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РОЗРАХУНКИ РЕЖИМІВ РІЗАННЯ ТОКАРНОЇ, СВЕРДЛИЛЬНОЇ Й ФРЕЗЕРНОЇ ОПЕРАЦІЙ

Навчальний посібник

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CALCULATIONS OF CUTTING CONDITIONS FOR TURNING, DRILLING AND MILLING OPERATIONS

Teacher’s aid

Харків «ХАІ» 2009

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Наведено методику проектування операцій механічної обробки точінням, свердленням, фрезеруванням заготовок з важкодеформівних матеріалів. Подано детальні алгоритми вибору та розрахунків технологічних режимів і основних енергосилових параметрів процесів. Викладений матеріал призначено для більш глибокого вивчення питань, пов'язаних з проектуванням операцій механічної обробки, конструкційними матеріалами, а також з різанням матеріалів, різальним інструментом та обладнанням.

Для студентів механічних спеціальностей при виконанні курсових і дипломних проектів з проектування технологічних процесів, а також для іноземних студентів з англійською мовою навчання.

Іл. 9. Табл. 43. Бібліогр.: 10 назв

Methods for planning of machining operations of turning, drilling, and milling of workpieces from hard-to-machine materials are submitted. Detailed algorithms of selection and calculations of technological conditions and main energy-force process parameters are given. Submitted information is destined for deeper studying of problems connected with planning of machining operations, structural materials, as well as with cutting of materials, cutting tools and equipment.

It is destined for students of mechanical specialties at performance of term and diploma projects on planning of manufacturing processes and for foreign students educating in English language.

Figures 9. Tables 43. Bibliogr.: 10 references

Рецензенти: д-р техн. наук, проф. М.В. Верезуб,
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Introduction

Development of technology is connected with creation and mastering of processes for machining of workpieces from steels and alloys with special physical and mechanical properties, the most important of them are corrosion resistance in various mediums, high-temperature strength and large strength. Development of manufacturing processes for production of parts from such materials is connected with difficulties because of absence of well-ordered data on machining of these materials and properly developed teaching aids on planning of machining operations.

This teaching aid is based on the work [1] and includes data for calculations of rational cutting conditions for turning, drilling and milling operations for machining of workpieces from hard-to-machine steels and alloys widely used in aircraft-engines industry. Short information about thermal and force phenomena in zone of chip formation is given for these materials, their classification and description of classification groups. Each calculation method is supplied with detailed algorithm of calculations including identification of work material. Selection of cutting-tool material, specifying the depth of cut and feed are considered, as well as calculations of main parameters of cutting process. The role of factors that influence these parameters is substantiated. Special emphasis is made on agreement of process parameters with equipment, on check of selected elements of cutting conditions.

Technological recommendations and calculation relationships for determination of velocity and force of cutting are trustworthy enough, because they are developed on the base of large volume of experimental data and results of industrial tests described in the book [2].

Calculation relationships are used for specified ranges of feed, geometric parameters of a tool's cutting point, tool materials and cutting fluids when machining workpieces in versatile machines. Changed conditions are described by correction coefficients. The recommendations are right when workpieces are machined after typical thermal treatment specified in Appendix 1 with observation of machining sequence given in Appendix 3.

When applying CNC machines, the single-tool machining is reasonable to perform: in turning machines (characterized by large rigidity of technological system) with cutting velocities 15…20 % more, and in drilling machine 10…15 % less than the calculated ones. The latter is explained by very short life of drills and their large "sensitivity" to cutting velocity. Multi-tool (up to 10 tools) machining is performed at velocities 10 % less than the calculated ones, and with larger quantity of tools – 15…20 % less.

General instructions

Planning of operation is begun from development of sketch of operation (Fig. 1.1). The sketch should include:

15 Turning

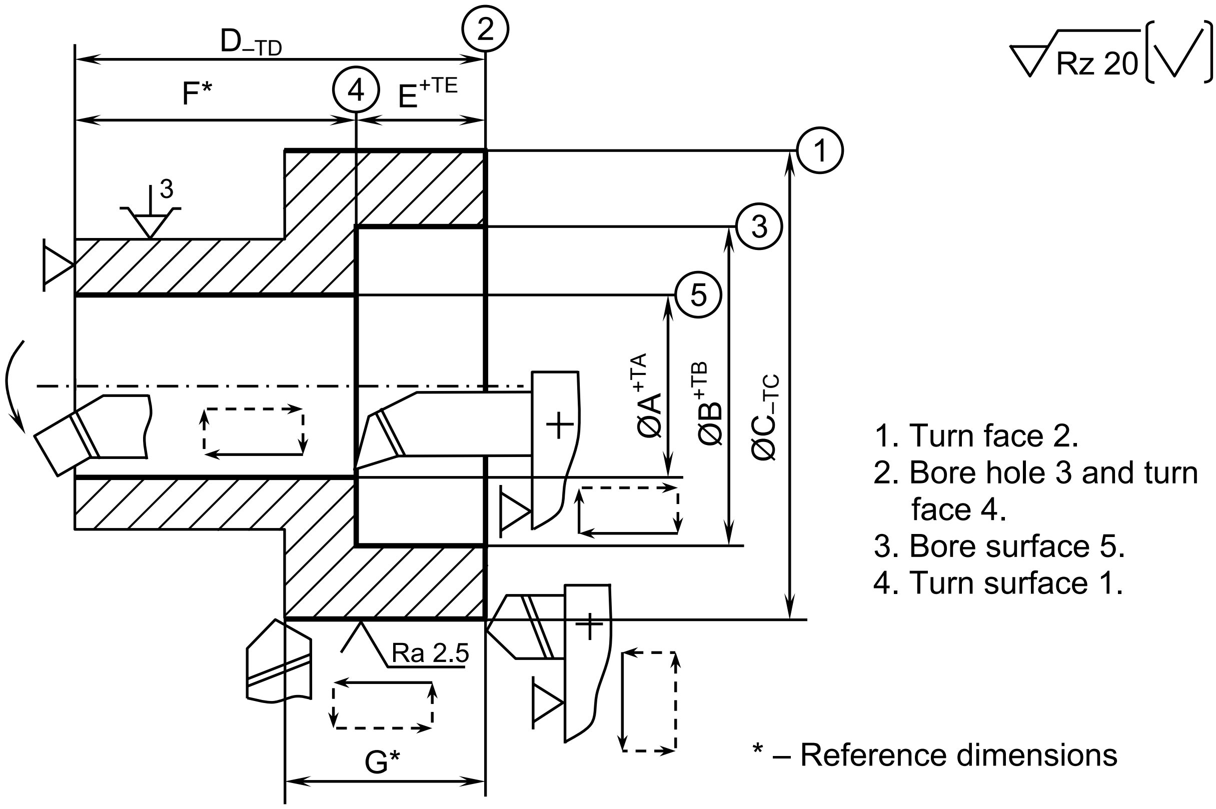


Figure 1.1. Sketch for turning operation

- Number of operation and its name according to the classification of manufacturing operations [3];
- Blank is shown in an arbitrary scale with approximate observation of dimensions ratios in the orientation corresponding to the working zone of a machine;
- Mounting and clamping elements are shown by conventional symbols according to the standard GOST 3.1107-81;
- Work surfaces should be marked with thick lines and numbered;
- Operation dimensions are specified with limits directed “into metal”. Reference dimensions are specified if necessary;
- Roughness of surfaces is shown according to the standard GOST 2.309-73;
- Cutting tools (fragments) are shown at the end of work strokes;
- Cyclogram of cutting tool’s motions is shown near to cutting tool: work strokes – solid lines; auxiliary strokes – dashed lines;
- Manufacturing steps are written in the imperative mode according to the standard GOST 3.1702-79 in the order of their performance.

Report on planning of operation should include:

– Exact and laconic description of operation planning;
– Substantiation of selected parameters;
– Paragraphs containing calculations are to be supplied with algorithm and example of calculations; initial data and calculation results for all manufacturing steps are included into the corresponding tables.

1. TURNING

1.1. Identification of work material

The first stage of operation planning is identification of work material with one of the materials given in the classification (Appendix 1). The extract from GOST 5632-72 [4] is given in Appendix 2 for the same purpose. The identification is performed by chemical composition, structure, physical and mechanical properties, machinability. Machinability is characterized by cutting velocity (by its maximal value at non-monotonic character of relationship "velocity-life") corresponding to the certain life of tool of optimal design for machining of considered material.

Materials with high specific strength find wide application in modern propulsion engineering. But when machining these materials it is necessary to reduce cutting velocities because of their lower machinability. Thus, when machining the workpieces from high-temperature steels cutting forces are 1.2…1.5 times, and from high-temperature alloys – 2 times more than forces appeared when machining workpieces from the steel 45. Large cutting forces result in evolving of large amount of heat in the cutting zone. Moreover, the most of hard-to-machine materials possesses low thermal conductivity that, in its turn, results in high temperatures, 2-3 times more than in machining of ordinary structural materials.

Because of large forces for cutting these materials it is necessary that rigidity of system "machine-device-workpiece-tool" (MDWT) would be high. Increase of contact temperatures is a main cause of low life of cutting tools. In order to avoid a temperature rise the machining of difficult-to-cut materials is performed at low cutting velocities.

The classification (ref. Appendix 1) divides hard-to-machine materials [2] into 8 groups (the data of group VIII are not given). Each of them combines steels and alloys of approximately similar chemical composition, similar mechanical properties, and similar machinability. Machinability coefficients with respect to steel 45 and approximate values of cutting velocities used, when machining with tools from cemented carbides for optimal (recommended) conditions are given. In the case of machining with tools from high-speed steels (HSS) the cutting speed is reduced 4 times in average, when machining the titanium alloys – 3 times, and when machining the alloys of group VI the HSS cutting tools are not applied totally.

In the Handbook [2] the following determinations of special steels and alloys are submitted:

1) Heat-resistant steels are those possessing ability to resist to deformation and fracture under a mechanical load in the temperature range of less than 550ºC, when there is no danger of intensive scaling;

2) Corrosion-resistant steels are those possessing resistance to electrochemical corrosion (atmospheric, soil, alkaline, acid, salt, seawater, etc.);

3) Scale-resistant (refractory, oxidation-resisting) steels and alloys are those possessing ability to resist chemical surface decomposition in gaseous mediums at temperatures more than 550ºC and operating in unloaded and low-loaded condition;

4) High-temperature (creep-resisting) steels and alloys are those possessing ability to operate in loaded condition at high temperature (more than 700ºC) during specified period of time and having sufficient scale-resistance;

5) High-strength steels are those having ultimate strength $\boldsymbol{\sigma_u} \geq 1600$ MPa.

Steels placed into the **group I** are characterized by chromium content of up to 6 %, nickel – up to 3 %, molybdenum and vanadium – up to 1 % each and silicon – up to 2 %. They are heat-resistant materials and may be applied for production of intake and exhaust valves of motors, blades and disks of turbines operating at temperatures of 500…600ºC. Machinability of the I group steels is quite satisfactory, it is near to machinability of carbon and low-alloyed structural steels of corresponding strength.

Steels of **group II** are characterized by high content (more than 10…12 %) of chromium and low content (up to 4 %) of other alloying elements. They are mainly applied for fittings, body-type parts, turbine blades and disks operating at temperatures up to 500…550ºC.

Machining of this group steels is performed both after annealing and after hardening and tempering to $\boldsymbol{\sigma_u}$ = 1000…1400 MPa. In the annealed condition these steels have satisfactory machinability: cutting velocity 1.5 times lower those applied for machining of steel 45. With increase of the strength characteristics of steels resulted from their heat treatment, the machinability of high-chromium steels decreases abruptly.

When machining steels of this group in annealed condition it is difficult to obtain low surface roughness, especially when performing thread cutting, broaching, slab milling and other operations, when surface is formed by tool blades of large length. With increase of steel strength the roughness of machined surface improves.

Austenitic steels ascribed to **group III** contain big amount of chromium (more than 15 %) and nickel (more than 5 %), as well as small amount of other alloying elements (titanium, silicon, etc.). This group also includes steels of austenitic-martensitic and austenitic-ferritic classes. After annealing the machinability of austenitic-martensitic steels is near to machinability of steel 12X18H10T (12H18N10T), and after hardening and tempering – to steels of the II group of the corresponding strength.

Steels of this group are applied as acid-resistant, corrosion-resistant and scale-resistant materials almost in all brunches of industry for production of compressor vanes, fire tubes and other components operating under conditions causing metal corrosion or under conditions of high temperatures (up to 800ºC). Cutting velocities for machining these steels are approximately 2 times lower as compared with steel 45.

Group IV includes composite-alloyed steels of austenitic class containing chromium in large amount (12…25 %), less amount of manganese, molybdenum, titanium, tungsten, vanadium and other alloy elements. In some steels the content of nickel is reduced due to increase of amount of cheaper and not so scarce manganese. Steels of this group are used for manufacturing disks and blades of gas turbines, parts of gas pipelines and fastenings operating at temperatures of up to 650…750ºC, and at moderate stresses – up to 800…950ºC. Machinability of these steels is 3–4 times lower than machinability of steel 45.

Group V includes high-temperature wrought alloys on nickel and iron-nickel bases alloyed with large amount of chromium (10…20 %) and less amount of titanium, aluminium, tungsten, molybdenum, cobalt and other elements. They are applied for production of parts operating at big loads and high temperatures of up to 750…950ºC (disks, rotor and guide blades and other components of gas turbines).

When machining workpieces from these alloys, cutting tools from cemented carbides are mainly used for continuous cutting. In many cases of non-continuous cutting (face and end milling) it is reasonable to use tools from high-speed steels. One of the causes of rapid wear and crumbling of tools from cemented carbides at non-continuous cutting is sticking (adhesion) of work material particles to cutting edges of tool at the moment of its exit from metal. At the sequent moment of cutting-in the adhered particles are torn away from edges together with particles of cemented carbides. Machinability of alloys of this group is 6…12 times lower than machinability of steel 45.

Cast high-temperature alloys on the nickel and chromium bases are included into **group VI**. They are widely applied for manufacture of nozzle blades, integrally cast rotors and other parts of gas turbines. They possess bigger high-temperature strength than wrought high-temperature alloys due to more additions of alloying elements.

In these alloys there is large amount of intermetallic and carbide compounds, because of which cutting tools from high-speed steels are rapidly worn. Therefore nearly in all operations of machining the workpieces from cast high-temperature alloys the tools with cemented carbides tips should be used. Phenomena causing adhesive wear of tools appear here in significantly less measure (than in machining of the V group alloys) due to lower strength and plasticity of cast alloys. Cutting velocity at machining of workpieces from cast high-temperature alloys 12…20 times lower than at machining of steel 45.

Alloys of the **VII group** on the titanium base are widely used in various branches of industry and especially in aircraft engines building. In a number of designs they force out aluminium alloys and corrosion-resistant steels due to high specific strength, high-temperature strength, thermal stability and corrosion resistance up to certain temperatures. Large group (more than 30 grades) of titanium-base alloys is applied with wide range of machinability that mainly depends on alloy ultimate strength. Blanks from titanium-base alloys with σ_u < 1000 MPa without scale, crust and alphated (saturated with gases) layer are relatively easily machined by tools of high-speed steels and cemented carbides. Machining of workpieces from alloys with σ_u > 1000 MPa by tools of high-speed steels is difficult. And at machining with scale and alphated layer only cemented-carbides tools should be applied.

Turning, milling and drilling of workpieces from titanium alloys do not involve specific difficulties. However, owing to large elasticity of these alloys thread cutting with taps, reaming and broaching of holes is problematic because of tool cramping along side and end relief surfaces. In this connection the side and end relief tool angles should be specified 3…5º larger than angles for machining the structural steels.

Most titanium-base alloys are applied in the annealed condition. However, the alloys hardened by quenching and aging, as well as by thermomechanical treatment (BT14 (VT14), BT15 (VT15), BT3-1 (VT3-1), BT22 (VT22)), are used for production of many critical components. Machinability of these alloys after the mentioned types of hardening is 20…25 % lower than after annealing.

Titanium alloys differing by high chemical inertness actively react with gases at higher temperatures starting from 600ºC. The most active element at gasing is oxygen. Hardness of layer saturated with gases greatly increases (3…5 times). Thickness of scale and depth of alphated layer depend on temperature and exposure time. Therefore, method for production of blanks from titanium alloys influences the machinability with crust. Thickness of defective layer in castings can reach several millimetres, in forgings – 1 mm, in rolled products – 0.5 mm. Machinability with crust of forged bars is lower than rolled ones. Cutting velocities at machining of workpieces from titanium alloys depending on their ultimate strength is 1.5…4 times lower relative to steel 45. When machining with crust, the cutting velocities are additionally 2 times decreased.

1.2. Selection of design and geometric parameters of cutting tools

Selection of a cutting tool (its design and geometric parameters) is determined by configuration of work surface, workpiece material and thickness of removed layer.

Outside, internal and butt open surfaces (which do not mate with surfaces that prevent advance and retract of tool in the direction of feed) are machined with straight turning tools with side cutting-edge angle φ = 45º and end cutting-edge angle φ_1 = 15º (Fig. 2), except boring tools that have φ = 60º and φ_1 = 30º. If cylindrical surface mates with a face, the side-facing or turning-and-facing tool (at very small width of face) is applied. Slotting, parting, form and other types of tools are used too.

So as machining of workpieces from hard-to-machine materials is accompanied with large forces, applied to the MDWT technological system, it is recommended to select machines of increased stiffness and cutting tools with larger cross-section of shank and small overhang (1.0…1.5 of the shank cross-section height) from tool post. Tools are applied both with brazed tips and with changeable polyhedral tips.

Recommended geometric parameters of tool cutting point in dependence on work material and feed are given in the Table 1.1 (ref. Fig. 2). Other parameters of tools are described in the corresponding standards (GOSTs).

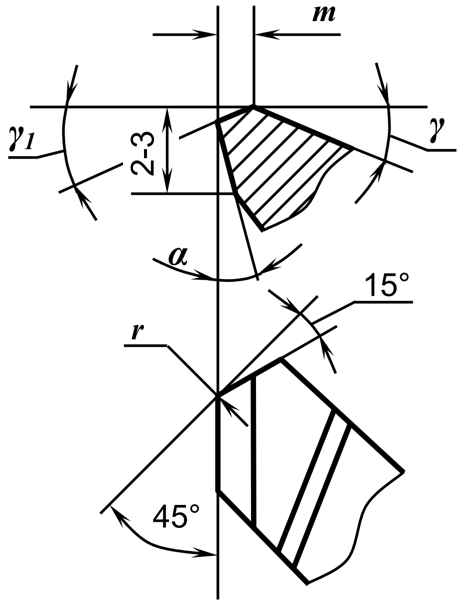


Figure 1.2. Geometric parameters of tool cutting point: α – side relief angle; γ and γ_1 – rake angles; r – nose radius; m – corrective margin

In cemented carbide tools, operating with feeds more than 0.1 mm/rev, margin (chamfer) is made with zero or negative angle on the rake surface that results in increase of their life, but also causes increase of cutting force and press-out of tool.

Main geometric parameters of cutting points of tools from high-speed steels are the same as for cemented carbide tools.

Table 1.1

Geometric parameters of cutting points of tools from cemented carbides for turning of workpieces from hard-to-machine steels and alloys when working with feed values of more than 0.06 mm/rev

Workpiece material		***f***, mm/rev	γ	α	γ_1*	***m****	***r***
Group number	σ_u, MPa		degree			mm	
I, II, III	600…900	≤ 0.3 0.3…0.5	16	8	0… –3	0.1…0.2 0.3…0.4	0.5…1.0 1.0
		0.6…0.8 > 0.8	20 24	6	0… –5	0.5…0.7 0.8…1.0	1.5 2.0
IV	700…1000	0.3 0.3...0.5	10 12	10		0.1…0.2 0.3…0.4	0.5…1.0 1.0
V & VI	700…1300	≤ 0.3 0.3…0.5	5 10	15 10		0.1…0.2 0.3…0.4	0.5…1.0 1.0
II	1200	≤ 0.3	–5	8…10	–	2…3	0.5…1.0
VII	600…1400	≤ 0.8	0…–5	10			

Note. * – Only for cemented carbides

In calculation paper a sketch of one of cutting tools is depicted, for other tools only cutting points of upward view are shown. Main parameters are to be written into the numbered table with headline.

1.3. Selection of cutting tool material and cutting fluid

Turning and boring of workpieces from hard steels and alloys are performed mainly by tools with tips of cemented carbides. In some cases – when turning and boring non-continuous surfaces, when machining surfaces of complicated profile with form tools, when producing special types of threads in automatic machines – it is reasonable to apply tools of high-speed steels.

1.3.1. Tool cemented carbides

For machining workpieces from hard-to-machine steels and alloys the cutting tools from the following cemented carbides are applied: 1) on the tungsten base, which structure consists of grains of tungsten carbide bound with cobalt; 2) on the titanium-tungsten base, which structure consists of grains of solid solution of tungsten carbide in titanium carbide and excessive grains of tungsten carbide bound with cobalt, or only of solid solution of tungsten carbide in titanium carbide bound with cobalt; 3) on the tantalum-titanium-tungsten base, which structure consists of grains of solid solution of titanium carbide – tantalum carbide – tungsten carbide bound with cobalt.

Groups of cemented carbides are divided by chemical composition, physical, mechanical and operation properties.

Alloys of tungsten group of the similar chemical composition differ by dimensions of grains of carbide elements that determine their physical-chemical properties and applications. Cemented carbides (for example, ВК8 (VK8)) with grain size of 3…5 micrometer have coarse-grained structure. Alloys (for example, ВК6М (VK6M)) with grain size of 0.5…1.5 μm are named fine-grained ones. Alloys (for example, ВК6-ОМ (VK6-OM)) having 70 % grains of size less than 1 μm are superfine-grained or with superfine structure.

As compared with coarse-grained, the fine-grained alloys, having less porosity, at cutting of thin chips are more abrasion-resistant due to smaller thickness of cobalt binder that results in higher resistance to diffusion abrasion. At finish and semi-finish machining the abrasion-resistance of tools made of ВК6М (VK6M) is higher than one of ВК8 (VK8), and of ВК6-ОМ (VK6-OM) is higher than of ВК6М (VK6M). Application of ВК6-ОМ (VK6-OM) is especially reasonable, when it is needed to work with tools of high dimensional durability.

Tools of fine-grained structure alloys (ВК3М (VK3M), ВК6М (VK6M)), as well as of superfine structure (ВК6-ОМ (VK6-OM)), due to their higher abrasion-resistance than alloys ВК3 (VK3) and ВК6 (VK6), but of a little less operation strength, resistance to shocks, vibrations and cyclic loads, are recommended to apply for finish and semi-finish operations for machining workpieces of all groups of hard-to-machine materials.

As compared with fine-grained alloys, the coarse-grained ones possess lower abrasion-resistance and thermal endurance, but higher strength; they resist much better to shocks and cyclic loads. Due to these features, tools of BK8 (VK8) alloy are reasonable to apply for rough turning of workpieces at conditions of large runout, deep scale, large surface cavities, cracks and hair seams, that is, when tools of cemented carbides of other grades crumble, and tools of high-speed steels have very low endurance.

Tools made of cemented carbides of titanium-tungsten group are applied for rough (T15K10), semi-finish and finish (T15K6) machining of steels of groups I and II. Tools of the T15K6 alloy are also partially applied for semi-finish and finish turning workpieces from steels of groups III and IV.

Tools of three-carbide alloys are used for hard rough, semi-finish turning and other types of machining that make rigid demands to resistance of an alloy to thermal and mechanical cyclic loads.

Chemical composition and characteristics of physical and mechanical properties of cemented carbides are given in the Appendix 4, and data about application of cemented carbides for machining the workpieces from hard-to-machine materials at various operations are submitted in the Table 1.2.

1.3.2. High-speed steels

Steels of normal and improved productivity (thermal endurance) are mainly applied:

– Steels of normal productivity: P6AM5 (R6AM5), P6M5 (R6M5), P6AMФ3 (R6AMF3), P6M5K5 (R6M5K5), P6AM5Ф3 (R6AM5F3) and others. Hardness of these steels is HRC = 62…66, thermal endurance – 620…640°C, ultimate bending strength σ_b = 3000…4000 MPa;
– Steels of improved productivity: P12Ф3 (R12F3), P9K5 (R9K5), P9M4K8 (R9M4K8) and other. Hardness of these steels is HRC = 63…68, thermal endurance – 630…650°C, ultimate bending strength σ_b = 2200…3500 MPa.

Tools made of improved-productivity alloys (dispersion-hardening) have very high endurance when machining high-temperature steels and especially titanium-based alloys. But because of low strength these alloys are of restricted application.

Main characteristics of physical and mechanical properties of high-speed steels are given in Appendix 5. Grades of high-speed steels are selected from the Table 1.2 and Appendix 6 assuring the longest tool life.

Wear along relief surface should be used as a criterion of tool dulling when turning workpieces from hard-to-machine steels and alloys:

- 0.3 mm for finish turning;
- 0.3…0.5 mm for semi-finish turning;
- 0.8…1.0 mm for preliminary and rough turning;
- 1.5…2.0 mm for coarse turning.

