V. F. Skvortsov

FUNDAMENTALS OF MECHANICAL ENGINEERING

LABORATORY WORKS

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Coursework guidelines are examined and recommended for publication by the methodological seminar of the Department of Automated Mechanical Manufacturing Engineering

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Head of the Department of Automated Mechanical Manufacturing Engineering
Associate professor, Doctor of Science (Technical) _____ A.Yu. Arlyapov

CONTENTS

Laboratory work 1: Industrial investigation of a lathe rigidity (4 hours)

Laboratory work objectives:
1. To familiarize with procedure of determining rigidity of a lathe.
2. To define the range of dispersion of sizes obtained after machining a batch of parts with allowances of 0.5 to 2.5 mm.
3. To define whether is it possible to ensure dimensional accuracy of 0.05 mm during the one-pass cutting on the machine tool set to the required dimension.

Equipment and tools
1. Lathe.
2. Right-hand turning cutter (carbide grade T15K6, $\alpha=10°$, $\gamma=0°$, $\lambda=0°$, $\varphi=45°$, $\varphi_1=10°$, r=1 mm).
3. Face-plate with a clamp, a dog, centers, chuck key, tool post key, safety goggles.

Guidelines

The ability of a machine tool to withstand deforming action of the cutting forces is called rigidity. Rigidity is the ratio of a radial component of a cutting force to a radial displacement of a cutter with respect to the workpiece:

$$j = \frac{P_y}{y},\qquad(1)$$

where P_y is the radial component of a cutting force, N; y is the displacement of a point of force application or displacement of the cutting edge relatively to the workpiece, mm or μm.

To simplify engineering calculations, the concept *compliance* is commonly used. Compliance is a value reciprocal to rigidity:

$$W = \frac{1}{j}, \text{ mm or μm}\qquad(2)$$

Machine tool rigidity depends on deformations of individual components of the machine, contact deformation of joints and deformation of fasteners (bolts, wedges, etc.).

Calculation of rigidity or compliance can be made with the help of equations of elasticity theory, theory of strength of materials and contact stiffness. However, these calculations are very complex.

The most common methods of turning machines rigidity determination are as follows:

– loading of a non operating machine tool and subsequent measurement of deflections values;

– machining of specialized samples and subsequent measurement of actual dimensions, which being compared to the planned values, help to determine elastic deflections.

The latter method is called industrial method. It is carried out as follows. A substantially rigid workpiece is cut by a rigid cutter. In this case, rigidity of the system (machine-fixture-tool-workpiece) is reduced to rigidity of a machine tool. Three short stepped surfaces are machined on the workpiece. Layers of material with depths of cut t_1 and t_2 are severed from these three surfaces. Other cutting parameters (feed arte, cutting speed and geometry of the cutter) are constant. Cutting of a stepped workpiece generates different radial components of the cutting force (with respect to the difference in the depths of cut), which results in offsets on the machined surfaces.
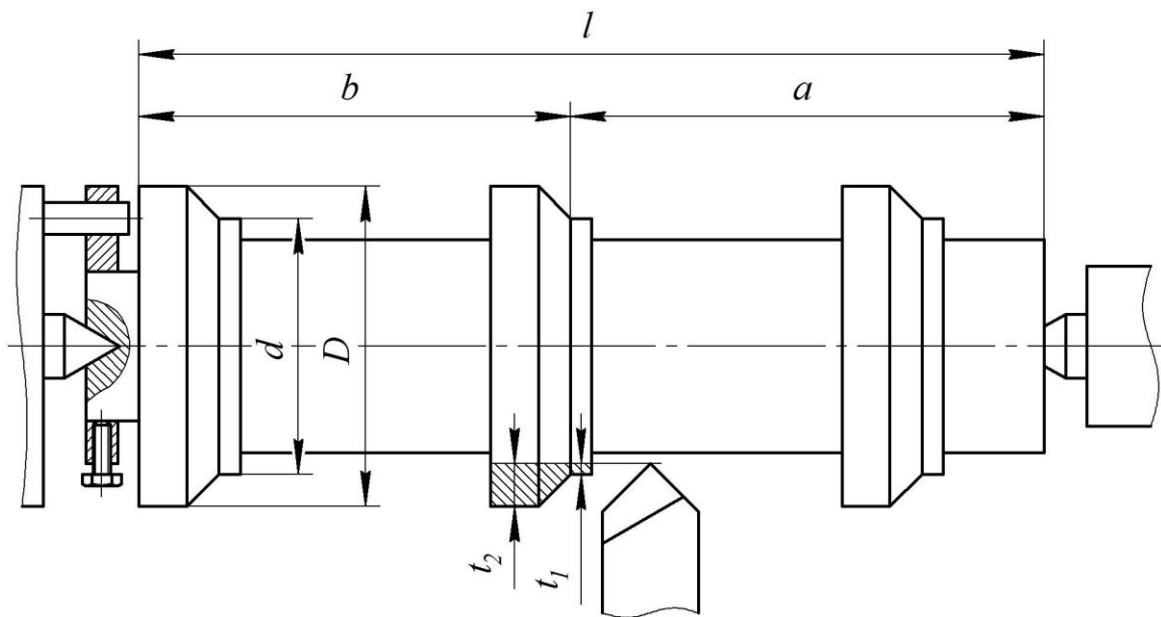

Fig. 1 Workpiece mounted on a lathe

Let us examine a diagram of loading and elastic deflections of the machine tool components during machining of a workpiece mounted in centers (Fig. 2).

It can be seen from the diagram that with the movement of the point of force application along the workpiece, the value of total deflection of the machine components varies, and, thus the value of total rigidity/compliance varies as well.
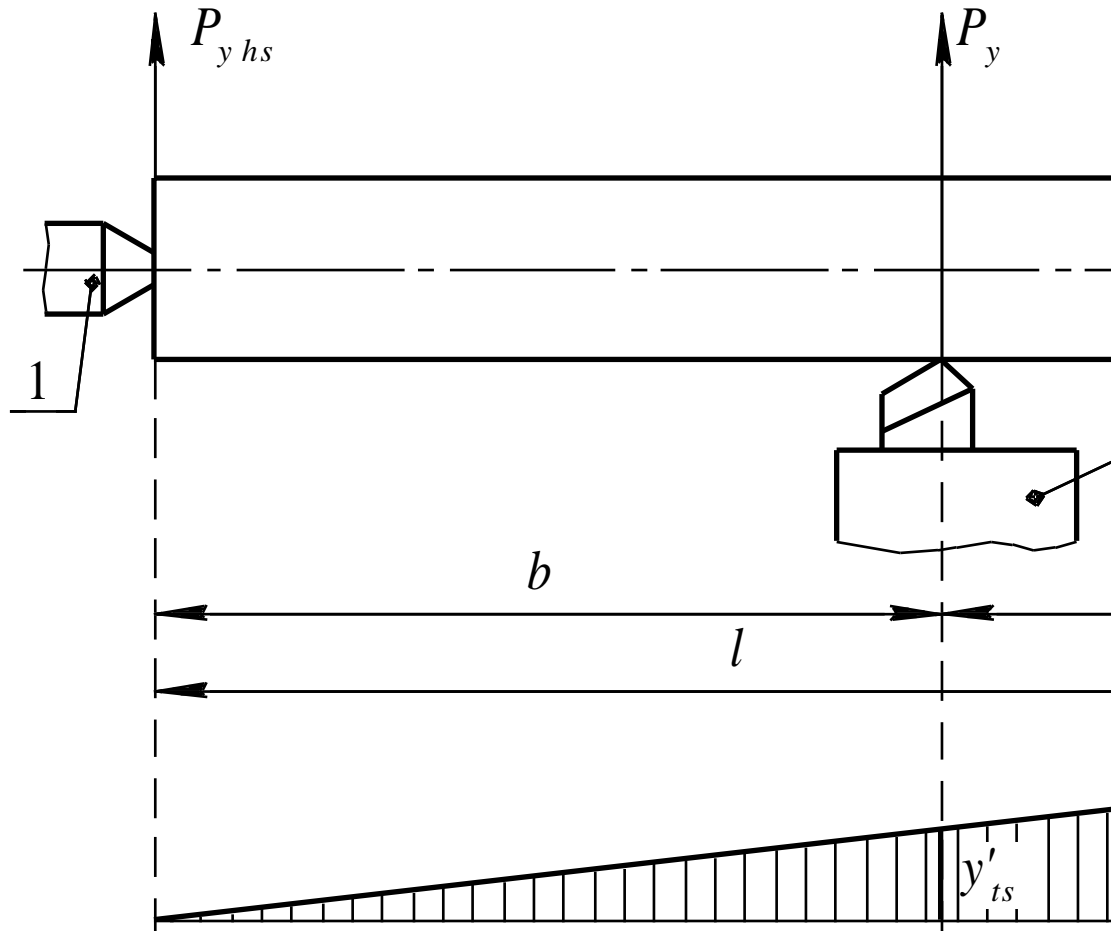

Fig. 2 Diagram of loading and elastic deflections of the lathe components during machining with centers:
1 – head stock; 2 – carriage; 3 – tail stock;
P_{yhs}, P_{yts} – forces acting on the head stock and tail stock due to radial component of the cutting force P_y.

