



Article

# Experimental Study of Improving the Durability of a Cup Cutter by Pre-Processing

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**Abstract:** This article presents the results of an experimental study on improving the durability of cup cutters through pre-processing. A review of existing methods of increasing the durability of metal-cutting tools is carried out. The conducted experiments and simulations confirmed the application of pre-processing to increase the durability of cup cutters and the hardening of the cutting part after pre-processing, which approves the formation of a secondary contact structure in the pre-processing process. Dependence for determining a period of the durability of cup cutters at various regimes of pre-processing is deduced.

**Keywords:** pre-processing; tool life period; cup cutter; hardening; secondary structure



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## 1. Introduction

Ensuring high development rates in mechanical engineering is inextricably linked to the intensification of processes of machining materials by cutting. Analysis of scientific and technical studies has shown [1,2] that at the present stage of scientific and technological progress, strength, toughness, hardness, and other characteristics of heat-, corrosion-, and wear-resistant materials, composites, and coatings are increasing so rapidly that the equipment and tools available in production, in some cases, do not allow for highly efficient machining. Also, when machining such materials, the consumption of metal-cutting tools is very high because these materials belong to the class of hard-to-machine materials, and rapid premature wear or chipping of the cutting edge of the instrument occurs.

Wear due to friction is characteristic of all tools, without exception. In this regard, many domestic and foreign scientists are focusing research on improving cutting tools' durability. In [3], the results of experimental research to determine the best combination of cutting parameters that enhances the work of a mixed ceramic tool (70% Al<sub>2</sub>O<sub>3</sub> + 30% TiC) when turning hardened steel C45 (40 HRC) in terms of tool life and productivity, as well as their correlation with the quality of the machined surface, are given. Good results in terms of tool life, productivity, and surface quality were achieved with a combination of cutting speed (200 m/min), feed (0.08 mm/rev), and depth of cut (0.3 mm). It is proven that tool wear is more influenced by cutting speed than feed rate.

In work [4], the wear resistance of steam-assisted coatings on WC/Co-cemented carbide cutting inserts was investigated. It was found that by understanding the relevant processes in the surface layers of the cutting tool during machining, it is possible to select the optimal machining parameters in order to obtain reduced wear and greater durability

of the cutting tool. Tool wear certainly affects the tool life and integrity of the workpiece surface (residual stresses, surface quality, hardening, etc.), so the choice of optimized process parameters is of great importance.

In another work, the interaction between WC/Co-cemented carbide cutting inserts with TiN coating and uncoated and SAE 1045 normalized steel workpieces during dry turning with constant material removal under different machining parameters was investigated. It was found that an increase in load (feed rate or cutting speed) on the cutting tool leads to a rise in the wear rate with respect to lateral wear, and the formation of growing edges, growing layers, and dead zones were found on uncoated carbide cutting tools. Wear was investigated using metallographic slices, and it was found that the wear mechanisms were adhesion and abrasion. The wear improvement of TiN-coated carbide cutting tools is due to the low adhesion of the selected workpiece material (SAE 1045) to the TiN coating.

The paper [5] presents the results of a study of dislocation densities of a cutting tool made of P6M5 high-speed steel, its parameters of hardening of secondary structures on the contacting surfaces when machining a part made of 40Cr steel, as well as the results of X-ray structural and tribotechnical analysis of the working surfaces of a P6M5 cutter when turning stainless steel and heat-resistant cast iron.

In [6], the possibility of using the technology of friction treatment with agitation for tool steel hardening was investigated. The authors proposed to use it as a hardening technology in the manufacture of cutting tools, with hardening performed only in the area of the cutting edge. The results of hardening tool steels 1089 (Fe97%, C0.8%), 3343 (Fe80%, C0.9%, Cr4%, Mo5%, W6%, V2%), and 440C (Fe78%, Cr18%, C0.95%) are presented. As a result of hardening, the microhardness of carbon tool steel is increased more than three times and the average grain size in the treated area is reduced more than ten times concerning the base material. It is noted that the wear resistance increases due to the increased hardness of the material; therefore, the tool made by the investigated hardening technology will have a significantly longer service life.

The known methods of increasing the stability of cutting tools are practically exhausted, as they do not exclude the leading cause of tool wear—the presence of sliding friction in the cutting zone—but only reduce the harmful effects of friction. Interaction of a cutting tool with a workpiece is characterized by outstripping updating of the processed surface in relation to the working surfaces of the instrument, which leads to their intensive wear.

In works [7–9], processes of rotary cutting machining, which also renew a cup cutter's contact surfaces, are investigated. These investigations defined conditions under which partial replacement of sliding friction by rolling friction is carried out, increasing tool durability.

To be more precise, rotary cutting is also accompanied by an increase in the length of the cutting blade, parts of which periodically participate in the removal of the allowance from the workpiece and cool outside the cutting zone, which also contributes to increasing the durability of the rotary tool. However, experimental studies have revealed that the normative durability period of cup cutters is only sometimes maintained [10,11]. Wear and crushing out of the cutting part of cup cutters was observed.

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The research aim is to develop an effective and affordable way to improve the wear resistance of metal-cutting tools in the conditions of domestic machine-building industries. The work aims to use the pre-processing method to improve the durability of cup cutters.