Table 1.2

Tool cemented carbides and high-speed steels for machining workpieces from hard-to-machine steels and alloys

<table>
<tr><th colspan="2">Workpiece material</th><th colspan="4">Turning and boring</th><th colspan="4">Drilling with drills of type</th></tr>
<tr><th>Group number</th><th>$\boldsymbol{\sigma_u}$, MPa</th><th>Rough</th><th>Preliminary</th><th>Finish</th><th>With HSS tools</th><th>Flat
$\boldsymbol{D}$ = 1…3 mm</th><th>Solid twist
$\boldsymbol{D}$ < 7 mm</th><th>With tips of cemented carbide
$\boldsymbol{D}$ = 7…30 mm</th><th>Twist of HSS</th></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td></tr>
<tr><td rowspan="2">I</td><td>600 – 800</td><td rowspan="2">T5K10</td><td rowspan="2">T15K6</td><td rowspan="2">T15K6</td><td>P6AM5
(R6AM5)
P6AMΦ3
(R6AMF3)
P6M5K5
(R6M5K5)</td><td colspan="3" rowspan="3">High-speed steel</td><td>P6M5(R6M5)
P6M5Φ3
(R6M5F3)
P6M5K5
(R6M5K5)</td></tr>
<tr><td>900 – 1300</td><td>P6M5K5
(R6M5K5)
P9K5(R9K5)
P6AM5
(R6AM5)</td><td>P6M5K5
(R6M5K5)
P9K5 (R9K5)
P6M5(R6M5)</td></tr>
<tr><td rowspan="2">II</td><td>1200</td><td>T5K10
BK8(VK8)</td><td>T15K6
T5K10</td><td rowspan="2">T15K6
BK3M(VK3M)
BK6-OM
(VK6-OM)</td><td>P6M5K5
(R6M5K5)
P9K5(R9K5)
P6AM5Φ3
(R6AM5F3)</td><td>P6M5K5
(R6M5K5)
P9K5 (R9K5)
P6M5Φ3
(R6M5F3)</td></tr>
<tr><td>1200</td><td>–</td><td>T15K6
BK6M
(VK6M)</td><td>P9M4K8
(R9M4K8)
P6MK5
(R6MK5)
P9K5(R9K5)</td><td>BK6M(VK6M)
BK10-OM (VK10-OM)
BK10M(VK10M)</td><td>BK10M
(VK10M)
BK6M
(VK6M)
BK8
(VK8)</td><td>BK6M
(VK6M)
BK10M
(VK10M)
BK8
(VK8)</td><td>P9M4K8
(R9M4K8)
P10K5Φ5
(R10K5F5)
P9M6K5
(R9M6K5)</td></tr>
</table>

Table 1.2, finished

<table>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th></tr>
<tr><td>III</td><td>600 – 1000</td><td>BK8(VK8)
BK10M
(VK10M)
BK10-OM
(VK10-OM)</td><td>BK6M(VK6M)
BK8 (VK8)
BK10-OM
(VK10-OM)</td><td>T15K6
BK3M
(VK3M)
BK6-OM
(VK6-OM)</td><td>P6M5K3
(R6M5K3)
P6M5Ф3
(R6M5F3)
P6M5
(R6M5)</td><td colspan="3" rowspan="3">High-speed steel</td><td>P6M5K5
(R6M5K5)
P9K5 (R9K5)
P6M5Ф3
(R6M5F3)</td></tr>
<tr><td rowspan="2">IV</td><td>No Ti</td><td>BK8 (VK8)</td><td>BK6M(VK6M)
T15K6</td><td>BK3M(VK3M)
T10K6</td><td rowspan="3">P9M4K8
(R9M4K8)
P6M5K5
(R6M5K5)
P9K5
(R9K5)</td><td rowspan="3">P9M4K8
(R9M4K8)
P6M5K5
(R6M5K5)
P9K5 (R9K5)</td></tr>
<tr><td>Ti is pre-sent</td><td>BK10M
(VK10M)</td><td>BK6M(VK6M)
BK10-OM
(VK10-OM)</td><td>BK3M (VK3M)
BK6-OM
(VK6-OM)</td></tr>
<tr><td>V</td><td>750 – 1250</td><td rowspan="2">BK8
(VK8)
BK10M
(VK10M)</td><td rowspan="2">BK6M
(VK6M)
BK10-OM
(VK10-OM)
BK8 (VK8)</td><td rowspan="4">BK3M
(VK3M)
BK6-OM
(VK6-OM)
BK6M
(VK6M)</td><td>BK6-OM
(VK6-OM)
BK10-OM
(VK10-OM)
BK10M(VK10M)</td><td>BK10-OM
(VK10-OM)
BK8 (VK8)
BK15M
(VK15M)</td><td>High-speed steel</td></tr>
<tr><td>VI</td><td>800 – 1100</td><td>P9M4K8 *
(R9M4K8)
P6M5K5
(R6M5K5)</td><td rowspan="3">BK6-OM
(VK6-OM)
BK6M (VK6M)
BK10-OM
(VK10-OM)</td><td colspan="2" rowspan="3">BK6M (VK6M)
BK10-OM (VK10-OM)
BK10M (VK10M)</td><td>P9M4K8 *
(R9M4K8)
P6M5K5
(R6M5K5)</td></tr>
<tr><td rowspan="2">VII</td><td>450 – 900</td><td rowspan="2">BK8(VK8)
BK10M
(VK10M)
BK15M
(VK15M)</td><td rowspan="2">BK8 (VK8)
BK6M
(VK6M)
BK4 (VK4)</td><td rowspan="2">P9M4K8
(R9M4K8)
P6M5K5
(R6M5K5)
P9K9
(R9K9)</td><td>P6M5K5
(R6M5K5)
P9K5 (R9K5)
P6M5(R6M5)</td></tr>
<tr><td>950 – 1500</td><td>P9M4K8
(R9M4K8)
P6M5K5
(R6M5K5)</td></tr>
</table>

Notes: 1. * – High-speed steels (HSS) are recommended for application only in those cases, when it is impossible to make tools from cemented carbides. 2. Chemical elements in tool materials are denoted by the following letters: in cemented carbides: B(V) – tungsten carbide, T – titanium carbide, K – cobalt; in high-speed steels: P(R) – tungsten, M – molybdenum, K – cobalt, Ф(F) – vanadium, A – nitrogen

1.3.3. Cutting fluids

Cutting fluids greatly influence cutting process and quality of work surfaces. Their application allows increasing life of a cutting tool. Cutting fluids mainly reduce abrasive and adhesion wear, decrease cutting temperature by 100…150°C. Machined surfaces have higher accuracy (decrease of heat distortions of cutting tool and work piece) and lower roughness (cutting fluid prevent adhesion of cutting point with chip and creation of built-up edges). Effective power of cutting decreases by 10…15 % (friction decreases between tool and chip and between tool and workpiece, deformation of removed layer becomes easier, etc.).

Special attention is paid to cutting fluids when high-speed steels are applied for cutting tools.

Some information about cutting fluids is given in Appendix 7, and recommendations for their application in operations of turning and drilling workpieces from hard-to-machine materials – in Table 1.3.

Table 1.3

Recommendations for application of cutting fluids for machining workpieces from hard-to-machine steels and alloys

Operation	Groups of workpiece materials		
	I, II, III	IV, V, VI	VII
Turning	1, 2, 3, 5	1, 2, 3, 5	1, 2, 6, 7
Drilling	1, 2, 3, 5	1, 2, 3, 4, 6, 7	2, 3, 5, 6, 7
Note: Cutting fluids denoted with Arabic figures: 1 – 5-% emulsion from Укринол-1 (Ukrinol-1) emulsol; 2 – 10-% emulsion from Укринол-1 (Ukrinol-1) emulsol; 3 – 5-% emulsion from Аквол-2 (Akvol-2) emulsol; 4 – 10-% emulsion from Аквол-2 (Akvol-2) emulsol; 5 – 5-% emulsion from Аквол-6 (Akvol-6) emulsol; 6 – МР-1у (MR-1u); 7 – МР-6 (MR-6)			

In order to exclude cyclic thermal loads the cooling of tools should be continuous, especially those made of cemented carbides.

Machining workpieces from the considered materials is non-manufacturable, because they are often machined 3…5 times, and in many cases (materials of groups V and VI) – 10…20 times worse in comparison with steel 45. Therefore the investigations are conducted to improve their machinability.

Thus, for finish and semi-finish turning workpieces from steels of groups I, II, III and IV, alloys of groups VI and VII application of polyhedral tips with wear-resistant coatings TiC and TiC+TiN, plated with GT or DT methods, allows to improve 2 times the endurance of tools. Application of brazed tools with TiN coatings plated with CIB method increases 1.5 times their life.

Short information about methods improving machinability of hard-to-machine materials is given in Appendix 8.

1.4. Specifying the depth of cut

To specify main elements of cutting conditions means to determine depth of cut, feed and cutting velocity. And those cutting conditions would be optimal that provide the highest productivity and economy (the least production cost) in some specified machine at the severe condition of high quality of machined surfaces.

First the maximal possible and reasonable cut depth is selected, then – maximal possible feed, and only then a cutting velocity is calculated taking into account maximal tool life and other parameters of machining.

It is recommended to work with maximal possible depth of cut under specified conditions. The limit of cut depth is machining allowance. Value of allowance is determined by requirements for surface roughness and machining accuracy, and depends on value of roughness, depth of defective layer and total spatial deflection (displacement and warping) resulted from previous machining operation and locating error in the performed operation. Machining allowances may be calculated or specified according to the norms for interoperation allowances.

Calculated value of cut depth for external straight turning is one-side maximal allowance or half the difference between maximal diameter of workpiece after previous manufacturing step and minimal diameter after the step to be performed:

$$t_c = z_{i\,max} = \frac{D_{i-1\,max} - D_{i\,min}}{2};$$

for boring

$$t_c = z_{i\,max} = \frac{D_{i\,max} - D_{i-1\,min}}{2};$$

for facing (***h*** tolerance band)

$$t_c = z_{imax} = L_{i\text{-}1max} - L_{imin}.$$

If it is possible to remove all allowance in one pass (small strength of cutting tool, low rigidity of workpiece or small power of machine), it is removed in several passes. For example, if there is a need of 2 passes, then 60-70% allowance is cut in the first pass, and the rest – in the second pass.

1.5. Calculation of feed value

In order to increase productivity by reduction of direct machining time it is reasonable to work with maximal permissible feed taking into account all other factors that influence feed value.

In rough turning, when there are no severe requirements for quality of machined surface, the cutting forces could be very large. Maximal feed may be limited by strength and stiffness of cutting tool (shank, tip), rigidity of workpiece, strength of components of feed gearing and mechanism of primary cutting motion, available power of a machine.

In other cases, when there are higher requirements for quality of machined surface, maximal feed is limited by specified surface finish, because the increase of feed would increase surface roughness.

Feed value is determined from norms (tables) developed on the base of wide laboratory investigations and production experience or from calculations. There are several relationships that describe correlation between roughness $\boldsymbol{R_z}$ and feed $\boldsymbol{f}$, various geometric parameters of cutting tool ($\boldsymbol{r}$, $\boldsymbol{\varphi}$, $\boldsymbol{\varphi_1}$) that influence roughness directly (geometrically). Influence of many other factors (cutting speed, angles of cutting tip, workpiece material and tool material, sharpness of cutting tool, presence of cutting fluid, etc.) is taken into account by product of coefficients that consider changed values of parameters relative to normative ones.

Calculated value of feed could be determined from the formula

$$f_c = \frac{\sqrt{R_{zi} \cdot 8r}}{k_R}, \text{ mm/rev},$$

where $\boldsymbol{r}$ – tool nose radius, mm; $\boldsymbol{k_R}$ – total correction coefficient (for the most of operations could be adopted as $\boldsymbol{k_R} = 2$); $\boldsymbol{R_z}$ – roughness to be obtained after the operation ($\boldsymbol{R_z} \approx 4 \cdot \boldsymbol{R_a}$), mm.

Solution of this relationship with the aid of nomograph is given in Appendix 9, where the total correction coefficient is equal to two.

The value of calculated feed is to be corrected according to the type of turning operation. Geometrically the type of machining does not influence roughness. But other factors can influence. For example, in boring operations, when the length of shank is large and chip-forming conditions are severe, it is necessary to apply corrective coefficient. The values of coefficient that depend on the length $\boldsymbol{l}$ and height $\boldsymbol{H}$ of tool shank for boring are the following:

l/H	1.0	1.5	2.0	2.5	3.0
k_s	0.7	0.6	0.4	0.3	0.24

Recommendations on selection of feeds when cutting off workpieces and turning grooves by tools with cemented carbide tips are submitted in the Table 1.4.

The calculated and corrected value of feed is to be agreed with technical data of selected turning machine.

Table 1.4

Feeds for cutting off workpieces and turning grooves by tools with tips from cemented carbides BK6M (VK6M) and BK8 (VK8)

Tool shank cross-section, mm	Sizes of tool head, mm		Feed $\boldsymbol{f}$, for workpiece material group, mm/rev	
	Width	Length	I-VII, $\sigma_u < 900$ MPa	II, IV, V, VI, VIII, $\sigma_u > 900$ MPa
Cutting off				
16 × 10	3	20	0.05…0.08	0.04…0.06
25 × 16	5	35	0.10…0.12	0.08…0.10

Table 1.4, finished

Tool shank cross-section, mm	Sizes of tool head, mm		Feed f, for workpiece material group, mm/rev	
	Width	Length	I-VII, σ_u < 900 MPa	II, IV, V, VI, VIII, σ_u > 900 MPa
32 × 20	6	40	0.10…0.15	0.08…0.10
40 × 25	8	60	0.08…0.10	0.06…0.08
Cutting grooves				
16 × 10	3	15	0.07…0.10	0.05…0.07
25 × 16	5	20	0.10…0.14	0.08…0.12
	10	25		
32 × 20	5	25	0.12…0.15	0.08…0.12
	8	30		
	12	40		

Note. Feed values are 1.5 times increased for tools from high-speed steels

1.6. Express calculation of cutting velocity, tangential constituent of cutting force and machine power

The values of calculated feed and geometric dimensions of workpiece are not sufficient data for the selection of turning machine. Power required for cutting process is quite necessary parameter for the selection of a machine. Express calculation is performed in order to estimate required power of machine from calculated values of feed and cutting velocity. Thus, minimal set of initial data for the selection of turning machine are sizes of its working zone and power of drive (electric motor).

Express calculation is performed according to the following formulas:

1) Cutting velocity V_c (Para 1.9) from depth of cut t_c (Para 1.4), calculated and corrected value of feed f_c (Para 1.5), tool life T (Para 1.9.1). It is necessary to determine values of corrective coefficients k_{vi} that takes into account influences of various parameters on cutting velocity;
2) Tangential constituent of cutting force P_z (Para 1.13) from the same parameters t_c, f_c and obtained value of V_c;
3) Machine power N_m (Para 1.15) from parameters P_z and V_c.

Initial data and results of calculations for all steps of manufacturing operation are written into the table:

Number of manufacturing step	t_c, mm	f_c, mm/rev	T, min.	V_c, m/min	P_z, N	N_m, kW

Another approach is applied for the case of reconstruction of production sector, when power of machine electric motor is insufficient for operation at selected conditions. It is needed to reduce cutting velocity or feed. Velocity reduction is more favourable because direct machining time will be equal to the one for the case of feed reduction, but tool life will increase.

1.7. Selection of turning machine

When planning operation of manufacturing process it is necessary to know all data characterizing technological equipment.

The choice of machine type is determined, first of all, by its capability to perform requirements for the workpiece parameters in this operation.

The following parameters should be considered when selecting a machine:

a) Correspondence of sizes of machine working zone to overall dimensions of work piece;
b) Correspondence of machine productivity to quantity of machined parts during planned period;
c) Capability of maximal utilization of machine by time and power, as well as sufficient value of power for machining at the most hard step of operation;
d) Real ability to purchase machine.

Critical factor in selection of a machine is economy (the least value of production cost) of workpiece machining. Choice of machine with larger sizes of working zone and higher power of drive is a mistake.

Minimal set of machine data includes:

- Name and type;
- Sizes of working zone;
- Minimal and maximal values of longitudinal feed and cross-feed;
- Number of feeds' steps or sequence (row) of feeds;
- Minimal and maximal values of spindle rotational speed;
- Number of rotational speed steps or sequence (row) of spindle speeds;
- Power of drive.

Report should contain a reference on the source of machine data.

1.8. Agreement of feed value with technical data of turning machine

Agreement of calculated longitudinal and cross feeds with a machine could be performed in 3 variants depending on available machine data.

In the first variant, when all technical data are known, that is, there is a row of feeds, agreement is performed easily: the nearest smaller feed is specified for further calculation and for setting-up the machine (or larger one, if it does not exceed the calculated value more than 5 %).

All considerations given in this Paragraph are totally valid also for agreement of calculated rotational speed of spindle with the machine data.

In the second variant, when only the values of minimal and maximal feeds and number of steps $\boldsymbol{m}$ are known, then the following algorithm is used.

It is known that machines are produced with step regulation of feeds. Rows of feeds are constructed in geometric progression. In machine-tool engineering 7 normalized geometric series are approved with following geometric ratios ξ: 1.06, 1.12, 1.26, 1.41, 1.58, 1.78, 2.00. Middle values 1.26 and 1.41 are often used for universal machines. The value 1.12 is mainly for universal machines when number of steps for feed regulation is large and more than number of steps for spindle rotational speed; the value 1.58 is for machines with small number of steps, for example, for some turret lathes and vertical drilling machines.

From geometric progression:

$$f_2 = f_{min} \cdot \xi,$$
$$f_3 = f_{min} \cdot \xi^2,$$
$$\ldots\ldots\ldots\ldots\ldots,$$
$$f_{max} = f_{min} \cdot \xi^{m-1}.$$

From formula for f_{max} one can derive

$$\xi = \sqrt[m-1]{\frac{f_{max}}{f_{min}}},$$

according to which the whole row of feeds is obtained.

The calculated ξ value could differ a little from normalized one.

Full row of feeds is written for use in other manufacturing steps of this operation or in operations of this manufacturing process.

In the third variant, when only the values of minimal and maximal feeds are known, the ξ^{m-1} value is derived from formula for f_{max}

$$\xi^{m-1} = \frac{f_{max}}{f_{min}}.$$

Then, using the table (Appendix 10) for normalized ratios ξ raised to a power [5], one can find value that equals or near to the calculated one. In the line of this found value the ξ^{m-1} is located in first column. The m value will be more by 1.

For example, for turret lathe of 1365 type the feeds of turret carriage are: f_{min} = 0.09 and f_{max} = 1.35 mm/rev. The ratio is 1.35/0.09 = 15. In the table this value appeared to be 15.60 in the column of $\xi = 1.41$. This corresponds to ξ^8 ($m - 1 = 8$) that means the number of regulation steps is $m = 9$.

Knowing f_{min}, f_{max}, m, ξ the row of feeds is calculated similar to the previous variant.

1.9. Calculation of cutting velocity

Calculation of cutting velocity is performed with using the calculated depth of cut and value of feed for the most favourable tool life.

A. For turning the workpieces from heat-resistant, rust-resisting and high-temperature steels and alloys with tools with tips of cemented carbides T15K6 and T5K10:

$$V_c = \frac{C_V'}{T^{0.35} t^{0.15} f^{0.15}} k_V, \text{ when } 0.07 \le f \le 0.20 \text{ mm/rev};$$

$$V_c = \frac{C_V''}{T^{0.35} t^{0.15} f^{0.45}} k_V \text{, when } f > 0.20 \text{ mm/rev.}$$

Here and after the cutting velocity is in m/min.

B. For turning the workpieces from heat-resistant, rust-resisting and high-temperature steels and alloys with tools with tips of cemented carbides BK6M (VK6M), BK8 (VK8) and BK8B (VK8V):

$$V_c = \frac{C_V'''}{T^{0.25} t^{0.15} f^{0.15}} k_V \text{, when } 0.07 \le f \le 0.20 \text{ mm/rev;}$$

$$V_c = \frac{C_V''''}{T^{0.25} t^{0.15} f^{0.45}} k_V \text{, when } f > 0.20 \text{ mm/rev,}$$

where C_V – coefficients characterizing workpiece material and cutting conditions; k_V – general correcting coefficient characterizing the changed cutting conditions as compared with those characterized by coefficient C_V. Coefficient k_V is equal to the product of particular correcting coefficients described below.

C. For turning the workpieces from titanium alloys with tools with tips of cemented carbides of the BK (VK) group:

$$V_c = \frac{C_V}{T^{0.35} t^{0.2} f^{0.4}} k_V \text{, when } f > 0.06 \text{ mm/rev.}$$

The values of coefficients C_V for typical materials of groups I–VI are given in the Table 1.5, for titanium alloys (group VII) – in the Table 1.6.

D. For finish turning the workpieces from hard-to-machine steels and alloys of the I–VI groups, when $f \le 0.06$ mm/rev:

$$V_c = \frac{C_V}{T^{0.4} t^{0.12} f^{0.2}} k_V \text{, when } f > 0.06 \text{ mm/rev.}$$

The values of coefficients C_V are given in the Appendix 11.

E. For finish turning the workpieces from titanium alloys, when $f \le 0.06$ mm/rev:

$$V_c = \frac{C_V}{T^{0.4} t^{0.12} f^{0.2}} k_V \text{, when } f > 0.06 \text{ mm/rev.}$$

The values of coefficients C_V are given in the Appendix 12.

Calculated values of cutting velocities for all manufacturing steps of operation are written into the table of Para 1.15.

Cutting velocity depends on the following factors [6]: life of cutting tool, physical and mechanical properties of workpiece material, material of cutting point, feed and depth of cut, geometric parameters of cutting point, dimensions of tool shank, cutting fluids, maximal permissible value of tool wear, and type of machining.

Table 1.5

Coefficients C_V and C_P for calculations of velocities and forces of cutting when turning workpieces from hard-to-machine steels and alloys

Group No.	Grade	σ_u, MPa	C_V'	C_V''	C_V'''	C_V''''	C_P
I	34ХН3М (34HN3M) 34ХН4МФ (34HN4MF)	600…650	1050	650	-	-	2900
	20Х3МВФ (20H3MVF)	900	700	430	-	-	3750
II	12Х13 (12H13)	600…700	815	505	-	210	3250
	1Х12Н2ВМФ (1H12N2VMF) 20Х13 (20H13)	800…900	700	430	-	180	3750
	14Х17Н2 (14H17N2) 09Х16Н4БА (09H16N4BA)	950…1100 1000 1300	580 640 350	360 395 215	- - 145	150 165 90	4300 3800 4900
III	12Х18Н10Т (12H18N10T) 20Х23Н18 (20H23N18)	600	580	360	240	150	3400
	12Х21Н5Т (12H21N5T)	700…800	490	308	204	128	3800
	Х15Н9Ю (H15N9U) Х17Н5М3 (H17N5M3)	850…1100	520	320	216	155	3900
IV	45Х14Н14В2М (45H14N14V2M) 08Х15Н24В4ТР (08H15N24V4TR)	700	465 -	288 -	192 145	90	3600
	07Х21Г7АН5 (07H21G7AN5)	1000	350	216	145	90	4350
	12Х25Н16Г7АР (12H25N16G7AR) 37Х12Н8Г8МФБ (37H12N8G8MFB)	800					
	10Х11Н23Т3МР (10H11N23T3MP)	900	-	-	110	69	4350
	15Х18Н21С4ТЮ (15H18N21S4TU)	700…750					3600
V	36ХНТЮ (36HNTU)	1200	-	-	76	47	6800
	ХН77ТЮР (HN77TUR)	1000					5000
	ХН36ВТЮ (HN36VTU)	950	-	-	58	36	4600
	ХН67ВМТЮ (HN67VMTU)	1000	-	-	48	30	5600
	ХН75МВЮ (HN75MVU)						
	ХН62ВМКЮ (HN62VMKU)	1250	-	-	36	23	800
	ХН60МВТЮ (HN60MVTU)	1150					
	ХН82ТЮМЕ (HN82TUME)	1350					
VI	ВЖ36-Л2 (VZh36-L2)	800	-	-	24	15	5400
	ЖС6К, ЖС3ДК (ZhS6K, ZhS3DK)	1000					
	ХН67ВМТЮЛ (HN67VMTUL)	750					

Table 1.6

Coefficients C_V and C_P for calculations of velocities and forces of cutting when turning workpieces from alloys of the VII group

Grade	σ_u, MPa	C_V	C_p
ВТ-1 (VT-1), ВТ1-1 (VT1-1), ВТ1-2 (VT1-2)	450…700	260	1800
ВТ3 (VT3), ВТ3-1 (VT3-1)	950…1200	125	2100
ОТ4, ОТ4-1, ВТ5 (VT5), ВТ5-1 (VT5-1)	700…950	175	2000
ОТ6, ОТ6С (OT6S)	900…1000	140	2000
ВТ14 (VT14), ВТ15 (VT15), ВТ22 (VT22)	1000	130	2200
ВТ14 (VT14), ВТ15 (VT15), ВТ22 (VT22)	1300…1400	90	3300

1.9.1. Life of cutting tool

The higher the cutting velocity, the lower the tool life will be as a result of dominating influence of cutting velocity on the heat generation in the cutting zone and tool wear.

The relationships for calculation of cutting velocity given above have been developed for the most reasonable ranges of cutting velocity at optimal tool life for the given cutting conditions. For finish, semi-finish and preliminary machining the tool life is set equal to 60 min., for rough machining – 120 min., for machining of workpieces from cast high-temperature alloys of group VI – 30 min. In the last case, like in several other cases, decrease of cutting velocity does not increase tool life. And so recommended tool lives are not to be changed without special need.

Generally tool life and corresponding cutting velocity should be of such values that provide high productivity and low production cost with obtaining specified quality of machined surface.

Depending on cutting conditions, design of cutting tool and machine, general technical level of production and other factors, the values of tool life and corresponding cutting velocity could be various. For example, for multi-tool machining (automatic and semi-automatic machines), when change of dull tool and its resetting are connected with large losses of time and labour, tool life should be longer than for single-tool and simpler operations.

Correlation between tool life and cutting velocity is expressed by correcting coefficient $\boldsymbol{k_{TV}}$:

Tool life $\boldsymbol{T}$, min	30	45	60	90	120
Coefficient $\boldsymbol{k_{TV}}$	1.15	1.06	1.00	0.92	0.87

1.9.2. Influence of workpiece material

Physical and mechanical properties of workpiece material have a large influence on cutting velocity permitted by tool. This influence is originated from heat generation during cutting process and distribution of heat between chip, workpiece, tool and surrounding environment. Also chemical composition of material, its thermal treatment and type of obtained structure have their influence. All these factors are taken into account by coefficient $\boldsymbol{C_V}$.

