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**Keywords:** cylindrical cutting tools; milling cutter; wheel working surface; locomotive wheelsets; wheel-milling machines

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## **INCREASING THE RESOURCE OF MILLING CUTTERS USED TO PROCESS THE LOCOMOTIVE WHEELSETS. PART 1: DETERMINATION OF CUTTING FORCES**

**Summary.** The purpose of this work is to increase the service life of milling cutters for wheel-milling machines KJ20, and to improve the processing quality of the working surface of wheelsets of railway vehicles. Questions of operation of cylindrical cutting tools are considered, force characteristics are determined, and also analyzed their stressed state.

### **1. INTRODUCTION**

During operation, the locomotive wheelsets receive various operational defects. It is periodically monitored and, as a consequence, can be found unfit for exploitation. Most of the defects of wheelsets can then be eliminated when they are repaired on the appropriate machines. Since the locomotive wheelset is usually part of the wheel–motor unit, it is difficult to remove it from this unit. Usually, this requires considerable time losses and can only be done in the conditions of specialized depots.

In this case, it is possible to process wheel working surfaces without dismantling wheelsets. For this, there are wheel-lathe and wheel-milling machines which are located below the level of the rails. As an example, the modern products of the Polish company RAFAMET, and machines UGE 180 N, UGE 300 N, or UGE 400 N can be cited [1]. Each of these wheel-lathe machines has a so-called tandem version, which allows processing two wheelsets simultaneously, for example, machine 2 UGE 180 N. At the same time, the German company HEGENSCHIEDT-MFD has similar machines, and in particular, the machines U2000-150 and U2000-400 [2].

The American company Simmons Machine Tool Corporation manufactures wheel-milling machines TN-84C [3] or Stanray M2, which can also make repair of the working surfaces of locomotive wheelsets without dismantling. One can argue about the principles of wheelsets machining. For example, article [4] indicates that the reason for the decrease in the machining quality of the working surfaces of wheels during their machining can be insufficient rigidity of the structures, which can lead to additional vibrations.

In the locomotive branch of the former USSR countries, wheel-milling machines, similar to the Simmons machines described above, were massively used. The main producer of such machines was the public joint-stock company “KZTS” (Kramatorsky Plant of Heavy Machines). This plant produced a whole series of machines under the general brand KJ20. At the present time, a new modification of this machine is named KJ20Tf1 [5].

On these machines, the re-profiling of the working surface of wheelsets is carried out at TO-3, TO-4, TR-1, and TR-2 (these are types of maintenance and repair according to the classification), without

dismantling of wheelsets [6]. For machining the surfaces of wheelsets, a set (right and left) of special prefabricated milling cutters is used, depending on the required profile.

The milling cutter [7] consists of the body 1 (fig. 1), in whose grooves the toolholders 2 are mounted. The toolholders are fixed with screws 3 and wedge-shaped gussets 4, while the end of the toolholder from the flange side should be pressed to the base ring 5 by the screws 8. Toolholders are installed in the grooves of the body in a strictly defined order and are marked in accordance with the numbers of the grooves. The left (base) ring 5 and the right ring 6 are fixed to the body with screws 7. The cutting elements of the milling cutters are hard-alloy cylindrical cutting tools 9, which are inserted into the holes of the toolholders and fixed in them with screws 10 and nuts 13. Under the cylindrical tools, compensating washers 12 of different thicknesses are installed. With their help, the necessary accuracy of the arrangement of the cutting tools is achieved when setting milling cutters. The left and right milling cutters are similar in design.

