ε_P = 0.02 mm [4].

Locating error of cylindrical workpiece in V-block of angle α = 90° is determined from the formula for the B_3 dimension

$$\varepsilon_L = \frac{T_d}{2}\left[\frac{1}{\sin(\alpha/2)}+1\right].$$

According to the standards *Ø80h10* = *Ø80*$_{-0.12}$ and then

$$\varepsilon_L = \frac{0.12}{2}\left[\frac{1}{\sin 45^\circ}+1\right] \approx 0.177 \text{ mm}.$$

For this case the clamping error ε_C = 0. Installation error of the device (V-block) does not exceed ε_i = 0.02 mm [4].

The resulting error is

$$\varepsilon = \varepsilon_P + 1.2\sqrt{\varepsilon_L{}^2 + \varepsilon_i{}^2} =$$
$$= 0.020 + 1.2\sqrt{0.177^2 + 0.020^2} \approx 0.198 \text{ mm}.$$

The designed device does not ensure the specified accuracy of dimension B_3 as (ε = 0.198 mm) > (T = 0.130 mm).

The problem can be solved without making more precise design of the device, just by applying the other operation dimension B_2 with another initial datum (see Figure 7.5). Then the locating error of workpiece is calculated from the formula

$$\varepsilon_L = \frac{T_d}{2\bullet\sin(\alpha/2)} = \frac{0.12}{2\bullet\sin 45^\circ} \approx 0.092 \text{ mm}.$$

At the same other conditions the resulting error is

$$\varepsilon = \varepsilon_P + 1.2\sqrt{\varepsilon_L{}^2 + \varepsilon_i{}^2} = 0.020 + 1.2\sqrt{0.092^2 + 0.020^2} \approx 0.114 \text{ mm}.$$

Now the designed device ensures the specified accuracy of operation dimension as (ε = 0.114 mm) < (T = 0.130 mm).

Example 4. Accuracy calculations are performed for drill jig with quick-change bushings for drilling holes *Ø10H8* in the workpiece (Figure 7.6), which is located by datum surface on rest plates and by hole *Ø12H8* – on diamond pin *Ø12g6*. Analysis shows that the *Ø10H8* hole accuracy is ensured by cutting tool (drill tool), and performance of coordinating dimension A_1 = *50± 0.1* mm with tolerance T_{A1} = 0.2 mm depends on accuracy of workholding device.

Processing error ε_P is negligible for this machining method with use of drill jig. It is assumed ε_P = 0 [4].

The jig installation error at drilling ε_i = 0, because coordinates of machined hole do not depend on accuracy of position of jig body on the drilling machine table.