If some material is not submitted in the Table 1.5, the $\boldsymbol{C_V}$ value is determined by interpolation by ultimate strength. But it would be right only in the range of one group, for materials near each other by chemical composition and after the similar heat treatment, that is, for materials similar by machinability.

In this case the main characteristic of machinability is cutting velocity at specified tool life. In other cases the roughness of work surface (that is very important for finish operations) or cutting forces could be used as such characteristic.

Cutting velocity also depends on type of initial blank and condition of its surface.

If blank is a rolled product, then for hot-rolled steel the influence of blank material on cutting speed could be estimated by coefficient equal to 1.0, and for cold-drawn steel – 1.1. If for machining of steel blank from rolled product or forging without crust (crust is already cut off or etched) the material influence could be estimated by coefficient equal to 1.0, then for a steel casting the coefficient of 0.9 is used.

In the case of machining of blanks with crust the correcting coefficient k_{MV} is applied: for materials of groups I-V – 0.75, for group VI – 0.70, for group VII – 0.50.

Depending on the number of factors total material coefficient k_{MV} may be a product of several particular coefficients.

1.9.3. Influence of cutting point material

Recommendations for selection of tool materials are submitted in the Para 1.3. There are differences in cutting ability between cemented carbides in each group – tungsten (single-carbide) and titanium-tungsten (two-carbide). These differences in cutting ability are taken into account by correcting coefficient k_{tV}:

- For single-carbide materials:

Grade of cemented carbide	BK3M (VK3M)	BK6-OM (VK6-OM)	BK6M (VK6M)	BK8 (VK8)	BK8B (VK8V)
Coefficient k_{tV}	1.25	1.25	1.00	0.80	0.60

- For two-carbide materials:

Grade of cemented carbide	T15K6	T5K10
Coefficient k_{tV}	1.00	0.60

1.9.4. Influence of feed and depth of cut

These parameters are taken into consideration by exponents of power in the formulas for determination of calculated cutting velocity. In general, power exponent of feed is more than power exponent of cut depth, that is, increase of feed produces stronger influence on decrease of cutting velocity than increase of depth. It is explained by greater thermodynamic load on the length unit of cutting edge. For similar cross-section of cut for ordinary cutting tool ($\varphi_1 > 0$, for $f < t$) it is easier to work with smaller feed and larger depth of cut.

1.9.5. Influence of geometric parameters of cutting point

Paragraph 1.2 and Table 1.1 contain optimal values of rake and relief angles for specified conditions under the following limitations:

1. The increase of positive **rake angle** (sharpening of cutting wedge) is accompanied with reductions of deformations, heat generation and forces applied to the tool that results in increase of tool life (or cutting velocity at the same tool life). But simultaneously with this, the increase of $+\gamma$ is accompanied with reduction of volume of cutting point, and, hence, with the decrease of its strength and heat sink

that results in shortening of tool life starting from the certain value.

2. The increase of **relief angle** is accompanied with reduction of friction of tool along a workpiece that results in reduction of wear and, hence, in increase of tool life. But simultaneously with this, reduction of volume of cutting point gives the known negative consequences.

Thus, recommended values of rake and relief angles, and data of corrective margin are to be used without changes.

Also values of **nose radii** given in the Table 1.1 should not be changed. But if the surfaces are machined finally in the planned operation and there is a need to perform the requirements of drawing with another radius specified, then the following correcting coefficient is applied:

Nose radius, mm	1.0	2.0	3.0	4.0
Coefficient k_{rV}	1.00	1.05	1.10	1.15

Here the increase of radius results in decrease of heat generation.

Side cutting edge angle greatly influences permissible value of cutting velocity. The greater the value of this angle, the larger thermodynamic load on length unit of cutting edge will be, and, hence, the shorter its life. Influence of this parameter is described by the following coefficients:

Side cutting edge angle φ, degree	10	20	30	45	60	75	90
Coefficient $k_{\varphi V}$	1.55	1.30	1.13	1.00	0.92	0.86	0.81

Influence of **end cutting edge angle** is expressed by the following values of coefficient $k_{\varphi 1V}$:

Side cutting edge angle φ_1, degree	15	20	30	45
Coefficient $k_{\varphi 1V}$	1.00	0.97	0.94	0.90

1.9.6. Influence of dimensions of tool shank

The larger the cross-section area of a tool shank, the more intensive heat sink from the cutting zone and the higher rigidity of tool is. Therefore the tool shank dimensions should be selected the largest according to dimensions of tool post.

It is clear that any of selected tools should be mounted in the tool post in such a position that its nose would be at the line of machine centres.

1.9.7. Influence of cutting fluids

The role of cutting fluids as means for intensification of machining is considered in the Para 1.3.3. Recommendations are given in the Table 1.3. If the operation is performed without a cutting fluid, the coefficient taking into account the changed cutting conditions is applied k_{cfV} = 0.7 (if the fluid is applied, k_{cfV} = 1.0).

1.9.8. Influence of permissible limit of tool wear

The increase of ultimate permissible wear along relief surface results in some increase of cutting velocity. But the limit values of wear given in the Para 1.3 should not be enlarged, because the costs for renewal of cutting ability (resharpening) and consumption of a tool material rise with decrease of planned number of possible resharpening operations.

1.9.9. Influence of type of turning operation

Cutting velocity for external straight turning, boring, facing, cutting and grooving is calculated from the same formula. But the conditions, under which tool operates, change depends on type of machining.

Thus, operation conditions of **boring tools** are much worse than of turning tools, because of more restrained conditions for chip formation, cutting fluid supply is more complicated, worse conditions for heat sink, and less rigidity (less cross-section area and larger overhang) of tool shank. Therefore in boring the cut depth in decreased and cutting velocity is reduced.

The smaller the diameter of bored hole, the lower cutting velocity is:

Hole diameter $\boldsymbol{D_h}$, mm	up to 75	75…150	250	250
Coefficient $\boldsymbol{k_{bV}}$	0.80	0.90	0.95	1.00

In the case of **cross-feed turning** (facing) the cutting conditions are more favourable than in straight turning, because during motion of tool from periphery to the centre of workpiece the diameter of turning gradually becomes smaller and, hence, cutting velocity decreases. Therefore at the beginning of work stroke it could be increased. The less ratio of final diameter $\boldsymbol{D_2}$ to initial one $\boldsymbol{D_1}$, the higher the permissible cutting velocity is:

$\boldsymbol{D_2 / D_1}$	up to 0.4	0.5…0.7	0.9
Coefficient $\boldsymbol{k_{crV}}$	1.25	1.20	1.05

Grooving and parting tools operate at high conditions, because small cutting edge angles and cross-section area of cutting point provide poor head sink. Depending on ratio of groove diameter $\boldsymbol{D_2}$ to initial one $\boldsymbol{D_1}$ the coefficient $\boldsymbol{k_{gpV}}$ is applied (use of a cutting fluid is obligatory):

$\boldsymbol{D_2 / D_1}$	0.4	0.7	0.9
Coefficient $\boldsymbol{k_{gpV}}$	0.65	0.60	0.50

For machining of face grooves $\boldsymbol{k_{gfV}}$ = 0.5. Besides this the recommended cutting conditions for parting are submitted in the Table 1.7.

Recommendations for operations with grooving and parting tools are also valid for operations with **form tools** that should be of cemented carbides, if possible.

Cemented carbide tools allow to increase approximately 4 times permissible cutting velocities as compared with high-speed steels, and productivity of machines in common with auxiliary time could be approximately 2 times improved. Therefore, their application is more preferable.

Table 1.7

Cutting velocity (m/min) for parting workpieces from hard-to-machine steels and alloys by parting tools with tips of cemented carbide ВК6М (VK6M) (***f*** = 0.07…0.12 mm/rev)

<table>
<tr><td rowspan="2">Workpiece material</td><td>D</td><td>B</td><td>D</td><td>B</td><td>D</td><td>B</td><td>D</td><td>B</td><td>D</td><td>B</td></tr>
<tr><td>20</td><td>4</td><td>30</td><td>4</td><td>40</td><td>4..5</td><td>50</td><td>5..6</td><td>60</td><td>6..8</td></tr>
<tr><td>34ХН3М (34HN3M), 34ХН3МФ (34HN3MF), 20Х3МВФ (20H3MVF)</td><td colspan="2">70…75</td><td colspan="2">75…80</td><td colspan="2">80…85</td><td colspan="2">85…90</td><td colspan="2">90…95</td></tr>
<tr><td>20Х13 (20H13), 09Х16Н4Б (09H16N4B), 14Х17Н2 (14H17N2)</td><td colspan="2">50…64</td><td colspan="2">54…68</td><td colspan="2">56…72</td><td colspan="2">58…75</td><td colspan="2">60…80</td></tr>
<tr><td>12Х18Н10Т (12H18N10T)
12Х21Н5Т (12H21N5T)
20Х23Н18 (20H23N18)</td><td colspan="2">40…52</td><td colspan="2">42…55</td><td colspan="2">45…58</td><td colspan="2">48…60</td><td colspan="2">50…62</td></tr>
<tr><td>45Х14Н14В2М (45H14N14V2M)
37Х12Н8Г8МФХБ (37H12N8G8MFHB)</td><td colspan="2">30…40</td><td colspan="2">32…43</td><td colspan="2">35…45</td><td colspan="2">36…47</td><td colspan="2">32…48</td></tr>
<tr><td>08Х15Н24В4ТР (08H15N24V4TR)
12Х25Н1617АР (12H25N1617AR)
07Х21Г7АН5 (07H21G7AN5)
15Х18Н12С4ТЮ (15H18N12S4TU)
10Х11Н23Т3МР (10H11N23T3MR)</td><td colspan="2">25…36</td><td colspan="2">29…38</td><td colspan="2">30…40</td><td colspan="2">31…41</td><td colspan="2">32…42</td></tr>
<tr><td>ХН77ТЮР (HN77TUR), 36НХТЮ (36HNTU), ХН60ВТ (HN60VT)</td><td colspan="2">17…23</td><td colspan="2">18…24</td><td colspan="2">19…25</td><td colspan="2">20…26</td><td colspan="2">20…26</td></tr>
<tr><td>ХН35ВТЮ (HN35VTU)
ХН56МВТЮ (HN56MVTU)
ХН67ВМТЮ (HN67BMTU)
ХН75МВЮ (HN75MVU)</td><td colspan="2">11…14</td><td colspan="2">12…15</td><td colspan="2">12…15</td><td colspan="2">13…16</td><td colspan="2">13…16</td></tr>
<tr><td>ХН72МВКЮ (HN72MVKU)
ХН60МВТЮ (HN60MVTU)
ХН82БЮМБ (HN82VUMB), ЖС6К (ZhS6K), ЖС3-ДК (ZhS3DK), ЭП202Л (EP202L)</td><td colspan="2">8…11</td><td colspan="2">9…12</td><td colspan="2">9…12</td><td colspan="2">10…13</td><td colspan="2">10…13</td></tr>
<tr><td>ВТ1 (VT1), ВТ1-1 (VT1-1),
ВТ1-2 (VT1-2)</td><td colspan="2">50…60</td><td colspan="2">53…63</td><td colspan="2">55…65</td><td colspan="2">58…68</td><td colspan="2">60…70</td></tr>
<tr><td>ВТ3 (VT3), ОТ4 (OT4), ВТ3-1 (VT3-1), ВТ5 (VT5), ВТ5-1 (VT5-1), ВТ6 (VT6), ВТ6С (VT6S), ВТ14 (VT14), ВТ15 (VT15), ВТ22 (VT22)</td><td colspan="2">32…40</td><td colspan="2">35…43</td><td colspan="2">37…45</td><td colspan="2">39…47</td><td colspan="2">40…50</td></tr>
</table>

Notes: 1. Emulsion cooling. 2. For tools made from cemented carbide ВК8 (VK8) the value of cutting velocity should be multiplied by 0.75. 3. Lower values of cutting velocity should be set at higher feeds. 4. Tools life is equal to 40…50 min. 5. Diameter of workpiece ***D*** and tool width ***B*** are given in mm.

Cemented carbide tools allow to increase permissible cutting velocities approximately 4 times in comparison with high-speed steels, and productivity of machines could be risen approximately 2 times taking into account auxiliary time [7]. Therefore their application is preferable.

In those cases when HSS tools are to be applied, the cutting conditions for external straight turning recommended in the Table 1.8 should be used.

Table 1.8

Cutting conditions for turning workpieces from hard-to-machine steels and alloys by tools from high-speed steel Р6М5К5 (R6M5K5)

Group No.	Grade	σ_u, MPa	t, mm, not more than	f, mm/rev	V, m/min
I	34ХН3М (34HN3M) 34ХН4МФ (34HN4MF) 20Х3МВФ (20H3MVF) 15Х5М (15H5M)	600	5	0.1…0.2	55…66
		900		0.1…0.2 0.3…0.4	30…40 20…30
II	12Х13 (12H13), 25Х13Н2 (25H13N2), 11Х11Н2ВМФ (11H11N2VMF) 1Х12Н2ВМФ (1H12N2VMF), 20Х13 (20H13), 30Х13 (30H13), 40Х13 (40H13)	850	5	0.1…0.2	30…40
				0.3…0.4	20…25
	09Х16Н4Б (09H16N4B), 95Х18 (95H18)	1100	3	0.1…0.2	10…15
III	12Х18Н10Т (12H18N10T) 10Х23Н18 (10H23N18) 20Х23Н18 (20H23N18)	600…800	5	0.1…0.2 0.3…0.4	25…30 10…20
	12Х21Н5Т (12H21N5T) 09Х15Н9Ю (09H15N9U) 09Х17Н5М3 (09H17N5M3) 07Х16Н6 (07H16N6)	800…1000		0.1…0.2 0.3…0.4	15…20 10…15
IV	45Х14Н14В2М (45H14N14V2M)	700	5	0.1…0.2	12…18
	08Х15Н24В4ТР (08H15N24V4TR) 07Х21Г7АН5 (07H21G7AN5) 12Х25Н16Г7АР (12H25N16G7AR)	800…1000			10…15
	37Х12Н8Г8МФБ (37H12N8G8MFB)	700…1000			6…8
	10Х11Н23Т3Р (10H11N23T3R) 10Х11Н23Т3МР (10H11N23T3MR) 15Х18Г21С4ТЮ (15H18G21S4TU)				
V	ХН60В (HN60V) ХН77ТЮР (HN77TUR)	800…1000	3	0.1…0.2	8…12
	36ХНТЮ (36HNTU) ХН35ВТЮ (HN35VTU) ХН56ВМТЮ (HN56VMTU)	1000…1100			6…8

Table 1.8, finished

Group No.	Grade	σ_u, MPa	t, mm, not more than	f, mm/rev	V, m/min
V	ХН70МВТЮ (HN70MVTU) ХН67МВТЮ (HN67MVTU) ХН75МВЮ (HN75MVU)	1000…1100	3	0.1…0.2	5…8
	ХН62МВКЮ (HN62MVKU) ХН60ВМТЮ (HN60VMTU) ХН82ТКМБ (HN82TKMB)	1150…1350			4…6
VI	ВЖ36-Л2 (VZh36-L2), 9П202Л (9P202L)	800			4…5^{*1} 4…8^{*2}
	ЖС6-К (ZhS6-K), ЖС3-ДК (ZhS3-DK) АНВ-300 (ANV-300)	800…1000			3…4^{*1} 4…6^{*2}
	ВХ4Л (VH4L)	1100			6…10
VII	ВТ1-0 (VT1-0), ВТ1 (VT1), ВТ1-1 (VT1-1) ВТ1-2 (VT1-2)	450…700	5	0.1…0.2 0.3…0.4	35…40 20…30
	ОТ4, ОТ4-1, ВТ5 (VT5), ВТ5-1 (VT5-1)	600…950		0.1…0.2 0.3…0.4	25…30 18…22
	ВТ6 (VT6), ВТ6С (VT6S), ВТ14 (VT14) ВТ14 (VT14)	900…1000		0.1…0.2 0.3…0.4	20…24 14…18
VII	ВТ3 (VT3), ВТ3-1 (VT3-1), ВТ22 (VT22)	900…1200		0.1…0.2 0.3…0.4	16…20 10…15
	ВТ3-1 (VT3-1), ВТ14 (VT14), ВТ15 (VT15)	1100…1350	3	0.1…0.2	15…16

Notes: 1. $*^1$ – continuous turning; $*^2$ – discontinuous turning. 2. Cooling with emulsion. 3. Life of tool from steel Р6М5К5 (R6M5K5) is near to 60 min; life of tools from other HSS grades is given in the Appendix 6. 4. Lower values of cutting velocity are selected for larger feeds and depths of cut.

In the case of finish turning of surfaces with high hardness with tools from superhard materials it is recommended to use conditions given in the Table 1.9.

Table 1.9

Finish turning by tools with tips from mineral ceramics*,
Эльбор-Р (Elbor-R), Гексанит-Р (Geksanit-R)

HRC material hardness number	Material of cutting point	Cutting conditions		
		t, mm	f, mm/rev	V, m/min
40 50	mineral ceramics В3 (V3), ВОК-60 (VOK-60), ВОК-63 (VOK-63)	0.5…1.5 0.5…1.0	0.1…0.2 0.08…0.12	250…300 180…200
55…60	В3 (V3), ВОК-60 (VOK-60), ВОК-63 (VOK-63)	0.2…0.5	0.05…0.08	80…120
60…55	Эльбор-Р (Elbor-R), Гексанит-Р (Geksanit-R)	0.2…0.3	0.04…0.07	60…80

Note. * – Apply only at rigid system “machine–fixture–tool–workpiece”.

Influence of above considered factors on cutting velocity permitted by a tool is recorded into the table:

Number of manufacturing step	k_{TV}	k_{MV}	k_{tV}	k_{rV}	$k_{\varphi V}$	$k_{\varphi 1V}$	k_{cfV}	k_{bV}	k_{crV}	k_{gpV}	k_{gfV}	k_V

1.10. Calculation of rotational speed of workpiece

Calculated rotational speed of workpiece (of machine's spindle) is derived from

$$n_c = \frac{1000 \cdot V_c}{\pi \cdot D}, \text{ rev/min},$$

where D – diameter of work surface – for external straight turning, mm; diameter of machined surface – for straight boring; maximal dimension ("diameter") of work face – for turning with cross feed.

Calculations of Paragraphs 1.10 – 1.12 are stated on the calculation paper for one manufacturing step. Data of all other steps are written into the table of Para 1.15.

1.11. Agreement of rotational speed value with technical data of turning machine

It is performed in similar way with agreement of feed value (Paragraph 1.8) besides cases, when machines with infinitely variable regulation of rotational speed are used. Agreement results in the n_m value. Row of spindle rotational speeds is submitted in the calculation paper.

1.12. Determination of actual cutting velocity

Actual cutting velocity is derived from formula

$$V_a = \frac{\pi \cdot D \cdot n_m}{1000}, \text{ m/min},$$

where the D values are the same as in Paragraph 1.10.

1.13. Calculations of constituents of cutting forces

Main constituent of a cutting force is a tangential one. It is used for determination of torque of machine spindle and power consumed by cutting. For different groups of workpiece materials, when f > 0.07 mm/rev, the tangential force is derived from:

A. For turning the workpieces from rust-resisting and high-temperature steels of groups I-IV:

$$P_z = C_p V^{-0.15} t^{0.95} f^{0.75}.$$

Here and after the cutting forces are expressed in Newtons (N).

B. For turning the workpieces from alloys of groups V, VI:

$$P_z = C_p V^{-0.15} t^{0.85} f^{0.75}.$$

C. For turning the workpieces from titanium alloys:

$$P_z = C_p V^{-0.10} t^{0.90} f^{0.75}.$$

The values of coefficients for typical materials of groups I – VI are given in the Table 1.5, for titanium alloys (group VII) – in the Table 1.6.

D. For finish turning the workpieces from steels and alloys of the I – VI groups, when $f \leq 0.06$ mm/rev:

$$P_z = C_p V^{-0.12} t^{0.80} f^{0.55}.$$

The values of coefficients C_p are given in the Appendix 11.

E. For finish turning the workpieces from titanium alloys, when $f \leq 0.06$ mm/rev:

$$P_z = C_p V^{-0.10} t^{0.80} f^{0.65}.$$

The values of coefficients C_p are given in the Appendix 12.

The values of actual cutting velocity, calculated depth of cut and agreed machine feed are used for calculations with above formulas.

Cutting forces depend on the following factors: properties of workpiece material, velocity, depth of cut, feed, rake and side cutting edge angles, nose radius, cutting fluids, tool wear. Influence of the first four factors is taken into account by the relationships, and other ones are selected as recommended values.

Values of constituents P_y and P_x of cutting force can be derived from empirical relationships similar to the P_z calculation. But in practice their values are determined as portions of P_z value. Forces ratios P_y / P_z and P_y / P_x are not constants, and vary depend on geometric parameters of tools, cutting conditions, tool wear. Thus, with the increase of side cutting edge angle the P_y force reduces, and P_x rises; with increase of feed the P_x force increases, etc.

For turning with cutting tool of the geometric parameters $\gamma = 15^o$, $\varphi = 45^o$, $\lambda = 0^o$ the ratios of cutting forces are the following: $P_y = (0.4\ldots0.5)\ P_z$, $P_x = (0.3\ldots0.4)\ P_z$.

Handbook [8] should be used for more exact data, if necessary.

The obtained results are written into the table of Para 1.15.

1.14. Calculation of torque

If a tool is subjected to the force P_z, then a workpiece is subjected to the same force of opposite direction. Moment of this force, that is, cutting moment

$$\boldsymbol{M_c} = \frac{\boldsymbol{P_z D}}{2000}, \text{ Nm,}$$

where the $\boldsymbol{D}$ value is the same as in Paragraph 1.10.

1.15. Calculation of machine drive power

Power consumed by cutting (effective power)

$$\boldsymbol{N_e} = \frac{\boldsymbol{P_z V_a}}{60 \cdot 1000}, \text{ kW.}$$

Power of electric motor necessary for cutting is determined with a machine's efficiency coefficient ($\boldsymbol{\eta_m}$ = 0.7…0.8)

$$\boldsymbol{N_{emc}} = \frac{\boldsymbol{N_e}}{\boldsymbol{\eta_m}}, \text{ kW.}$$

Results obtained in Paragraphs 4, 8-15 are written into the Table:

Number of manu-facturing step	$\boldsymbol{t_c}$, mm	$\boldsymbol{f_m}$, mm/rev	$\boldsymbol{V_c}$, m/min	$\boldsymbol{n_c}$, rev/min	$\boldsymbol{n_m}$, rev/min	$\boldsymbol{V_a}$, m/min	$\boldsymbol{P_z}$, N	$\boldsymbol{M_c}$, Nm	$\boldsymbol{N_{emc}}$, kW

1.16. Check of selected parameters of cutting conditions

Power of machine is checked, and for new-planned production section a machine power is selected. Power of electric motor for drive of the main work motion of selected machine $\boldsymbol{N_{ems}}$ should not be less than the calculated value $\boldsymbol{N_{emc}}$:

$$\boldsymbol{N_{ems}} \geq \boldsymbol{N_{emc}}.$$

It is necessary for cutting process that cutting moment is to be overcome by machine torque, that is, machine torque at the selected step of spindle rotational speed is not to be less than cutting moment:

$$\boldsymbol{M_m} \geq \boldsymbol{M_c}.$$

Machine torque (data are given the machine specification) is derived from

$$\boldsymbol{M_m} = 9550\frac{\boldsymbol{N_{ems}} \cdot \boldsymbol{\eta_m}}{\boldsymbol{n_m}}, \text{ Nm.}$$

1.16.1. Check of feed

Specified feed is checked by strength of parts of feed mechanism at rough turning, and in the rest of cases (non-stiff and hard conditions of cutting) – also by rigidity of a workpiece, by strength and rigidity of a tool.

A. By strength of parts of feed mechanism the feed is checked in the following way. Axial force at the selected feed should not be more than maximal force $\boldsymbol{P_m}$ permitted by machine's feed mechanism (the $\boldsymbol{P_m}$ value is given in the machine specification): $\boldsymbol{P_x} \leq \boldsymbol{P_m}$.

B. Ultimate values of feed permitted by strength and rigidity of a workpiece can be approximately derived from the formulas of “Mechanics of materials” subject. A workpiece is considered as a beam fixed in a specified manner. Thus, when mounting a shaft in a chuck with support by centre, the back end supported by centre is considered resting on the free support, and the end fixed in the chuck – tightly restrained. If compare 3 diagrams for mounting of long cylindrical shaft: in a chuck with support by rear centre, in centres, and only in the chuck, – then it would appear that ultimate permissible forces for the workpiece rigidity are in the ratio 25:16:1 respectively. Permissible bending deflection of a workpiece is: for rough turning – 0.2…0.4 mm; for turning before sequent grinding – ≤ 0.1 mm; for precise turning – ≤ 20 % tolerance value of machined dimension [6]. But for real parts with varying rigidity along the length a development of force diagram often is a difficult task.

C. By strength of tool shank the specified feed is checked by comparison of forces $\boldsymbol{P_z}$ and $\boldsymbol{P_{zstr}}$ (maximal load permitted by strength of tool shank in critical section):

$$\boldsymbol{P_{zstr}} = \frac{\boldsymbol{B} \cdot \boldsymbol{H}^2 \cdot \boldsymbol{\sigma_b}}{6 \cdot \boldsymbol{l}},$$

where $\boldsymbol{B}$ and $\boldsymbol{H}$ – respectively width and height of tool shank in critical section, m; $\boldsymbol{l}$ – tool’s overhang, m; $\boldsymbol{\sigma_b}$ – permissible working bending stress of tool shank material: $\boldsymbol{\sigma_b}$ = 200 MPa for unhardened carbon steel, $\boldsymbol{\sigma_b} \approx$ 400 MPa for hardened carbon steel.