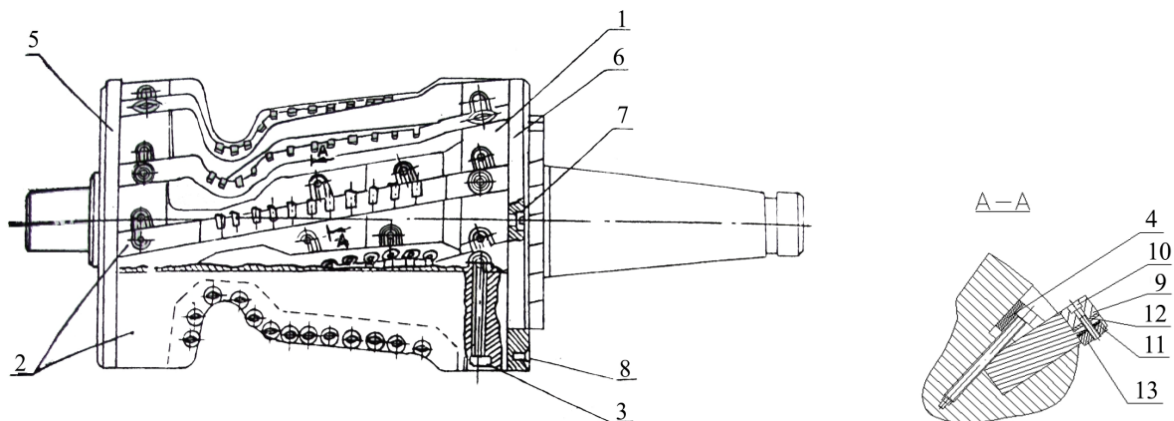


Fig. 1. The milling cutter for wheel-milling machines KJ20

The cutting tool is a key element in the technological system. It is designed to remove the defective layer and has the lowest reliability. In practice, in order to increase the service life of the cutting tool, the cutting conditions are often reduced, so increasing the strength of the cutting part is an urgent task [8]. The milling cutters described above are used to restore the profile of the working surface of wheelsets not only on the mainline, but also on industrial railway transport. The service life of special milling cutters is limited; in the example of industrial transport it is about 6 months. Fig. 2 shows some defects of special milling cutters.

To increase the service life, it would be necessary to increase the number of the toolholders, and accordingly the number of cylindrical cutting tools. This will reduce the load on one cylindrical tool and improve the quality of the wheelset working surfaces. It is not possible to install more than 10 toolholders into the existing milling cutter body. In the new construction (Fig. 3), all the above-listed shortcomings are taken into account [9].

In the conditions of increasing speeds and application of wheelsets with increased hardness [10, 11], there are requirements to increase the accuracy and quality of processing of the wheelsets working surface of railway vehicles, with simultaneous reducing costs of exploitation.

The rolling stock refers to the technique of increased danger; therefore, high demands are placed to the accuracy of the working profiles and quality of the wheel pairs with minimum costs for their renewal during repair.



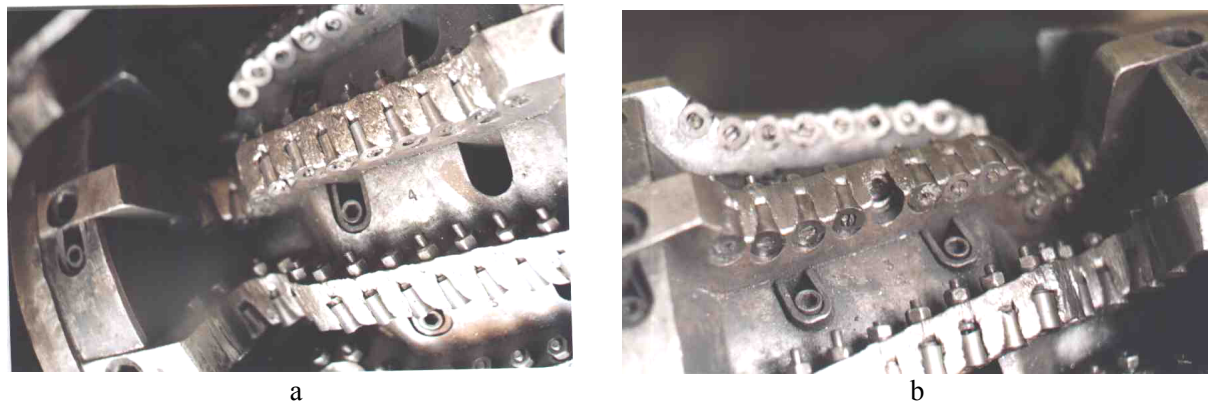


Fig. 2. Defects of special milling cutters: a) damage of the toolholders by a metal shell; b) the damaged place of cylindrical cutting tools