Pre-treatment, as a method of increasing tool durability and reliability, is economically justified with expensive tools, the work of which is associated with substantial material and technical costs [12,13].

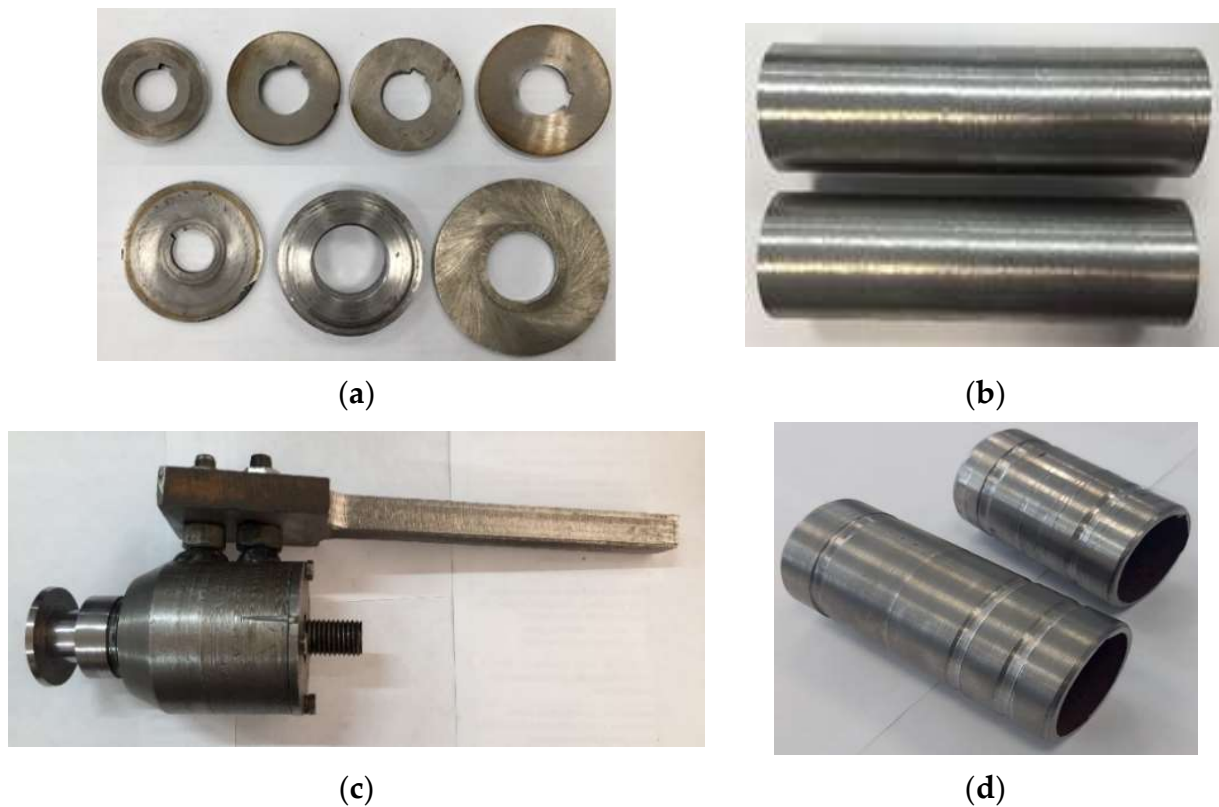
Furthermore, pre-processing can be performed after each tool pre-processing, as the method does not require any additional material and technical costs. The insignificant

economic losses associated with undercutting during pre-treatment can be partially compensated for by combining this process with tool setting to size.

## 2. Materials and Methods

The methodology of cup cutters pre-treatment is based on experimental research. Preliminary finishing of cup cutters was performed on a screw-cutting lathe 1K62 in the laboratory base of the department “Technological machines and equipment” of the S. Seifullin Kazakh Agricultural Research University. As a blank, bars  $\text{Ø}50$  mm of steel 45 and thick-walled tube  $\text{Ø}72$  mm of steel 20Cr were used. The hardness of steel 45 is Brinell scale HB 170 and the hardness of steel 20Cr is HB 179–217. A total of 16 cup cutters were used for pre-treatment. The material of the cup cutters is high speed steel R6M5.

Figure 1 shows photos of the rotary tool, workpiece, and cup cutters used in pre-processing.



**Figure 1.** Photos of the rotary tool, workpiece, and cup cutters used in the pre-processing process: (a) cup cutters (R6M5); (b) workpieces from bar  $\text{Ø}50$  mm (Steel 45); (c) rotary tool; (d) workpieces from thick-walled pipe  $\text{Ø}72$  mm (Steel 20Cr).

## 3. Results

In order to determine the durability time, the regression equation used will be  $x_1$ —pre-processing time, min;  $x_2$ —feed rate, mm/rev;  $x_3$ —pre-processing speed, rpm.

The number of experiments is  $N = 2^3$ . The model is built in the form of the following dependence:

$$Y = b_0 + b_1 \times x_1 + b_2 \times x_2 + b_3 \times x_3 \quad (1)$$

When planning experiments, the so-called coded values of the factors in question are used for simplification, and they do so with the help of some transformation:

$$x_j = \frac{\tilde{x}_j - x_{j0}}{I_j} \quad (2)$$

where  $\tilde{x}_j$ —the natural value of the factor;  $I_j$ —the interval of variation;  $x_{j0}$ —the main level;  $x_j$ —the coded value.