By rigidity of tool shank the specified feed is checked from condition $\boldsymbol{P_z} < \boldsymbol{P_{zrid}}$. Maximal load permitted by rigidity of tool shank:

$$\boldsymbol{P_{zrid}} = \frac{3 \cdot \boldsymbol{f_1} \cdot \boldsymbol{E} \cdot \boldsymbol{J}}{\boldsymbol{l}^3},$$

where $\boldsymbol{f_1}$ – permissible bending deflection of tool shank: $\boldsymbol{f_1} \approx 0.1 \cdot 10^{-3}$ m for preliminary turning, $\boldsymbol{f_1} \approx 0.05 \cdot 10^{-3}$ m for finish turning; $\boldsymbol{E}$ – elasticity modulus of tool shank material: $\boldsymbol{E} = 20 \cdot 10^4 \ldots 22 \cdot 10^4$ MPa for structural carbon steel; $\boldsymbol{J}$ – inertia moment of tool shank ($\boldsymbol{J} = \boldsymbol{BH}^3/\mathbf{12}$ for rectangular cross-section).

More detailed calculation procedure is given in the book [6].

Maximal feed is limited not only by strength of shank, but also by strength of cemented carbide tips. Recommended values of feed are much lower than breaking feeds.

Then the calculations of direct manufacturing time for all manufacturing steps, time per piece and for optimization of cutting conditions by time per piece are performed.

2. DRILLING

Turning operations usually precede drilling operations (Fig. 2.1). In spite of differences between turning and drilling there is much in common in planning of operations: practically most of calculations and algorithm itself coincide. Therefore when considering the drilling operation in many cases the references are given to the correspondent paragraphs of turning chapter to avoid repetitions.

2.1. Selection of geometric parameters and tool material for drill

Drilling workpieces from heat-resistant steels (group I), chromium corrosion-resistant steels with $\boldsymbol{\sigma_u}$ < 1000 MPa (group II) and chromium-nickel corrosion-resistant steels (group III) should be performed with standard drills from high-

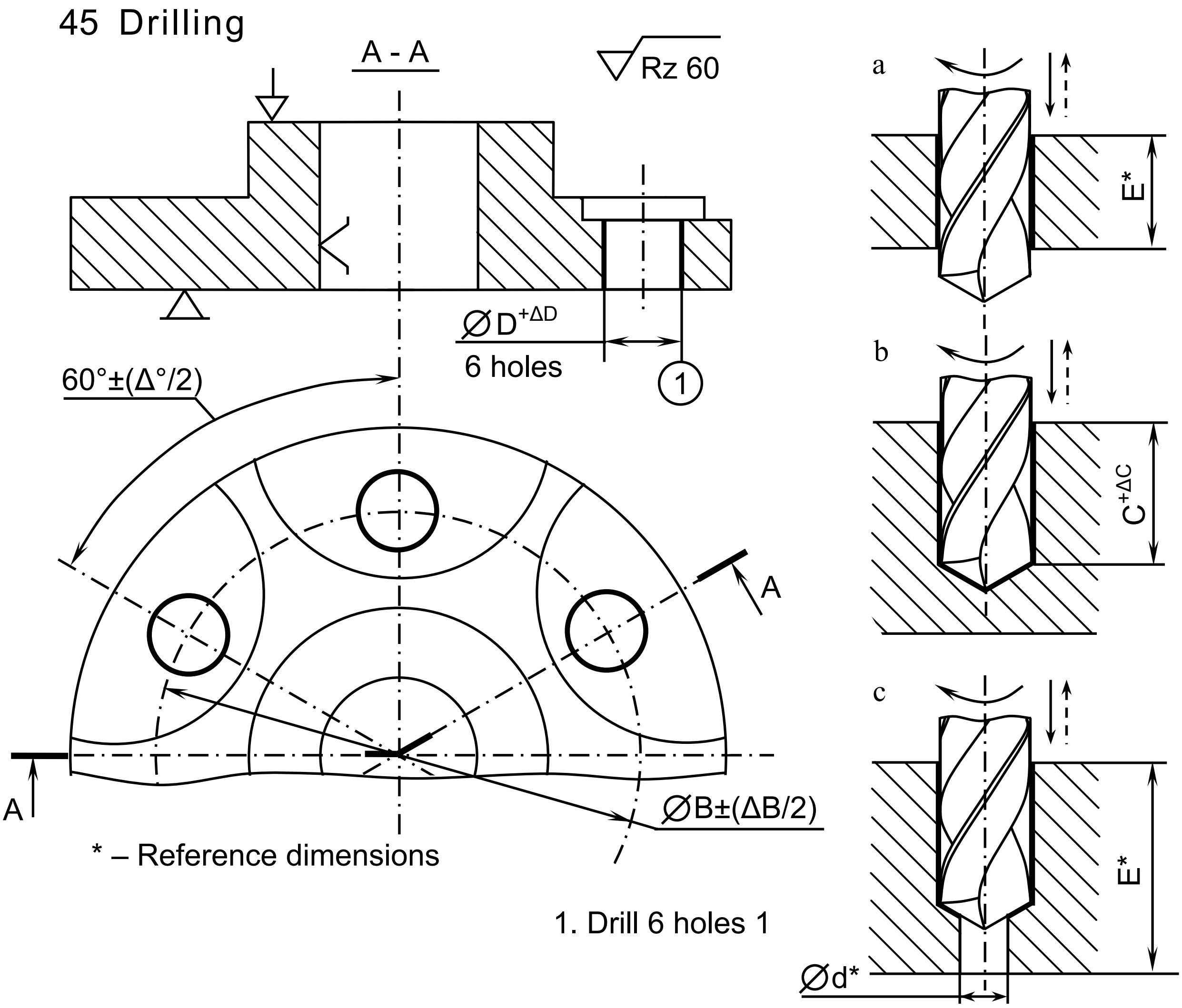


Figure 2.1. Sketch for drilling operation: a – through drilling; b – blind drilling; c – enlarging drilling (drilling-out). Note: Drill in the sketch “c” is shown conventionally not at the end of work travel

speed steels P6M5K5 (R6M5K5), P6M5 (R6M5) or others (ref. Table 1.2) with shortened body (up to 10 diameters).

Workpieces from high-temperature steels (group IV), high-temperature wrought alloys (group V) with σ_u < 1200 MPa, corrosion-resistant steels (group II) with σ_u > 1000 MPa and titanium alloys with σ_u > 1000 MPa are machined with special-purpose drills of increased rigidity from high-speed steels P6M5K5 (R6M5K5), P9M4K8 (R9M4K8) or other high-speed steels of improved thermal endurance. Length of drill body should not be more than 6-8 diameters. Web of drills with diameter of up to 5 mm should be approximately 0.4$\boldsymbol{D}$; drills with diameter of 6-10 mm – 0.3$\boldsymbol{D}$; drills with diameter of more than 10 mm – 0.25$\boldsymbol{D}$. Helix angle should be 30…35º, reverse taper – 0.1…0.15 mm per 100-mm length. Width and height of margins should be made possibly smaller, especially of drills for machining of workpieces from titanium alloys; point angle 2$\boldsymbol{\varphi}$ should be 140º; lip relief angle – 12º; rake angle of approximately 10º results from grinding of web to $\boldsymbol{w}$ = 0.1$\boldsymbol{D}$ (Fig. 2.2).

Drilling holes in workpieces from cast high-temperature alloys (group VI), high-chromium high-temperature steels (group II) and wrought high-temperature alloys (group V) with σ_u > 1000 MPa and titanium alloys (group VII) with σ_u > 1000 MPa should be performed with drills from cemented carbides recommended in the Table 1.2. Workpieces from titanium alloys could be machined with drills from high-speed steels, though when machining these alloys with σ_u > 1000 MPa the drills from cemented carbides provide higher productivity.

When drilling holes of diameter of up to 3 mm it is reasonable to apply spade drills from cemented carbide BK6-OM (VK6-OM); when drilling holes of diameter of 3…7 mm – solid twist drills from cemented carbides BK10M (VK10M), BK8 (VK8) or BK6M (VK6M). Holes with diameter of more than 8 mm are machined with drills with tips from cemented carbides BK8 (VK8) or BK6M (VK6M). Solid carbide drills of diameter of up to 12…15 mm are also recommended. They are stronger than drills with brazed carbide tips and larger feeds can be specified when working with them. However, drills with diameter of more than 8 mm are applied with brazed carbide tips for saving cemented carbides.

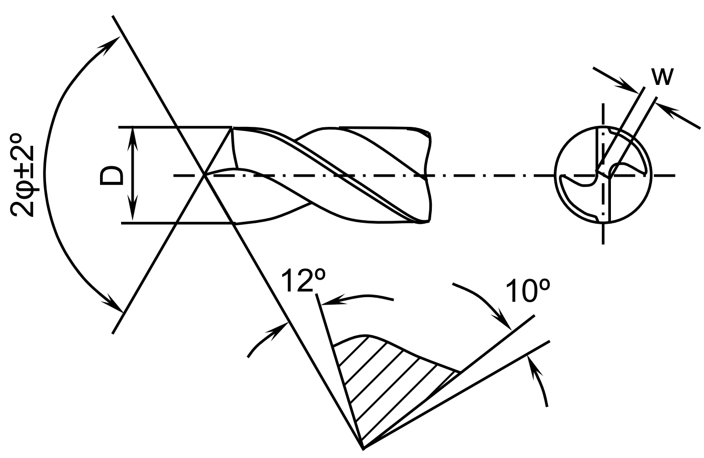


Figure 2.2. Geometric parameters of drills for machining of holes in workpieces from hard-to-machine materials

Drills from cemented carbides should have rake angle of 0º; relief angle – 12º; point angle – 140º; web should be ground to $\boldsymbol{w}$ = 0.1$\boldsymbol{D}$; body length – not more than 6 diameters. When drilling through holes it is reasonable to apply drills with double sharpening (2φ = 140º and $2\varphi_0$ = 90º on the length $\boldsymbol{b} \approx$ 0.1…0.15$\boldsymbol{D}$).

Data of tool materials are given in Para 1.3 and Appendices 4 – 6.

Wear along flank surface of drill periphery should be considered as a criterion of drill dulling. Values of wear for drills of various diameters from high-speed steels and cemented carbides are given in the Table 2.1.

Table 2.1

Permissible drill wear along relief surface

Tool material	Drill diameter $\boldsymbol{D}$, mm	Wear, mm
High-speed steels	1…3 4…7 7	0.2 0.4 0.6…0.8
Cemented carbides	1…3 4…7 7	0.15 0.3 0.4…0.5

Oil fluids are used as cutting fluids at drilling holes of up to 3 mm, at drilling larger diameters – water emulsions (ref. Table 1.3).

2.2. Calculation of cut depth

Depth of cut for drilling is considered to be the distance between machined hole surface and axis of drill, that is, $\boldsymbol{t = D/2}$.

For drilling-out (ref. Fig. 2.1,c) the depth of cut

$$\boldsymbol{t} = \frac{\boldsymbol{D - d}}{2},$$

where $\boldsymbol{D}$ – diameter of drill, mm; $\boldsymbol{d}$ – diameter of hole obtained earlier, mm.

2.3. Specifying a feed

Feed is specified depending on work material, work diameter, tool material and other technological factors. Recommended feeds for machining deep holes with drills from high-speed steels are given in the Table 2.2 and with drills from cemented carbides – in the Table 2.3.

When machining through holes with automatic feed, it is recommended to switch off feed at the moment of drill coming out the hole and complete drilling with hand feed to avoid drill break. If it is impossible to perform (for example, when machining in automatic or semi-automatic machines), the recommended feeds should be reduced by 20…25 %.

The deeper a hole, the worse conditions are for a drilling operation. Therefore, when specifying feed the ratio of drilling depth to diameter should be taken into account with correction coefficient k_{ls}:

l/D	3	5	7	10
k_{ls}	1.0	0.9	0.8	0.75

When drilling-out the table data are to be increased 1.5…2 times, that is, correction coefficient taking into account type of machining $k_{os} \approx 1.75$.

Table 2.2

Feeds for machining with drills from high-speed steels, mm/rev

Drill diameter, mm	Workpiece material	
	Steels of groups I, II (with σ_u < < 1200 MPa), III, titanium alloys with σ_u < 1000 MPa	Steels of groups II (with σ_u > 1200 MPa), IV, alloys of groups V, VI and titanium alloys with σ_u > 1000 MPa
1	0.010…0.015	0.006…0.010
2	0.020…0.030	0.010…0.020
3	0.030…0.070	0.020…0.030
5…6	0.050…0.080	0.030…0.050
8	0.070…0.120	0.050…0.090
10…12	0.090…0.150	0.070…0.100
15	0.100…0.180	0.080…0.120
18	0.120…0.200	0.100…0.150
20	0.120…0.220	0.100…0.150
24	0.150…0.250	0.120…0.180
30	0.180…0.300	0.150…0.200

Table 2.3

Feeds for machining with drills from cemented carbides, mm/rev

Drill diameter, mm	Workpiece material	
	Titanium alloys with σ_u < 1000 MPa	Titanium alloys with σ_u > 1000 MPa, steels of group II with σ_u = 1200…1600 MPa, alloys of groups V and VI
1	0.006…0.009	0.003…0.006
2	0.012…0.018	0.006…0.012
3	0.015…0.030	0.010…0.018
4	0.030…0.050	0.020…0.040
8	0.050…0.080	0.040…0.060
10	0.060…0.100	0.050…0.080
12	0.070…0.120	0.060…0.100
15	0.100…0.150	0.080…0.120
20	0.120…0.180	0.100…0.150

Note. Drills of 1…3 mm diameter – spade drills from carbides BK6-OM (VK6-OM), BK10-OM (VK10-OM); drills of 4…7 mm diameter – solid ones from carbide BK10-OM (VK10-OM); drills of diameter of more than 7 mm – with tips of carbides BK6M (VK6M), BK8 (VK8).

2.4. Express calculations of cutting velocity, torque and machine power

Purpose of the calculations is described in Para 1.6. Calculations are performed according to the following relationships:

1) Cutting velocity $\boldsymbol{V_c}$ from Para 2.7 for the given drilling diameter $\boldsymbol{D}$ according to the specified feed $\boldsymbol{f_c}$ (Para 2.3) and recommended drill life (Para 2.7.1);
2) Torque $\boldsymbol{M_c}$ from Para 2.12 with the same $\boldsymbol{D}$ and $\boldsymbol{f_c}$ values and obtained $\boldsymbol{V_c}$;
3) Machine power $\boldsymbol{N_{emc}}$ from Para 2.13 with the same $\boldsymbol{D}$ value and obtained $\boldsymbol{V_c}$ and $\boldsymbol{M_c}$.

If operation has several drilling steps, calculations with substitution of parameters into formulas are performed only for one step in the term project. Initial data and obtained results for all steps are written into the table similar to that given in the Para 1.6. Machine is selected according to the most powerful step.

2.5. Selection of machine

Selection of machine is performed in a similar manner to turning (Para 1.7).

It should be taken into account that machining small workpieces, when mass of a workpiece and drill jig are small and alignment of drill axis with axis of work hole (for example, through a jig bushing) is realized by displacement of jig with a workpiece along the table surface, is performed in vertical drilling machines, and of large workpieces – in radial drilling machines.

In the case, when drilling is a step of turning operation (for example, drilling central hole), the further calculations become easier, as rows of feeds and rotational speeds are already prepared for this turning operation. But some difficulties could arise, if power for drilling appears to be more than power of machine selected earlier. Then the machine should be changed or 2 manufacturing steps (if it would be enough) should be planned – machining with smaller drill diameter with sequent drilling-out to the specified diameter.

In the case of machining holes with parallel axes in turning machine (for example, with application of cumbersome indexing device), the critical factor for selection of machine could be its dimensions of work zone necessary for attachment of the device to machine's spindle.

2.6. Agreement of feed value with technical data of turning machine

General considerations for agreement of feed value with technical data of turning machine are given in Para 1.8.

Ratio of geometric row of feeds for drilling machines in most of cases is approximately equal to 1.41. Exceptions are vertical drilling machines with small number of feed steps (3…5), which have $\boldsymbol{\varphi} \approx 1.78$, and radial drilling machines with large for this type of machines number of feed steps (for instance, 18), which have $\boldsymbol{\varphi} \approx 1.26$. Row of feeds is shown in a term project.

If it is necessary to use hand feed an operation chart of machining is filled with the feed value specified according to the Para 2.3 with word “hand” in the corresponding column. This value is used in further calculations as a final one.

It is also applied for holes machining in turning machines that have non-mechanized (hand) drive of a tailstock.

2.7. Calculation of cutting velocity

The calculation is performed with the given value of workpiece diameter, feed agreed with a machine for the most favourable life of cutting tool.

A. For drilling the workpieces from steels and alloys of groups I-VI with drills from high-speed steels:

$$V_c = \frac{C_V D^{0.75}}{T^{0.25} f^{0.85}} k_V ,$$

where C_V – coefficients characterizing workpiece material and cutting conditions; k_V – general correcting coefficient characterizing the changed cutting conditions as compared with those characterized by coefficient C_V. Coefficient k_V is equal to the product of particular correcting coefficients described below.

Here and further the cutting velocity is in m/min.

Values of coefficients C_V for typical representatives of hard-to-machine materials of groups I-VI are given in the Table 2.4.

B. For drilling the workpieces from alloys of groups V and VI with drills from cemented carbides:

$$V_c = \frac{C_V D^{0.75}}{T^{0.25} f^{0.85}} k_V .$$

Values of coefficients C_V for alloys of groups V and VI are given in the Table 2.5.

C. For drilling the workpieces from titanium alloys of group VII with drills from high-speed steels:

$$V_c = \frac{C_V D^{0.7}}{T^{0.5} f^{0.6}} k_V .$$

D. For drilling the workpieces from titanium alloys of group VII with drills from cemented carbides:

$$V_c = \frac{C_V D^{0.65}}{T^{0.55} f^{0.65}} k_V .$$

The values of coefficients C_V for titanium alloys of group VII for Points **C** and **D** are given in the Table 2.6.

The above relationships for calculation of cutting velocity are for blind holes. When drilling through holes the values of cutting velocity should be multiplied by coefficient k_{TV} = 0.9 taking into account the type of a hole. When drilling holes of diameter of more than 15 mm, the large axial forces and torques appear, and so machining of such holes is reasonable to perform in 2 steps: to drill hole with a drill of diameter of 0.4…0.5 specified diameter, and to drill it out with a drill of specified diameter.

Cutting velocity at drilling is influenced by the following factors: tool life, material of drill point, depth of cut, physical and mechanical properties of work material, drill diameter, feed, shape of drill point, cutting fluids.

Table 2.4

Coefficients C_V, C_P, C_M for drilling workpieces from steels and alloys of groups I-VI with drills from high-speed steels

Group number	Grade	σ_u, MPa	C_V	C_P	C_M
I	34ХН3М (34HN3M), 34ХН4МФ (34HN4MF) 20Х3МВФ (20H3MVF)	900	1.07	1100	80
II	20Х13 (20H13), 1Х12Н2ВМФ (1H12N2VMF)	850…900	1.04		
	30Х13 (30H13), 09Х16Н4Б (09H16N4B) 20Х13 (20H13), 14Х17Н2 (14H17N2)	900…1000 1000…1100	0.95 0.80	1400	100
	09Х16Н4БА (09H16N4BA)	1300	0.47	-	-
III	12Х18Н10Т (12H18N10T)	600	0.08	1100	80
	12Х21Н5Т (12H21N5T) 45Х14Н14В2М (45H14N14V2M)	700	0.65 0.67	- -	- -
IV	Х15Н24В4Т (H15N24V4T) 07Х21Г7АН5 (07H21G7AN5) 12Х25Н16Г7АР (12H25N16G7AR) 37Х12Н8Г8МФБ (37H12N8G8MFB)	800…1000	0.48	1400	100
	10Х11Н23Т3МР (10H11N23T3MP) 15Х18Г21С4ТЮ (15H18N21S4TU)	700…900	0.38	1200	90
V	36ХНТЮ (36HNTU)	800…1200	0.28	1600	140
	ХН77ТЮР (HN77TUR)	1000			
	ХН35ВТЮ (HN35VTU)	1150…1300	0.21	1600	140
	ХН67ВМТЮ (HN67VMTU), ХН56ВМТЮ (HN56VMTU)	900…950	0.18		
	ХН75МВЮ (HN75MVU)	900…1000			
	ХН62МВКЮ (HN62MVKU) ХН60МВТЮ (HN60MVTU)	1000…1100	0.18		
	ХН82ТЮМБ (HN82TUMB)	1200…1400	0.13	1800	150
VI	ВЖ36-Л2 (VZh36-L2), АПВ-300 (APV-300), ЖС6К (ZhS6K), ЖС3ДК (ZhS3DK)	800…1000	0.09	1450	125
	ХН67ВМТЮЛ (HN67VMTUL)	750	0.09		

Note. Cooling with emulsion is obligatory.

Table 2.5

Coefficient C_V for drilling workpieces from alloys of groups V,VI with drills from cemented carbides

Group number	Grade	σ_u, MPa	C_V
V	36ХНТЮ (36HNTU), ХН77ТЮР (HN77TUR)	800…1200	0.64
	ХН35ВТЮ (HN35VTU)	1150…1300	0.48
	ХН75МВЮ (HN75MVU), ХН67ВМТЮ (HN67VMTU)	900…1000	0.40
	ХН62МВКЮ (HN62MVKU), ХН60МВТЮ (HN60MVTU)	1000…1100	
VI	ХН62МВКЮ (HN62MVKU), ХН60МВТЮ (HN60MVTU), ХН82ТЮМБ (HN82TUMB)	1200…1400	0.30
	ВЖ36-Л2 (VZh36-L2), ЖС6К (ZhS6K), ЖС3ДК (ZhS3DK), ХН67ВМТЮЛ (HN67VMTUL)	750…1000	0.20

Table 2.6

Coefficients C_V, C_P, C_M for drilling workpieces from alloys of group VII

Grade	σ_u, MPa	Drills from high-speed steels			Drills from cemented carbides
		C_V	C_P	C_M	C_V
ВТ-1 (VT-1), ВТ1-1 (VT1-1), ВТ1-2 (VT1-2)	450…700	4.2	-	-	6.3
ВТ3 (VT3), ВТ3-1 (VT3-1)	950…1200	2.1	-	-	3.1
ОТ4, ОТ4-1, ВТ5 (VT5), ВТ5-1 (VT5-1)	700…950	2.8	850	60	4.2
ВТ6 (VT6), ВТ6С (VT6S)	900…1000	2.3	-	-	3.5
ВТ14 (VT14), ВТ15 (VT15)	1000	2.1	-	-	3.1
ВТ14 (VT14), ВТ15 (VT15)	1300…1400	-	-	-	2.5

2.7.1. Life of cutting tool

The higher the cutting velocity, the greater is generation of heat, more intensive wear, a drill will faster become dull and shorter life it will have.

Calculation of the most reasonable cutting velocity from the above relationships is performed for the following values of drill life:

a) Drills from high-speed steel:

Drill diameter, mm	1…2	3…5	8…10	12…15	18…20	24	30
Drill life, min	4	6	10	12	15	20	25

b) Drills from cemented carbide:

Drill diameter, mm	1…2	3…5	6…8	10…12	15…20
Drill life, min	5	6	10	15	20

2.7.2. Material of drill point

The higher high-temperature material stability of a drill point, the higher admissible cutting velocity is.

Correction coefficients $\boldsymbol{k_{MV}}$ for cutting velocity in dependence on drill material for all groups of hard-to-machine materials are given in Table 2.7.

Table 2.7

Correction coefficients $\boldsymbol{k_{MV}}$ for cutting velocity in dependence on drill material

Group number, $\boldsymbol{\sigma_u}$, MPa	High-speed steels			Cemented carbides			
	P6M5 (R6M5)	P6M5K5 (R6M5K5)	P9M4K8 (R9M4K8)	BK6-OM (VK6-OM)	BK6M (VK6M)	BK8 (VK8)	BK10-OM (VK10-OM)
I	0.94	1.0	1.10	-	-	-	-
II < 1200	0.91	1.0	1.13	-	-	-	-
II > 1200	0.95	1.0	1.3	1.25	1.15	1.0	0.9
III	0.91	1.0	1.13	-	-	-	-
IV	0.86	1.0	1.30	-	-	-	-
V	0.88	1.0	1.40	-	-	-	-
V > 1200	-	-	-	1.25	1.15	1.0	0.9
VI	0.88	1.0	1.40	1.25	1.15	1.0	0.9
VII	0.73	1.0	1.29	1.25	1.15	1.0	0.9

2.7.3. Depth of drilling

With the increase of drilling depth the operation conditions for drill become more hard: chip coming-out gradually becomes more difficult (chip is in contact with drill and hole walls more time that is accompanied by friction); supply of cutting fluid to cutting zone worsens; strengthening of machined surfaces increases (that is, at large depth drill margins will rub against more hardened surfaces of hole). All these result in more heating of drill and reduction of its endurance (at greater degree for drills of small diameters). Therefore, when drilling at the depth more than 3$\boldsymbol{D}$, cutting velocity should be decreased. This is taken into account by correction coefficient $\boldsymbol{k_{lV}}$:

Hole depth in drill diameters, up to	3$\boldsymbol{D}$	4$\boldsymbol{D}$	5$\boldsymbol{D}$	6$\boldsymbol{D}$	8$\boldsymbol{D}$	10$\boldsymbol{D}$
Coefficient $\boldsymbol{k_{lV}}$	1.0	0.85	0.75	0.70	0.60	0.5

2.7.4. Physical and mechanical properties of work material

The higher mechanical properties of work material, the larger the work consumed for chip forming at drilling is, the bigger heat generation and thermodynamic load on length unit of cutting edge is, the more intensive drill wear and the less its endurance is, and, hence, the less the cutting velocity admitted by drill at the same drill life is.

2.7.5. Drill diameter

With the increase of drill diameter (all other things being equal) the cutting velocity admitted by drill increases. It is explained by more intensive heat sink from drill surfaces into its body and workpiece that reduces calorific intensity on the rubbing drill surfaces and improves its endurance in spite of the increase of cross-section area of cut and work consumed by cutting process. Larger volume of drill flutes makes easier chip coming out hole along with improvements in delivery of cutting fluid to chip-forming zone.