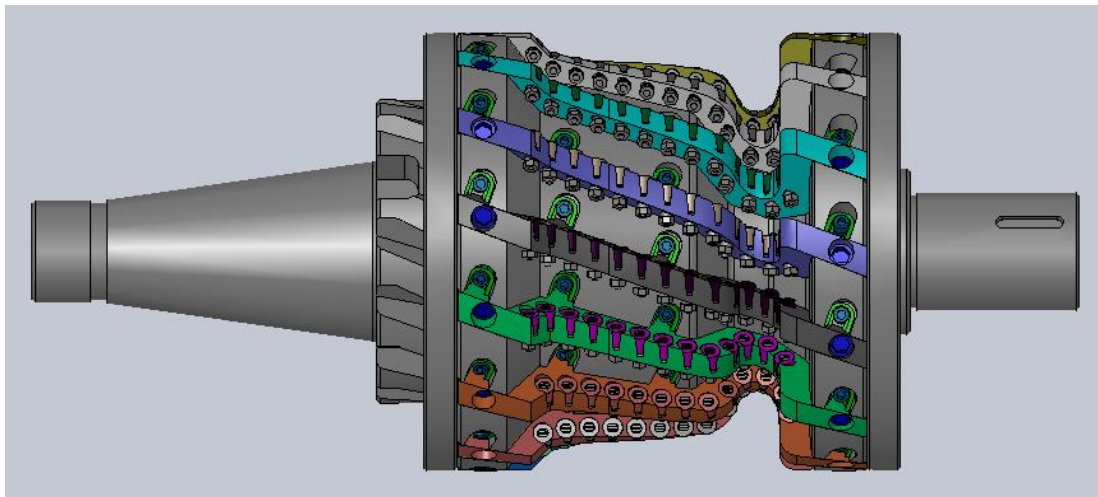


Fig. 3. Three-dimensional model of the milling cutter

## 2. RESEARCH OF THE DEFECTS OF CYLINDRICAL CUTTING TOOLS

Cylindrical cutting tools of a special milling cutter for the machines KJ20 are using plates RNUX 1212 MO TN from alloys KC-25 and T14K8 [12] (this designation was adopted in the countries of the former USSR, but it is still used today). The geometry of such tools is shown in Fig. 4.

The hard alloy T14K8 refers to titanium–tungsten alloys, which include titanium carbide, tungsten carbide, and cobalt. Denoted by the letters TK, the digits after the letter T denote the % content of titanium carbides, and after the letter K the cobalt content. This group includes the following brands: T5K10, T14K8, T15K6, and T30K4. The characteristics of the material T14K8 are presented in Table 1 [13-15].

Analogs are classified according to DIN4990 (ISO 513: 1990) and belong to the P20 subgroup [13, 14]. This material is used for material processing by cutting: for rough turning with an uneven cross-section and continuous cutting; for semifinished and fine turning with intermittent cutting; for rough milling of solid surfaces; for drilling cast and forged holes; for rough reaming and other similar types of processing of carbon and alloy steels.

Hard alloys are currently a common tool material widely used in the tool industry. Due to the presence of high-melting carbides in the structure, the carbide tool has a high hardness of HRA 80-92 (HRC 73-76), and heat resistance (800-1000 °C), so that they can work at speeds several times higher

than the cutting speed for high-speed steels. However, in contrast to high-speed steels, hard alloys have a reduced strength (1000-1500 MPa), but do not have impact strength. Hard alloys are non-technological: because of the great hardness, it is impossible to produce from them the single-piece tools with a complex shape. Products from them are limited by grinding—only by a diamond tool, so hard alloys are usually used in the form of plates, which are either mechanically fixed on toolholders or soldered to them [15].

Table 1  
Characteristics of the material T14K8

ISO 513:1990 alloy group	Alloy brand	Chemical composition, %					
		WC%	TiC%	Co%			
P20	T14K8	78	14	8			
Mechanical properties							
Bending strength, MPa	Hardness, HRA	Density, g/cm <sup>3</sup>	Thermal conductivity, W/m·°C	Young's modulus, GPa	Poisson's ratio	Shear modulus, 10 <sup>9</sup> Pa	Modulus of longitudinal elasticity, 10 <sup>10</sup> Pa
1250	89,5	11,6	16,7	520	0,21	225	55

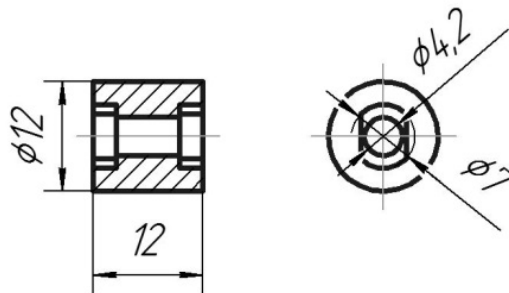


Fig. 4. Geometry of the cylindrical cutting tools T14K8

In the classification of the failures of working capacity of the tools, two main groups are identified: wear and destruction. Destruction, in turn, is usually divided into plastic and brittle, and brittle destruction—by spalling and chipping. The cause of the appearance of chipping (separation of small particles within the contact zone) is considered to be cyclic thermal and force stresses in the cutting edge, which lead to fatigue destruction of the material of the cutting tool. Chipping is the destruction of the cutting part, caused solely by an unfavorable force load on the side of the shear layer. The nature of the damage—the chipping of large parts of the blade, which develops from the front surface area, located beyond the contact of the tool with the chips—leads to the conclusion that critical tensile stresses in this zone exceed the ultimate strength of the tool material [16].