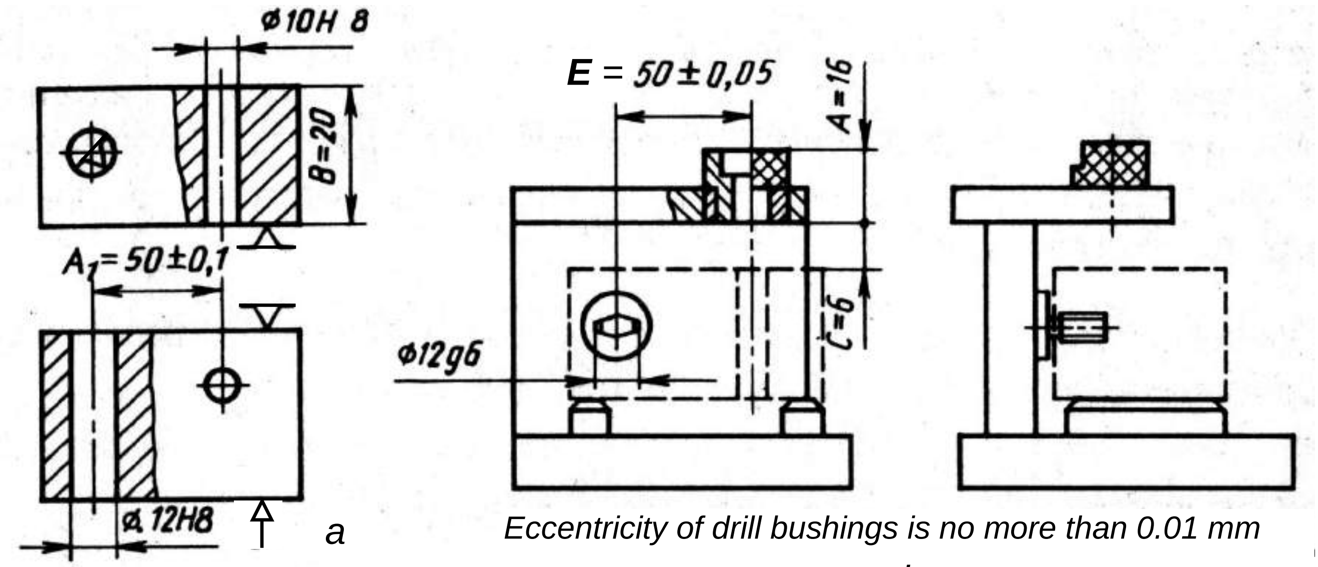


Figure 7.6 – Diagrams for calculations of the drill jig accuracy at machining the hole *Ø10H8* in workpiece: *a* – workpiece sketch; *b* – workholding device

Analysis shows that the jig error ε_D depends on the locating accuracy ε_L of workpiece in the jig body and the manufacturing and assembling error ε_{MA} of guide elements (drill bushings).

Locating error ε_L equals the maximum clearance between surfaces of workpiece hole *Ø12H8* and jig diamond pin *Ø12g6*.

According to the standards $Ø12H8 = Ø12^{+0.027}$, $Ø12g6 = Ø12^{-0.006}_{-0.017}$, then

$$\varepsilon_L = S_{max} = D_{max} - d_{min} = ES - ei = +0.027 - (-0.017) = 0.044 \text{ mm}.$$

Error of guide elements ε_{MA} depends on error of axis displacement ε_{Di} relative to its nominal position and error of the hole axis run-off ε_R

$$\varepsilon_{MA} = \sqrt{\varepsilon_{Di}^2 + \varepsilon_R^2}.$$

The error of axis displacement relative to nominal position

$$\varepsilon_{Di} = \sqrt{(T_E/2)^2 + e_p^2 + (S_B/2)^2 + e_q^2}.$$

In the Figure 7.6 tolerance for dimension $E = 50 \pm 0.05$ mm from diamond pin to bushing axis is T_E = 0.1 mm, eccentricity of permanent bushing e_p = 0.01 mm, eccentricity of quick-change bushing e_q = 0.01 mm. Quick-change bushing is inserted into permanent bushing by fit *Ø15H7/g6*.

According to the standards $Ø15H7 = Ø15^{+0.018}$, $Ø15g6 = Ø12^{-0.006}_{-0.017}$, hence, maximum clearance between bushings equals

$$S_B = D_{max} - d_{min} = ES - ei = +0.018 - (-0.017) = 0.035 \text{ mm}.$$

The calculated error of axis displacement relative to nominal position

$$\varepsilon_{Di} = \sqrt{0.050^2 + 0.010^2 + 0.0175^2 + 0.010^2} \approx 0.055 \text{ mm}.$$

Error of hole axis run-off $\boldsymbol{\varepsilon_R}$ is calculated from the formula constructed from the jig geometry in Figure 7.6

$$\boldsymbol{\varepsilon_R} = \boldsymbol{S_{max}}\left(\frac{\boldsymbol{B}+\boldsymbol{C}}{\boldsymbol{A}}+0.5\right).$$