As a result,  $x_j$  achieves values within  $x_j = \pm 1$ , at the main level  $x_j = 0$ . Let us note the ranges of variation of the factors:  $x_{imin}x$ —the lower level;  $x_{imax}x$ —the upper level;  $i = 1, 2$ . Let us find the middle of these ranges—the primary levels [14,15]:

$$x_{j0} = \frac{x_{imin} + x_{imax}}{2} \tag{3}$$

and the step of variation of the factor:

$$I_j = \frac{x_{imin} - x_{imax}}{2} \tag{4}$$

Substituting the values in (3) and (4), we obtain:

$$x_{10} = \frac{1 + 20}{2} = 10.5; x_{20} = \frac{0.07 + 4.16}{2} = 2.115; x_{30} = \frac{12.5 + 50}{2} = 31.25;$$

$$I_1 = \frac{20 - 1}{2} = 9.5; I_2 = \frac{4.16 - 0.07}{2} = 2.045; I_3 = \frac{50 - 12.5}{2} = 18.75.$$

Let us write down the levels of variation in a simplified way: the upper level corresponds to +1, the lower to 1, and the main 0 (Table 1).

**Table 1.** Levels of variation.

Levels	$x_1$	$x_2$	$x_3$
Basic level $x_{j0}$	10.5	2.115	31.25
Variation interval $I_j$	9.5	2.045	18.75
Lower level −1	1	0.07	12.5
Upper level +1	20	4.16	50

Let us fix the conditions of this experiment with the planning matrix (Table 2).

**Table 2.** Planning matrix.

Experience Number	$x_0$	$x_1$	$x_2$	$x_3$	$T$
1	+	+	+	+	$T_1$
2	+	−	+	+	$T_2$
3	+	+	−	+	$T_3$
4	+	−	−	+	$T_4$
5	+	+	+	−	$T_5$
6	+	−	+	−	$T_6$
7	+	+	−	−	$T_7$
8	+	−	−	−	$T_8$

The results of determining the period of durability of cup cutters are shown in Table 3. To exclude the influence of random errors, not considering factors of the experiment, we will use the table of random numbers, writing out from it consecutive numbers in the number of experiments. These numbers determine the sequence of experiments [14], p. 125.

**Table 3.** Values of the durability period after pre-processing.

Experience Number	x <sub>0</sub>	x <sub>1</sub>	x <sub>2</sub>	x <sub>3</sub>	T <sub>1</sub>	T <sub>2</sub>	T <sub>2</sub>	Y <sub>av</sub>
1	+	+	+	+	160	161	161	161
2	+	−	+	+	145	145	145	145
3	+	+	−	+	180	179	179	179
4	+	−	−	+	160	162	163	162
5	+	+	+	−	133	134	132	133
6	+	−	+	−	118	119	118	118
7	+	+	−	−	144	143	143	143
8	+	−	−	−	129	129	130	129

The results of the experiments will help to find the sample coefficients  $b_0, b_i,$  and  $b_y,$  which can be estimated to find the theoretical regression coefficients  $\beta_0, \beta_i,$  and  $\beta_y,$  i.e.,

$$b_i \rightarrow \beta_i; b_y \rightarrow \beta_0 + \sum \beta_{ii} + \sum \beta_{iii} + \dots$$

Let us check the experimental data for the presence of gross errors. To determine gross errors, we use Student’s  $t$ -test.

$$t = \frac{(y - y_{av})}{\sigma} < t_{table} \tag{5}$$

where  $t$  is Student’s  $t$ -test;  $t_{table}$  is Student’s  $t$ -test taken at significance level  $\alpha = 0.05$  and the number of degrees of freedom  $f_1$ ;  $\sigma$  is root mean square error.

$$\sigma = \sqrt{S_y^2}$$

Let us calculate the variance of the experiment using the formula:

$$S_y^2 = \frac{\sum_i^N (y_i - y_{av})^2}{n - 1} \tag{6}$$

where  $N$ —number of experiments;  $n$ —number of repeated experiments.

The results of calculating line-by-line variance are shown in Table 4.

**Table 4.** Linear variance.

No.	y <sub>1</sub>	y <sub>2</sub>	y <sub>3</sub>	$\sum_i^N S_{y_i}^2$
1	1	0	0	1
2	0	0	0	0
3	1	0	0	1
4	4	0	1	5
5	0	1	1	2
6	0	1	0	1
7	1	0	0	1
8	0	0	1	1

We obtain the variance of the experiment:

$$S_y^2 = \frac{12}{2} = 6.$$

Then, the root mean square error is:

$$\sigma = \sqrt{6} = 2.45.$$

Student's *t*-test:

$$t = \frac{5}{2.45} < t_{table},$$

The tabulated value of Student's test at a significance level of 0.05 and the number of degrees of freedom  $f_1 = N(n - 1) = 8(3 - 1) = 16$ ,  $t_{table(0.05;16)} = 2.12$ .

Comparing the tabulated value of Student's *t*-test with the calculated:

$$2.04 < 2.12.$$

Consequently, there are no gross errors in the experimental data.