Fig. 5 shows some defects of cylindrical cutting tools used in shaped milling cutter, obtained during repair of the wheelsets working surface.

A set of cylindrical cutting tools of a special milling cutter for the machine KJ20, when using them from both sides, should provide the restoration of the profile of the working surface for 16-18 locomotive wheelsets [7]. As can be seen from Fig. 5, by the number of chips on the cutting surface of the cylindrical cutting tools, and also from observations, it can be concluded that the average number of machined wheelsets is about half of the targets. The quality of the treated surface depends on the condition of the cylindrical cutting tools.



Fig. 5. Defects of cylindrical cutting tools

### 3. THEORETICAL DEFINITION OF FORCES ACTING ON CYLINDRICAL CUTTING TOOLS

For blade hard-alloy cutting tools, in addition to providing wear resistance, it is important to ensure strength and reliability. The impact of increased power and temperature loads often leads to “sudden” failures of the tool’s performance due to its destruction—chipping and spalling during the cutting process. With roughing, intermittent cutting, and other difficult conditions, brittle fracture in 60% or more cases occurs long before reaching extreme wear [17].

The brittle fracture of the cutting part of the hard-alloy tool is an unregulated type of performance failure, leading either to permanent damage to the tool, or to large losses in the recesses, which reduces the efficiency of machining the parts [18]. Since the cutting force is the key factor that influences the destruction of the cutting elements, its definition is necessary for the further determination of the stressed state of both the cutting elements and the milling cutters as a whole. When determining the cutting force, there is a dependence on many factors, the most important of which are the mechanical properties of the material being processed, its hardness, strength, and the ability to harden.

To determine the cutting force [19], we use the simplified expression

$$P_z = 9,807 \cdot \rho \cdot f, \quad [\text{N}] \quad (1)$$

where  $\rho$  – specific cutting pressure, for steel with tensile strength for stretching  $\sigma_m = 1000$  MPa,  $\rho = 2350$  MPa;  $f$  – transverse area of the cut layer,  $\text{mm}^2$ .

We define the cross-sectional area by means of the integral

$$f = \int_b^a \sqrt{r^2 - (x-t)^2} - \sqrt{r^2 - x^2} dx - \int_c^a d - \sqrt{r^2 - x^2} dx, \quad [\text{mm}^2], \quad (2)$$

where, according to Fig. 6:  $r$  – radius of a cylindrical cutting tool,  $r = 6$  mm;  $a$ —abscissa of the point of contact of the circumference of the tool at the output;  $b$  – abscissa of the intersection point of the tools circles;  $c$  – abscissa of the contact point of the cutter circumference at the input;  $d$  – distance from the center of the tool to the line of contact with the surface to be treated;  $l$  – center-to-center distance between tools in neighboring toolholders:

$$l = \frac{L_\Sigma}{n_\Sigma}, \quad [\text{mm}], \quad (3)$$

where  $L_\Sigma$  – total length of sections of the working surface of the profile;  $n_\Sigma$  – total number of cylindrical cutting tools of the milling cutter.

The cutting force acting on one cylindrical cutter depends to a small extent also on the profile of the machined surface of the wheel. The locomotive wheels with a profile of the working surface of the DMetI LR were taken as the main object of research. In work [20], the questions of development and



operation are considered and the advantages of DMetI profiles for wheelsets working surfaces of rail transport vehicles are indicated. Profiles DMetI entered to the “Instruction on the formation, repair and maintenance of traction rolling stock of the railways with gauge 1520 mm” of Ukraine, Russia, and Kazakhstan [21, 22].

The cross-sectional area for the milling cutter with 130 tools is  $f_{130} = 0,88 \text{ mm}^2$  (fig. 6a) and cutting force is  $P_{z\ 130} = 2030 \text{ N}$ . For the milling cutter with 182 tools, the cross-sectional area is  $f_{182} = 0,62 \text{ mm}^2$  (fig. 6b) and cutting force is  $P_{z\ 182} = 1430 \text{ N}$ .