2.7.6. Feed

The increase of feed raises cross-section area of cut that results in increase of forces applied to drill, increase of work consumed by the cutting process, and, hence, total quantity of evolved heat. All these raise thermodynamic loading of drill and reduce its endurance (or cutting velocity at the same life).

2.7.7. Shape for drill grinding

Optimal geometric parameters of drills for making holes in workpieces from hard-to-machine materials are recommended in Para 2.1. Double-angle grinding with angle $2\varphi_0 = 90°$ gives an opportunity to increase the cutting velocity approximately by 15…20 %. It is connected with that the cutting edge becomes longer, chip at the edge formed by additional grinding will be thinner, and corner (at the place of mating of cutting edges and margins) being the weakest element of drill becomes more massive. This improves strength of the corner and reduces thermodynamic loading on the length unit of cutting edge.

2.7.8. Cutting fluids

Along with improvement of chip-forming process and reduction of drill temperature the cutting fluids contribute to the increase of drills endurance (or cutting velocity) and improvement of quality of a machined surface. Recommendations for application of cutting fluids are given in the Para 1.3.3. If the operation is performed without cutting fluid, the coefficient taking into account the changed cutting conditions is applied $k_{cfV} = 0.7$ (if the fluid is applied, $k_{cfV} = 1.0$).

Thus, almost all main factors having influence on the cutting velocity are taken into account either by calculation relationships or by selection of recommended parameters. Total correction coefficient k_V would include only k_{MV} taking into account influence of tool material, k_{lV} taking into account depth of drilling and k_{cfV}.

2.8. Calculation of drill rotational speed

Calculated rotational speed of drill

$$n_c = \frac{1000 V_c}{\pi \cdot D}.$$

2.9. Agreement of rotational speed with technical data of drilling machine

Agreement of rotational speed is performed similarly to agreement of feed.

It is worth pointing that the ratio of geometric row of speeds, as a rule, for vertical drilling machines approximately equals 1.41, and for radial drilling machines – $\varphi \approx 1.26$.

As a result of agreement the n_m value is obtained. Row of rotational speeds of machine spindle is written in the explanatory note.

2.10. Determination of actual cutting speed

Actual cutting speed

$$V_a = \frac{\pi \cdot D \cdot n_m}{1000}.$$

2.11. Calculation of axial cutting force

For all groups of hard-to-machine materials when machining with drills from high-speed steels the axial cutting force is derived from

$$P_o = C_P \cdot D \cdot f_m^{\ 0.7}.$$

Here and further the axial force is expressed in newtons (N).

Values of coefficient C_P for typical materials of groups I-VI are given in Table 2.4, for titanium alloys – in Table 2.6.

2.12. Calculation of torque

For all groups of hard-to-machine materials when machining with drills from high-speed steels the torque is derived from

$$M_c = C_M V_a^{\ -0.15} D^{1.9} f_m^{\ 0.8}.$$

Here and further torque is in N·cm.

Values of coefficient C_M for typical materials of groups I-VI are given in Table 2.4, for titanium alloys – in Table 2.6.

The following main factors influence the axial force and total torque of cutting at drilling: work material, geometric parameters of drill, cutting fluids, drill wear, depth of drilling, cutting velocity, drill diameter, feed.

The last three factors are taken into account by calculation relationship (for example, for determination of M_c), and other – either by selection of recommended parameters, for which the relationship is right, or by corresponding correction coefficient.

2.13. Calculation of machine drive power

Power consumed by cutting (effective power), kW:

$$\boldsymbol{N}_{e} = \frac{\boldsymbol{M}_{c}\boldsymbol{V}_{a}}{3000\boldsymbol{D}}.$$

Power of electric motor necessary for cutting is determined with machine efficiency coefficient (η_m = 0.7…0.8), kW:

$$\boldsymbol{N}_{emc} = \frac{\boldsymbol{N}_{e}}{\eta_{m}}.$$

Short-time overloading of electric motor up to 25 % its nominal power is permitted.

If drilling operation consists of several manufacturing steps, the obtained results for each step are written into the table similar to one of Para 1.15.

2.14. Check of selected parameters of cutting conditions

Check is performed on the strength of weak element of machine feed mechanism, strength of weak element of machine main motion mechanism (when operating at small spindle rotational speed) and on the adequacy of power of machine electric motor.

If strength of weak element of feed mechanism would appear to be insufficient, that is $P_o > P_{max}$, or of main motion mechanism, that is $M_c > M_m$ or $N_{emc} > N_{ems}$, another, more powerful machine is selected, or feed is reduced.

Machine torque, N·cm:

$$\boldsymbol{M}_{m} = 955000\frac{\boldsymbol{N}_{ems} \cdot \eta_{m}}{\boldsymbol{n}_{m}}.$$

Check on adequacy of power of machine electric motor is performed from condition that $N_{emc} \le N_{ems}$ (or $M_c \le M_m$). If it would appear that $M_c > M_m$ (or $N_{emc} >$ $> N_{ems}$), another machine is selected, or rotational speed n_m (and, respectively, velocity V) is reduced.

3. MILLING

Milling is a machining process for producing various shapes with rotating multiple-edged tools called milling cutters. Milling involves simultaneous rotary motion of the cutter and, usually, linear feed motion of the workpiece [9].

Milling may be done, insofar as the directions of cutter rotation and workpiece feed are concerned, by either of two methods: 1) up, or conventional, milling in which the work is fed against the cutter rotation and 2) down, or climb, milling in which the cutter rotation and work feed directions coincide.

In conventional milling the load on each tooth of the cutter gradually increases and reaches its maximal value as the tooth leaves the cut. This ensures smoother operation of the milling machine and less tool wear if castings with a chilled skin or forgings with scale are milled. Not a very high quality of surface finish is attained, however, and therefore this method is used in roughing.

In climb milling the cutter tooth cuts a chip of maximal thickness at the beginning as it enters the cut so that it is subject to maximal load. This method can never be used in a machine unless it is equipped with a backlash eliminator on the feed screw. The forces are directed downwards in milling by this method (the opposite being true for conventional milling); this facilitates the clamping of workpieces that cannot be easily held. Another advantage is the better finish obtained.

The cutting velocity V is the peripheral speed of the cutter measured at its outside diameter. Cutting velocity depends upon the properties of the material being milled, the cutter material, diameter and life of the cutter, feed, depth and width of cut, as well as the number of cutter teeth, cooling facilities, etc.

The feed f in milling is the movement of the workpiece relative to the cutter axis in a unit of time. It may be expressed as feed per tooth (mm/tooth), feed per cutter revolution (mm/rev) or feed per minute (mm/min). The heaviest feasible feed is employed for rough milling; thus, for high-speed steel plain milling cutters the feed may be 0.05 to 0.6 mm/tooth for milling steel and 0.1 to 0.8 mm/tooth for cast iron. In semi-finish and finish milling the rate of feed is limited by the specified surface finish that must be obtained.

The depth of cut t is the thickness of the layer of metal removed in one cut. A depth of cut from 3 to 8 mm is common in roughing operations and from 0.5 to 1.5 mm in finishing.

The width of cut $\boldsymbol{B}$ is the width of the work surface contacting the cutter in a direction perpendicular to the feed.

Machining time in milling is the time required for the process of metal cutting in one pass of the cutter. When calculating the machining time it is necessary to take into consideration the total travel of table (or cutter) in the direction of feed (including cutter approach and over-travel), the rate of feed and the number of passes.

3.1. Selection of diagram and cutter for milling operation

In a term paper the sketch of milling operation should be developed according to the General instructions (see p. 3) and standards GOST 3.1107-81 (mounting and clamping elements), GOST 2.309-73 (surface roughness), GOST 3.1702-79 (list of manufacturing steps).

Configuration of work surface and type of equipment determine type of applied milling cutter (Fig. 3.1). Its dimensions are specified by dimensions of work surface and depth of removed layer. Cutter diameter is selected as small as possible for reduction of direct manufacture time and consumption of tool material, taking into account rigidity of technological system, cutting diagram, shape and dimensions of work piece [10].

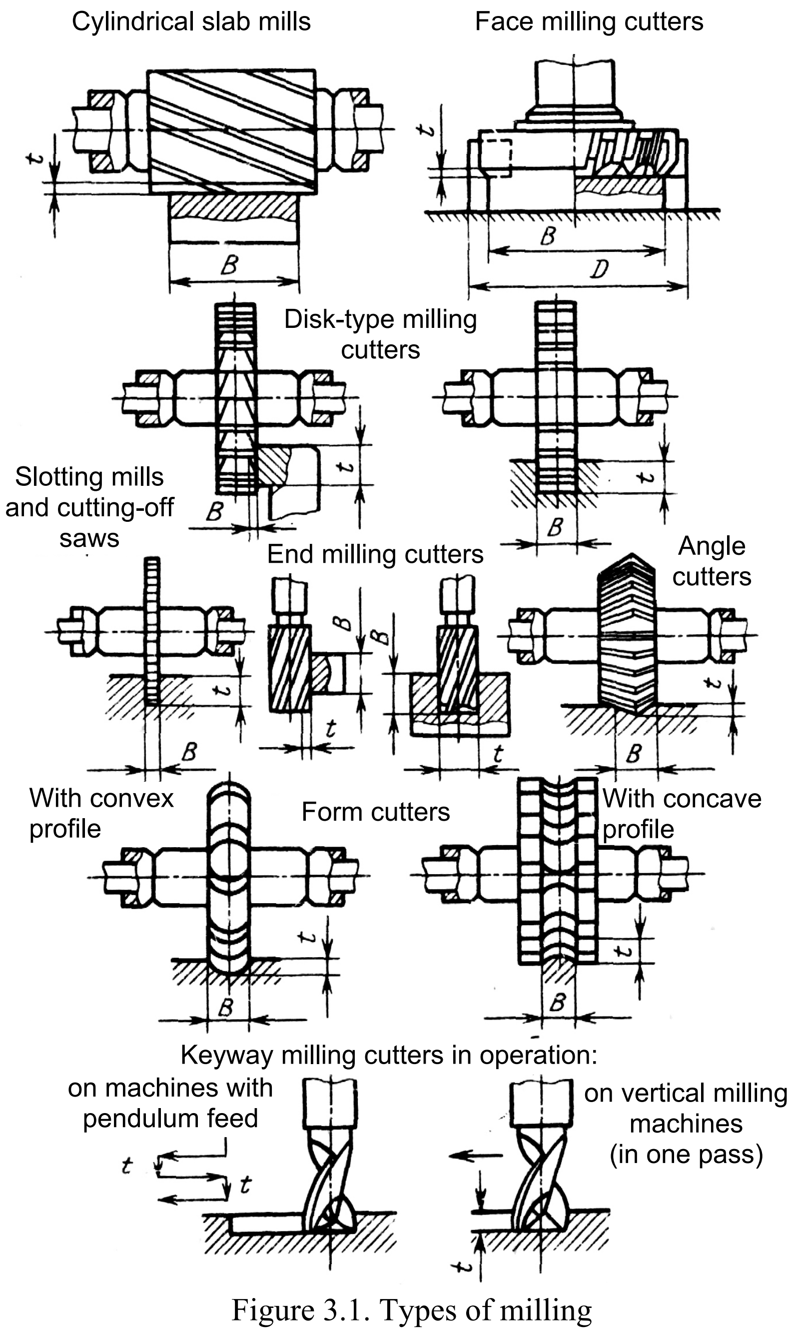


Figure 3.1. Types of milling

For providing high-productive cutting conditions at face milling the diameter of milling cutter ***D*** should be more than width of milling ***B***, that is, $D = (1.25\ldots1.5)B$, and at machining steel workpieces their asymmetrical position relative to milling cutter is obligatory: for workpieces from structural carbon and alloyed steels – their displacement to the side of cutter tooth cutting-in (Fig. 3.2,a) that assures start of cutting at small thickness of removed layer; for workpieces from high-temperature and corrosion-resistant steels – displacement of a workpiece to the side of exit of the cutter tooth from cutting process (Fig. 3.2,b) that assures exit

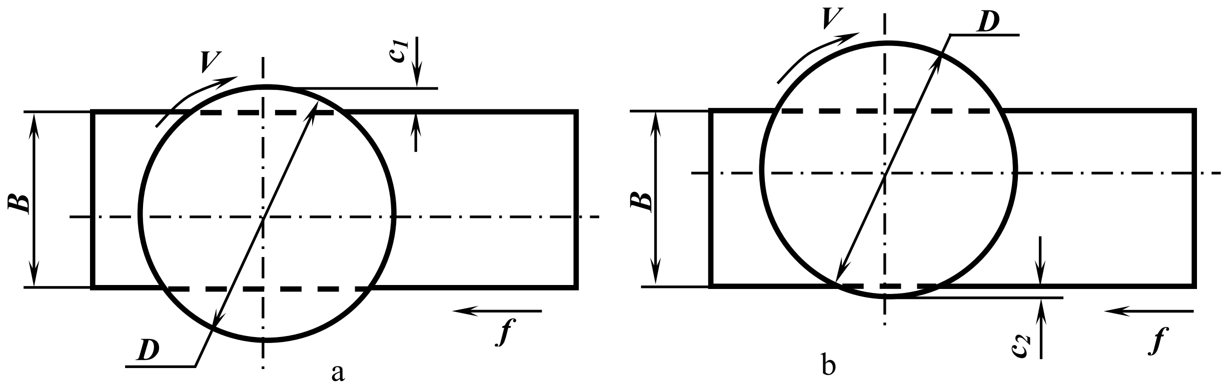


Figure 3.2. Position of steel workpiece relative to the milling cutter at face milling: a – cutting-in of cutter tooth at c_1 = (0.03…0.05D); b – exit of cutter tooth at c_2 = 0

from cutting process with minimal thickness of removed layer. Violation of these rules results in significant reduction of tool life.

This paragraph should be completed with the sketch of selected milling cutter and data about the type, number of teeth, material, and geometric parameters.

3.2. Depth and width of milling

The depth of milling t and the width of milling B are definitions connected with dimensions of workpiece layer removed during milling (ref. Fig. 3.1). In all types of milling, except face milling, t determines duration of contact of a cutter tooth with workpiece; t is measured in direction perpendicular to the cutter axis. Width of milling B determines the length of blade of cutter tooth engaged in cutting; B is measured in direction parallel to the cutter axis. At the face milling these definitions change the places.

3.3. Feed

At milling there are feed per one tooth f_z, feed per one revolution f and feed per one minute f_m, mm/min, which are in the following relationship

$$f_m = f\,n = f_z\,z\,n,$$

where n – rotational speed of milling cutter, mm/rev; z – quantity of teeth of milling cutter.

Initial value of feed for rough milling is its value per one tooth f_z, for finish milling – per one revolution of milling cutter f that further is used for calculation of feed per one tooth

$$f_z = f\,/\,z.$$

Recommended values of feed for various milling cutters are given in Tables 3.1 – 3.6. When using Tables 3.1 and 3.2, the smallest power of machine (up to 5 kW) should be selected for the first iteration. The condition of Para 3.8 is checked after performance of calculations according to Paragraphs 3.4 – 3.7.

In Tables 3.1 and 3.2 the rigidity of system "workpiece-workholding device" is to be selected with taking into account the following considerations. Rigidity of workpiece depends on its design features: material, shape, thickness of wall, presence of holes, ratio of length to diameter, etc. Hollow, long parts of small cross-section area possess low rigidity. Such parts would be deformed elastically (and sometime plastically) by cutting forces applied to their surfaces during the cutting process.

Table 3.1

Feeds at rough milling with face, cylindrical and disk-type milling cutters with carbide tips

Machine power, kW	Steel		Cast iron and copper alloys	
	Feed f_z, mm per cutter's tooth, for cemented carbide			
	T15K6	T5K10	BK6 (VK6)	BK8 (VK8)
5 – 10	0.09 – 0.18	0.12 – 0.18	0.14 – 0.24	0.20 – 0.29
More than 10	0.12 – 0.18	0.16 – 0.24	0.18 – 0.28	0.25 – 0.38

Notes: 1. The given values of feed for cylindrical mills are actual at milling width of $B \leq 30$ mm; at $B > 30$ mm the table values should be reduced by 30 %. 2. The given values of feed for disk-type mills are actual for milling of planes and steps; when milling slots the table values should be 2 times reduced. 3. When milling with the feeds specified in the table, the roughness parameter $R_a = (0.8 \div 1.6)$ µm is obtained.

Table 3.2

Feeds at rough milling with face, cylindrical and disk-type milling cutters from high-speed steels

Power machine or milling head, kW	Stiffness of system workpiece–fixture	Milling cutters			
		Face and disk-type		Cylindrical	
		Feed f_z, mm per cutter's tooth, at machining of			
		Structural steel	Cast iron and copper alloys	Structural steel	Cast iron and copper alloys
Mills with coarse teeth and mills with inserts					
More than 10	Increased	0.20 – 0.30	0.40 – 0.60	0.40 – 0.60	0.60 – 0.80
	Middle	0.15 – 0.25	0.30 – 0.50	0.30 – 0.40	0.40 – 0.60
	Lower	0.10 – 0.15	0.20 – 0.30	0.20 – 0.30	0.25 – 0.40
5 – 10	Increased	0.12 – 0.20	0.30 – 0.50	0.25 – 0.40	0.30 – 0.50
	Middle	0.08 – 0.15	0.20 – 0.40	0.12 – 0.20	0.20 – 0.30
	Lower	0.06 – 0.10	0.15 – 0.25	0.10 – 0.15	0.12 – 0.20
Up to 5	Middle	0.06 – 0.07	0.15 – 0.30	0.08 – 0.12	0.10 – 0.18
	Lower	0.04 – 0.06	0.10 – 0.20	0.06 – 0.10	0.08 – 0.15
Mills with fine teeth					
5 – 10	Increased	0.08 – 0.12	0.20 – 0.35	0.10 – 0.15	0.12 – 0.20
	Middle	0.06 – 0.10	0.15 – 0.30	0.06 – 0.10	0.10 – 0.15
	Lower	0.04 – 0.08	0.10 – 0.20	0.06 – 0.08	0.08 – 0.12
Up to 5	Middle	0.04 – 0.06	0.12 – 0.20	0.05 – 0.08	0.06 – 0.12
	Lower	0.03 – 0.05	0.08 – 0.15	0.03 – 0.06	0.05 – 0.10

Notes: 1. Larger values of feed should be selected for smaller depth and width of milling, the smaller – for larger values of depth and width. 2. When milling the high-temperature and corrosion-resistant steels, the feeds should be selected the same for structural steel, but not more than 0.3 mm/tooth.

Table 3.3

Feeds at milling of steel workpieces with various mills from high-speed steel

Mill diameter ***D***, mm	Mills	Feed f_z, mm per tooth, at depth of milling t, mm								
		3	5	6	8	10	12	15	20	30
16	End	0.08–0.05	0.06–0.05	–	–	–	–	–	–	–
20	End	0.10–0.06	0.07–0.04							
25	End	0.12–0.07	0.09–0.05	0.08–0.04						
35	End	0.016–0.10	0.12–0.07	0.10–0.05						
35	Angle & form	0.08–0.04	0.07–0.05	0.06–0.04						
40	End	0.20–0.12	0.014–0.08	0.12–0.07	0.08–0.05					
40	Angle & form	0.09–0.05	0.07–0.05	0.06–0.03	0.06–0.03					
40	Slotting	0.009–0.005	0.007–0.003	0.01–0.007	–					
50	End	0.25–0.15	0.15–0.10	0.13–0.08	0.10–0.07					
50	Angle & form	0.10–0.06	0.08–0.05	0.07–0.04	0.06–0.03					
50	Slotting	0.010–0.006	0.008–0.004	0.012–0.008	0.012–0.008					
60	Angle & form	0.10–0.06	0.08–0.05	0.07–0.04	0.06–0.04	0.05–0.03				
60	Slotting	0.013–0.0008	0.010–0.005	0.015–0.01	0.015–0.01	0.015–0.01				
60	Cutting-off	–	–	0.025–0.015	0.022–0.012	0.02–0.01				
75	Angle & form	0.12–0.08	0.10–0.06	0.09–0.05	0.07–0.05	0.06–0.04	0.06–0.03			
75	Slotting	–	0.015–0.005	0.025–0.01	0.022–0.01	0.02–0.01	0.017–0.008	0.015–0.007		
75	Cutting-off		–	0.03–0.015	0.027–0.012	0.025–0.01	0.022–0.01	0.02–0.01		
90	Angle & form	0.12–0.08	0.12–0.05	0.11–0.05	0.010–0.05	0.09–0.04	0.09–0.04	0.07–0.03	0.05–0.03	
90	Cutting-off	–	–	0.03–0.02	0.028–0.016	0.027–0.015	0.027–0.015	0.022–0.012	0.023–0.013	
110	Cutting-off			0.03–0.025	0.03–0.02	0.03–0.02	0.03–0.02	0.025–0.02	0.025–0.015	
150-200	Cutting-off			–	–	–	–	0.03–0.02	0.028–0.016	0.02–0.01

Notes: 1. When milling cast iron, copper and aluminum alloys, the feeds may be increased by 30-40 %. 2. The feeds are given for form mills with convex smooth profile; for the same mills with abrupt or concave profile the feeds should be reduced by 40 %. 3. Feeds for slotting and cutting-off mills with small tooth are specified for milling depth of up to 5 mm, with large tooth – for depth of more than 5 mm.

Table 3.4

Feeds at milling of planes and steps in steel workpieces with carbide end mills

Rough milling								
Type of carbide element	Mill diameter ***D***, mm	Feed f_z, mm per one tooth of mill, at depth *t*, mm						
		1–3	5	8	12	20	30	40
Crown	10 – 12	0.01–0.03	–	–	–	–	–	–
	14 – 16	0.02–0.06	0.02–0.04	–	–	–	–	–
	18 – 22	0.04–0.07	0.03–0.05	0.02–0.04	–	–	–	–
Helical plates	20	0.06–0.10	0.05–0.08	0.03–0.05	–	–	–	–
	25	0.08–0.12	0.06–0.10	0.05–0.10	0.05–0.08	–	–	–
	30	0.10–0.15	0.08–0.12	0.06–0.10	0.05–0.09	–	–	–
	40	0.10–0.18	0.08–0.13	0.06–0.11	0.05–0.10	0.04–0.07	–	–
	50	0.10–0.20	0.10–0.15	0.08–0.12	0.06–0.10	0.05–0.09	0.05–0.08	0.05–0.06
	60	0.12–0.20	0.10–0.16	0.10–0.12	0.08–0.12	0.06–0.10	0.06–0.10	0.06–0.08

Finish milling				
Mill diameter *D*, mm	10 – 16	20 – 22	25 – 35	40 – 60
Mill feed *f*, mm/rev	0.02 – 0.06	0.06 – 0.12	0.12 – 0.24	0.3 – 0.6

Notes: 1. At rough milling of cast iron the feeds given for rough milling of steel may be increased by 30 – 40 %; at finish milling of cast iron the feeds are the same as recommended for finish milling of steel. 2. Upper values of feeds at rough milling should be applied for small width of milling on machines of high stiffness, lower values – at large width of milling on machines of insufficient stiffness. 3. When working with feeds for finish milling, the roughness parameter R_a = 0.8÷0.6 μm is obtained.

Table 3.5

Feeds, mm/rev, at finish milling of planes and steps with face, disk-type and cylindrical mills

Parameter of surface roughness R_a, μm	Face and disk-type mills with inserted blades		Cylindrical mills from high-speed steel with diameter, mm, depending on workpiece material					
	From cemented carbide	From high-speed steel	Structural carbon and alloy steel			Cast iron, copper and aluminium alloys		
			40 – 75	90 – 130	150 – 200	40 – 75	90 – 130	150 – 200
6.3	–	1.2 – 2.7	–	–	–	–	–	–
3.2	0.5 – 1.0	0.5 – 1.2	1.0 – 2.7	1.7 – 3.8	2.3 – 5.0	1.0 – 2.3	1.4 – 3.0	1.9 – 3.7
1.6	0.4 – 0.6	0.23 – 0.5	0.6 – 1.5	1.0 – 2.1	1.3 – 2.8	0.6 – 1.3	0.8 – 1.7	1.1 – 2.1
0.8	0.2 – 0.3	–	–	–	–	–	–	–
0.4	0.15	–	–	–	–	–	–	–

Short workpieces of solid cross-section with holes of small diameter have high stiffness. These parts would not be deformed elastically in a noticeable magnitude under action of cutting forces.

Rigidity of thin-walled parts (and whole system “workpiece-workholding device") could be improved with the application of special-purpose devices, which have their own high stiffness, and special elements (mandrels, etc.) that assure additional (auxiliary) support to the workpiece.

Such workholding devices have complicated design and high cost. Therefore their manufacture and application is economically sound under batch production conditions and when high accuracy is to be obtained for thin-walled and flexible parts.

In pilot and small-batch production, as a rule, the standardized fixtures are applied: vices (high stiffness), screw clamps (low rigidity), V-blocks, etc.

When performing the calculations of cutting conditions one should estimate and specify rigidity of a workpiece, workholding device and their total rigidity as a system, taking into account experience and those mentioned above.

Table 3.6

Feeds at milling steel workpieces with keyway mills from high-speed steels

Mill diameter D, mm	Milling on keyseaters with pendulum feed at milling depth per one double stroke as a part of key-slot depth		Milling on vertical milling machines per one pass	
			Axial cutting-in at depth of key slot	Traverse travel at milling of key slot
	Milling depth t, mm	Feed f_z, mm per one tooth		
6	0.3	0.10	0.006	0.020
8		0.12	0.007	0.022
10		0.16	0.008	0.024
12		0.18	0.009	0.026
16	0.4	0.25	0.010	0.028
18		0.28	0.011	0.030
20		0.31	0.011	0.032
24		0.38	0.012	0.036
28	0.5	0.45	0.014	0.037
32		0.50	0.015	0.037
36		0.55	0.016	0.038
40		0.65	0.016	0.038

Note. Feeds are given for structural steel with $\sigma_u \leq 750$ MPa; at machining steels of higher strength the feeds are reduced by 20 – 40 %.