Deflection (total value) of the lathe components at the given coordinate is equal to:

$$y_{lathe} = y_{car} = y'_{ts} + y'_{hs}, \qquad (3)$$

where $y'_{ts} = y_{ts}\dfrac{b}{l}$; $y'_{hs} = y_{hs}\dfrac{a}{l}$; $y_{ts} = P_{yts}W_{ts}$; $y_{hs} = P_{yhs}W_{hs}$; $y_{car} = P_y W_{car}$;

$P_{yts} = P_y\dfrac{b}{l}$; $P_{yhs} = P_y\dfrac{a}{l}$.

Substituting these values into Equation (3), we obtain:

$$y_{lathe} = P_y W_{car} + P_y W_{ts} \frac{b^2}{l^2} + P_y W_{hs} \frac{a^2}{l^2}.$$

Substituting the y_{car} by the $y_{car}=P_y W_{lathe}$, we obtain equation for determination of compliance and rigidity of the machine tool, depending on the coordinate of a cutter position along the workpiece:

$$\left.\begin{aligned} W_{lathe} &= W_{car} + W_{ts} \frac{b^2}{l^2} + W_{hs} \frac{a^2}{l^2} \\ \frac{1}{j_{lathe}} &= \frac{1}{j_{car}} + \frac{1}{j_{ts}} \cdot \frac{b^2}{l^2} + \frac{1}{j_{hs}} \cdot \frac{a^2}{l^2} \end{aligned}\right\}. \qquad (4)$$

Having determined the rigidity of the machine at three positions of a carriage and solving a system of three equations, we can calculate separately the rigidity of the machine components (headstock, carriage and tailstock).

The radial component of the cutting force P_y can be expressed through the tangential component P_z as follows:

$$P_y = K_y P_z, \qquad (5)$$

where K_y is the coefficient that characterizes the ratio of P_y/P_z depending on the geometry of the cutter, cutting edge condition and mechanical properties of the cutting tool material.

P_z can be defined using the equation of Chelyustkin:

$$P_z = C_p t S^{0.75}, \qquad (6)$$

where C_p is the coefficient that depends on the mechanical properties of the workpiece material and cutting angle (for the conditions under consideration $C_p=360$). Then:

$$P_y = K_y C_p t S^{0.75}, \qquad (7)$$

where t is the depth of cut, mm; S is the feed rate, mm/rev; coefficient $K_y=0.4$.

Obviously, the larger is the difference in diameters of the workpiece, i.e. the difference between the depths of cut $(t_2 - t_1)$, the greater is the difference between the respective radial components of the cutting force $(P_{y2} - P_{y1})$. In turn, the greater is the difference between the force components, the greater is the offset step Δt obtained after machining the workpiece with depths of cut t_1 and t_2. Let us denote this difference in depths of cut as Δ_{work}, i.e.:

$$\Delta_{work} = t_2 - t_1.$$

The ratio $\varepsilon = \Delta_{work}/\Delta t$, which indicates how many times has the "inaccuracy" of the workpiece decreased after machining, is called "improvement". Having the value ε determined for all three positions (at a headstock, at a tail-

stock and in an intermediate position), the rigidity of a machine can be determined for each of the three positions:

$$j_{lathe}^{I} = K_y C_P S^{0.75} \varepsilon_1 \qquad (8)$$

$$j_{lathe}^{II} = K_y C_P S^{0.75} \varepsilon_2 \qquad (9)$$

$$j_{lathe}^{III} = K_y C_P S^{0.75} \varepsilon_3 \qquad (10)$$

However, for a manufacturing engineer, the determination of rigidity of the whole machine or of its individual components is not exactly an aim. It is the influence of the varying elastic deformations of the technological system on the machining accuracy which is of primary interest for an engineer.

Let us consider a batch of workpieces with different allowance values for machining. Suppose that the smallest allowance in the batch is equal to t_1, and the biggest allowance is equal to t_2. The difference between the allowances is equal to half the tolerance of the workpiece diameter. Then, the step height on the machined surface of the sample Δt will correspond to the range of dispersion of sizes that arise due to various deformation of the technological system components during machining of a batch of workpieces with varying allowance (or non-uniform hardness).

Procedure

1. Set the machine to the following cutting parameters: V=80-100 m/min; S=0.15...0.21 mm/rev.
2. Using equation (7), calculate value of the radial component of the cutting force during machining with cutting depths t_1=0.5 and t_2=2.5 mm.
3. Mount the workpiece in centers, make measurements of the diameters for all three stepped sections, as well as of the sizes a and b for each stepped section (see Figure 1).
4. Machine all three stepped sections with predetermined cutting depths t_1 and t_2, which are equal to 0.5 and 2.5 mm, respectively.
5. Determine heights of the three resulting steps with accuracy of 0.01 mm. Perform measurements with the help of a micrometer (Figure 3).
6. Determine the rigidity of the machine for all three positions.
7. Give answers to the questions given in the section "objectives"
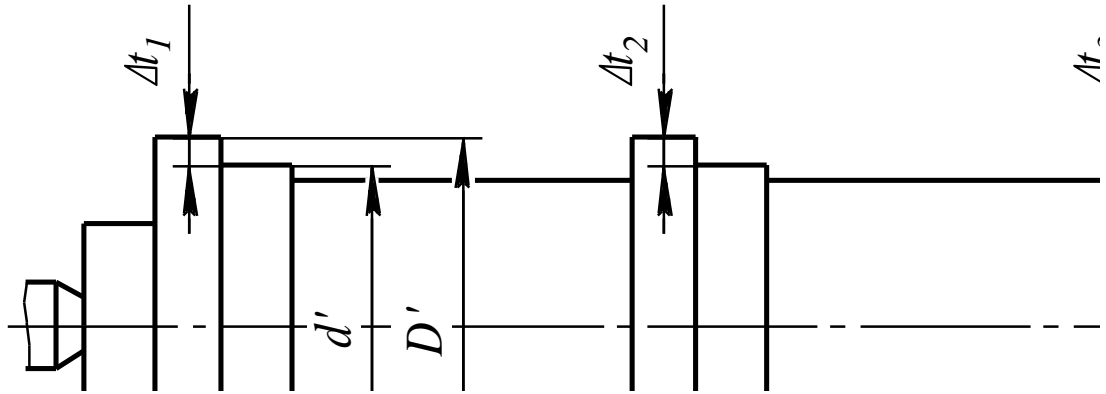8. Write a report.

Fig. 3 Sizes of the sample after machining

Contents of a report

In a report to be given:

1. The name and purpose of the work.

2. Diagram of the forces and the elastic displacement of the machine and a sketch of the workpiece.

3. Brief description of the machine, workpiece material, tool geometry, cutting conditions.

4. Characteristics of the measuring instrument.

5. The results of measurements and calculations of forces.

6. Calculation of machine rigidity for 3 positions.

7. Conclusions about the accuracy of a batch of blanks on this machine.

Laboratory work 2: Statistical analysis of machining accuracy
(4 hours)

Laboratory work objective

Objective is to study statistical methods of machining accuracy analysis, which allows for the most reliable estimate of the actual machining accuracy, quality of machine setting and allows to determine the probable percentage of defected parts in the given operation.

Guidelines

Depending on the machining conditions, error distribution may be subject to various laws. Numerous studies have shown that the distribution of dimensions errors most often corresponds to the normal distribution (Gaussian). In this connection, the mentioned method is considered in relation to the analysis of errors with normal distribution.

Construction of a histogram and a curve of error distribution

To construct a histogram and empirical distribution curve, the accurate measurement of the parameters in a sample (group of components), which is taken from the statistical population (the whole batch of workpieces), is made. To make decisions about the distribution of the given accuracy parameter in the statistical population, based on the sample data, the sample should be representative. For this purpose, it should be random and have the necessary volume (parts quantity).

The sample is called random if all the objects (parts) of the general population have an equal chance of being selected. To ensure the use of random sampling, the selection by lot or by thoroughly mixing the parts(components of the general population) in a bin and their random selection from the different locations of the bin is used. The sample size n is usually 50...100 parts.

Construction of an empirical error distribution curve and a histogram is made in the following sequence:

1. According to the measurements of parts of a sample, the difference between the largest and smallest dimensions is determined (sampling range R). Then the value $R=x_{max}-x_{min}$ is divided into equal intervals (see Table 1). When the sample size $n=50...100$ parts, the number of intervals f is recommended to be equal 6...8. Afterwards, the width of an interval $a=R/f$ is determined. To compensate for the measure-

ment error, the width of intervals should be taken approximately twice the scale interval of the measuring instrument.

2. Then it is needed to count frequency n_i – number of parts that fall into each interval, or relative frequency n_i/n – the ratio of the frequency to the sample size. It should be noted, that every interval includes parts with dimensions lying within an interval range from the smallest value inclusive to the largest value exclusive. Then the middles of the intervals (average sizes of the intervals) x_i are determined. The results are written to a table, similar to Table 1.