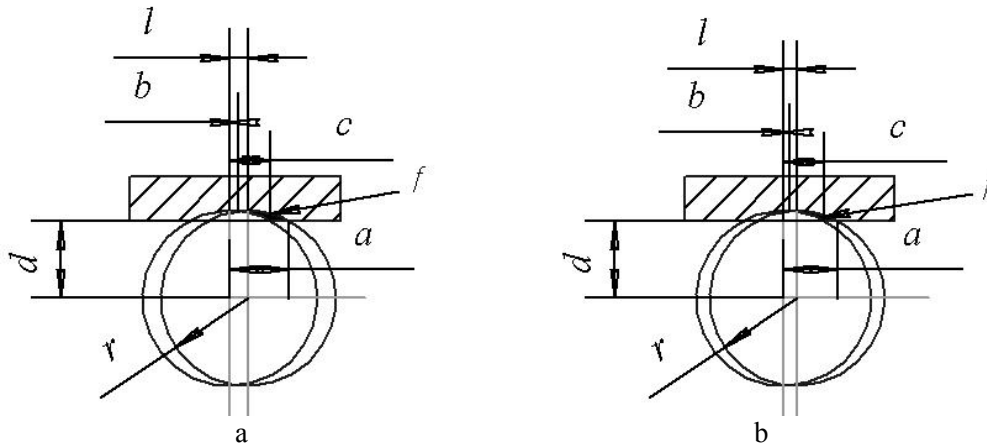


Fig. 6. To determine the transverse area of the cut layer: a) for the milling cutter with 10 toolholders and 130 tools, b) for the milling cutter with 14 toolholders and 182 tools

#### 4. EXPERIMENTAL RESEARCH OF CUTTING FORCE

The milling cutter for the machine KJ20 is a constructively and technologically complex structure. In order to determine the force acting on one cylindrical cutting tool, it is necessary to carry out technically difficult feasible preparatory measures. To do this, it is necessary initially to convert the working milling cutter to the test cutter, with which it would be possible to carry out measurements of the cutting force. In addition, it is necessary to make changes in the schedule of works on the repair of the rolling stock, i.e., to stop repair work for several days. It is necessary to reequip the machine KJ20 and to plug the measuring equipment to it. It is practically impossible to carry out this, because neither the chief mechanic nor the chief engineer of the locomotive depot will agree to such an event.

To carry out the task, for definition of cutting force, a device was designed and built as shown in Fig. 7. This device consists of the body of tool holder 1, in which a cylindrical cutting tool 2 is mounted. This cutting tool has the same angle of inclination as in the toolholder of the milling cutter at the time of machining. The tool is fixed by screw 3 and nut 4. To the toolholder 1 were attached two plates 5, on one of which the hour-type indicator 6 is fixed. In the body of the toolholder 1, a milling and transverse section was done to ensure the receipt of indications from the indicator of the hourly type of characteristics, allowing to determine the forces acting on the cutting tool.

The study of the vertical component of the cutting force was carried out using the 16A20 lathe-screw-cutting machine. The cylindrical Ø210-mm billet was selected and installed.

To establish the relationship between the cutting force  $P_z$  and the amount of movement of the indicator's foot, the cutter is replaced by a bar of a certain length (Fig. 8). Increasing the arm of applying bending force from 30 mm to 500 mm allows to reduce the amount of load  $Q$ , the lengths  $l_1$  and  $l_2$  fit for this case.

$$P_z = Q \cdot \frac{l_1}{l_2} \quad (4)$$

To exclude the influence of the mass of the bar and the load hanger fixed to the bar, the arrow of the indicator is initially set to zero. Then on the load hanger, one after another weights of a certain mass are placed (load  $Q$ ) and in each case the indication of the indicator is fixed.