3.4. Cutting velocity

The cutting velocity is considered to be equal to peripheral velocity of milling cutter

$$V_c = \frac{C_V D^q}{T^m t^x f_z^{\,y} B^u z^p} k_V \text{, m/min.}$$

Values of coefficient C_V and indexes of power are given in Table 3.7, and values of tool life ***T*** – in Table 3.8.

Table 3.7

Values of coefficient C_V and indexes of power in formula for cutting velocity at milling

Mills	Material of cutting point	Operation	Parameters of cut layer, mm			Coefficient and indexes of power in formula for cutting velocity						
			B	***t***	f_z	C_V	***q***	***x***	***y***	***u***	***p***	***m***
Machining of structural carbon steel, σ_u = 750 MPa												
Face	T15K6*[1]	Milling of planes	-	-	-	332	0.2	0.1	0.4	0.2	0	0.2
	P6M5*[2] (R6M5)		-	-	≤ 0.1 > 0.1	64.7 41	0.25	0.1	0.2 0.4	0.15	0	0.2
Cylindri-cal	T15K6*[1]		≤ 35	≤ 2 > 2	-	390 443	0.17	0.19 0.38	0.28	– 0.05	0.1	0.33
			> 35	≥ 2 > 2		616 700	0.17	0.19 0.38	0.28	0.08	0.1	0.33
	P6M5*[2] (R6M5)		-	-	≤ 0.1 > 0.1	55 35.4	0.45	0.3	0.2 0.4	0.1	0.1	0.33
Disk-type with in-serts	T15K6*[1]	Milling of planes and steps	-	-	< 0.12 ≥ 0.12	1340 740	0.2	0.4	0.12 0.4	0	0	0.35
		Milling of slots	-	-	< 0.06 ≥ 0.06	1825 690	0.2	0.3	0.12 0.4	0.1	0	0.35
	P6M5*[2] (R6M5)	Milling of planes, steps and slots	-	-	≤ 0.1 > 0.1	75.5 48.5	0.25	0.3	0.2 0.4	0.1	0.1	0.2
Disk-type solid	P6M5*[2] (R6M5)		-	-	-	68.5	0.25	0.3	0.2	0.1	0.1	0.2
End with crowns	T15K6*[1]		-	-	-	145	0.44	0.24	0.26	0.1	0.13	0.37
End with brazed tips			-	-	-	234	0.44	0.24	0.26	0.1	0.13	0.37
End solid	P6M5*[2] (R6M5)		-	-	-	46.7	0.45	0.5	0.5	0.1	0.1	0.33
Slotting and cut-ting-off	P6M5*[2] (R6M5)	Cutting slots and cutting-off	-	-	-	53	0.25	0.3	0.2	0.2	0.1	0.2
Form with con-vex pro-file	P6M5*[2] (R6M5)	Form mill-ing	-	-	-	53	0.45	0.3	0.2	0.1	0.1	0.33
Angle and form with con-cave pro-file		Milling of angle grooves and form milling				44	0.45	0.3	0.2	0.1	0.1	0.33
Keyway two-lipped	P6M5*[2] (R6M5)	Milling of key slots	-	-	-	12	0.3	0.3	0.25	0	0	0.26

Table 3.7, continued

Mills	Material of cutting point	Operation	Parameters of cut layer, mm			Coefficient and indexes of power in formula for cutting velocity						
			B	***t***	f_z	C_V	***q***	***x***	***y***	***u***	***p***	***m***
Machining of high-temperature steel 12X18H9T (12H18N9T) in as-delivered condition												
Face	BK8*[1] (VK8)	Milling of planes	-	-	-	108	0.2	0.06	0.3	0.2	0	0.32
Face	P6M5*[2] (R6M5)	Milling of planes	-	-	-	49.6	0.15	0.2	0.3	0.2	0.1	0.14
Cylindrical	P6M5*[2] (R6M5)	Milling of planes	-	-	-	44	0.29	0.3	0.34	0.1	0.1	0.24
End	P6M5*[2] (R6M5)	Milling of planes and steps	-	-	-	22.5	0.35	0.21	0.48	0.03	0.1	0.27
Machining of grey cast iron, HB 190												
Face	BK6*[1] (VK6)	Milling of planes	-	-	-	445	0.2	0.15	0.35	0.2	0	0.32
Face	P6M5*[1] (R6M5)	Milling of planes	-	-	-	42	0.2	0.1	0.4	0.1	0.1	0.15
Cylindrical	BK6*[1] (VK6)	Milling of planes	-	< 2.5	≤ 0.2 > 0.2	923 588	0.37	0.13	0.19 0.47	0.23	0.14	0.42
Cylindrical	BK6*[1] (VK6)	Milling of planes	-	≥ 2.5	≤ 0.2 > 0.2	1180 750	0.37	0.40	0.19 0.47	0.23	0.14	0.42
Cylindrical	P6M5*[1] (R6M5)	Milling of planes	-	-	≤ 0.15 > 0.15	57.6 27	0.7	0.5	0.2 0.6	0.3	0.3	0.25
Disk-type with inserts	P6M5*[1] (R6M5)	Milling of planes, steps and slots	-	-	-	85	0.2	0.5	0.4	0.1	0.1	0.15
Disk-type solid	P6M5*[1] (R6M5)	Milling of planes, steps and slots	-	-	-	72	0.2	0.5	0.4	0.1	0.1	0.15
End	P6M5*[1] (R6M5)	Milling of planes and steps	-	-	-	72	0.7	0.5	0.2	0.3	0.3	0.25
Slotting and cutting-off	P6M5*[1] (R6M5)	Cutting slots and cutting-off	-	-	-	30	0.2	0.5	0.4	0.2	0.1	0.15
Machining of malleable cast iron, HB 150												
Face	BK6*[1] (VK6)	Milling of planes	-	-	≤ 0.18 > 0.18	994 695	0.22	0.17	0.1 0.32	0.22	0	0.33
Face	P6M5*[2] (R6M5)	Milling of planes	-	-	≤ 0.1 > 0.1	90.5 57.4	0.25	0.1	0.2 0.4	0.15	0.1	0.2
Cylindrical	P6M5*[2] (R6M5)	Milling of planes	-	-	≤ 0.1 > 0.1	77 49.5	0.45	0.3	0.2 0.4	0.1	0.1	0.33
Disk-type with inserts	P6M5*[2] (R6M5)	Milling of planes, steps and slots	-	-	≤ 0.1 > 0.1	105.8 68	0.25	0.3	0.2 0.4	0.1	0.1	0.2
Disk-type solid	P6M5*[2] (R6M5)	Milling of planes, steps and slots	-	-	-	95.8	0.25	0.3	0.2	0.1	0.1	0.2

Table 3.7, finished

Mills	Material of cutting point	Operation	Parameters of cut layer, mm			Coefficient and indexes of power in formula for cutting velocity						
			B	***t***	f_z	C_V	***q***	***x***	***y***	***u***	***p***	***m***
End	P6M5*[2] (R6M5)	Milling of planes and steps	-	-	-	68.5	0.45	0.3	0.2	0.1	0 1	0 33
Slotting and cutting-off	P6M5*[2] (R6M5)	Cutting slots and cutting-off	-	-	-	74	0.25	0.3	0.2	0.2	0.1	0.2
Machining of heterogeneous copper alloys of middle hardness, HB 100 – 140												
Face	P6M5*[1] (R6M5)	Milling of planes	-	-	0.1 0.1	136 86.2	0.25	0.1	0.2 0.4	0.15	0.1	0.2
Cylindrical	P6M5*[1] (R6M5)		-	-	0.1 0.1	115.5 74.3	0.45	0.3	0.2 0.4	0.1	0.1	0.33
Disk-type with inserts	P6M5*[1] (R6M5)	Milling of planes, steps and slots	-	-	0.1 0.1	158.5 102	0.25	0.3	0.2 0.4	0.1	0.1	0.2
Disk-type solid	P6M5*[1] (R6M5)		-	-	-	144	0.25	0.3	0.2	0.1	0.1	0.2
End	P6M5*[1] (R6M5)	Milling of planes and steps	-	-	-	103	0.45	0.3	0.2	0.1	0 1	0 33
Slotting and cutting-off	P6M5*[1] (R6M5)	Cutting slots and cutting-off	-	-	-	111.3	0.25	0.3	0.2	0.2	0.1	0.2
Machining of silumins and cast aluminium alloys, σ_u = 100÷200 MPa, HB ≤ 65 *and duralumin,* σ_u = 300÷400 MPa, HB ≤ 100												
Face	P6M5*[1] (R6M5)	Milling of planes	-		≤ 0.1 > 0.1	245 155	0.25	0.1	0.2 0.4	0.15	0.1	0.2
Cylindrical	P6M5*[1] (R6M5)		-	-	≤ 0.1 > 0.1	208 133.5	0.45	0.3	0.2 0.4	0.1	0.1	0.33
Disk-type with inserts	P6M5*[1] (R6M5)	Milling of planes, steps and slots	-	-	≤ 0.1 > 0.1	285 183.4	0.25	0.3	0.2 0.4	0.1	0.1	0.2
Disk-type solid	P6M5*[1] (R6M5)		-	-	-	259	0.25	0.3	0.2	0.1	0.1	0.2
End	P6M5*[1] (R6M5)	Milling of planes and steps	-	-	-	185.5	0.45	0.3	0.2	0.1	0.1	0.33
Slotting and cutting-off	P6M5*[1] (R6M5)	Cutting slots and cutting-off	-	-	-	200	0.25	0.3	0.2	0.2	0.1	0.2

*[1] Without cooling. *[2] With cooling.

Note. Cutting velocity for face mills calculated from the table data is actual at side angle φ = 60°. At other values of this angle the values of velocity should be multiplied by coefficients: at φ = 15° – by 1.6; at φ = 30° – by 1.25; at φ = 45° – by 1.1; at φ = 75° – by 0.93; at φ = 90° – by 0.87.

Table 3.8

Mean values of life periods T for milling cutters

Milling cutters	Life T, min, at milling cutter diameter, mm											
	20	25	40	60	75	90	110	150	200	250	300	400
Face	-		120	180					240		300	400
Cylindrical with inserts and solid with coarse teeth	-					180			240	-		
Cylindrical solid with fine teeth	-		120		180		-					
Disk-type	-					120		150	180	240	-	
End	80	90	120	180	-							
Slotting and cutting-off	-				60	75	120		150	-		
Form and angle	-		120			180	-					

Total correction coefficient for cutting velocity that takes into account actual cutting conditions is

$$k_V = k_{MV} \times k_{SV} \times k_{TV} \times k_{cfV},$$

where k_{MV} – coefficient describing the quality of workpiece material (Tables 3.9 – – 3.12); k_{SV} – coefficient describing condition of workpiece surface (Table 3.13); k_{TV} – coefficient describing the milling cutter material (Table 3.14); k_{cfV} – coefficient taking into account the application of cutting fluid (if the fluid is applied, k_{cfV} = 1.0). For milling the considerations for cutting fluids application are similar to those given in Para 1.9.7.

Rotational speed is calculated from formula

$$n_c = \frac{1000 \cdot V_c}{\pi \cdot D}, \text{ rev/min},$$

where D – diameter of milling cutter, mm.

3.5. Cutting force

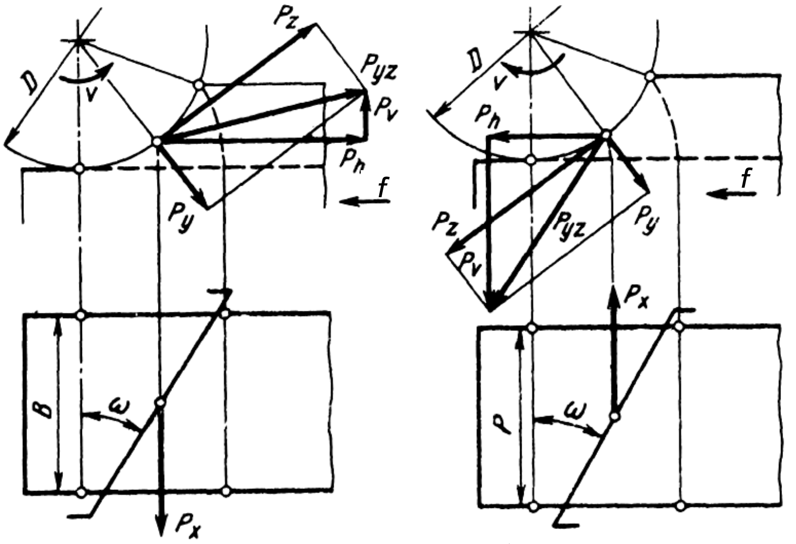
Main constituent of cutting force at milling is peripheral force

$$P_z = \frac{10 C_P t^x f_z{}^y B^u z}{D^q n_c{}^w} k_{MP}, \text{ N},$$

where z – number of milling cutter teeth; n_c – calculated rotational speed of milling cutter, mm/rev.

Values of coefficient C_P and indexes of power are given in Table 3.15. Correction coefficient for quality of workpiece material k_{MP} for steel and cast iron is given in Table 3.16, and for copper and aluminium alloys – in Table 3.17.

Values of other constituents of cutting force (Fig. 3.3 and 3.4): horizontal (feed force) P_h, vertical P_v, radial P_y, axial P_x are determined from relationship with



a b

Figure 3.3. Constituents of cutting force at milling with a cylindrical mill: a – at conventional (up) milling (opposite to feed); b – at climb (down) milling (in direction of feed)

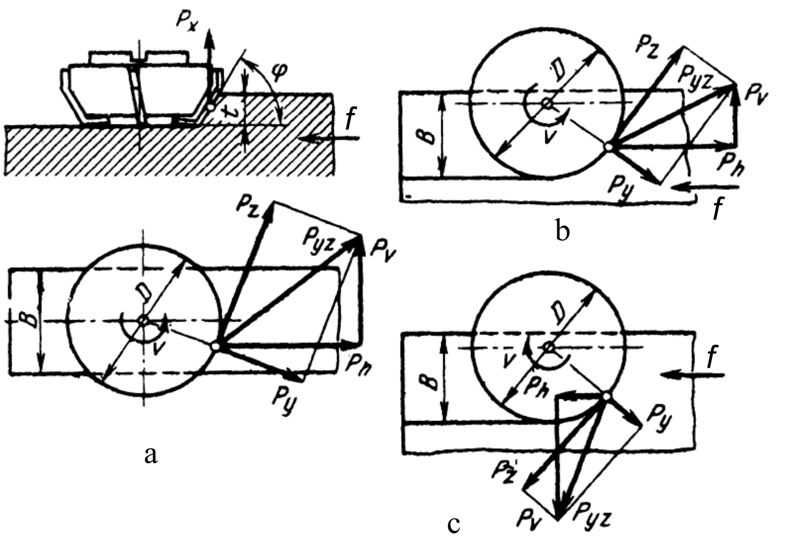


Figure 3.4. Constituents of cutting force at face milling: a – symmetrical; b – asymmetrical conventional; c – asymmetrical climb

main constituent P_z specified in Table 3.18.

Formula for calculation of arbour under bending is

$$P_{yz} = \sqrt{P_y^2 + P_z^2}\text{, N.}$$

3.6. Torque

Torque of spindle

$$M = \frac{P_z \cdot D}{2 \cdot 1000}\text{, N·m,}$$

where D – diameter of milling cutter, mm.

3.7. Power of cutting

Effective power of cutting

$$N_e = \frac{P_z V}{1020 \cdot 60}\text{, kW.}$$

Power of electric motor necessary for cutting is determined with a machine efficiency coefficient (η_m = 0.7…0.8)

$$N_{emc} = \frac{N_e}{\eta_m}\text{, kW.}$$

If power N_{emc} necessary for cutting is more than initially adopted value (for example, up to 5 kW), then one should select larger power of machine in the Tables 3.1 and 3.2 and repeat calculations according to Paragraphs 3.3 – 3.7.

The results of calculations are written down into the Table

Number of manufacturing step	t, mm	B, mm	f_z, mm/tooth	k_{MV}	k_{SV}	k_{TV}	k_V	V_c, m/min	n_c, rev/min	P_z, N	M, Nm	N_{emc}, kW

3.8. Selection of machine

When planning operation of manufacturing process it is necessary to know all data characterizing technological equipment.

The choice of a machine type is determined, first of all, by its capability to perform requirements for the workpiece parameters in this operation.

The following parameters should be considered when selecting machine:

a) Correspondence of machine type and sizes of machine working zone to overall dimensions of work piece (ref. Fig. 3.1 and the sketch of operation);
b) Capability of maximal utilization of machine by time and power, as well as sufficient value of power for machining at the most hard step of operation;
c) Correspondence of machine's productivity to quantity of machined parts during planned period;
d) Real ability to purchase machine.

Critical factor in selection of a machine is economy (the least value of production cost) of workpiece machining.

The choice of a machine with larger sizes of working zone and higher power of drive is a mistake.

Minimal set of machine data includes: name and type; sizes of working zone; minimal and maximal values of traverse, cross and vertical feed; number of feeds steps or sequence (row) of feeds; minimal and maximal values of spindle rotational speed; number of rotational speed steps or sequence (row) of spindle speeds; power of drive.

Power of electric motor for drive of the main work motion of the selected machine $\boldsymbol{N_{ems}}$ should not be less than the calculated value $\boldsymbol{N_{emc}}$:

$$\boldsymbol{N_{ems}} \geq \boldsymbol{N_{emc}}.$$

Term project paper should contain a reference on the source of machine technical data.

Table 3.9

Correction coefficient $\boldsymbol{k_{MV}}$ taking into account influence of physical and mechanical properties of workpiece material on cutting velocity

Workpiece material	Calculation formula
Steel	$\boldsymbol{k_{MV}} = \boldsymbol{k_G}\left(\frac{750}{\boldsymbol{\sigma_u}}\right)^{\boldsymbol{n_V}}$
Gray cast iron	$\boldsymbol{k_{MV}} = \left(\frac{190}{\boldsymbol{HB}}\right)^{\boldsymbol{n_V}}$
Malleable cast iron	$\boldsymbol{k_{MV}} = \left(\frac{150}{\boldsymbol{HB}}\right)^{\boldsymbol{n_V}}$

Notes: 1. $\boldsymbol{\sigma_u}$ and HB are actual parameters characterizing work material, for which a cutting velocity is calculated. 2. Find coefficient $\boldsymbol{k_G}$ characterizing group of steel by machinability and index of power $\boldsymbol{n_V}$ in Table 3.10.

Table 3.10

Values of coefficient k_G and indexes of power n_V in the formula for calculation of machinability coefficient for steels given in Table 3.9

Work material	Coefficient k_G for tool material		Indexes of power n_V at machining with					
			single-point cutting tools		drills, core drills, reamers		milling cutters	
	from high-speed steel	from cemented carbide	from high-speed steel	from cemented carbide	from high-speed steel	from cemented carbide	from high-speed steel	from cemented carbide
Steel:								
carbon (C ≤ 0.6 %), σ_u, MPa:								
< 450	1.0	1.0	–1.0		–0.9		–0.9	
450-550	1.0	1.0	1.75		–0.9		–0.9	
> 550	1.0	1.0	1.75		0.9		0.9	
free-cutting steel	1.2	1.1	1.75		1.05		-	
chromium	0.85	0.95	1.75				1.45	
carbon (C > 0.6 %), chromium-nickel, chromium-molybdenum-vanadium	0.8	0.9	1.5				1.35	
chromium-manganese, chromium-silicon, chromium-silicon-manganese, chromium-nickel-molybdenum, chromium-molybdenum-aluminium	0.7	0.8	1.25	1.0	0.9	1.0		1.0
chromium-vanadium	0.85	0.8	1.25				1.0	
manganese	0.75	0.9	1.5					
chromium-nickel-tungsten, chromium-molybdenum	0.8	0.85	1.25					
chromium-aluminium	0.75	0.8	1.25					
chromium-nickel-vanadium	0.75	0.85	1.25					
high-speed	0.6	0.7	1.25					
Cast iron:								
grey	-	-	1.7	1.25	1.3	1.3	0.95	1.25
malleable	-	-	1.7	1.25	1.3	1.3	0.85	1.25

Table 3.11

Correction coefficient k_{MV} taking into account influence of physical and mechanical properties of high-temperature and corrosion-resistant steels and alloys on cutting velocity

Grade of steel or alloy	σ_u, MPa	Mean value of coefficient k_{MV}	Grade of steel or alloy	σ_u, MPa	Mean value of coefficient k_{MV}
12Х18Н9Т (12H18N9T)	550	1.0	ХН60ВТ (HN60VT)	750	0.48
13Х11Н2В2МФ (13H11N2V2MF)	1100 –1460	0.8 – 0.3	ХН77ТЮ (HN77TU)	850 – 1000	0.40
14Х17Н2 (14H17N2)	800 – 1300	1.0 – 0.75	ХН77ТЮР (HN77TUR)		0.26
13Х14Н3В2ФР (13H14N3V2FR)	–	0.5 – 0.4	ХН35ВТ (HN35VT)	950	0.50
37Х12Н8Г8МФБ (37H12N8G8MFB)	700 – 1200	0.95 – 0.72	ХН70ВМТЮ (HN70VMTU)	1000 – 1250	0.25
45Х14Н14В2М (45H14N14V2M)	700	1.06 – 0.85	ХН55ВМТКЮ (HN55VMTKU)	1000 – 1250	0.25
10Х11Н20Т3Р (10H11N20T3R)	720 – 800	0.65	ХН65ВМТЮ (HN65VMTU)	900 – 1000	0.20
12Х21Н5Т (12H21N5T)	820 –10000	0.80	ХН35ВТЮ (HN35VTU)	900 – 950	0.22
20Х23Н18 (20H23N18)	600 – 620	0.40	ВТ3-1 (VT3-1); ВТ3 (VT3)	950 – 1200	0.40
31Х19Н9МВБТ (31H19N9MVBT)		0.50	ВТ5 (VT5); ВТ4 (VT4)	750 – 950	0.70
15Х18Н12С4ТЮ (15H18N12C4TU)	730	0.75	ВТ6 (VT6); ВТ8 (VT8)	900 – 1200	0.35
			ВТ14 (VT14)	900 – 1400	0.53 – 0.43
ХН78Т (HN78T)	780	0.53	12Х13 (12H13)	600 – 1100	1.5 – 1.2
ХН75МБТЮ (HN75MBTU)	–		30Х13 (30H13); 40Х13 (40H13)	850 – 1100	1.3 – 0.9

Table 3.12

Correction coefficient k_{MV} taking into account influence of physical and mechanical properties of copper and aluminium alloys on cutting velocity

Copper alloys	k_{MV}	Aluminium alloys	k_{MV}
Heterogeneous: HB > 140 HB 100 – 140	 0.7 1.0	Silumin and cast alloys (hardened), σ_u = 200…300 MPa, HB > 60	0.8
Leaded with basic heterogeneous structure	1.7	Duralumin (hardened), σ_u = 400…500 MPa, HB > 100	
Homogeneous Alloys with lead content < 10 % with basic homogeneous structure Copper	2.0 4.0 8	Silumin and cast alloys, σ_u = 100…200 MPa, HB ≤ 65. Duralumin, σ_u = 300…400 MPa, HB ≤ 100	1.0
Alloys with lead content > 15%	12.0	Duralumin, σ_u = 200…300 MPa	1.2

Table 3.13

Correction coefficient k_{SV} taking into account influence of workpiece surface condition on cutting velocity

Workpiece surface condition					
without crust	with crust				
	Rolled product	Forging	Steel and iron castings with crust		Copper and aluminium alloys
			normal	with large amount of impurities	
1.0	0.9	0.8	0.8 – 0.85	0.5 – 0.6	0.9 – 1.0

Table 3.14

Correction coefficient k_{TV} taking into account influence of tool material on cutting velocity

Work material	Values of coefficient k_{TV} depend on grade of tool material						
Structural steel	T5K12B (T15K12V) 0.35	T5K10 0.65	T14K8 0.8	T15K6 1.00	T15K6 1.15	T30K4 1.4	BK8 (VK8) 0.4
Corrosion-resistant and high-temperature steels	BK8 (VK8) 1.0	T5K10 1.4	T15K6 1.9	P18 (R18) 0.3	-		
Hardened steel	HRC 35-50			HRC 51-62			
	T15K6 1.0	T30K4 1.25	BK6 (VK6) 0.85	BK8 (VK8) 0.83	BK4 (VK4) 1.0	BK6 (VK6) 0.92	BK8 (VK8) 0.74
Gray and malleable cast iron	BK8 (VK8) 0.83	BK6 (VK6) 1.0	BK4 (VK4) 1.1	BK3 (VK3) 1.15	BK3 (VK3) 1.25	-	
Steel, cast iron, copper and aluminium alloys	P6M5 (R6M5) 1.0	BK4 (VK4) 2.5	BK6 (VK6) 2.7	9XC (9HS) 0.6	XBГ (HVG) 0.6	У12A (U12A) 0.5	-

Table 3.15

Values of coefficient C_P and indexes of power in formula for peripheral force P_z at milling

Milling cutters	Material of cutting point	Coefficient and indexes of power					
		C_p	x	y	u	q	w
Machining of structural carbon steel, σ_u = 750 MPa							
Face	Cemented carbide	825	1.0	0.75	1.1	1.3	0.2
	High-speed steel	82.5	0.95	0.8	1.1	1.1	0
Cylindrical	Cemented carbide	101	0.88	0.75	1.0	0.87	0
	High-speed steel	68.2	0.86	0.72	1.0	0.86	0
Disk, slotting and cutting-off	Cemented carbide	261	0.9	0.8	1.1	1.1	0.1
	High-speed steel	68.2	0.86	0.72	1.0	0.86	0
End	Cemented carbide	12.5	0.85	0.75	1.0	0.73	–0.13
	High-speed steel	68.2	0.86	0.72	1.0	0.86	0

Table 3.15, finished

Milling cutters	Material of cutting point	Coefficient and indexes of power					
		C_p	x	y	u	q	w
Form and angle	High-speed steel	47	0.86	0.72	0.1	0.86	0
Machining of high-temperature steel 12X18H9T (12H18N9T) in as-delivered condition, HB 141							
Face	Cemented carbide	218	0.92	0.78	1.0	1.15	0
End	High-speed steel	82	0.75	0.6	1.0	0.86	0
Machining of grey cast iron, HB 190							
Face	Cemented carbide High-speed steel	54.5 50	0.9 0.9	0.74 0.72	1.0 1.14	1.0 1.14	0 0
Cylindrical	Cemented carbide High-speed steel	58 30	0.9 0.83	0.8 0.65	1.0 1.0	0.9 0.83	0 0
Disk, end, slotting and cutting-off	High-speed steel	30	0.83	0.65	1.0	0.83	0
Machining of malleable cast iron, HB 150							
Face	Cemented carbide High-speed steel	491 50	1.0 0.95	0.75 0.8	1.1 1.1	1.3 1.1	0.2 0
Cylindrical, disk, end, slotting and cutting-off	High-speed steel	30	0.86	0.72	1.0	0.86	0
Machining of heterogeneous copper alloys of middle hardness, HB 100-140							
Cylindrical, disk, end, slotting and cutting-off	High-speed steel	22.6	0.86	0.72	1.0	0.86	0

Notes: 1. Calculate peripheral force $\boldsymbol{P_z}$ at milling of aluminium alloys similar to steel with application of coefficient 0.25. 2. Peripheral force $\boldsymbol{P_z}$ calculated from the table data corresponds to operation of milling cutter without dulling. When dulling up to permissible value of wear the force rises: at machining of mild steel ($\boldsymbol{\sigma_u}$ < 600 MPa) 1.75 – 1.9 times; in all other cases – 1.2 – 1.4 times.