3. To construct a histogram (Fig. 1), the intervals are plotted along the abscissa and on the basis of the intervals, a rectangle whose height is proportional to the frequency or relative frequency is constructed. Connecting the upper middle points of the rectangles with line segments, the graph (Fig. 1) which is called an empirical curve or frequency polygon is obtained.
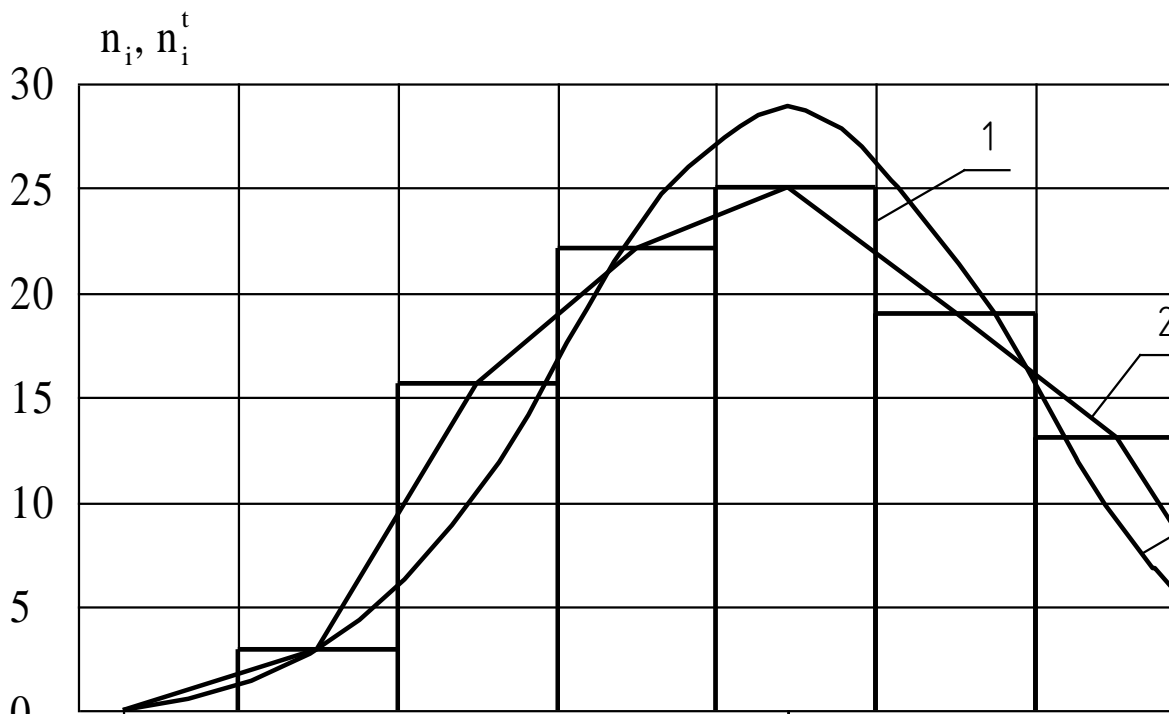

Fig. 1 Histogram (1), empirical curve (2) and curve of normal distribution (3)
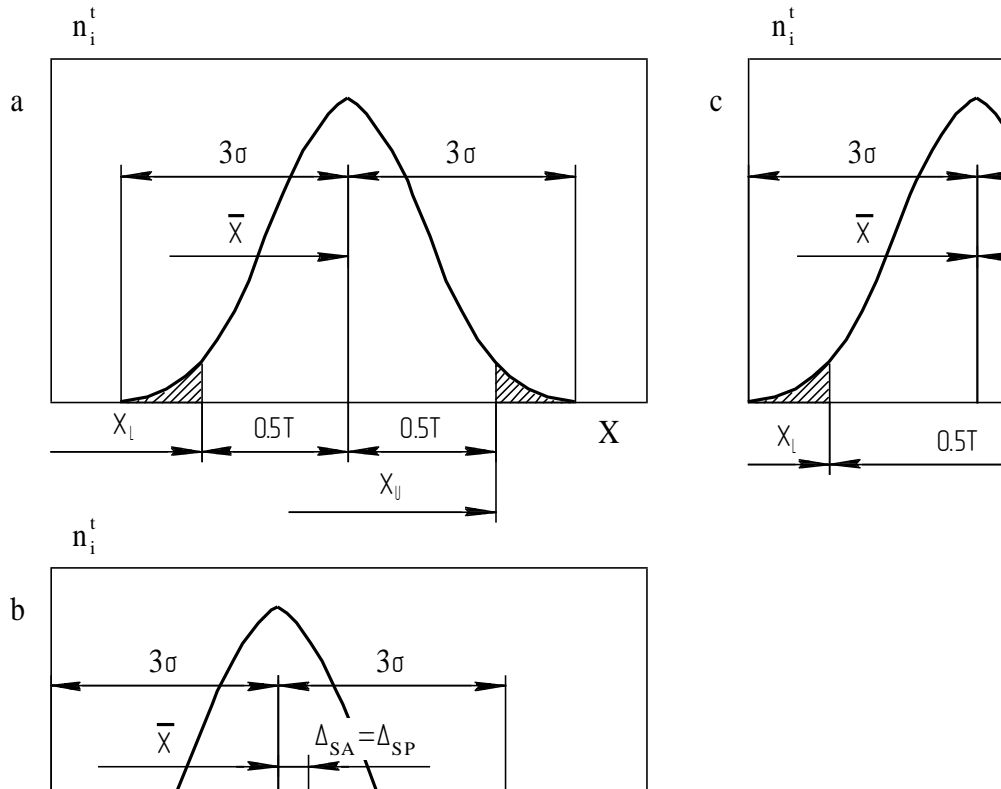
Fig. 2 On defining accuracy of a machine and probable reject rate with the help of curve of normal distribution

Table 1

Size intervals		Middle of interval, x_i	Empirical frequency, n_i	t	Z_t	Theoretical frequency, n_i^t	Theoretical frequency, n_i^t (rounded.)
from	too						
19.86	19.88	19.87	3	2.07	0.0468	3.40	3
19.88	19.90	19.89	16	1.35	0.1604	11.50	11
19.90	19.92	19.91	22	0.64	0.3251	23.50	23
19.92	19.94	19.93	25	0.072	0.3980	28.55	29
19.94	19.96	19.96	19	0.785	0.2940	21.45	22
19.96	19.98	19.97	13	1.50	0.1295	9.20	9
19.98	20.00	19.99	2	2.20	0.0355	2.60	3

Construction of the theoretical curve of error normal distribution

Appearance of the empirical curve can help to approximately establish the law of errors distribution in the population. For a more accurate conclusion the empirical distribution curve should be compared with the suggested

theoretical one. For this purpose, for each interval of values x, it is necessary to calculate theoretical frequency or relative frequency and construct theoretical distribution curve according to these frequencies.

The equation of the normal distribution curve is:

$$\varphi(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\bar{x}_0)^2}{2\sigma^2}}, \qquad (1)$$

where $\varphi(x)$ is the probability density (probability of occurrence of a particular value of a random variable);

σ is the standard deviation of a random variable ;

$\bar{x}_0$ is the average value of a random variable;

x is the random variable current value;

e is the base of natural logarithms.

In experimental studies, as approximate estimates of the general population parameters $\bar{x}_0$ and σ, the sample mean $\bar{x}$ and sample standard deviation S are used, which are calculated by the following equations:

$$\bar{x} = \frac{\sum\limits_{i=1}^{f} x_i n_i}{n}; \qquad (2)$$

$$S = \sqrt{\frac{\sum\limits_{i=1}^{f} n_i (x_i - \bar{x})^2}{n}}. \qquad (3)$$

In the construction of the theoretical curve of a normal distribution, it is assumed that $\bar{x}_0 = x$ and $\sigma = S$.

Approximately we can assume that

$$\varphi(x) \approx \frac{n_i^t}{n \cdot a} = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\bar{x}_0)^2}{2\sigma^2}}, \qquad (4)$$

where n_i^t is the theoretical frequency, a is the width of an interval (this value is put in Equation (4) to bring the theoretical normal distribution curve to the same scale in which the empirical curve is drawn).

From equation (4) we have

$$n_i^t = \frac{n \cdot a}{\sigma} \cdot \frac{1}{\sqrt{2\pi}} e^{-\frac{(x-\bar{x}_0)^2}{2\sigma^2}}. \qquad (5)$$

If the Equation (5) is substituted with

$$t = \frac{x - \bar{x}_0}{\sigma},$$

then we get

$$n_i^t = \frac{n \cdot a}{\sigma} \cdot \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}}.$$

Let us denote $\frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} = Z_t$ and assume that $\sigma = S$.

Then Equation (5) takes the following form

$$n_i^t = \frac{n \cdot a}{S} \cdot Z_t. \tag{6}$$

The value Z_t is calculated for different values of t and is given in the table in Appendix 1. The values of t for each size range are found as follows:

$$t = \frac{|x_i - \bar{x}|}{S} \tag{7}$$

Thus, to calculate theoretical frequency, it is needed for each size interval to determine value t according to Equation (7), then with the help of table of Appendix 1 find Z_t, and then use Equation (6). In calculating the theoretical frequencies it is rational to use the table (see Table 1). Theoretical curve of normal distribution is usually combined with the empirical curve diagram (Fig. 1). It should be noted that the theoretical curve of normal distribution may also be constructed by characteristic points. Coordinates of the characteristic points of the normal distribution curve are shown in Table 2.

Table 2

Characteristic points	Abscissa	Ordinate
Curve peak	x	$n_i^T = 0{,}4\dfrac{n \cdot a}{S}$
Bending point	$x \pm S$	$n_i^T = 0{,}24\dfrac{n \cdot a}{S}$
Bending point	$x \pm 2S$	$n_i^T = 0{,}054\dfrac{n \cdot a}{S}$
-	$x \pm 3S$	$n_i^T = 0$

Assessment of the machine tool setting and identification of reject percentage for the operation

For a normal distribution the range of errors dispersion (in the population) is calculated as:

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$$\omega_c = 6\sigma. \tag{8}$$

A sample standard deviation S, as already mentioned, is an approximate estimate of σ. Error of estimate of σ in relation to S depends on the sample size. With this in mind, it is necessary to determine the value of σ [4], when using the formula (8), as:

$$\sigma = Z_2 \cdot S, \tag{9}$$

where Z_2 is the coefficient that depends on the sample size and can be taken according to Table 3.