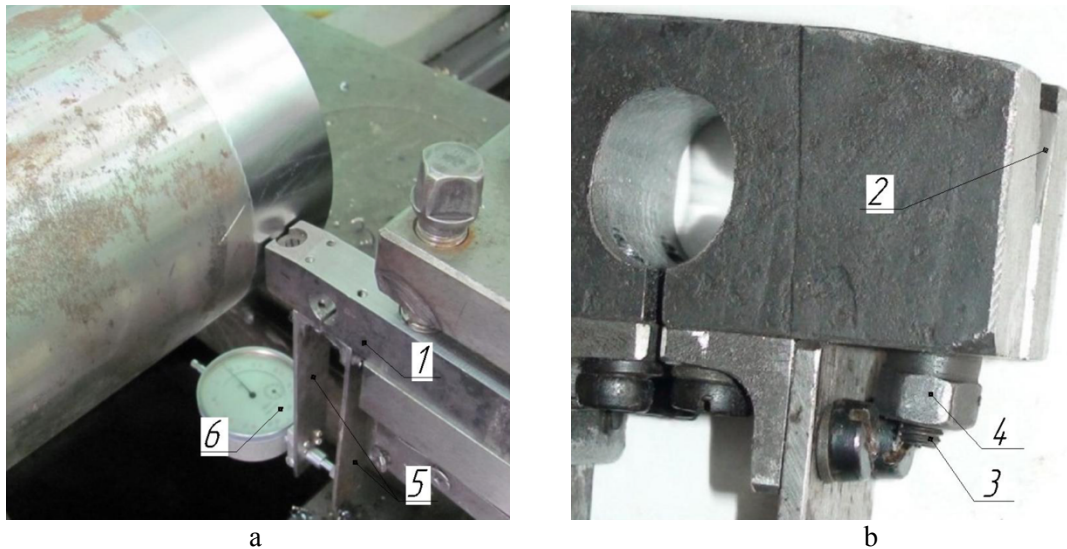


Fig. 7. Device for measuring of the cutting force: a) general view, b) enlarged view

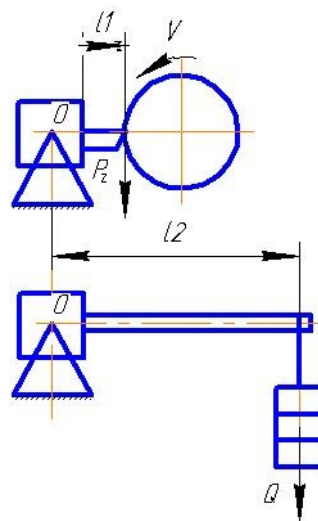


Fig. 8. Scheme of the measurement of cutting force and calibration

The received results of research are given in table 2.

Table 2

Test results (calibration)

Measurement No.	Load weight $Q$ , kg		Indicator reading $\Delta$	Cutting force $P_z$ , N
1	4,5		9	270
2	9		18	540
3	13,5		27	810
4	18		36	1080
5	22,5		45	1350
6	27		54	1620

It should be noted that the main parameters that affect the amount of cutting force are cutting depth, tool feed, and spindle speed. The studies were carried out with the following parameters: cutting depth  $t = 0,1 \div 0,5$  mm, tool feed  $S = 0,3 \div 2,2$  mm/rot, and spindle speed  $V = 40 \div 160$  rpm. For each of the parameters, five tests were carried out with the other parameters unchanged. The results of the experiments are recorded in Table 3.

The method for determining the value of the normal component of the cutting force during turning is described in several papers [23, 24], where in particular the following formula is given

$$P_z = C_{P_z} \cdot t^{X_{P_z}} \cdot S^{Y_{P_z}} \cdot V^{n_{P_z}}, \text{ [N]}, \quad (5)$$

where  $t$  – cutting depth, mm;  $S$  – tool feed, mm/rot;  $V$  – spindle speed, m/min;  $C_{P_z}$  – processing condition factor;  $X_{P_z}, Y_{P_z}, n_{P_z}$  – exponents.

Table 3

The results of the experiments

No	Diameter of the billet d, mm	Rotational speed of the spindle n, rpm	Cutting depth t, mm	Tool feed S, mm/rot	Cutting speed V, m/min	Indicator reading $\Delta$	Component of cutting force $P_z$ , N, 130 tools	Component of cutting force $P_z$ , N, 182 tools
$P_z = C_1 \cdot t^{X_{P_z}}$								
1	210	94	0,1	1,1	62	5,5	162	114
2			0,2			11	340	239,5
3			0,3			17	510	359
4			0,5			28	851	599
5			0,6			34	1021	719
6			0,7			41	1231	867
$P_z = C_2 \cdot S^{Y_{P_z}}$								
1	210	94	0,4	0,4	62	12,5	379	267
2				0,7		18	533	375,5
3				0,9		21,5	644	454
4				1,2		27	799	563
5				1,5		31,5	945	666
6				1,9		38	1128	795
$P_z = C_3 \cdot V^{n_{P_z}}$								
1	210	160	0,4	1,1	106	9,5	285	201
2		120			79	13,5	406	286
3		100			66	17	512	361
4		80			53	20,5	617	435
5		60			40	27,6	827	583
6		40			26	36	1072	755