In the drilling operation the first manufacturing step is drilling of hole *Ø9.8H11* and than (the second manufacturing step) the hole is reamed to *Ø10H8*. The drill tool is manufactured as $Ø9.8h8\left(_{-0.022}\right)$. Hole diameter in quick-change bushing is $Ø9.8F7\left(^{+0.028}_{+0.013}\right)$. Then, the maximum clearance between quick-change bushing and drill is

$$\boldsymbol{S_{max}} = \boldsymbol{D_{max}} - \boldsymbol{d_{min}} = \boldsymbol{ES} - \boldsymbol{ei} = +0.028 - (-0.022) = 0.050 \text{ mm}.$$

The error of workpiece hole axis run-off in the drill jig is

$$\boldsymbol{\varepsilon_R} = 0.050\left(\frac{20+6}{16}+0.5\right) = 0.106 \text{ mm}.$$

Thus, the resulting error of operation dimension $\boldsymbol{A_1}$ is

$$\boldsymbol{\varepsilon} = 1.2\sqrt{\boldsymbol{\varepsilon_L}^2+\boldsymbol{\varepsilon_{Di}}^2+\boldsymbol{\varepsilon_R}^2} = 1.2\sqrt{0.044^2+0.055^2+0.106^2} \approx 0.153 \text{ mm}.$$

The designed drill jig ensures the specified accuracy of operation dimension $\boldsymbol{A_1}$ as ($\boldsymbol{\varepsilon}$ = 0.153 mm) < ($\boldsymbol{T_{A1}}$ = 0.200 mm).

7.3.2 Calculations of clamping reliability

Clamping mechanisms are used for fixation of workpieces in workholding devices. When selecting a clamping mechanism, first of all it is necessary to observe condition of clamping reliability, that is, to guarantee that a workpiece in a machining process under the action of all forces and moments would not displace from the fixed position, rush around or break loose from the clamps.

When solving this task, one selects direction and place for application of clamping force, and then the required value of clamping force is determined. For simplification of calculations of required force for clamping of workpiece it is assumed that machining occurs at steady cutting process and system "workholding device – workpiece" is rigid. The static task of equilibrium of solid body is solved under the action of all applied forces and moments: cutting, inertia, workpiece gravity, clamping, friction in places of contact of workpiece with rest and clamping elements of device. Calculation diagram is plotted for the most unfavourable position of cutting tool along machined surface of workpiece.

In most cases when calculating the required clamping force only cutting forces and moments are considered. Their values are determined from special formulas for different metal-cutting processes. But in machining process the actual cutting forces can significantly differ from the calculated values, because of deviations of mechanical properties of workpiece material, strainhardening and surface crust in workpiece, dulling of cutting tools, thickness non-uniformity of machining allowance. Furthermore at the selected diagram for calculations of clamping force the different conditions of contact surfaces are possible (rumpled surfaces, presence of lubricant, different surface roughness, etc.) between rest surfaces of device and workpiece, workpiece and clamping element.

All these deviations in cutting forces and contact surfaces conditions are impossible to take into account. Therefore in practice the calculated value of cutting force is multiplied by coefficient of clamping reliability ***K***, which is assumed as 1.5…2.5 (the smaller values are for finish machining, the larger – for rough machining). Hence, calculations of clamping force are performed with clamping reliability coefficient.

In those cases when machining of workpiece is performed with big rotational speed (more than 2000 rpm), the centrifugal forces are considered.

After determination of the required clamping force, the final selection of clamping device design and drive are performed.

Calculation formulas, diagrams of clamping mechanisms and drives are considered in Chapter 3.

7.3.3 Economic substantiation for introduction of workholding device

Calculations of cost efficiency are based on comparison of savings and annual costs. The savings ***E*** are created due to decrease of production costs for workpiece machining, and sometimes due to decrease of labour grade. Annual costs ***C*** include capital allowances and costs for device service. Device is expedient for application, if

$$\boldsymbol{E} > \boldsymbol{C},$$

where ***E*** – expected savings due to use of device per year; ***C*** – costs for device per year.