<div align="right">Table 3</div>

n	25	50	75	100	200
Z_2	1.39	1.25	1.19	1.16	1.11

A necessary condition for machining without reject is

$$\omega_c < T, \tag{10}$$

where T is the tolerance of a dimension.

If this condition is not satisfied (Fig. 2, *a*), the reject is inevitable.

Condition (10) is a necessary, but not sufficient, since in practice reject is possible if the machine setting is made with the actual error Δ_{sa}, larger than the permissible Δ_{sp} (see Fig. 2, *b*, *c*). Therefore, the second condition for the machining without reject is:

$$\Delta_{sa} < \Delta_{sp} \tag{11}$$

The value of Δ_{sa} is found from the expression:

$$\Delta_{sa} = \left| \bar{x} - \frac{x_u + x_l}{2} \right|, \tag{12}$$

where x_u, x_l are the maximum and minimum limits of size according to the drawing.

Permissible error of setting:

$$\Delta_{sp} = \frac{T}{2} - \frac{\omega_c}{2}. \tag{13}$$

If the conditions (10) and (11) are not fulfilled, it is necessary to calculate the probable reject.

The area under the curve of distribution is equal to 1 or, which is the same, 100%.

The probability of a random variable having a normal distribution to fall into the interval $[x_1, x_2]$ is equal to (expressed as a decimal):

$$P = \frac{1}{\sigma\sqrt{2\pi}} \int_{x_1}^{x_2} e^{-\frac{(x-\bar{x}_0)^2}{2\sigma^2}} \, dx. \tag{14}$$

If x_1 and x_2 are the limits of size, according to the part drawing (Fig. 2, a), it is obvious that P is the probability of obtaining the accepted parts. Therefore, the probability of the rejected parts is equal to 1-P.

The probability of a random value to fall in the range $\bar{x}_0 \pm 3\sigma$ is 99.73 %, thus, in practical calculations, the specified range of x values dispersion is taken as the value of the range of dispersion of errors ω_i.

Moving to a new variable $t = \dfrac{x - \bar{x}_0}{\sigma}$, and considering that $x = t\sigma + \bar{x}_0$ and $dx = \sigma dt$, we obtain the following expression for calculation of probability of a random variable to fall in the interval $[x_1, x_2]$

$$P = \frac{1}{\sqrt{2\pi}} \int_{t}^{t_2} e^{-\frac{t^2}{2}} \, dt. \tag{15}$$

The right-hand side of Equation (15) can be written as the sum of two integrals

$$P = \frac{1}{\sqrt{2\pi}} \int_{t}^{t_2} e^{-\frac{t^2}{2}} \, dt - \frac{1}{\sqrt{2\pi}} \int_{0}^{t_1} e^{-\frac{t^2}{2}} \, dt$$

The integral $\dfrac{1}{\sqrt{2\pi}} \int_{0}^{t} e^{-\frac{t^2}{2}} \, dt = \phi(t)$ is called a normalized error function (Laplace function), its values for various t are given in the table in Appendix 2. To determine value of the error function, the values of t are taken in absolute magnitude.

Thus, if a tolerance and limits of size x_u, x_l of the part are given, the probable reject rate will be:

for the upper limit of the tolerance

$$P_{бru} = \left[0.5 - \Phi(t_u)\right] \cdot 100\% ; \tag{16}$$

for the lower limit of tolerance.

$$P_{rl} = \left[0.5 - \Phi(t_l)\right] \cdot 100\% . \tag{17}$$

In expressions (16) and (17)

$$t_u = \frac{x_u - \bar{x}}{\sigma}; \quad t_l = \frac{x_l - \bar{x}}{\sigma}. \tag{18}$$

Construction of a theoretical distribution curve (Fig. 2) can be performed approximately, to scale only for the horizontal axis.

Procedure

1. In accordance with the instructions of a teacher, make measurements of parts of the sample. Write results of the measurement into a report.

2. Determine the difference between the largest and the smallest size of parts in the sample (sample range $R = x_{max} - x_{min}$). Divide the R by f=5...8 intervals. Find the width of an interval $a = R/f$.

3. Determine the midpoints of intervals x_i. Calculate frequency for each interval. Write the results of calculations in to Table 1.

4. Construct a histogram and empirical distribution curve (see Fig. 1). The scale on the abscissa should be such that R value equals to 120...150 mm, and the ordinate is such that the height of the empirical curve is 0.6...0.7 times its length.

5. By Equations (2) and (3), calculate the sample mean $\bar{x}$ and sample standard deviation S of the sizes.

6. Using Equations (7) and (6) and the table in Appendix 1, determine the theoretical frequencies n_i^t of normal distribution for each interval. Write the results of calculations in to Table 1.

7. Draw a graph of the theoretical distribution curve, combining it with the empirical curve (Fig. 1).

8. Using Equations (8) and (9), find standard deviation and range of dispersion ω_c.

9. Observing the scale along the abscissa, plot the curve of a normal distribution of sizes of parts in the batch (see Figure 2). Designate the tolerance zone and limits of size according to the drawing (take the data from a teacher).

10. Using Equations (12) and (13), define actual and permissible errors of a machine tool setting.

11. Determine whether the conditions (10) and (11) are met, i.e. machining is performed with no reject.

12. Using Equations (16), (17), (18) and the table in Appendix 2, find the probable reject rate, both repairable and irrepairable.

13. Propose measures to improve the machining accuracy and reduce reject of the operation.

Values of Z_t

T	0	1	2	3	4	5	6	7	8	9
0.0	0.3989	3989	3989	3988	3986	3984	3982	3980	3977	3973
0.1	3970	3965	3961	3956	3951	3945	3939	3932	3925	3918
0.2	3910	3902	3894	3885	3876	3867	3856	3847	3836	3825
0.3	3814	3802	3790	3778	3765	3752	3739	3726	3712	3696
0.4	3683	3668	3653	3637	3621	3605	3589	3589	3555	3538
0.5	0.3521	3503	3485	3467	3448	3429	3410	3391	3372	3352
0.6	3332	3312	3292	3271	3251	3230	3209	3189	3166	3144
0.7	3123	3101	3079	3056	3034	3011	2989	2966	2943	2920
0.8	2897	2874	2850	2827	2803	2780	2755	2732	2709	2685
0.9	2661	2637	2613	2589	2565	2541	2516	2492	2468	2444
1.0	0.2420	2395	2372	2347	2323	2299	2275	2251	2227	2203
1.1	2179	2155	2131	2107	2083	2059	2036	2012	1989	1965
1.2	1942	1919	1895	1872	1849	1826	1804	1781	1758	1736
1.3	1714	1691	1669	1647	1626	1604	1582	1561	1539	1518
1.4	1497	1476	1456	1435	1415	1394	1374	1354	1334	1315
1.5	0.1295	1276	1257	1238	1219	1200	1182	1163	1145	1127
1.6	1109	1092	1074	1057	1040	1023	1006	0989	0973	0957
1.7	0940	0925	0909	0893	0878	0863	0848	0833	0818	0804
1.8	0790	0775	0761	0748	0734	0721	0707	0694	0681	0669
1.9	0656	0644	0632	0620	0608	0596	0584	0573	0562	0552
2.0	0.0540	0529	0519	0508	0498	0488	0478	0468	0459	0449
2.2	0355	0347	0339	0332	0325	0317	0310	0303	0297	0290
2.4	0224	0219	0213	0208	0203	0198	0194	0189	0184	0180
2.6	0136	0132	0129	0126	0122	0119	0116	0113	0110	0107
2.8	0079	0077	0075	0073	0071	0069	0067	0065	0063	0061
3.0	0044	0043	0042	0040	0039	0038	0037	0036	0035	0034

Values of error function

t	A(t)	t	A(t)	t	A(t)	t	A(t)	t	A(t)
0.00	0.000	0.23	0.0910	0.46	0.1770	0.88	0.3105	1.85	0.4680
0.01	0.004	0.24	0.0950	0.47	0.1810	0.90	0.3160	1.90	0.4715
0.02	0.008	0.25	0.0985	0.48	0.1845	0.92	0.3210	1.95	0.4744
0.03	0.012	0.26	0.1025	0.49	0.1880	0.94	0.3265	2.00	0.4775
0.04	0.016	0.27	0.1065	0.50	0.1915	0.96	0.3315	2.10	0.4820
0.05	0.020	0.28	0.1105	0.52	0.1985	0.98	0.3365	2.20	0.4860
0.06	0.024	0.29	0.1140	0.54	0.2045	1.00	0.3415	2.30	0.4895
0.07	0.028	0.30	0.1180	0.56	0.2125	1.05	0.3530	2.40	0.4920
0.08	0.032	0.31	0.1215	0.58	0.2190	1.10	0.3645	2.50	0.4940
0.09	0.036	0.32	0.1255	0.60	0.2255	1.15	0.3749	2.60	0.4955
0.10	0.040	0.33	0.1295	0.62	0.2325	1.20	0.3850	2.70	0.4965
0.11	0.044	0.34	0.1330	0.64	0.2390	1.25	0.3945	2.80	0.4975
0.12	0.048	0.35	0.1370	0.66	0.2455	1.30	0.4030	2.90	0.4980
0.13	0.0515	0.36	0.1405	0.68	0.2557	1.35	0.4115	3.00	0.4986
0.14	0.0555	0.37	0.445	0.70	0.2580	1.40	0.4190	3.20	0.4993
0.15	0.0595	0.38	0.1480	0.72	0.2640	1.45	0.4265	3.40	0.4996
0.16	0.0635	0.39	0.1515	0.74	0.2705	1.50	0.4330	3.60	0.4998
0.17	0.0675	0.40	0.1555	0.76	0.2765	1.55	0.4395	3.80	0.4999
0.18	0.0715	0.41	0.1590	0.78	0.2825	1.60	0.4450	4.00	0.4999
0.19	0.0755	0.42	0.1630	0.80	0.2880	1.65	0.4505		
0.20	0.0795	0.43	0.1665	0.82	0.2940	1.70	0.4555		
0.21	0.0830	0.44	0.1700	0.84	0.2995	1.75	0.4600		
0.22	0.0870	0.45	0.1735	0.86	0.3050	1.80	0.4640		