Before proceeding, to determine the model of the experiment in the form of the regression equation, it is necessary to check the experiment's reproducibility for the object under study. The reproducibility of the investigation is estimated with the Cochran criterion *G*. The experiment is considered reproducible if  $G_{max} < G_{table}$ :

$$G_{max} = \frac{S_{y_{max}}^2}{\sum_{i=1}^N S_y^2} \tag{7}$$

where  $G_{table}$  is the tabular value of the Cochran criterion.

The table value of Cochran's criterion is determined with the table depending on the number of degrees of freedom numerator  $p_1 = m - 1 = 3 - 1 = 2$ , denominator  $v_2 = N = 8$ , and the chosen probability *P*. For technical calculations, take  $P = 0.95$ . If the reproducibility check of the experiment gives a negative result, the investigation is considered non-reproducible.

$$G_{table} = 0.83;$$

$$G_{max} = \frac{5}{12} = 0.41.$$

Given that  $0.41 < 0.83$ , the condition of the Cochran criterion is fulfilled, and the experiment is considered reproducible. According to the planning matrix, we find the *b<sub>i</sub>* coefficients using the following formulas:

$$b_0 = \frac{y_1+y_2+y_3+y_4+y_5+y_6+y_7+y_8}{8}; b_1 = \frac{y_1-y_2+y_3-y_4+y_5-y_6+y_7-y_8}{8};$$

$$b_2 = \frac{y_1+y_2-y_3-y_4+y_5+y_6-y_7-y_8}{8};$$

$$b_3 = \frac{y_1 + y_2 + y_3 + y_4 - y_5 - y_6 - y_7 - y_8}{8}; b_4 = \frac{y_1 + y_2 + y_3 + y_4 + y_5 + y_6 + y_7 + y_8}{8}.$$

We calculate the model coefficients:

$$b_0 = 146.25; b_1 = 7.75; b_2 = -7; b_3 = 15.5.$$

From these data, we derive a regression equation to determine the durability period:

$$T = 146.25 + 7.75x_1 - 7x_2 + 15.5x_3 \tag{8}$$

As well as determining the regression coefficients of these equations, we get an idea of the influence of the factors under study on the process, the interaction of the factors, and the direction of movement toward the optimum region. The problem is considered to be solved when the linear model falls into the area close to the optimum; otherwise, it is necessary to pass to polygons of higher powers to describe the optimum region adequately. Let us check the statistical significance of each model coefficient with Student’s test. For this purpose, we first of all calculate the variance of the coefficients:

$$S_b^2 = \frac{S_y^2}{N \cdot n} \tag{9}$$

From this, we obtain

$$S_b^2 = \frac{27}{8 \cdot 3} = 1.125.$$

The root mean square error of the model coefficients will be:

$$S_b = \sqrt{S_b^2} = \sqrt{1.125} = 1.06$$

Consequently, we can construct a confidence interval:

$$\Delta b_i = \pm t_{table} \cdot S_b \tag{10}$$

where  $t_{table}$ —the tabular value of Student’s test,  $t = 2.01$ .

$$\Delta b_i = \pm 2.12 \cdot 1.06 = \pm 2.25$$

The coefficient is statically significant if its absolute value is greater than the interval, as

$$|b_i| > |\Delta b_i| \tag{11}$$

$|b_0| > |\Delta b_i|$ , which means  $|146.25| > |2.25|$ ;  $|b_1| > |\Delta b_i|$ , which means  $|7.75| > |2.25|$ ;  $|b_2| > |\Delta b_i|$ , which means  $|7| > |2.25|$ ;  $|b_3| > |\Delta b_i|$ , which means  $|15.5| > |2.25|$ .

All coefficients are statically significant. The coefficients of the second equation are also statically significant.

Eventually, we check for adequacy of the obtained dependence; we find, based on experimental data, the variance of adequacy:

$$S_{ad}^2 = \frac{1}{f_1} \sum_{i=1}^N (y_{av} - y_i)^2 \tag{12}$$

where  $f_1 = N - r$  is the degree of freedom;

$N$ —number of experiments;

$r$ —number of statistically significant coefficients.

$$f_1 = 8 - 4 = 4.$$

The results of the variance are presented in Table 5.

**Table 5.** Dispersion of model adequacy.

Experience Number	$y_{av}$	$y_i$	$(y_{av} - y_i)^2$
1	161	162.5	2.25
2	145	147	4
3	179	176.5	6.25
4	162	161	1
5	133	131.5	2.25
6	118	116	4
7	143	145.5	6.25
8	129	130	1
	$\Sigma$		27

Based on the results in the table, let us determine the variance of adequacy with the number of degrees of freedom  $f_1$ :

$$S_{ad}^2 = 6.75.$$

And also determine the variance of the experience with the number of degrees of freedom  $f_2 = 8 - 1 = 7$ :

$$S_y^2 = 3.86.$$

The hypothesis about the adequacy of the model is tested with Fisher’s criterion:

$$F = \frac{S_{ad}^2}{S_y^2} < F_{table}, \tag{13}$$

The table value of the Fisher criterion is taken at the significance level  $\alpha = 0.05$  and the number of degrees of freedom  $f_1$  and  $f_2$

$$F_{table} = 4.12;$$

$$F = \frac{6.75}{3.86} < F_{table};$$

$$1.75 < 4.12.$$

Since  $S_{ad}^2 < S_y^2$ , the resulting model with a given confidence probability (95%) can be recognized as adequate and suitable for calculating the parameter T (durability period) in a given range of running conditions. Having obtained the adequacy of the accepted model (13), let us convert the coded values of the model into natural values using Formula (3):

$$x_1 = \frac{\tau_p - 10.5}{9.5}, x_2 = \frac{S - 2.115}{2.045}, x_3 = \frac{n_{sp} - 31.25}{18.75}.$$