As mentioned above, the cutting force depends on three main factors. Determining immediately the dependence on all factors is quite difficult. According to the cited technique, it is first necessary to determine the dependencies on each factor separately, leaving the remaining two factors unchanged. In this case, formula (5) can be simplified and written for each factor separately:

$$\begin{aligned} P_z &= C_1 \cdot t^{X_{P_z}}, \\ P_z &= C_2 \cdot S^{Y_{P_z}}, \\ P_z &= C_3 \cdot V^{n_{P_z}}. \end{aligned} \quad (6)$$

where

$$\begin{aligned} C_1 &= C_{P_z} \cdot S^{y_{P_z}} \cdot V^{n_{P_z}}; \\ C_2 &= C_{P_z} \cdot t^{x_{P_z}} \cdot V^{n_{P_z}}; \\ C_3 &= C_{P_z} \cdot t^{x_{P_z}} \cdot S^{y_{P_z}}. \end{aligned} \quad (7)$$

If we take the logarithm from the right and left sides of equation (6), we can write

$$\begin{aligned} \lg P_z &= \lg C_1 + x_{P_z} \cdot \lg t; \\ \lg P_z &= \lg C_2 + y_{P_z} \cdot \lg S; \\ \lg P_z &= \lg C_3 + n_{P_z} \cdot \lg V. \end{aligned} \quad (8)$$

The dependences obtained as a result of the experiment (Table 3) can be drawn using logarithmic scales along the abscissa and ordinate axes (Fig. 9). Consider first the case of a milling cutter with 130 tools (the penultimate column in Table 3).

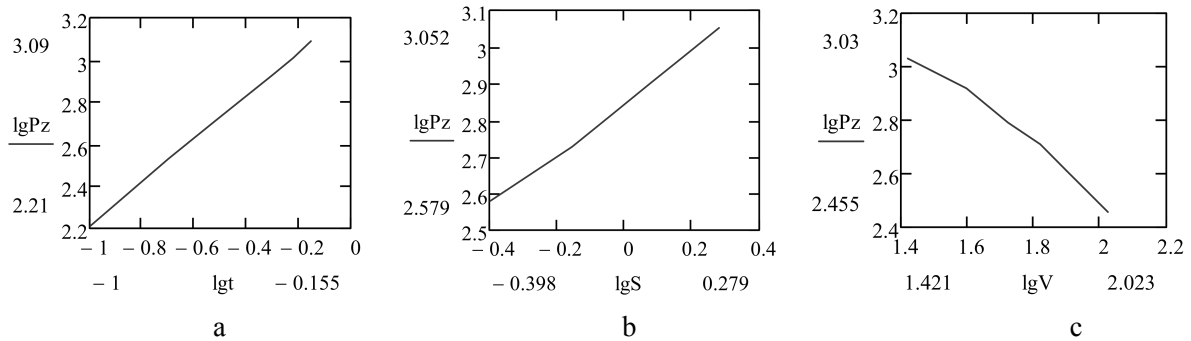


Fig. 9. Dependency graphs: a)  $P_z = C_1 \cdot t^{x_{P_z}}$ ; b)  $P_z = C_2 \cdot S^{y_{P_z}}$ ; c)  $P_z = C_3 \cdot V^{n_{P_z}}$ .

The exponents  $x_{P_z}$ ,  $y_{P_z}$ ,  $n_{P_z}$  can be determined both graphically and analytically

$$\begin{aligned} x_{P_z} &= \operatorname{arctg} \frac{b_t}{a_t}, \\ y_{P_z} &= \operatorname{arctg} \frac{b_S}{a_S}, \\ n_{P_z} &= \operatorname{arctg} \frac{b_V}{a_V}. \end{aligned} \quad (9)$$

where

$$\begin{aligned} a_t &= \lg t_{\max} - \lg t_{\min} \\ b_t &= \lg P_{z\max} - \lg P_{z\min}, \\ a_S &= \lg S_{\max} - \lg S_{\min} \\ b_S &= \lg P_{z\max} - \lg P_{z\min}, \\ a_V &= \lg V_{\max} - \lg V_{\min} \\ b_V &= \lg P_{z\max} - \lg P_{z\min}. \end{aligned} \quad (10)$$

The values of the exponents  $x_{P_z}$ ,  $y_{P_z}$ ,  $n_{P_z}$  we determine for mean values in the experiment are  $t=0,4$  mm;  $S=1,1$  mm/rot;  $V=62$  m/min.