Values of χ^2 in relation to k and P(χ^2)

k	P(χ^2)									
	0.95	0.90	0.80	0.70	0.50	0.30	0.20	0.10	0.05	0.02
1	0.004	0.016	0.064	0.148	0.455	1.074	1.642	2.71	3.84	5.41
2	0.103	0.211	0.446	0.713	1.386	2.41	3.22	4.60	5.99	7.82
3	0.352	0.584	1.005	1.424	2.37	3.66	4.64	6.25	7.25	9.84
4	0.711	1.064	1.649	2.20	3.36	4.88	5.99	7.78	9.49	11.67
5	1.145	1.610	2.34	3.00	4.35	6.06	7.29	9.24	11.07	13.39
6	1.635	2.20	3.07	3.83	5.35	7.23	8.56	10.64	12.59	15.03
7	2.17	2.83	3.82	4.37	6.35	8.38	9.80	12.02	14.07	16.62
8	2.73	3.49	4.59	5.53	7.34	9.52	11.03	13.36	15.51	18.17

Laboratory work 3: Measurement of thermal deformation of a cutter in finish turning (2 hours)

Laboratory work objective:
− to determine thermal deformation of a turning cutter.

Guidelines

During machining processes, an intensive heating of cutting tools occurs due to the heat generated in the cutting zone. The size of a cutter varies and causes the machining errors.

In turning, the value of the thermal deformation (elongation) of a cutter depends mainly on the cutting parameters (speed V, feed rate S and depth of cut t), cooling conditions, mechanical properties of the workpiece material (hardness, tensile strength σ_v), design of the cutter (holder cross-section, thickness of carbide insert, geometric parameters) and cutter overhang.

Thermal equilibrium of a cutter generally occurs quite rapidly, and in a few minutes after the cutting has started, its thermal elongation reaches a maximum and then remains unchanged.

Temperature elongation of a cutter can be found according to its shortening during the cooling (shortening of a cutter is equal to the elongation of the cutter during the cutting process). Measurement of a cutter shortening during cooling is performed as follows. After a certain period of time of cutting, the process is stopped, the cutter is quickly withdrawn from the workpiece and the tool holder is rotated, providing contact of the top of the insert with the dial indicator (Fig. 1) mounted on the cross slide of the machine tool. Then the displacement of the indicator pointer, which corresponds to the shortening of the cutter when it is cooled to ambient temperature, is defined.
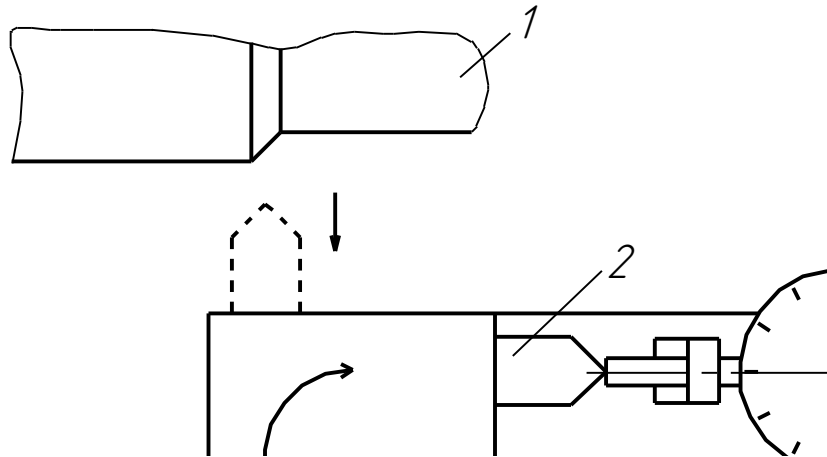
Fig. 1 Scheme for measurement of the cutter shortening:
1 – workpiece; 2 – cutter; 3 – dial indicator; 4 – tool holder; 5 – cross slide

Procedure

1. Mount the workpiece and the indexable cutting tool on the machine tool.
2. Measure the cutter overhang.
3. Clamp the mechanical indicator (1MIG) with a stand on the cross slide of the machine tool, the indicator spindle should be compressed for about 0.5 mm.
4. Set the machine to the required cutting parameters: V=150...200 m/min; S=0.2...0.25 mm/rev; t≈0.5 mm.
5. Switch on the machine and automatic longitudinal feed. After 1 minute of cutting, switch the longitudinal feed off, withdraw the cutter away from the workpiece and quickly rotate the tool holder until the top of the tool touches the tip of the indicator. In this position let the cutter to cool to ambient temperature. Record the amount of the cutter shortening.
6. Repeat the step 5 for all the time intervals of cutting (2, 5, 10 min).
7. After the cutting for 10 minutes, measure shortening of the cutter depending on the time of its cooling (1, 2, 5, 10, 20 min).
8. Plot the curves for dependence of the cutter elongation Δ' on cutting time (t_p) and dependence of the cutter shortening Δ" (after t_p=10 min) on the cooling time (t_0).
9. Make a report.

Contents of a report

1. Title of the laboratory work;
2. The name and model of the machine;
3. Workpiece material grade and its hardness (HB);
4. Geometry of the cutter, carbide grade, size and shape of the cutting blade, cross-section of the holder, overhang and cutting parameters;
5. Parameters of the measuring instruments and tools (scale interval, range of measurement);
6. Scheme of measurement of the cutter shortening;
7. Experimental results (Tables 1 and 2);
8. Diagrams of cutter elongation Δ' depending on cutting time and cutter shortening Δ" depending on cooling time (Fig. 2);
9. Conclusions.

Table 1

Cutting time, min	Cutter shortening after complete cooling, μm
1	
2	
5	
10	

Table 2

Cooling time, min	Cutter shortening, μm
1	
2	
5	
10	
20	
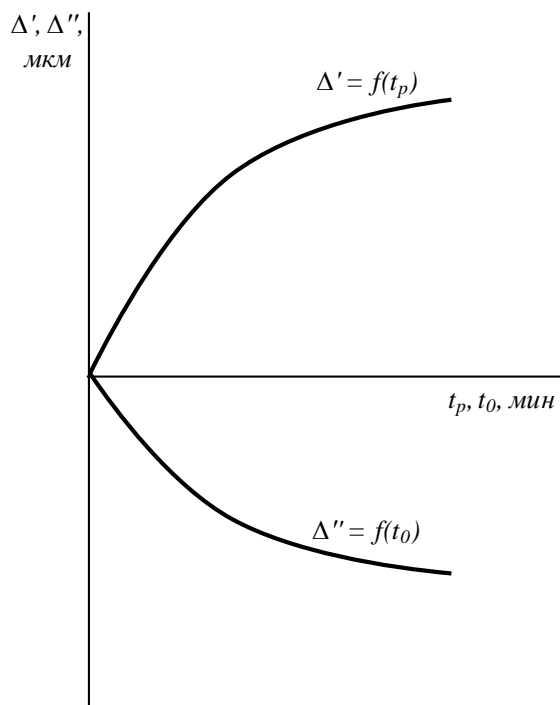
Fig. 2

Laboratory work 4: Influence of cutting parameters and diamond burnishing on surface finish (4 hours)

Laboratory work objective:
– to study the effect of cutting speed and feed rate on surface roughness in longitudinal turning;
– to study surface roughness obtained in the subsequent diamond burnishing.

Theoretical information

Performance characteristics of machine parts and devices are largely determined by the quality of their surfaces. It is characterized by roughness, waviness and a set of physical-chemical properties of the surface layer.

Roughness, defined as a set of surface microirregularities with relatively small spacing within a base length, is one of the most important indicators of the surface quality. Despite the relatively small size of the irregularities that constitute the roughness, they have a significant impact on a variety of operating characteristics of parts and their couplings, which are: friction and wear, contact deformation, stress concentration and fatigue strength, corrosion resistance, durability of press-fit connection, vibration activity, electro-contact resistance; strength and quality of coatings, as well as many other properties. Therefore, standardization and manufacturing ensuring of the required surface roughness are very demanding tasks in engineering.

The roughness of the part (or workpiece) surface is determined by a combination of operations and methods used during the manufacture. In general, surface roughness is formed at the final operation. However, in some cases, a significant effect of previous operations is observed due to phenomena of technological heredity.

The surface roughness after machining process depends on many factors: cutting parameters, cutting tool geometry and wear, properties and structure of the workpiece and tool materials, cooling and lubrication conditions, and rigidity of the technological system (machine tool, fixture, cutting tool, workpiece) etc. By changing cutting parameters, it is possible to control quality of the surface layer. However, the possibility of achieving optimum performance characteristics for the surface quality parameters by the machining processes is limited, therefore there is a need for other methods of processing.