Table 3.16

Correction coefficient $\boldsymbol{k_{MP}}$ for steel and cast iron taking into account influence of quality of work material on force calculation relationships

Work material	Formula	Power index $\boldsymbol{n}$ when determining		
		constituent $\boldsymbol{P_z}$ of cutting force when machining with single-point cutting tools	torque $\boldsymbol{M}$ and axial force $\boldsymbol{P_o}$ when drilling, drilling-out and core drilling	peripheral force $\boldsymbol{P_z}$ when milling
Structural carbon and alloy steel, $\boldsymbol{\sigma_u}$, MPa: ≤ 600 > 600	$k_{MP} = \left(\frac{\sigma_u}{750}\right)^n$	0.75/0.35 0.75/0.75	0.75/0.75 0.75/0.75	0.3/0.3 0.3/0.3
Cast iron	$k_{MP} = \left(\frac{HB}{190}\right)^n$	0.4/0.55	0.6/0.6	1.0/0.55
Malleable iron	$k_{MP} = \left(\frac{HB}{150}\right)^n$	0.4/0.55	0.6/0.6	1.0/0.55

Note. In nominator the values of power index $\boldsymbol{n}$ are given for cemented carbide, in denominator – for high-speed steel.

Table 3.17

Correction coefficient $\boldsymbol{k_{MP}}$ for force calculation relationships taking into account influence of copper and aluminium alloys

Copper alloys	k_{MP}	Aluminium alloys	k_{MP}
Heterogeneous:		Aluminium and silumin	1.0
HB 120	1.0	Duralumin, σ_u, MPa:	
HB > 120	0.75	250	1.5
Leaded with basic heterogeneous structure and leaded with lead content 10 % with basic homogeneous structure	0.65 – 0.70	350	2.0
		> 350	2.75
Homogeneous	1.8 – 2.2		
Copper	1.7 – 2.1		
With lead content > 15 %	0.25 – 0.45		

Table 3.18

Relative values of constituents of cutting force at milling

Type of milling	$P_h : P_z$	$P_v : P_z$	$P_y : P_z$	$P_x : P_z$
Cylindrical, disk, end[1], angle and form mills (ref. Fig. 3.3)*				
Conventional (opposite feed)	1.1 – 1.2	0 – 0.25	0.4 – 0.6	(0.2 – 0.4) $tg\omega$
Climb (in direction of feed)	–(0.8 – 0.9)	0.7 – 0.9		
Face and end[2] mills (ref. Fig. 3.4)*				
Symmetrical	0.3 – 0.4	0.85 – 0.95	0.3 – 0.4	0.5 – 0.55
Asymmetrical conventional	0.6 – 0.8	0.6 – 0.7		
Asymmetrical climb	0.2 – 0.3	0.9 – 1.0		

Notes: *[1] Mills operating by diagram of cylindrical milling, when face teeth do not participate in cutting. *[2] Mills operating by diagram of face milling. Changes of constituents P_y and P_x at face milling depend on side angle φ see in Handbook [10].

3.9. Agreement of rotational speed with technical data of milling machine

All considerations given in the Para 1.8 are totally valid also for agreement of calculated rotational speed of spindle with the machine data and determination of machine rotational speed n_m.

3.10. Agreement of feed with technical data of milling machine

Agreement of feed for milling machines has one peculiarity as compared with turning and drilling machines. Rows of feeds for a milling machine are typically given as minute feed f_m in mm/min, and calculations are performed with the application of feed per tooth f_z in mm/tooth. And so before agreement the selected feed f_z should be converted into the feed f_m using the formula of Para 3.3

$$f_{mc} = f_z \, z \, n_m.$$

Agreement of calculated traverse, cross and vertical feeds with a machine should be performed according to the Para 1.8 by one of 3 variants depending on available machine data.

The final point of the agreement is the value of minute feed $\boldsymbol{f_{mm}}$ selected from the machine row of feeds.

3.11. Actual parameters of cutting process

Actual cutting velocity

$$\boldsymbol{V_a} = \frac{\pi \cdot \boldsymbol{D} \cdot \boldsymbol{n_m}}{1000}, \text{ m/min.}$$

Actual feed per tooth $\boldsymbol{f_{za}}$ is calculated with application of the minute feed agreed with machine's data

$$\boldsymbol{f_{za}} = \boldsymbol{f_{mm}} /(\boldsymbol{z}\ \boldsymbol{n_m}), \text{ mm/tooth.}$$

Actual main constituent of the cutting force $\boldsymbol{P_z}$ and other constituents are calculated from formulas of Para 3.5 with the application of actual tooth feed $\boldsymbol{f_{za}}$ and rotational speed $\boldsymbol{n_m}$.

Actual torque $\boldsymbol{M_a}$ and power of cutting $\boldsymbol{N_{ema}}$ are calculated from formulas of Paragraphs 3.6 and 3.7.

The results of calculations and selection are written down into the Table

Number of manufac-turing step	t, mm	B, mm	f_{mm}, mm/min	f_{za}, mm/tooth	n_m, rev/min	V_a, m/min	P_{za}, N	M_a, Nm	N_{ema}, kW	N_{ems}, kW

Calculations are repeated for all steps of milling operation. If necessary, a machine of another type is selected according to the maximal value of calculated cutting power $\boldsymbol{N_{emc}}$.

APPENDIX 1

Classification of hard-to-machine steels and alloys by their machinability

Grade	Heat treatment	σ_u, MPa	HB (HRC)	Approximate cutting velocity with tools from cemented carbides, m/min[*1]	K_{V45}[*2]
I. Heat-resistant chromium, chromium-nickel, chromium-molybdenum steels of perlitic, martensitic-ferritic and martensitic classes					
34XH3M (34HN3M) 34XH3MФ (34HN3MF)	Annealing	600 – – 800	– –	250 – 300	1
20X3MBФ (20H3MVF)	Quenching and tempering	900 – – 1300	269 – 331	120 – 150	0.5
15X5M (15H5M) 15X6CЮ (15H6SU)	Annealing	≥ 650	– –	200 – 250	0.9
II. Corrosion-resistant chromium and compound-alloyed steels of ferritic, martensitic-ferritic and martensitic classes					
12X13 (12H13)	Quenching and tempering	≥ 600	197 – – 229	180 – 220	0.7
25X13H2 (25H13N2)	Annealing	700 – – 1000	207 – –265	200 – 250	0.9
11X11H2BMФ (11H11N2VMF) 1X12H2BMФ (1H12N2VMF)	Quenching and tempering	≥ 750	– –	170 – 220	0.65
20X13 (20H13) 30X13 (30H13)		1100 – 1400	180 – 249 –	80 – 100	0.3
40X13 (40H13)	Annealing	≈ 900	143 – 229	120 – 150	0.5
09X16H4Б (09H16N4B)	Quenching and tempering	> 1000 > 1300	(27 – 31.5) (> 38)	130 – 160 70 – 90	0.55 0.3
14X17H2 (14H17N2)		> 1100	–	120 – 150	0.5
20X17H2 (20H17N2)			–		
95X18 (95H18)	Annealing Quenching and tempering	≈ 900 ≥ 1900	≤ 225 (< 66)	90 – 120 20 – 30	0.45 0.12
III. Corrosion-resistant, acid-resistant, oxidation-resisting chromium-nickel steels of austenitic, austenitic-ferritic and austenitic-martensitic classes					
12X18H10T (12H18N10T)	Austenization	> 560	180	120 – 150	0.5
10X23H18 (10H23N18) 20X23H18 (20H23N18)				140 – 180	0.6
12X21H5T (12H21N5T)		> 700	–		
09X15H9Ю (09H15N9U)		850 – – 1100	–	110 – 130	0.45
08X17H5M3(08H17N5M3)	Normalization		–		
07X16H6 (07H16N6)	Normalization and tempering	≥ 1100	–	120 – 150	0.5

Grade	Heat treatment	σ_u, MPa	HB (HRC)	Approximate cutting velocity with tools from cemented carbides, m/min*1	K_{V45}*2
IV. High-temperature, oxidation-resistant, acid-resistant chromium-nickel, chromium-nickel-manganese compound-alloyed steels of austenitic and austenitic-ferritic classes					
10Х11Н20Т3МР(10H11N20T3MR) 10Х11Н23Т3МР(10H11N23T3MR) 37Х12Н8Г8МФБ(37H12N8G8MFB)	Austenization and aging	> 900	255 – 321 275 – 309	50 – 60	0.23
45Х14Н14В2М (45H14N14V2M)		> 700	–	100 – 120	0.40
08Х15Н24В4ТР (08H15N24V4TR)	Aging		–	70 – 90	0.30
15Х18Н12С4ТЮР(15H18N12S4TUR)	Austenization	700 – 900	–	50 – 60	0.23
07Х21Г7АН5 (07H21G7AN5)		800 – – 1000	–	80 – 100	0.30
12Х25Н16Г7АР (12H25N16G7AR)	Austenization and aging		190 – 220		
V. High-temperature wrought alloys on iron-nickel and nickel bases					
36НХТЮ (36NHTU)	Austenization and aging	1200	(32 – 42)		
ХН60ВТ (HN60VT)	Austenization	800	–	40 – 50	0.16
ХН38ВТ (HN38VT) ХН77ТЮР (HN77TUR)	Austenization and aging	1000	– 321 – 225		
ХН35ВТЮ (HN35VTU)		> 950	–	27 – 28	0.12
ХН56ВМТЮ (HN56VMTU)	Austenization	900	–	20 – 25	0.1
ХН67ВМТЮ (HN67VMTU) ХН70ВМТЮ(HN70VMTU) ХН75ВМЮ (HN75VMU)	Austenization and aging	> 1000	321 – 329 310 –		
ХН62МКВЮ (HN62MKVU) ХН60МВТЮ (HN62MVTU)		1250 1150	–	18 – 20	0.08
ХН82ТЮМВ (HN82TUMV)		1350	–		
VI. Oxidation-resisting and high-temperature cast alloys on nickel and chromium bases					
ВЖ36-Л2 (VZh36-L2) АНВ-300 (ANV-300) ЖС6-К (ZhS6-K) ЖС3-ДК (ZhS3-DK) ХН67ВМТЮЛ (HN67VMTUL)	Austenization and aging	800 850 1000 750	– – –	18 – 20	0.05
ВХ4-Л (VH4-L)	Annealing	1100	250	20 – 25	0.1
VII. Alloys on titanium base					
ВТ1-0 (VT1-0), ВТ1 (VT1), ВТ1-1 (VT1-1), ВТ1-2 (VT1-2)	Annealing	450 – 700	–	100 – 150	0.5
ВТ3 (VT3), ВТ3-1 (VT3-1)		950 – 1200	(27 – 36)	50 – 70	0.28
ОТ4 (OT4), ОТ4-1 (OT4-1)		600 – 850	200 – 300	70 – 100	0.4
ВТ5 (VT5), ВТ5-1 (VT5-1)		700 – 950	–		
ВТ6 (VT6), ВТ6С (VT6S)		900 – 1000	–	60 – 80	0.32
ВТ14 (VT14), ВТ15 (VT15), ВТ22 (VT22)		1000 – – 1100	–	50 – 75	0.3

Grade	Heat treatment	σ_u, MPa	HB (HRC)	Approximate cutting velocity with tools from cemented carbides, m/min*1	K_{V45}*2
BT14 (VT14), BT15 (VT15)	Quenching and aging	1150 – – 1300	340 – – 420	45 – 60	0.24
BT3-1 (VT3-1), BT22 (VT22)	Quenching, aging, thermo-mechanical treatment	1300 – – 1500	(41 – – 44)		

Notes: 1. *1 – approximate cutting velocity at machining with tools from high-speed steel is equal to 0.25 of cutting velocity of tools from cemented carbides. 2. *2 – machinability coefficient in respect to steel 45. 3. The table contains cutting velocities and relative machinability for semi-finish and finish turning after typical heat treatment for the given material. 4. The given data corresponds to the tool life of 45…60 min.

APPENDIX 2

Fragments from GOST 5632-72 “Alloyed steels and corrosion-resistant, scale-resistant and high-temperature alloys. Grades and technical requirements”

The standard is effective for wrought steels and alloys on iron, iron-nickel and nickel bases designed for operation in corrosion-active mediums and at high temperatures.

High-alloy steels are those with iron content of more than 45 %, and total content of alloying elements is not less than 10 %, when taking into account the upper limit, at content of one of the elements not less than 8 % at the lower limit.

Alloys on iron-nickel base are those alloys that have main structure of solid solution of chromium and other alloying elements in iron-nickel base (total amount of nickel and iron is more than 65 % at approximate ratio of nickel to iron 1:1.5).

Alloys on nickel base are those that have main structure of solid solution of chromium and other alloying elements in nickel base (nickel content is not less than 55 %).

1. Classification

Steels and alloys are divided into groups depending on basic properties:

I – corrosion-resistant (stainless) steels and alloys having resistance to electrochemical and chemical corrosion (atmospheric, soil, alkaline, acidic, salty), intercrystalline corrosion, corrosion under stress, etc;

II – oxidation-resistant (scale-resistant) steels and alloys possessing resistance to chemical surface decomposition in gaseous mediums at temperatures more than

550ºC and operating in unloaded or low-loaded condition;

III – high-temperature (creep-resisting) steels and alloys possessing ability to operate in loaded condition at high temperature (more than 700ºC) during specified period of time and having sufficient oxidation-resistance.

Steels are divided into classes depending on structure:

- Martensitic – steels with main structure of martensite;
- Martensite-ferritic – steels that contain not less than 10 % ferrite in structure beside martensite;
- Ferritic – steels having structure of ferrite (without $\alpha \leftrightarrow \gamma$ transformations);
- Austenite-ferritic – steels having structure of austenite and ferrite (ferrite content is more than 10 %);
- Austenitic – steels having structure of austenite.

2. Grades of steels and alloys

The table contains new and old designations of 127 grades of wrought steels and alloys with specifying the groups and classes.

Grades of steels and alloys			Group		
No.	New designation	Old designation	I – corrosion-resistant	II – oxidation-resisting	III – high-temperature
Steels					
1. Steels of martensitic class					
1-1	15Х5 (15H5)	Х5 (H5)	–	+ +	+
1-2	15Х5М (15H5M)	Х5М (H5M)	–	–	++
1-3	15Х5ВФ (15H5VF)	Х5ВФ (H5VF)	–	–	+
1-4	12Х8ВФ (12H8VF)	1Х8ВФ (1H8VF)	–	–	+
1-5	40Х9С2 (40H9S2)	4Х9С2 (4H9S2)	–	+ +	+
1-6	40Х10С2М (40H10S2M)	4Х10С2М (4H10S2) ЭИ107 (EI107)	–	+ +	+
1-7	15Х11МФ (15H11MF)	1Х11МФ (1H11MF)	–	–	+
1-8	18Х11МНФБ (18H11MNFB)	2Х11МФБН (2H11MFBN) ЭП291 (EP291)	–	– +	+
1-9	20Х12ВНМФ (20H12VNMF)	2Х12ВНМФ (2H12VNMF) ЭП428 (EP428)	–	–	+
1-10	11Х11Н2В2МФ (11H11N2V2MF)	Х12Н2ВМФ (H12N2VMF)	–	–	+
1-11	16Х11Н2В2МФ (16H11N2V2MF)	2Х12Н2ВМФ (2H12N2VMF) ЭИ962А (EI962A)	–	–	+
1-12	20Х13 (20H13)	2Х13 (2H13)	+	–	+
1-13	30Х13 (30H13)	3Х13 (3H13)	+	–	–
1-14	40Х13 (40H13)	4Х13 (4H13)	+	–	–
1-15	30Х13Н7С2 (30H13N7S2)	3Х13Н7С2 (3H13N7S2) ЭИ72 (EI72)	–	+	–
1-16	13Х14Н3В2ФР (13H14N3V2FR)	Х14НВФР (H14NVFR) ЭИ736 (EI736)	–	–	+

Grades of steels and alloys			Group		
No.	New designation	Old designation	I – corrosion-resistant	II – oxidation-resisting	III – high-temperature
1-17	25Х13Н2 (25H13N2)	2Х14Н2 (2H14N2) ЭИ474 (EI474)	+	–	–
1-18	20Х17Н2 (20H17N2)	2Х17Н2 (2H17N2)	+	–	–
1-19	95Х18 (95H18)	9Х18 (9H18), ЭИ229 (EI229)	+	–	–
1-20	09Х16Н4Б (09H16N4B)	1Х16Н4Б (1H16N4B) ЭП56 (EP56)	+	–	–
1-21	13Х11Н2В2МФ (13H11N2V2MF)	1Х12Н2ВМФ (1H12N2VMF)	–	–	+
2. Steels of martensite-ferritic class					
2-1	15Х6СЮ (15H6SU)	Х6СЮ (H6SU)	–	+	–
2-2	15Х12ВНМФ (15H12VNMF)	1Х12ВНМФ (1H12VNMF) ЭИ802 (EI802)	–	–	+
2-3	18Х12ВМБРФ (18H12VMBRF)	2Х12ВМБФР (2H12VMBRF) ЭИ993 (EI993)	–	–	+
2-4	12Х13 (12H13)	1Х13 (1H13)	+	+	+
2-5	14Х17Н2 (14H17N2)	1Х17Н2 (1H17N2) ЭИ268 (EI268)	+	–	+
3. Steels of ferritic class					
3-1	10Х13СЮ (10H13SU)	1Х12СЮ (1H12SU) ЭИ404 (EI404)	–	+	–
3-2	08Х13 (08H13)	0Х13 (0H13) ЭИ496 (EI496)	+	–	+
3-3	12Х17 (12H17)	Х17 (H17)	+	+	–
3-4	08Х17Т (08H17T)	0Х17Т (0H17T) ЭИ645 (EI645)	+	+ +	–
3-5	15Х18СЮ (15H18SU)	Х18СЮ (H18SU) ЭИ484 (EI484)	–	+	–
3-6	15Х25Т (15H25T)	Х25Т (H25T) ЭИ439 (EI439)	+	+ +	–
3-7	15Х28 (15H28)	Х28 (H28) ЭИ349 (EI349)	+	+ +	–
3-8	08Х18Т1 (08H18T1)	0Х18Т1 (0H18T1)	+	+ +	–
4. Steels of austenite-martensitic class					
4-1	20Х13Н4Г9 (20H13N4G9)	2Х13Н4Г9 (2H13N4G9) ЭИ100 (EI100)	+	–	–
4-2	09Х15Н8Ю (09H15N8U)	Х15Н9Ю (H15N9U) ЭИ904 (EI904)	+	–	–
4-3	07Х16Н6 (07H16N6)	Х16Н6 (H16N6) ЭП288 (EP288)	+	–	–
4-4	09Х17Н7Ю (09H17N7U)	0Х17Н7Ю (0H17N7U)	+	–	–
4-5	09Х17Н7Ю1 (09H17N7U1)	0Х17Н7Ю1 (0H17N7U1)	+	–	–

Grades of steels and alloys			Group		
No.	New designation	Old designation	I – corrosion-resistant	II – oxidation-resisting	III – high-temperature
4-6	08Х17Н5М3 (08H17N5M3)	Х17Н5М3 (H17N5M3) ЭИ925 (EI925)	+	–	–
5. Steels of austenite-ferritic class					
5-1	08Х20Н14С2 (08H20N14S2)	0Х20Н14С2 (0H20N14S2) ЭИ732 (EI732)	–	+	–
5-2	20Х20Н14С2 (20H20N14S2)	Х20Н14С2 (H20N14S2) ЭИ211 (EI211)	–	+	–
5-3	08Х22Н6Т (08H22N6T)	0Х22Н5Т (0H22N5T) ЭП53 (EP53)	+	–	–
5-4	12Х21Н5Т (12H21N5T)	1Х21Н5Т (1H21N5T) ЭИ811 (EI811)	+	–	–
5-5	08Х21Н6М2Т (08H21N6M2T)	0Х21Н6М2Т (0H21N6M2T) ЭП54 (EP54)	+	–	–
5-6	20Х23Н13	Х23Н13 ЭИ319	–	+	–
5-7	08Х18Г8Н2Т	0Х18Г8Н2Т КО-3	+	–	–
5-8	15Х18Н12С4ТЮ	ЗИ654	+	–	–
6. Steels of austenitic class					
6-1	08Х10Н20Т2 (08H10N20T2)	0Х10Н20Т2 (0H10N20T2)	+	–	–
6-2	10Х11Н20Т3Р (10H11N20T3R)	Х12Н20Т3Р (H12N20T3R) ЭИ696 (EI696)	–	–	+
6-3	10Х11Н23Т3МР (10H11N23T3MR)	Х12Н22Т3МР (H12N23T3MR) ЭП33 (EP33)	–	–	+
6-4	37Х12Н8Г8МФБ (37H12N8G8MFB)	ИХ12Н8Г8МФБ (IH12N8G8MFB) ЭИ481 (EI481)	–	–	+
6-5	10Х14Г14Н3 (10H14G14N3)	Х14Г14Н3 (H14G14N3) ДИ-6 (DI-6)	+	–	–
6-6	10Х14Г14Н4Т (10H14G14N4T)	Х14Г14Н3Т (H14G14N3T) ЭИ711 (EI711)	+	–	–
6-7	10Х14Г15 (10H14G15)	Х14АГ15 (H14AG15) ДИ-13 (DI-13)	+	–	–
6-8	45Х14Н14В2М (45H14N14V2M)	4Х14Н14В2М (4H14N14V2M) ЭИ69 (EI69)	–	–	+
6-9	09Х14Н16Б (09H14N16B)	1Х14Н16Б (1H14N16B) ЭИ694 (EI694)	–	+	+
6-10	09Х14Н19В2БР (09H14N19V2BR)	1Х14Н18В2БР (1H14N18V2BR) ЭИ695Р (EI695R)	–	–	+
6-11	09Х14Н19В2БР1 (09H14N19V2BR1)	1Х14Н18В2БР1(1H14N18V2BR1) ЭИ726 (EI726)	–	–	+
6-12	40Х15Н7Г7Ф2МС (40H15N7G7F2MS)	4Х15Н7Г7Ф2МС (4H15N7G7F2MS) ЭИ388 (EI388)	–	–	+
6-13	08Х16Н13М2Б (08H16N13M2B)	1Х16Н13М2Б (1H16N13M2B) ЭИ680 (EI680)	–	–	+

Grades of steels and alloys			Group		
No.	New designation	Old designation	I – corrosion-resistant	II – oxidation-resisting	III – high-temperature
6-14	08Х15Н24В4ТР (08H15N24V4TR)	Х15Н24В4Т (H15N24V4T) ЭП164 (EP164)	–	–	+
6-15	03Х16Н15М3 (03H16N15M3)	00Х16Н15М3 (00H16N15M3) ЭИ844 (EI844)	+	–	–
6-16	03Х16Н15М3Б (03H16N15M3B)	00Х16Н15М3Б (00H16N15M3B) ЭИ844Б (EI844B)	+	–	–
6-17	09Х16Н15М3Б (09H16N15M3B)	Х16Н15М3Б (H16N15M3B) ЭИ847 (EI847)	–	–	+
6-18	15Х17Г14 (15H17G14)	Х17АГ14 (H17AG14) ЭП213 (EP213)	+	–	–
6-19	12Х17Г9АН4 (12H17G9AN4)	Х17Г9АН4 (H17G9AN4) ЭИ878 (EI878)	+	–	–
6-20	03Х17Н14М2 (03H17N14M2)	000Х17Н13М2 (000H17N13M2)	+	–	–
6-21	08Х17Н13М2Т (08H17N13M2T)	0Х17Н13М2Т (0H17N13M2T)	+	–	–
6-22	10Х17Н13М2Т (10H17N13M2T)	Х17Н13М2Т (H17N13M2T) ЭИ448 (EI448)	+	–	–
6-23	10Х17Н13М3Т (10H17N13M3T)	Х17Н13М3Т (H17N13M3T) ЭИ432 (EI432)	+	–	–
6-24	08Х17Н15М3Т (08H17N15M3T)	0Х17Н16М3Т (0H17N16M3T) ЭИ580 (EI580)	+	–	–
6-25	12Х18Н9 (12H18N9)	Х18Н9 (H18N9)	+ +	+	–
6-26	17Х18Н9 (17H18N9)	2Х18Н9 (2H18N9)	+	–	–
6-27	12Х18Н9Т (12H18N9T)	Х18Н9Т (H18N9T)	+ +	+	+
6-28	04Х18Н10 (04H18N10)	00Х18Н10 (00H18N10) ЭИ842 (EI842), ЭП550 (EP550)	+	–	–
6-29	08Х18Н10 (08H18N10)	0Х18Н10 (0H18N10)	+ +	+	–
6-30	08Х18Н10Т (08H18N10T)	0Х18Н10Т (0H18N10T) ЭИ914 (EI914)	+ +	+	–
6-31	12Х18Н10Т (12H18N10T)	Х18Н10Т (H18N10T)	+ +	+	+
6-32	12Х18Н10Е (12H18N10E)	Х18Н10Е (H18N10E) ЭП47 (EP47)	+	–	–
6-33	03Х18Н11 (03H18N11)	000Х18Н11(000H18N11)	+	–	–
6-34	06Х18Н11 (06H18N11)	0Х18Н11 (0H18N11) ЭИ684 (EI684)	+	–	–
6-35	03Х18Н12 (03H18N12)	000Х18Н12 (000H18N12)	+	–	–
6-36	08Х18Н12Т (08H18N12T)	0Х18Н12Т (0H18N12T)	+	–	–