Total benefit of device usage is equal to difference

$$\boldsymbol{E_t} = \boldsymbol{E} - \boldsymbol{C}.$$

Expected savings ***E*** are determined from the formula

$$\boldsymbol{E} = (\boldsymbol{t_P} - \boldsymbol{t_P}^e) \times \boldsymbol{c_m} \times \boldsymbol{N}.$$

where $\boldsymbol{t_P}$ – time per piece in manufacturing operation without special-purpose workholding device; $\boldsymbol{t_P}^e$ – expected time per piece in manufacturing operation after introduction of special-purpose workholding device; $\boldsymbol{c_m}$ – production cost of one machine minute; ***N*** – planned annual program, pieces.

During development of device it is usual to compare economy of various design variants of device and to choose the most profitable.

7.4 Performance of drawings for workholding devices

Development of drawing of workholding device is performed in a certain sequence. First the contours of machined workpiece are drawn in a proper projection. Then the mounting and clamping elements are shown attached to the projection of workpiece, as well as, guide and dividing elements, if any. After that the body part of device is drawn. Design of body should be simple in order to produce it from standardised initial blanks. And then the auxiliary and other necessary parts are drawn.

In drawing a workholding device is shown in work position with all necessary projections, sections and sectional views that allow explaining designs of all device elements and their interaction (Figure 7.7).