One of the simplest and most effective ways to improve surface quality is the methods of surface plastic deformation (cold working), among which an important role is played by the diamond burnishing.

Diamond burnishing is performed with a tool which tip is made of natural or synthetic diamond (Fig. 1) with the working surface in the form of sphere, cylinder or cone. The kinematics of burnishing (Fig. 2), in most cases, is similar to turning. The process is performed under conditions of sliding friction. A certain preload force that presses a diamond tip to the surface of a workpiece develops plastic deformation. In this case, an intense smoothing of initial roughness, increase in surface hardness and formation of favorable residual compressive stresses take place.
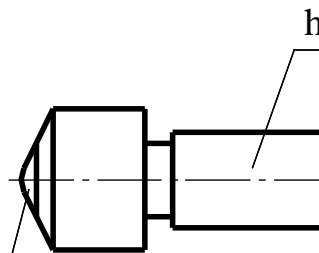
Fig. 1 Diamond burnishing tool

The extremely high hardness of diamond (up to six times greater than that of tungsten carbide) and a low coefficient of friction (0.03...0.12) allows to machine almost all metals that prone to plastic deformation, including hardened steels. The small tool tip radius (0.5...4 mm) creates small burnishing force (50 to 300N), which allows machining of parts of low rigidity.
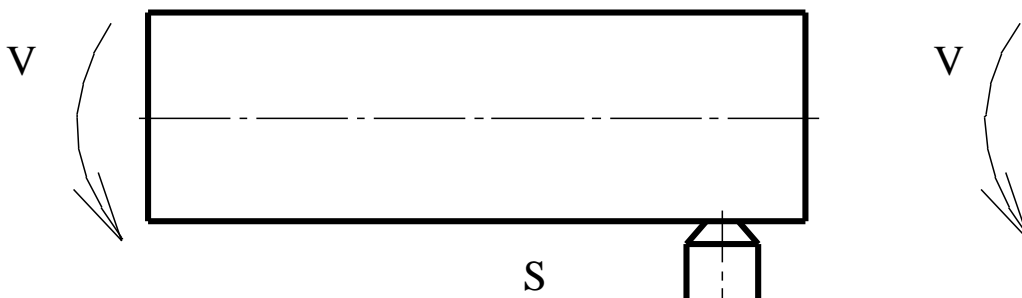
Fig.2 Diagram of burnishing: a –of a cylinder; b – of a plane

Diamond burnishing is applied after turning or grinding operation. As a result, burnishing ensures reduction of surface roughness in 2...6 times, increasing the bearing capacity of the surface up to 10 times, work hardening of the surface layer by 20...200 %.

Burnishing is performed on a lathe. The sample used consists of a set of rings made of steel with hardness of 200...250 HB, mounted on a rigid arbour (Fig. 3).
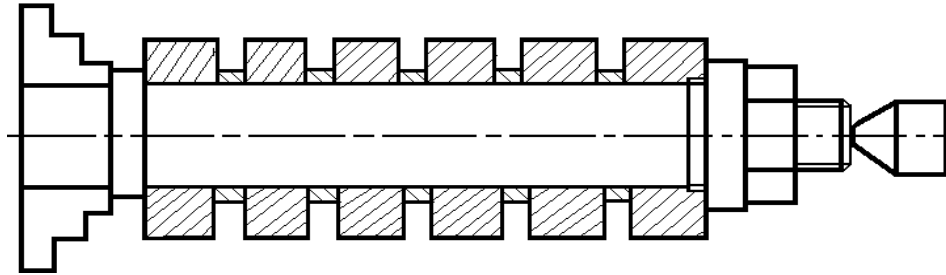

Fig. 3 Diagram of mounting workpieces on a machine

Turning is made with a carbide cutter without use of coolant. The geometrical parameters of a cutting tool: $\varphi=\varphi_1=45°$, $r=0.5$ mm, $\gamma=0°$, $\alpha=8°$, $\lambda=0°$.

Burnishing is performed by the tip of the artificial diamond with a radius R=3 mm, fastened to an elastic holder (Fig. 4).

damper   holder
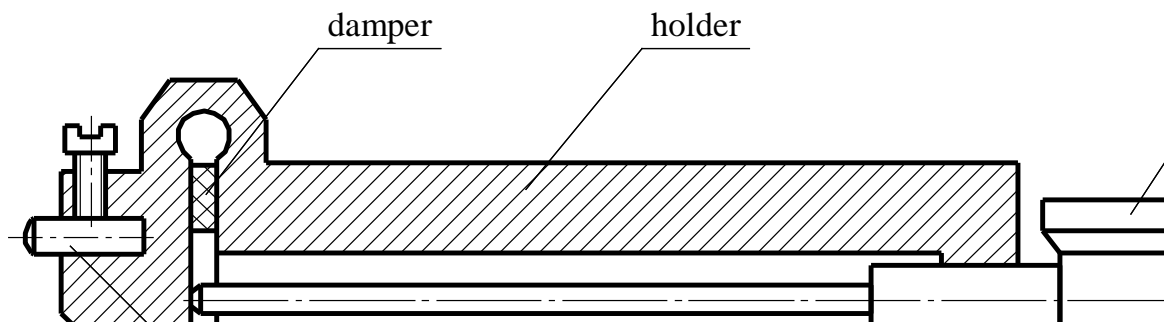
Figure 4 Holder for diamond burnishing .

The required normal force of burnishing is set with the help of the dial indicator, which indicates elastic displacement of the holder under the load. The holder is pre-calibrated using a reference dynamometer. Burnishing is carried out with lubricant oil "Industrial 20".

Roughness measurement

Inspection of surface roughness in this study is performed by a parameter Rz (ten-point height). Rz is defined as the mean distance between the five highest peaks and the five deepest valleys within the specified length (Fig. 5):

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$$R_z = \frac{1}{5}\left(\sum_{i=1}^{5}\left|y_{pi}\right| + \sum_{i=1}^{5}\left|y_{vi}\right|\right),$$

where y_{pi} is the height of the ith highest peak of the profile; y_{vi} is the depth of the ith deepest valley of the profile.
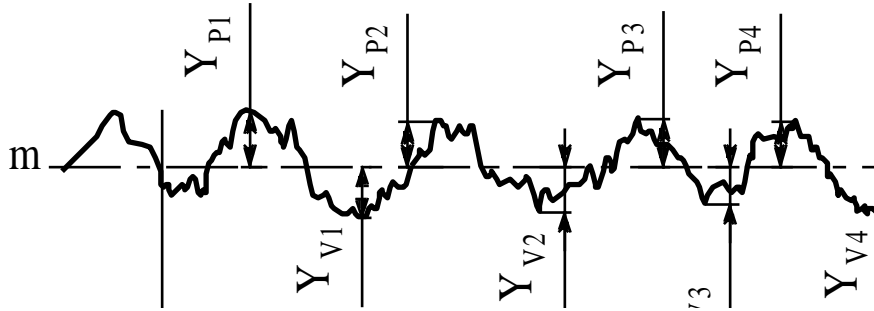

Fig. 5 Profilogram

To measure parameter Rz, a double microscope MIS-11 is used (Fig. 6), which is a combination of two microscopes: the projection one and observation one. The device allows to define parameters Rz and Rmax in the range of 0.8 to 63 μm. Measurement of the irregularities height is based on the principle of "optical section", which is explained in Fig. 7.

Light from the lamp *1* via the slit diaphragm *2* of the projection microscope is directed at an angle α=45° to the sample surface with roughness height *h*. The intersection of the surface with the plane of the light beam, in the form of a curved line, is projected by the lens of the observational microscope *4* onto a grid of an ocular micrometer *5*. The angle between the axes of projection and observation microscopes is 90°.

Light sectional profile is observed through an eyepiece *6* in enlarged form. The observed profile is distorted due to the fact that α=45°.

Optical magnification depends on the interchangeable lenses *3* and *4* used that have the same focal distance.

For the convenience of measurement, the reticle of the ocular plate is moved by a micrometer with a thimble scale interval equal to 0.01 mm. Reticle is at an angle α=45° to the center line of a profile (Fig. 8). Therefore, the actual value of the height of irregularities is:

$$h = \frac{B \cdot \sin\alpha \cdot \sin\beta}{N} = \frac{B}{2N},$$

where *B* is the difference in readings of a ocular micrometer thimble; *N* is the magnification of microscope objectives.
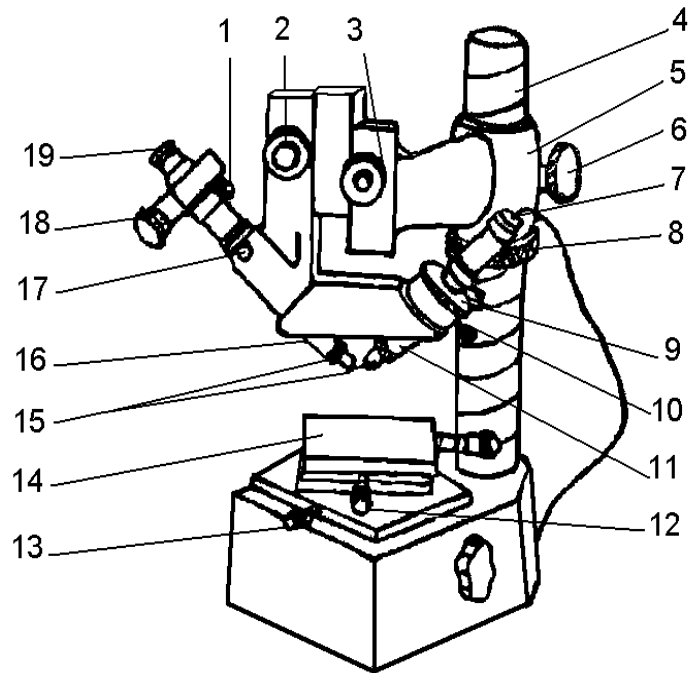
Fig. 6 Microscope MIS-11: 1 – locking screw; 2, 3 – rack mechanisms; 4 – column; 5 – bracket; 6 – locking screw; 7 – eliminating light; 8 – nut; 9 – adjusting nut; 10 – screw; 11 – illuminator; 12 – micrometer screw; 13 – locking screw; 14 – table; 15 – lenses; 16 – microscope tube; 17 – locking screw; 18 – ocular micrometer thimble; 19 – eyepiece
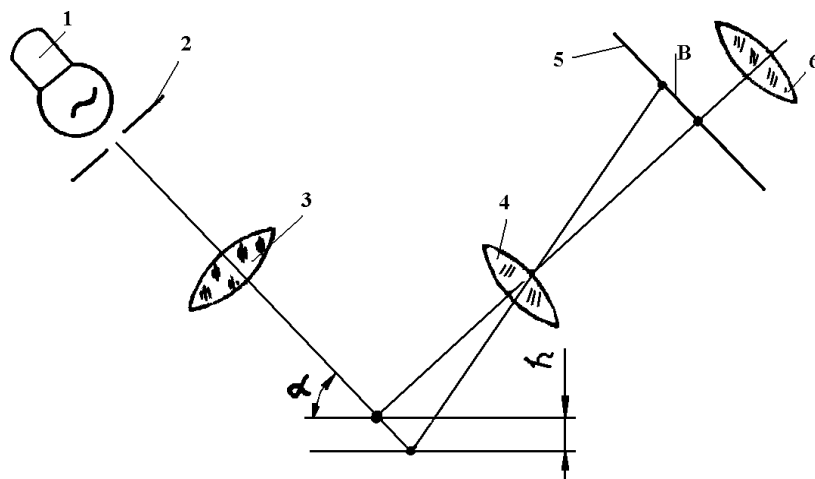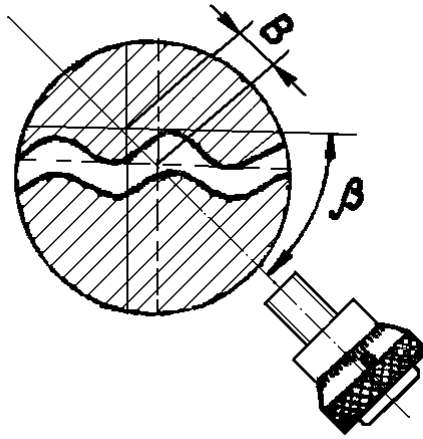

Fig.7. Light beam trajectory

Fig.8 View in microscope eyepiece

Microscope is supplied with a set of interchangeable lenses, which characteristics are given in Table 1.

Table 1

Lens code	Focal distance, mm	Lens magnifiation, N	Field of view, mm	Measurement range R_z, μm
OC-39	25	5.9	2.00	6.3...62.5
OC-40	13.5	10.5	1.08	3.2...18.7
OC-41	8.0	18.0	0.67	1.6...10.0
OC-42	4.25	34.5	0.33	0.8...3.2

Rz parameter is defined as follows. Sample is placed on the sample table *14* (see Figure 6). Microscopes is set at required distance from the sample by moving the bracket *5* along the rack with the help of the nut *8*, the bracket is clamped by a screw *6*. Then, by a handwheel *3* and screw *2* of the fine-adjustment mechanism, the microscopes are moved, ensuring clear image of light beam on the sample surface. Screw *10* is used to locate the image of the slit in the middle of the eyepiece, and a nut *9* is used to define width of the slit. By rotating the thimble of the ocular micrometer *18* about its axis, the horizontal line of reticle is aligned with the general direction of the slit image. By rotating the thimble *18*, the horizontal line of the reticle is fed to touch the crests of the roughness irregularity. In this position, the first reading of the ocular microscope is made. Successively, by aligning the reticle line with five highest points of the profile (within the sampling length), readings of the thimble a_1, a_2, a_3, a_4, a_5 are made. Then the reticle is aligned with the

five deepest valleys of the profile, writing readings $a_1', a_2', a_3', a_4', a_5'$, respectively.

The value of Rz is determined as follows:

$$R_z = \frac{(a_1 + a_2 + a_3 + a_4 + a_5) - (a_1' + a_2' + a_3' + a_4', + a_5')}{2N}.$$

Since the field of view of the lens may be less than the sampling length, the measurements should be made at several sites of the sample. In this case, the number of measured valleys in each field of view must be equal to the number of measured peaks to eliminate errors due to the possible offset of the reference line while moving the sample.

Error of Rz measurement with a microscope MIS-11 is 7.5 to 24%, increasing with decreasing Rz.

In addition to measurement, surface roughness is also determined by calculation in the laboratory work.

Calculation of surface roughness

Surface roughness in turning can be calculated based on the geometric relationships. In turning by a cutter with a nose radius *r* (see Fig. 9), when only the radius part of the cutter is involved in the formation of the microirregularities (this condition is satisfied in this experiment), the estimated value of Rz$_{calc}$ is determined by the equation:

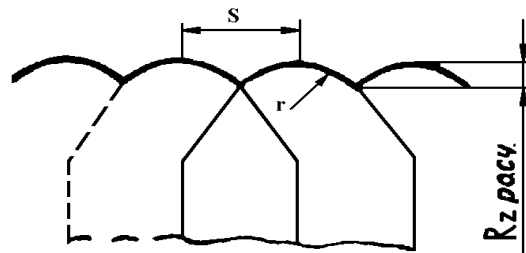$$R_{z\,calc} = r - \sqrt{r^2 - \frac{S^2}{4}}$$

Fig.9 Diagram of irregularity formation during turning

Procedure

1. Install the mandrel with a set of rings on a lathe and clamp it in a chuck and tailstock center.

2. Set a cutter and diamond burnisher in the toolpost.

3. Perform the turning of the rings (they are numbered prior to machining) with the corresponding cutting parameters.

To study the relationship $Rz=f(V)$, perform machining at 4 different cutting speeds, in the range 20 to 150 m/min, with constant feed rate and depth of cut ($S=0.1...0.2$ mm/rev, $t=0.5$ mm).

When studying the relationship $Rz=f(S)$, perform machining at 4 different feed rates, ranging from 0.05 to 0.5 mm/rev, having constant speed and cutting depth ($t=0.5$ mm, and $V=100$ m/min).

4. Without removing the mandrel from the machine, make diamond burnishing of the machined rings so that onlt half length of each ring is treated. Burnishing parameters: $P \approx 200$ N, $S \approx 0.05$ mm/rev, $V \approx 60$ m/min.

5. Remove the mandrel from the machine, and for each ring determine value of Rz of the turned and burnished parts on the microscope MIS-11. Results of measurement and processing parameters write in Table 2.

Table 2

№ of a sample	Cutting parameters			R_z^T	$R_{z\,calc}^T$	Burnishing parameters			R_z^B
	V, m/min	S, mm/rev	t, mm			V, m/min	S, mm/rev	P, N	

6. Plot diagrams of $R_z^T = f(V)$ and $R_z^T = f(S)$, as well as $R_z^B = f(R_z^T)$, where R_z^T, R_z^B are the heights of micro-irregularities measured after turning and burnishing, respectively.

7. According to the given above formula, calculate the micro-irregularities height $R_{z\text{расч.}}^T$ after turning. Write the calculation results in Table 2. Plot diagrams $R_{z\,calc}^T = f(V)$ and $R_{z\,calc}^T = f(S)$, combining them with diagrams of $R_z^T = f(V)$ and $R_z^T = f(S)$.

Contents of a report
1. Name and purpose of the work.
2. Model and characteristics of the machine.
3. Workpiece material grade and its mechanical characteristics.
4. Name of the tool, its geometric parameters and material.
5. Sketches of the used fixture.
6. Information on microscope MIS-11.
7. Experimental results (Table 2)
8. Diagrams of the dependencies.
9. Conclusions.

Laboratory work 5: Accuracy analysis of the process of ring manufacturing (4 hours)

Laboratory work objectives:
− to acquire skills in the field of tolerance analysis to identify shortcomings of the existing and new manufacturing processes in which the individual functional dimensions are not directly ensured.

Equipment and tools
1. Surface grinder model 371 M1 with a magnetic chuck.
2. Surface plate.
3. Vernier height gauge ШР-250.
4. Stand with a dial indicator with scale interval of 0.01 mm.
5. Micrometers MC 0-25 and MC 25-50.
6. Etalon for surface grinding machine setting.
7. A set of workpieces (machined rings) with dimensions as those given in Table 2.

Theoretical information

The highest dimensional accuracy of parts is achieved if the functional dimensions (dimensions specified on the drawing) coincide with the manufacturing dimensions, i.e. when the functional dimensions are ensured directly. However, in some cases, it is impossible or impractical to directly ensure functional dimensions in the manufacture. This reduces accuracy of the functional dimensions, as they are obtained in the form of resulting dimensions in the manufacturing dimensional chains.