Substituting the exponents in dependence (6), we obtain

$$\begin{aligned} P_{z1\text{cp}} &= C_1 \cdot t^{1,0178}, \\ P_{z2\text{cp}} &= C_2 \cdot S^{0,6987}, \\ P_{z3\text{cp}} &= C_3 \cdot V^{-0,167}. \end{aligned} \quad (11)$$

Thus, three experimental dependences of the cutting force on each of the factors influencing its magnitude are determined.

Each of the equations (11) corresponds to its factor affecting the cutting force, i.e.,  $t$ ,  $S$ , and  $V$ . Based on formulas (6) and (7), we can write the expression for the coefficient  $C_{P_z}$

$$C_{P_z} = \frac{P_z}{t^{X_{P_z}} \cdot S^{Y_{P_z}} \cdot V^{n_{P_z}}}. \quad (12)$$

Coefficient  $C_{P_z}$  is determined for the average values  $t$ ,  $S$ , and  $V$ , which are indicated above. In addition, as a force value determined as a result of the experiment, we use one of three average values. These data are contained in the penultimate column of Table 3. In particular, the average value of the force for a variable value of the parameter  $t$  is obtained as the average value of 6 experimental data from 162 N to 1231 N. As a result, we calculate  $P_{z1}^{av}=686$  N. Similarly, we calculate the average value of the force for the variable parameter  $S$   $P_{z2}^{av}=738$  N, and also for the variable parameter  $V$   $P_{z3}^{av}=620$  N. Substituting the values found in formula (12), three values of the coefficient  $C_{P_z}^i$  for each of the parameters can be found. The average value  $C_{P_z}^{av}$  is defined as the arithmetic mean from expression

$$C_{P_z}^{av} = \frac{C_{P_z}^1 + C_{P_z}^2 + C_{P_z}^3}{3} \quad (13)$$

Substituting the required quantities into formula (5), we obtain

$$P_z = 3226 \cdot t^{1,0178} \cdot S^{0,6987} \cdot V^{-0,167} \quad \text{N} \quad (14)$$

In the obtained formula (14), we substitute the extreme values of the experimental data  $t=0,7$  mm;  $S=1,9$  mm/rot;  $V=26$  m/min, and as a result of the calculation, we obtain updated data on the value of the normal component of the cutting force of a milling cutter with 130 cylindrical tools— $P_{z130}=2039$  N.

These results obtained in using the experimental–theoretical technique correspond to a milling cutter with 130 cylindrical tools. To compare the values of the normal component of the cutting force for a milling cutter with 130 tools with the values of the normal component of the cutting force for a milling cutter with 182 cylindrical tools, we calculate the force values by the formula

$$P_{z182} = P_{z130} \cdot \frac{\int_{-b}^a \rho \cdot \cos \varphi \cdot f_{182} d\varphi}{\int_{-b}^a \rho \cdot \cos \varphi \cdot f_{130} d\varphi}, \quad \text{N} \quad (15)$$

where  $P_{z130}$  —the experimental value of the normal component of the cutting force for a milling cutter with 130 cylindrical tools;  $a$ —positive angle value  $\varphi$ ;  $b$ —negative angle value  $\varphi$ ;  $\rho$  —specific cutting pressure (1);  $\varphi$  —angle of the segment being cut;  $f_{130}$ ,  $f_{182}$  —the cross-sectional area of the cut material, respectively, for a milling cutter with 130 tools and for a milling cutter with 182 tools.

Using formula (15), we determine the value of the normal component of the cutting force of a milling cutter with 182 cylindrical tools, which is— $P_{z182}=1436$  N.

It was noted in the article [25] that the main reason for the wear of locomotive wheels operating in the conditions of industrial transport and mining enterprises is a 2-fold increase in the axle loads on the wheels. The solution to this problem can be the use of new profiles of the working surfaces of the wheels, which requires a modern machining tool.

## 5. CONCLUSION

In the proposed work, it was possible to determine cutting forces acting on one cylindrical cutting tool of a milling cutter, by means of which the profiles of locomotive wheelsets on the machines of KJ20 are restored. This information was obtained by two methods, with the help of a theoretical

calculation, and also with the help of an experimental–theoretical technique. The results obtained are in good agreement with each other.

It should be noted that these results are preliminary, but necessary for further calculation of the entire design of the milling cutter using the finite element method. This calculation will be presented to the readers in the next part.

In conclusion, we also note that at the present time, there has been a tendency to change the technology of production and operation of wheelsets, as a result of which the hardness of the surface layers of the metal increases. This leads to more complicated working conditions of the processing tool and, accordingly, to a decrease in its durability. The constructive changes proposed in the work should contribute to solving this problem.

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