As a result, we obtain the final model for determining the durability period:

$$T = 119.13 + 0.816t - 3.42S + 0.83n_{sp} \tag{14}$$

The error of the regression model for determining the durability period of a cup cutter is less than 2%, which is quite acceptable.

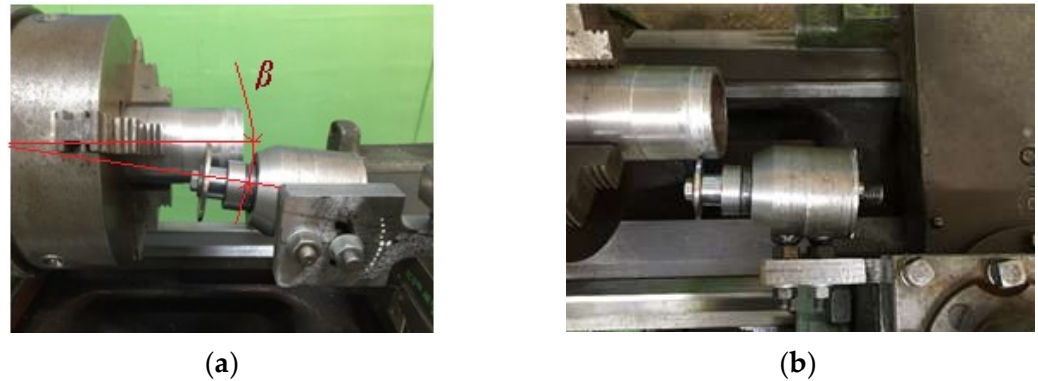
Estimating the character and degree of influence of the considered factors shows that the most strongly influencing parameter is feed  $x_2(S)$ , at its increased value of the period increases. The next most effective is the pre-processing speed  $x_3(n_{sp}$ —spindle revolution), and the least influential is the running-in time  $x_1(\tau_p)$ . The ranking of the factors makes



it possible to adjust the considered parameters and build a more rational scheme of the technological process [16].

#### Experimental study on the pre-processing of cup cutters.

Figure 2 shows photos of the pre-processing process of cup cutters.



**Figure 2.** Photos of the cup cutter pre-processing operation: (a) pre-processing operation using workpiece  $\varnothing 50$  mm of steel 45; (b) pre-processing process using workpiece  $\varnothing 72$  mm of steel 20X;  $\beta$ —angle of a cup cutter.

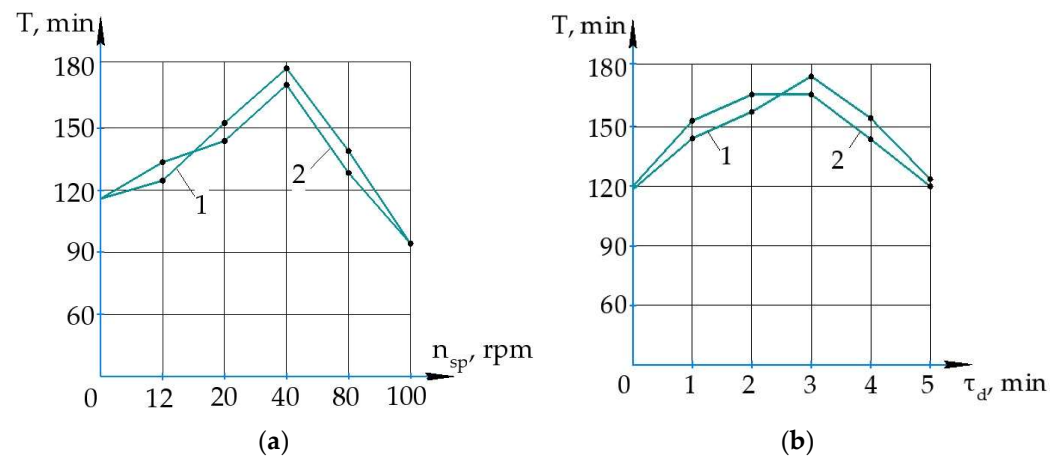
For the pre-processing of cup cutters, eight experiments were carried out, varying the values of the spindle revolution ( $n_{sp}$ ) and the duration ( $\tau_d$ ) of the pre-treatment. At the same time, the importance of the cup pick setting angle ( $\beta$ ), feed ( $S$ ), and cutting depth ( $t$ ) remained constant.

Figure 3 shows the machined workpieces made of different materials during the pre-treatment of cup picks.