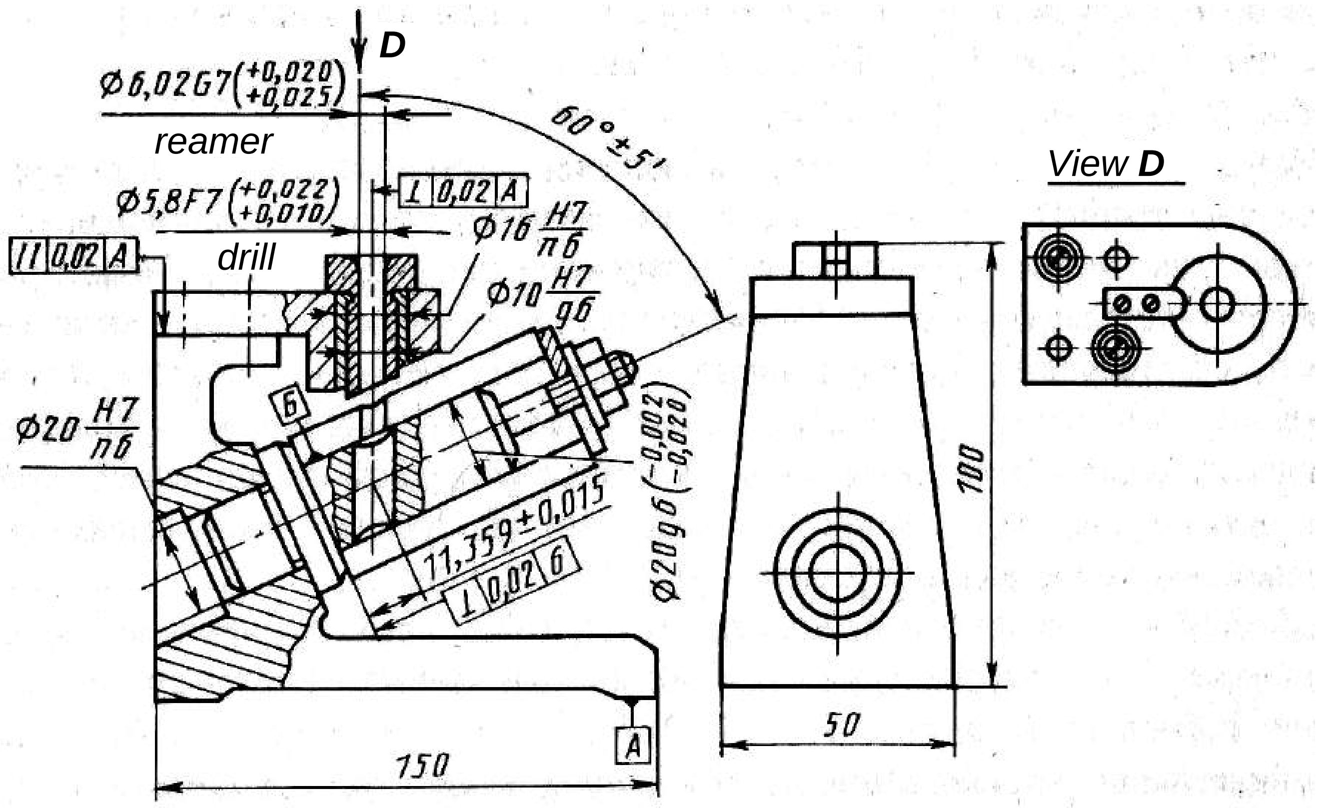


Figure 7.7 – Fragment of general view drawing of the drill jig

Standardised units and parts should be used as many as possible in the design of device. It may reduce costs for the device development by 25 % and production costs – by 20…30 %. Geometric shapes and dimensions of original parts are determined from the strength analysis or assigned from the design consideration.

General view of device is drawn, as usual, in scale 1:1. Overall and coordinating dimensions, fits, dimensions of guide elements are specified in the drawing, as well as, dimensions of elements connecting the device with a machine. Furthermore, technical requirements that determine assembling accuracy of device and its installation in machine, service conditions, terms for check of accuracy parameters, etc. are developed and written down.

The selection of structural materials is based on correlation between mechanical properties and operation conditions of parts in workholding device. Most of parts (housings, clamps, shafts, axles, pivots, spindles, toothed gear wheels, etc.) are subjected to big loads and should be rigid and strong enough. The first criteria for material selection for such elements as guide, mounting, dividing, self-centring is wear-resistance, because their wear directly influences on accuracy of workholding devices and machined workpieces.

According to the standards of Unified System of Design Documentation (USDD) a general view drawing should contain: a) representations of an item (projections, sections, sectional views), text, captions, tables necessary for understanding an item design, interaction of its components and principle of operation; b) names of those components, for which the technical data, material, quantity, principle of operation are given, and names of those components, which are mentioned in explanation of drawing, description of operation principle, etc.; c) necessary design dimensions, as well as, overall, attachment and installation dimensions; d) scheme of item, if needed; e) technical requirements for an item and its technical data. In item representations the components are shown with simplified symbols, if it does not prevent proper understanding design, interaction of components and principle of operation. Components are numbered, and numbers are depicted on shelves of extension lines. Names and designations of components are usually given in the table located over title block. Textual part of drawing is placed over the table.

The USDD standards state the following requirements for performance of assembly drawings. Representations of item (projections, sections, sectional views) should give complete understanding of location and interaction of item components and realise assembly and check of item. The following dimensions should be specified in assembly drawing: checked and other dimensions necessary for assembling procedure, overall, installation, attachment and needed information dimensions. Movable parts of item are shown in extreme (or intermediate) position by thin dash double-dot line. It is permitted to show neighbour items ("circumference") by thin continuous line. In the drawings related to production process (dies, moulds, workholding devices, etc.) it is possible to draw an operation sketch in the top right corner of drawing. Technical characteristics (data and requirements) of item are written over title block. All components (assembly units and parts) are numbered, and numbers are depicted on shelves of extension lines. The numbers, designations and names of components are written in specification. Attached to the assembly drawing a specification document is performed in sheets of A4 format. Specification is a main design document in the form of table, which contains list of all components of item, as well as, list of all design documents.

General-view drawing and assembly drawing are performed according to certain stage in standardised procedure for development of design documentation.

QUESTIONS

1. What are the initial materials (data) necessary for development of workholding device?

2. What are the stages in the development procedure for workholding device?

3. Describe algorithm of accuracy calculations of workholding device.

4. What are the principles of calculations of reliability of clamping?

5. Describe economic analysis of introduction of workholding device.

6. What are the standard rules for performance of general-view and assembly drawings?

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CONTENT

Навчальне видання

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