Let us consider, as an example, the process of manufacturing involute disk cutters. After turning operations, workpiece of a mill is of a form shown in Fig. 1. Next, cutter flutes are cut, and heat treatment (hardening and tempering) of the workpiece is performed. After that, the hole and a face of the mill are ground in a single setup on the internal grinding machine (see Fig. 2), which provides required perpendicularity of the said surfaces. The face is ground with a predetermined allowance of $0.1^{+0.1}$ mm. The latter is motivated by the desire to reduce the time needed to grind the face, which is particularly unproductive on the surface grinder. On one of the last operations, the second face is ground to the required width for several parts simultaneously (see Fig. 3).
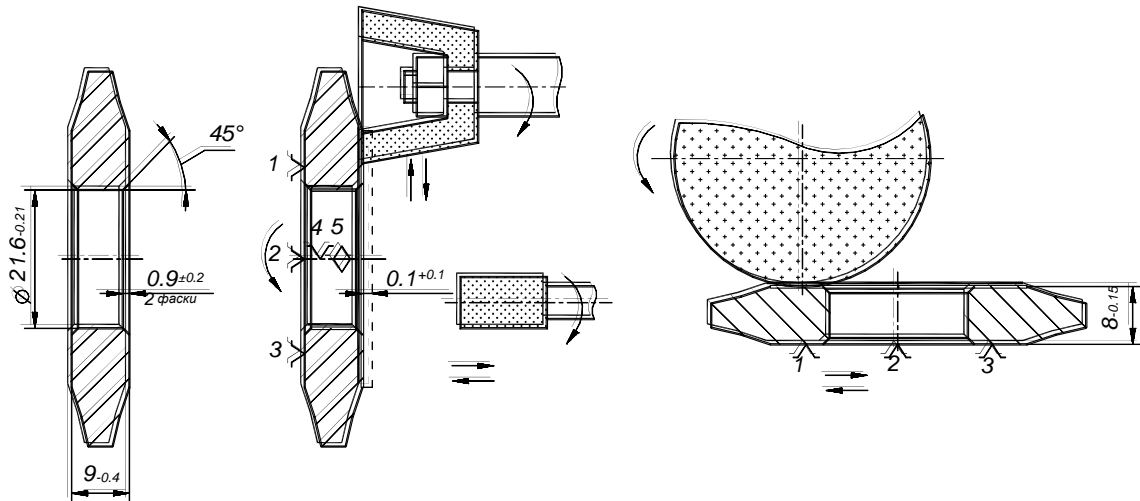
Fig. 1   Fig. 2   Fig. 3

Thus, the functional dimension of chamfers ($K=0.5\pm0.3$) in the hole are not ensured directly. Tolerance analysis shows that, with the specified manufacturing dimensions (see Figures 1-3), the size of chamfers will vary exceeding the tolerance limits. High dimensional accuracy of chamfers, of course is not required. However, they are needed to facilitate mounting of the mill on a arbour. At the same time, chamfers should not be too large, since it will lead to a decrease in the length of the hole. The drawbacks of the manufacturing process, revealed during the tolerance analysis, were subsequently eliminated.

The discussed design of the manufacturing process quite frequently can be found in production. Moreover, significantly more important functional dimensions, than those described in the example, are not directly ensured during manufacture. Therefore, the task of ensuring accuracy of functional dimensions during manufacture of parts is quite common.

Guidelines

The laboratory work is based on the process similar to the above described process; machining is performed for the ring shown in Fig. 4 (for ease of measurement, chamfers in the hole are replaced by recesses).

Sketch of the ring after turning operation is shown in Fig. 5. Functional (K_i) and manufacturing (A_i) dimensions of rings of different design versions are given in Table 1.
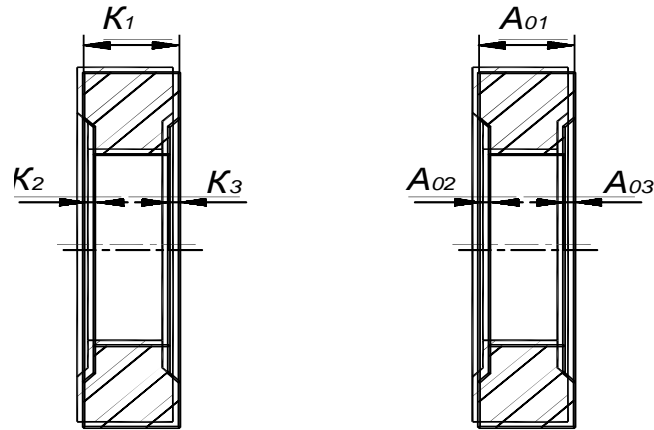
Fig. 4 General view of the toolmaker microscope

Table 1

Versions		1	2	3	4	5	6	7	8
Workpiece	A_{01}	30.5	28.5	26.5	24.5	22.5	20.5	18.5	16.5
		Limit deviations (-0.3)							
	$A_{02}=A_{03}$	0.55±0.15							
Finished part	$K_1=A_2$	30	28	26	24	22	20	18	16
		Limit deviations (-0.2)							
	$K_2=K_3$	0.4±0.2							

Turning operation is followed by two surface grinding operations (Fig. 6 and 7). On the first grinding operation (Fig. 6), one ring is mounted on the machine table and its face is ground with removal of definite allowance $A_1=0.1^{+0.1}$ mm (the allowance value is determined by the machine dial from the moment of touching the ring surface). On the second grinding operation (Fig. 7) the second face of the ring is ground to the final size $A_2= K_1$ (grinding is carried out until the wheel touches surface of the etalon, which is adjusted to the desired size). The described process can be easily performed in a university laboratory and studied experimentally.
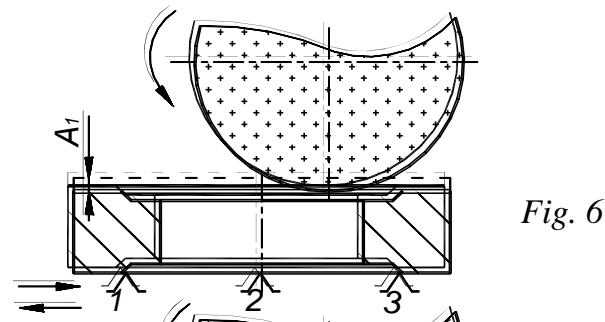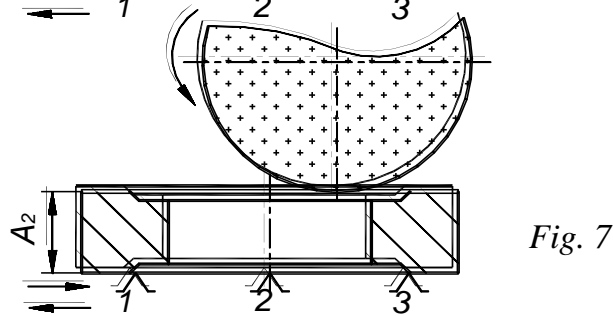
34

Fig. 6

Fig. 7

Procedure

1. Build a dimensional diagram of the process of ring manufacturing and graph of the manufacturing dimensional chains. Using the maximum-minimum method, calculate tolerances and limits of size of recesses (chamfers) after machining. Compare calculated dimensions of recesses with their functional dimensions and determine quality of the manufacturing process.

2. Experimentally investigate dimensional accuracy of the manufactured rings. For doing this, take two turned rings (ask a teacher or academic assistant), which dimensions are at the limits of tolerance (for different versions of the rings, these dimensions are given in Table 2). Measure the height of the ring and sizes of the ring recesses. Perform grinding of faces according to the manufacturing process (Fig. 6 and 7). Repeat measurement of the height and size of the recesses and compare them with the functional dimensions.

Table 2

№ of workpiece in a set	Dimensions	Sets of workpieces							
		1	2	3	4	5	6	7	8
Workpiece №1	A_{01}	30.5	28.5	26.5	24.5	22.5	20.5	18.5	16.5
		Limit deviations ±0.03							
	$A_{02}=A_{03}$	0.4±0.03							
Workpiece №2	A01	30.2	28.2	26.2	24.2	22.2	20.2	18.2	16.2
		Limit deviations ±0.03							
	$A_{02}=A_{03}$	0.7±0.03							

3. Propose actions to redesign the manufacturing process to increase accuracy of the recesses dimensions. These activities can consist in changing the dimensioning of the process, changing locating of the rings, introduction of additional operations, etc. Proposals should be supported by calculations.

4. Build a dimensional diagram of the process of involute disk cutters manufacture (Fig. 1-3) and graph of the manufacturing dimensional chains. Determine dimensions of chamfers after the ring machining?

Contents of a report

The report should contain the objective, content and order of work implementation. It should contain all of the issues outlined in the previous section. It should also include operational sketches, dimensional diagrams of the process, graphs of the manufacturing dimensional chains, results and conclusions of the tolerance analysis. The following should also be explained in the report:

- in which case it may be necessary to carry out machining (grinding) of one part, and in which cases – several parts can be machined?
- how to measure sizes of the ring?
- how was a surface grinding machine set for grinding of faces of a ring?
- how was an etalon adjusted to the required size?

Educational Edition

СКВОРЦОВ Владимир Федорович

ОСНОВЫ ТЕХНОЛОГИИ МАШИНОСТРОЕНИЯ

Методические указания

к выполнению лабораторных работ по дисциплине «Основы технологии машино-
строения»

На английском языке

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