**Figure 3.** Machined workpieces made of different materials during cup cutter pre-processing: (a) bars  $\varnothing 50$  mm of steel 45; (b) thick-walled pipes  $\varnothing 72$  mm of steel 20X; 1— $n_{sp} = 40$  rpm (revolution per minute); 2— $n_{sp} = 80$  rpm; 3— $n_{sp} = 20$  rpm; 4— $n_{sp} = 12$  rpm; 5— $\tau_d = 4$  min; 6— $\tau_d = 3$  min; 7— $\tau_d = 2$  min; 8— $\tau_d = 1$  min.

Figure 4 shows graphs showing the dependence of cup cutters' durability period on the pre-processing regimes.



**Figure 4.** Graphs of dependence of the durability period of cup cutters on the regimes of pre-processing: (a) graphs as a function of spindle speed;  $\beta = 100$ ;  $S = 0.81 \text{ mm/rev}$ ;  $t = 0.5$ ;  $\tau_d = 3 \text{ min}$ ; (b) graphs as a function of durability time of cup cutters as a function of the duration of the preliminary break-in; 1—during processing steel 45; 2—during processing steel 20Cr;  $n_{sp} = 40 \text{ rpm}$ ;  $\beta = 100$ ;  $S = 0.81 \text{ mm/rev}$ ;  $t = 0.5$ .

From the diagram in Figure 4, it is visible that the increase in the frequency of rotation of a spindle up to 40 rpm positively influences the rise of value of the period of durability of a cup cutter. At  $n_{sp} = 40 \text{ rpm}$ , the maximum value of the cup cutters' durability period ( $T = 170\text{--}178 \text{ min}$ ) is reached in the processing of workpieces from steels 45 and 20Cr.

Further increase in the spindle's rotation frequency sharply decreases the values of the cup cutters' durability period in the processing of workpieces from steels 20Cr and 45 (Figure 4a, curves 1, 2).

The influence of duration (time) of pre-processing also has a non-monotone character (Figure 4b). An increase in duration (time) of pre-processing up to 3 min promotes the growth of the durability period of cup cutters (up to  $T = 165\text{--}175 \text{ min}$ ) when machining workpieces from steels 45 and 20Cr. Further, an increase in the duration (time) of pre-processing influences the value of the period of durability of cup cutters (Figure 4b, curves 1, 2).

It is known that the hardness of the machined material during pre-processing also has an ambiguous effect on the durability period of the cutting tools, and the durability period decreases with increasing hardness [17,18]. This is also confirmed in our experiments (Figure 4a,b, curves 1, 2).

#### The modeling of the pre-processing.

The extreme character of the dependence of the pre-processing rate effect on the wear resistance of the tool contact surfaces, as well as the presence of the cutting speed limit (in our case 40 rpm) above which there is no effect of pre-treatment (Figure 4a,b), confirms the dominant role of deformation hardening in the secondary structure adaptation process.

In this regard, to test this issue, a simulation of the pre-burn-in process was carried out using the computer program ANSYS Workbench, and the problem was solved in a three-dimensional formulation. Applying software systems like ANSYS allows us not only to simulate of a complex cutting process with high reliability but also to visualize it in real time. Computer modeling is significantly more economical than cost-effective experimental studies and allows you to obtain several parameters of the cutting process that are not available for direct measurement.

Cutting with a cup cutter was simulated, and the size of the tool feed was taken into account due to the width of the cut. For the study, the pre-processing of the cup cutter in steel 45 and steel 20Cr processing was selected. As a result of modeling, stress and strain fields of the rolled material and the tool were obtained, and the thickness of the hardened layer of the cutting part of the cup cutter was compared when processing two types of steel.

Input data:  $n_{sp} = 40 \text{ rpm}$ ;  $\beta = 100$ ;  $S = 0.81 \text{ mm/rev}$ ;  $t = 0.5$ ;  $\tau_d = 3 \text{ min}$ .

A plastic kinematic model (15), which is isotropic, a hardening kinematic model, or a combination of both with strain rate and fracture rate dependence, is used for modeling. The strain rate is taken into account using the Cowper–Symonds model, which scales the yield strength using the strain rate dependence coefficient [19,20].

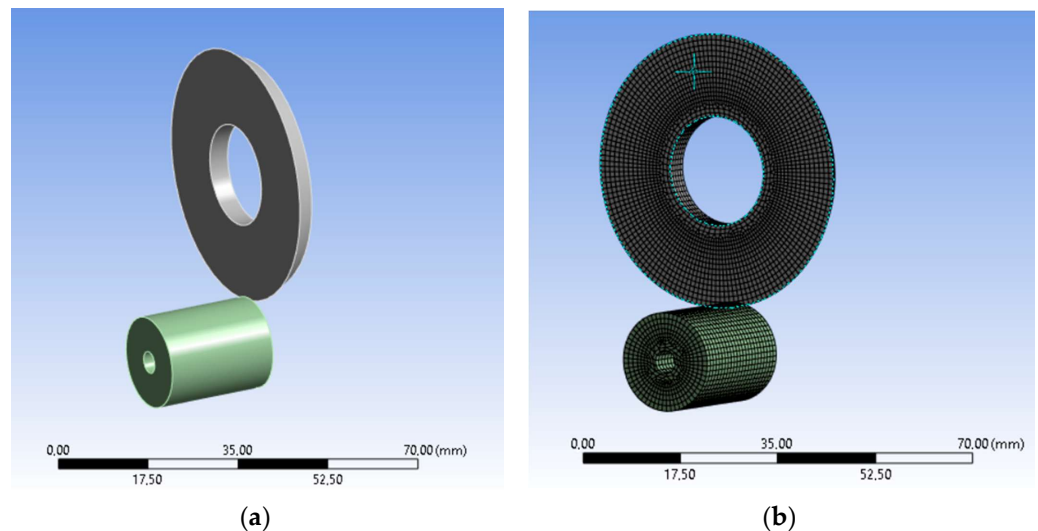
$$\sigma_Y = \left[ 1 + \left( \frac{\dot{\epsilon}}{C} \right)^{\frac{1}{P}} \right] (\sigma_0 + \beta E_p \epsilon_p^{\text{eff}}) \tag{15}$$