Grades of steels and alloys			Group		
No.	New designation	Old designation	I – corrosion-resistant	II – oxidation-resisting	III – high-temperature
6-37	12Х18Н12Т (12H18N12T)	Х18Н12Т (H18N12T)	+ +	+	+
6-38	08Х18Н12Б (08H18N12B)	0Х18Н12Б (0H18N12B) ЭИ402 (EI402)	+	–	–
6-39	31Х19Н9МВБТ (31H19N9MVBT)	3Х19Н9МВБТ (3H19N9MVBT) ЭИ572 (EI572)	–	–	+
6-40	36Х18Н25С2 (36H18N25S2)	4Х18Н25С2 (4H18N25S2)	–	+	–
6-41	55Х20Г9АН4 (55H20G9AN4)	5Х20Н4АГ9 (5H20N4AG9) ЭП303 (EP303)	–	+	+
6-42	07Х21Г7АН5 (07H21G7AN5)	Х21Г7АН5 (H21G7AN5) ЭП222 (EP222)	+	–	–
6-43	03Х21Н21М4ГБ (03H21N21M4GB)	00Х20Н20М4Б (00H20N20M4GB) ЭИ35 (EI35)	+	–	–
6-44	45Х22Н4М3 (45H22N4M3)	4Х22Н4М3 (4H22N4M3) ЭП48 (EP48)	–	+	+
6-45	10Х23Н18 (10H23N18)	0Х23Н18 (0H23N18)	–	+ +	+
6-46	20Х23Н18 (20H23N18)	Х23Н18 (H23N18) ЭИ417 (EI417)	–	+ +	+
6-47	20Х25Н20С2 (20H25N20S2)	Х25Н20С2 (H25N20S2) ЭИ283 (EI283)	–	+	–
6-48	12Х25Н16Г7АР (12H25N16G7AR)	Х25Н16Г7АР (H25N16G7AR) ЭИ835 (EI835)	–	+ +	+
6-49	10Х11Н20Т2Р (10H11N20T2R)	Х12Н20ТТ2Р (H12N20T2R) ЭИ696А (EI696A)	–	–	+
Alloys					
7. Alloys on iron-nickel base					
7-1	ХН35ВТ (HN35VT)	ЭИ612 (EI612)	–	–	+
7-2	ХН35ВТЮ (HN35VTU)	ЭИ787 (EI787)	–	–	+
7-3	ХН32Т (HN32T)	Х20Н32Т (H20N32T) ЭП670 (EP670)	–	–	+
7-4	ХН38ВТ(HN38VT)	ЭИ703 (EI703)	–	+ +	–
7-5	ХН28ВМАБ (HN28VMAB)	Х21Н28В5М3БАР (H21N28V5M3BAR) ЭП126 (EP126)	–	+	–
7-6	06ХН28МДТ (06HN28MDT)	0Х23Н28М3Д3Т (0H23N28M3D3T) ЭИ943 (EI943)	+	–	–
7-7	03ХН28МДТ (03HN28MDT)	000Х23Н28М3Д3Т (000H23N28M3D3T) ЭП516 (EP516)	+	–	–
7-8	06ХН28МТ (06HN28MT)	0Х23Н28М2Т (0H23N28M2T) ЭИ628 (EI628)	+	–	–

Grades of steels and alloys			Group		
No.	New designation	Old designation	I – corrosion-resistant	II – oxidation-resisting	III – high-temperature
8. Alloys on nickel base					
8-1	Н70МФ (N70MF)	Н70М27Ф (N70M27F) ЭП496 (EP496)	+	–	–
8-2	ХН65МВ (HN65MV)	0Х15Н65М16В (0H15N65M16V) ЭП567 (EP567)	+	–	–
8-3	ХН60ВТ (HN60VT)	ЭИ868 (EI868)	–	+	+ +
8-4	ХН60Ю (HN60U)	ЭИ559А (EI559A)	–	+ +	+
8-5	ХН70Ю (HN70U)	ЭИ652 (EI652)	–	+ +	+
8-6	ХН78Т (HN78T)	ЭИ435 (EI435)	–	+ +	+
8-7	ХН75МБТЮ (HN75MBTU)	ЭИ602 (EI602)	–	+ +	+
8-8	ХН80ТБЮ (HN80TBU)	ЭИ607 (EI607)	–	–	+
8-9	ХН77ТЮР (HN77TUR)	ЭИ437Б (EI437B)	–	–	+
8-10	ХН70ВМЮТ (HN70VMUT)	ЭИ765 (EI765)	–	–	+
8-11	ХН70ВМТЮ (HN70VMTU)	ЭИ617 (EI617)	–	–	+
8-12	ХН67МВТЮ (HN67MVTU)	ЭП202 (EP202)	–	–	+
8-13	ХН70МВТЮБ (HN70MVTUB)	ЭИ598 (EI598)	–	–	+
8-14	ХН65ВМТЮ (HN65VMTU)	ЭИ893 (EI893)	–	–	+
8-15	ХН56ВМТЮ (HN56VMTU)	ЭП199 (EP199)	–	–	+
8-16	ХН70ВМТЮФ (HN70VMTUF)	ЭИ826 (EI826)	–	–	+
8-17	ХН57МТВЮ (HN57MTVU)	ЭП590 (EP590)	–	–	+
8-18	ХН55МВЮ (HN55MVU)	ХН55М6ВЮ (HN55M6VU) ЭП454 (EP454)	–	–	+
8-19	ХН75ВМЮ (HN75VMU)	ЭИ827 (EI827)	–	–	–
8-20	ХН62МВКЮ (HN62MVKU)	ХН62ВМКЮ (HN62VMKU) ЭИ867 (EI867)	–	–	–
8-21	ХН56ВМКЮ (HN56VMKU)	ЭП109 (EP109)	–	–	–
8-22	ХН55ВМТКЮ (HN55VMTKU)	ЭИ929 (EI929)	–	–	–

Notes: 1. Chemical elements in grades of steels and alloys are designated by the following letters: А – nitrogen, В (V) – tungsten, Д (D) – copper, М – molybdenum, Р (R) – boron, Т – titanium, Ю (U) – aluminium, Х (H) – chromium, Б (B) – niobium, Г (G) – manganese, Е – selenium, С (S) – silicon, Ф (F) – vanadium, K – cobalt, Ц (Ts) – zirconium. 2. Names of alloys grades include only letter symbols of elements excluding nickel, after which digits show its average percentage. 3. Symbol "+" denotes application of steel (alloy) for the specified purpose, symbol "++" denotes basic application. 4. Steels and alloys produced with special methods are additionally designated via dot at the end of grade name with the following letters: ВД (VD) – vacuum-arch remelting, Ш (Sh) – electric-slag remelting, ВИ (VI) – vacuum-induction melting.

APPENDIX 3

Recommended sequence for machining and thermal treatment of workpieces from hard-to-machine materials

<table>
<tr><th rowspan="2">Group No.</th><th colspan="2">Workpiece material</th><th colspan="2">Shape of part</th><th rowspan="2">Sequence of processing</th></tr>
<tr><th>Typical thermal treatment</th><th>σ_u, MPa</th><th>Simple</th><th>Complex</th></tr>
<tr><td rowspan="3">I</td><td>Annealing</td><td>600 – 800</td><td>+</td><td>+</td><td rowspan="2">Thermal treatment, machining</td></tr>
<tr><td rowspan="2">Quenching and tempering</td><td rowspan="2">900 – 1300</td><td>+</td><td></td></tr>
<tr><td></td><td>+</td><td>Preliminary machining, thermal treatment, finish machining</td></tr>
<tr><td rowspan="4">II</td><td>Annealing or Quenching and tempering</td><td>600 – 1000</td><td>+</td><td>+</td><td rowspan="2">Thermal treatment, machining</td></tr>
<tr><td rowspan="3">Quenching and tempering</td><td rowspan="2">1100 – 1400</td><td>+</td><td></td></tr>
<tr><td></td><td>+</td><td rowspan="2">Preliminary machining, thermal treatment, finish machining</td></tr>
<tr><td>1700 – 1900</td><td>+</td><td>+</td></tr>
<tr><td rowspan="3">III</td><td>Austenization</td><td>550 – 800</td><td>+</td><td>+</td><td rowspan="2">Thermal treatment, machining</td></tr>
<tr><td rowspan="2">Normalization or Normalization and tempering</td><td rowspan="2">1000 – 1100</td><td>+</td><td></td></tr>
<tr><td></td><td>+</td><td>Preliminary machining, thermal treatment, finish machining</td></tr>
<tr><td>IV</td><td>Austenization or Austenization and aging</td><td>700 – 1000</td><td>+</td><td>+</td><td rowspan="2">Thermal treatment, machining</td></tr>
<tr><td rowspan="3">V</td><td rowspan="2">Austenization and aging</td><td rowspan="2">950 – 1350</td><td>+</td><td></td></tr>
<tr><td></td><td>+</td><td>Preliminary machining, thermal treatment, finish machining</td></tr>
<tr><td>Austenization</td><td>800 – 900</td><td>+</td><td>+</td><td>Thermal treatment, machining</td></tr>
<tr><td>VI</td><td>Austenization and aging</td><td>750 – 1100</td><td>+</td><td>+</td><td rowspan="3">Thermal treatment, machining</td></tr>
<tr><td rowspan="3">VII</td><td>Annealing</td><td>450 – 1200</td><td>+</td><td>+</td></tr>
<tr><td rowspan="2">Quenching and aging</td><td rowspan="2">1150 – 1500</td><td>+</td><td></td></tr>
<tr><td></td><td>+</td><td>Preliminary machining, thermal treatment, finish machining</td></tr>
</table>

APPENDIX 4

Chemical composition and characteristics of physical-mechanical properties of cemented carbides*

Grade	Alloy composition				Bending ultimate strength, MPa	Density, g/cm^3	HRA
	Tungsten carbide	Titanium carbide	Tantalum carbide	Cobalt			
Tungsten group							
ВК3М (VK3M)	97	–	–	3	1180	15.0…15.3	91.0
ВК4 (VK4)	96	–	–	4	1520	14.9…15.2	89.5
ВК6М (VK6M)	94	–	–	6	1420	14.8…15.1	90.0
ВК6-ОМ (VK6-OM)	92	–	2	6	1270	14.7…15.0	90.5
ВК8 (VK8)	92	–	–	8	1660	14.4…14.8	87.5
ВК8В (VK8V)	92	–	–	8	1800	14.4…14.8	86.5
ВК10М (VK10M)	90	–	–	10	1600	14.3…14.6	88.0
ВК10-ОМ (VK10-OM)	88	–	2	10	1470	14.3…14.6	88.5
ВК15М (VK15M)	85	–	–	15	1850	13.8…14.1	87.0
ВК15-ОМ(VK15-OM)	83	–	2	15	1500	13.8…14.3	87.0
Titanium-tungsten group							
Т15К6	79	15	–	6	1170	11.1…11.6	90.0
Т5К10	85	5	–	10	1420	12.4…13.1	88.5

Notes: 1. * Data for cemented carbides of titanium-tantalum-tungsten group are not submitted.
2. Thermal endurance of cemented carbides is 900…1000°C.

APPENDIX 5

Characteristics of mechanical properties of high-speed steels

Grade	σ_{bu}, MPa	HRC$_e$, after quenching and tempering	HB in annealed condition	Red-hardness, °C
Р18* (R18)	2600…3000	63…65	255	620
Р6АМ5 (R6AM5)	3200…3600	64…66	255	620
Р6АМ5Ф3 (R6AM5F3)	2700…3100	65…67	269	630
Р12Ф3 (R12F3)	2400…2800	64…67	269	630
Р18К5Ф2 (R18K5F2)	–	64…66	285	640
Р9К5 (R9K5)	2300…2700	64…67	269	630
Р6М5К5 (R6M5K5)	2600…3000	65…67	269	630
Р9М4К8 (R9M4K8)	2200…2600	65…68	285	630

Note. * Application is not recommended.

APPENDIX 6

Relative endurance* of tools from high-speed steel

Group No.	Grade of high-speed steel			
	P6AM5 (R6AM5)	P6M5K5 (R6M5K5)	P9K5 (R9K5)	P9M4K8 (R9M4K8)
I	1.0	1.2	1.2	1.5
II	1.0	1.2	1.2	2.0
III	1.0	1.2	1.2	2.0
IV	0.8	1.5	1.5	2.0
V	1.0	2.0	2.0	3.0
VI	1.0	2.0	2.0	3.0
VII	0.8	1.5	1.5	2.5

Note. * Ratio of tool life from this steel to the tool life from steel P18 (R18).

APPENDIX 7

Cutting fluids applied for machining hard-to-machine materials

Cutting fluids are divided into two categories depending on their influence on cutting process.

1. Fluids having cooling and partially lubricant properties: water solutions of mineral electrolytes and water emulsions. They are mainly applied in rough and semi-finish operations, when cooling property of fluid providing improvement of tool life is of great importance. In some cases emulsions are used in finish operations (for example, in reaming).

2. Fluids possessing lubricant and partially cooling properties: mineral, vegetable and animal oils, kerosene, solutions of surface-active substances in oil or in kerosene. They are applied in finish operations, when fluids' lubricant properties reducing roughness of machined surfaces and improving a tool life are of great significance.

Water emulsions are produced from ready-made emulsols: Укринол-1 (Ukrinol-1), Аквол-2 (Akvol-2), РЗ-СОЖ8 (R3-SOZh8) and other.

Soda solutions, compositions with borax, with trisodiumphosphate and other are applied as electrolytes, if absence of fat particles on the machined parts' surfaces should be guaranteed according to operation conditions.

МР-1у (MR-1u), МР-6 (MR-6), МР-99 (MR-99), sulphofrezol and others are applied as oil cutting fluids.

APPENDIX 8

Methods applied for improvement of machining hard-to-machine steels and alloys

Intensification of machining of hard-to-machine materials is provided by: 1) improvement of operability of the cutting tool, 2) supply of additional energy into cutting zone.

1. At present great attention is paid to improvement of operability of the cutting tool by application of wear-resistant coatings (hardening) to its work surfaces. The widest use found the following methods of hardening:

- Condensation of gaseous compositions from gas medium with creation of hard films on surfaces of a cutting tool (GT method);
- Thermal diffusion of hard compositions from metallic powders into the tool material (DT method);
- Condensation of substances from plasma phase under conditions of ionic bombardment (CIB method).

First two methods are high-temperature ones: temperature of tool base (backing) reaches 1000°C at hardening process. Therefore they are applied only for deposition of coatings on the tools from cemented carbides, mainly on detachable polygonal tips.

When hardening is performed with the CIB method, temperature of backing is relatively low (450°C). This allows using it for hardening of cutting tool both from cemented carbides and from high-speed steels.

Coatings of titanium carbides (TiC) or double-layer coatings of titanium carbides and nitrides (TiC + TiN) are applied with GT and DT methods to detachable polygonal tips from cemented carbides. Coatings of titanium nitrides are applied with the CIB method. So as efficiency of wear-resistant coatings applied with GT and DT methods is higher and these both methods are more productive than CIB method, the latter is not reasonable to use for polygonal tips from cemented carbides. Coatings of titanium carbides and nitrides deposited with GT and DT methods on polygonal tips from cemented carbides 1.5…2 times elongate tool life at the same cutting velocity or allow to increase the cutting velocity by 10…20 % at the same tool life.

CIB method allows hardening: brazed and solid tools from cemented carbides difficult in production (fine-module gear cutters, taps, and form cutting tools); tools from high-speed steel – gear cutters, hobs, taps, broaches, reamers, end milling cutters, form and other cutting tools.

Hardening 1.2…2 times improves a tool life.

Endurance of tool from high-speed steel is similarly improved by carbonitriding in gaseous products of decomposition of carbamide (urea), nitriding, liquid carbonitriding (lower manufacturability).

Regular replacement of tools, centralized sharpening and careful preparation of surfaces for coatings play important role in improvement of cutting tool endurance.

2. When cutting hard-to-machine steels and alloys the methods with supply of additional energy into cutting zone are applied: machining with preliminary heating of the cut layer; machining with vibrations of low frequency; machining with oscillations of ultrasonic frequency.

Machining with preliminary heating of cut layer, for example, rough turning of blanks from titanium alloys with crust or cutting with heating by plasma arch (plasma-mechanical machining), are applied not often, because of high complexity of manufacturing process.

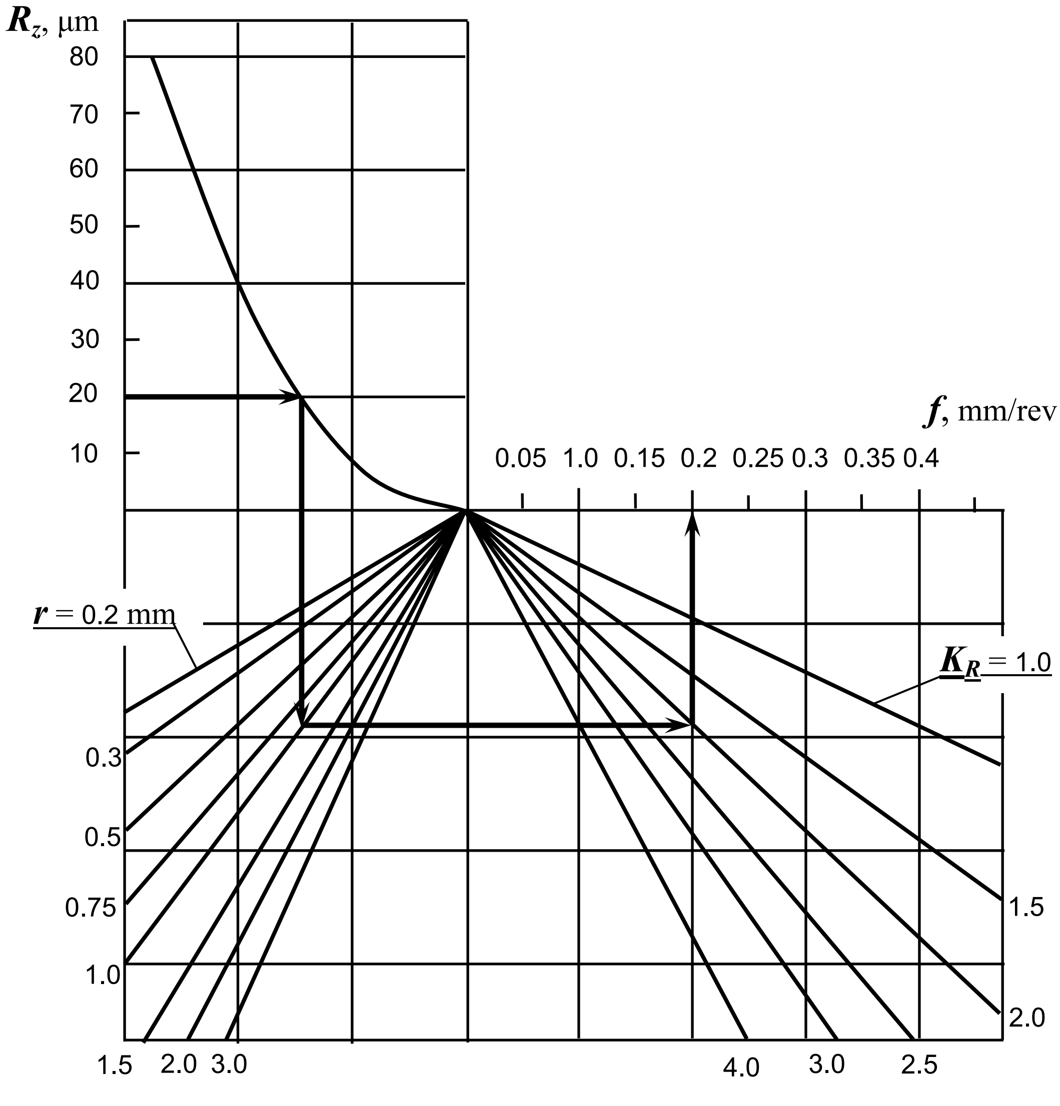
Machining with vibrations of low frequency finds application at drilling of holes in workpieces from high-temperature alloys and from alloys on titanium base.

Oscillations of ultrasonic frequency are used at threading with taps in workpieces from high-temperature alloys.

Workpieces from high-temperature alloys and from titanium alloys with diameter of more than 60…100 mm are reasonable to be cut off with anode-mechanical method. Form (shaped) surfaces, elements with difficult access, holes with diameter less than 1 mm are reasonable to be machined with electro-impulse, electrospark or electrochemical methods, slots and holes with dimension less than 0.2 mm – with electronic or laser beam.

APPENDIX 9

Nomograph for determination of feed value at turning



Values of normalized geometric ratios ξ raised to the power

ξ	1.06	1.12	1.26	1.41	1.58	1.78	2.00
ξ^2	1.12	1.26	1.50	2.00	2.50	3.16	4.00
ξ^3	1.19	1.41	2.00	2.80	4.00	5.64	8.00
ξ^4	1.26	1.58	2.50	3.95	6.32	10.08	16.00
ξ^5	1.34	1.78	3.18	5.57	10.08	17.92	32.00
ξ^6	1.41	2.00	4.00	7.86	16.00	32.00	64.00
ξ^7	1.49	2.24	5.04	11.08	25.28	56.80	128.00
ξ^8	1.58	2.50	6.36	15.60	40.00	104.66	–
ξ^9	1.67	2.81	8.00	22.03	64.00	186.29	–
ξ^{10}	1.78	3.16	10.09	31.06	101.12	–	–
ξ^{11}	1.89	3.55	12.71	45.12	159.77	–	–
ξ^{12}	2.00	4.00	16.00	64.00	258.00	–	–
ξ^{13}	2.12	4.48	20.18	90.24	406.00	–	–
ξ^{14}	2.24	5.04	25.42	127.24	646.00	–	–
ξ^{15}	2.36	5.64	32.00	179.41	–	–	–
ξ^{16}	2.50	6.32	40.36	254.00	–	–	–
ξ^{17}	2.65	7.12	50.85	328.00	–	–	–
ξ^{18}	2.81	8.00	64.07	504.00	–	–	–
ξ^{19}	2.98	8.96	80.77	–	–	–	–
ξ^{20}	3.16	10.08	101.72	–	–	–	–
ξ^{21}	3.35	11.28	128.17	–	–	–	–
ξ^{22}	3.55	12.64	161.40	–	–	–	–
ξ^{23}	3.77	14.24	203.48	–	–	–	–
ξ^{24}	4.00	16.00	256.39	–	–	–	–
ξ^{25}	4.24	17.92	323.05	–	–	–	–
ξ^{26}	4.48	20.16	–	–	–	–	–
ξ^{27}	4.75	22.56	–	–	–	–	–
ξ^{28}	5.04	25.28	–	–	–	–	–
ξ^{29}	5.34	28.48	–	–	–	–	–
ξ^{30}	5.64	32.00	–	–	–	–	–
ξ^{31}	5.98	–	–	–	–	–	–
ξ^{32}	6.32	–	–	–	–	–	–
ξ^{33}	6.70	–	–	–	–	–	–
ξ^{34}	7.12	–	–	–	–	–	–
ξ^{35}	7.55	–	–	–	–	–	–

APPENDIX 11

Coefficients C_v and C_p for turning workpieces from hard-to-machine steels and alloys with $f \le 0.06$ mm/rev

Group No.	Grade	σ_u, MPa	C_v	C_p
I	20Х3МВФ (20H3MVF)	900	350	2000
II	20Х13 (20H13)	850	310	2000
	09Х16Н4Б (09H16N4B)	1500	108	3300
III	12Х18Н10Т (12H18N10T)	600	150	1800
IV	5Х18Н12С4ТЮ (5H18N12S4TU)	750	68	1900
V	36ХНТЮ (36HNTU)	HRC_e 36…42	54	2800
		HRC_e 45	42	–
	ХН67ВМТЮ (HN67VMTU)	1000	54	3500
	ХН62ВМКЮ (HN62VMKU)	1250	15	4000

APPENDIX 12

Coefficients C_v and C_p for turning of workpieces from titanium alloys of group VI with $f \le 0.06$ mm/rev

Grade	σ_u, MPa	C_v	C_p
ВТ1 (VT1), ВТ1-1 (VT1-1), ВТ1-2 (VT1-2)	500…700	58	1300
ОТ4, ОТ4-1, ВТ5 (VT5), ВТ5-1 (VT5-1)	700…900	39	1450
ВТ3 (VT3), ВТ3-1 (VT3-1)	950…1200	29	1500
ВТ6 (VT6), ВТ6С (VT6S), ВТ14 (VT14), ВТ15 (VT15), ВТ22 (VT22)	900…1000	32	1450
ВТ14 (VT14), ВТ15 (VT15), ВТ22 (VT22) (after quenching and aging)	1300	25	2300

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Content

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Редактор Л.М. Лобачова

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