where  $\sigma_0$ —initial yield strength;  
 $\dot{\epsilon}$ —velocity of deformation;  
 $C$  and  $P$ —parameter of the velocity Cowper–Symonds deformation;  
 $\epsilon_p^{\text{eff}}$ —effective plastic deformation;  
 $E_p$ —plastic hardening modulus (16).

$$E_p = \frac{E_{\text{tan}} E}{E - E_{\text{tan}}} \tag{16}$$

where  $E_{\text{tan}}$ —tangential slope.

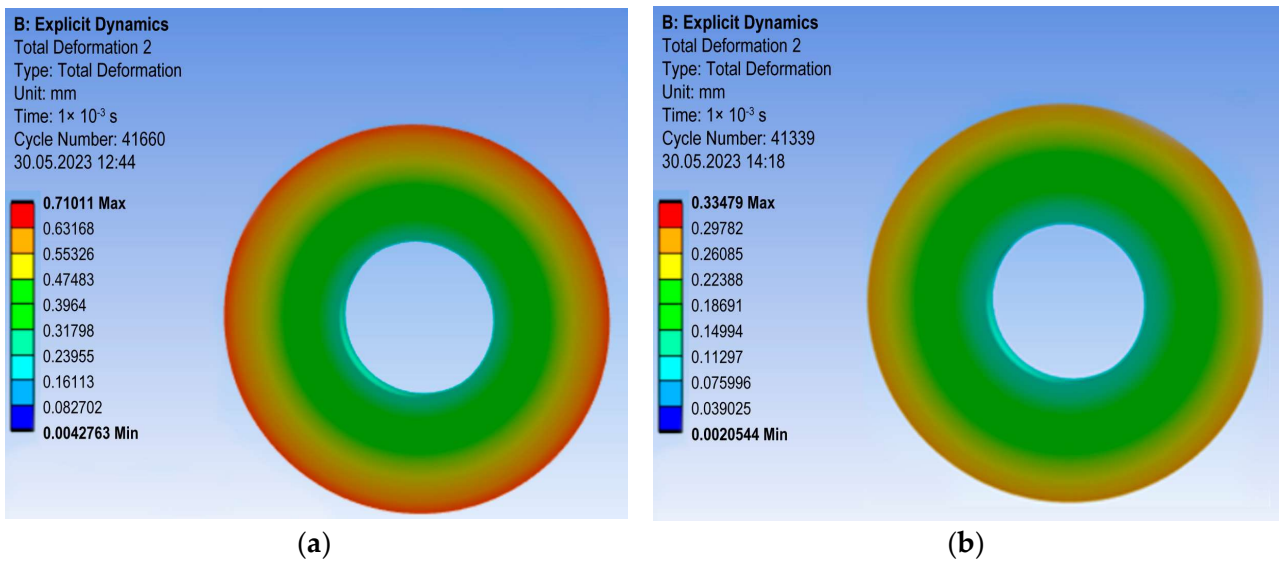
Figure 5 shows the workpiece’s three-dimensional machining model and the mesh’s creation.



**Figure 5.** Three-dimensional model of workpiece machining and mesh creation: (a) three-dimensional model; (b) mesh creation.

Figure 6 shows the hardening patterns of the cutting part of cup cutters when machining different materials.

It is known that force and thermal processes during material cutting cause intensive plastic deformation of the contact surfaces of the cutting tool, leading to the development of secondary structures [21,22]. Secondary structures differ in form and properties from the original tool material, but these structures largely ensure the tool performance, productivity, and quality of machining [23,24]. The primary role in the developing of secondary structures during the contact interaction is played by the processes of generating various crystalline structure defects initiated by plastic deformation, proceeding against the background of high temperatures and their gradients.



**Figure 6.** Models of hardening of the cutting part of cup cutters during machining different materials: (a) during machining steel 45; (b) during machining steel 20Cr.

The extreme character of the dependence of the wear resistance of the secondary structure on the cutting speed can be explained as follows. As the cutting speed increases, the sliding speed in the friction contact zone increases, leading to an increase in the rate and degree of plastic deformation of the contact layers of the tool. It leads to an increase in the density of crystalline structure defects, which determine the hardening value.

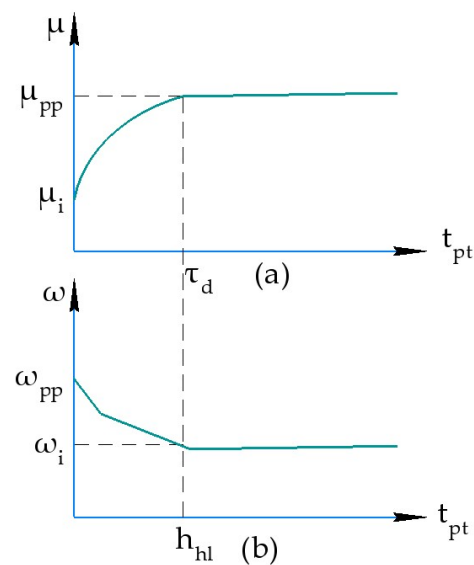
The optimum mode of pre-processing of the tool provides the best deformation and thermal conditions for hardening a cutting part of the tool. The research results have shown that after the pre-processing operation, a hardened layer is formed on the cutting part of the cup cutter (Figure 6). Depending on the hardness of the processed material, the thickness of the hardened layer varies. In the processing of steel 45, the thickness of the hardened layer of a cutter’s cutting part is 0.7 mm (Figure 6a), and in the processing of steel 20Cr, it is 0.3 mm (Figure 6b). It is revealed that with an increase in the hardness of processed material, the approached tool’s firmness decreases.

It is assumed that hardening is achieved by increasing the dislocation density. This case refers to hardening technologies based on purely deformational phenomena when, in the hardened zone, there are no sources of active chemical elements (for example, coatings or films) which could enter into metallographic interactions with the increasing density of crystalline structure defects, blocking the mobility of the latter [25]. The kinetics of this process, referred to as the uppermost layer, can be represented by the hypothetical dependencies graphically depicted in Figure 7.

The dislocation interacts with the periodic field of the lattice as it moves along the sliding plane. The breaking and subsequent restoration of interatomic bonds accompany each elementary act of dislocation movement associated with overcoming the energy barrier. The resistance that a crystal lattice offers to dislocation displacement (lattice friction force or Payer’s stress) [26],

$$\tau_{crit} = \frac{2G}{1 - \mu} \cdot \exp\left(-\frac{2\pi a}{(1 - \mu)b}\right) \tag{17}$$

where  $\tau_{crit}$ —the stress necessary for the movement of a single dislocation and describes the resistance to dislocation movement from the lattice itself;  $G$ —the shear modulus;  $\mu$ —the Poisson’s ratio;  $a$ —the spacing between planes;  $b$ —the distance between atoms in the shear direction.



**Figure 7.** Hypothetical kinematic characteristics of the tool pre-processing operation: (a) change of chemical potential; (b) presentation of wear intensity;  $\mu_i$ ,  $\mu_{pp}$ —values of chemical potentials of initial and secondary contact structure;  $\tau_d$ —duration of running-in period;  $h_{hl}$ —thickness of hardened layer;  $t_{pt}$ —processing time;  $\omega_i$  and  $\omega_{pp}$ —represent wear intensity of initial and running-in contact structure.

The peculiarity of the pre-processing of the hardened tool is that its working surfaces already have an increased value of chemical potential in comparison with the primary tool material while possessing a lower energy absorption capacity or a complete absence of it. The intensity of the initial wear will naturally decrease in this case. The running-in process itself, in this case, may have three varieties depending on the internal energy state of the hardened surface structure [27,28]:

1. The hardened surface structure still has the potential to absorb elastic internal energy.
2. The strengthened surface structure is in a state of thermodynamically stable limiting saturation and cannot absorb elastic internal energy.
3. The strengthened surface structure is in the state of thermodynamically unstable limiting saturation; it is unable to absorb elastic internal energy and seeks to get rid of it.

#### 4. Discussion

The results of experimental studies of the pre-treatment process showed that the modes of running-in have an ambiguous effect on the durability period of cup cutters. Increasing the rotation frequency and duration of running-in time positively affects the durability period of cup cutters to a particular optimal value:  $n_{sp} = 40$  rpm;  $\tau_d = 3$  min. However, their further increase leads to a decrease in the durability period (Figure 4a,b, curves 1, 2).

It has been experimentally confirmed that the hardness of the machined material also affects the tool's life period. With the increase in the hardness of the machined material, the value of the durability period of cup cutters decreases (Figure 4a,b, curves 1, 2). In the processing of steel 45, the value of the period of durability is  $T = 175$ – $178$  min, and in the processing of steel 20Cr,  $T = 165$ – $170$  min.

The ambiguous influence of the hardness of the processed material on the tool lifetime is confirmed with computer simulation results. In the processing of steel 45, the hardening of the cutting part of a cup cutter is 0.7 mm, and in the processing of steel 20Cr it is 0.3 mm.



## 5. Conclusions

The results of experimental studies of the pre-processing operation showed that, using the optimal modes of pre-processing ( $n_{sp} = 40$  rpm;  $\beta = 100$ ;  $S = 0.81$  mm/rev;  $t = 0.5$ ;  $\tau_n = 3$  min), the durability period can be increased by 25–30 min.

The dependence for determining the durability period of cup cutters is derived. The influence of the hardness of the processed material on the tool's durability period is confirmed, and it is established that the durability period decreases with the hardness increase. It is revealed that, with the increasing hardness of machined material, the durability period of a lapped tool decreases.

The results of computer modeling of the pre-treatment process confirmed the formation of a secondary contact structure due to intensive plastic deformation of the contact surfaces of the cutting tool.

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