The Investigation and Improvement of the Hardness of the Clad Surface by Thermal Friction Milling Methods

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***Abstract*—This article presents the research results aimed at solving the problem of ensuring the hardness of welded surfaces after a machining treatment. Two methods of the thermal friction milling are proposed as a mechanical treatment – a traditional thermal friction milling and a thermal friction milling with a pulse cooling. For the experimental research the planning of experiment was carried out and the necessary number of the carried-out experiments was determined. For a processing were prepared special samples with a welded layer of the welding material, which is used in the production of LLP "Electric locomotive assembly factory" (Nur-Sultan, Kazakhstan). The results of the experimental studies have shown that both methods of the thermal friction milling provide an increase in the hardness of the welded surface. The influence of the milling modes on the hardness of the machined surface was also investigated. Optimal values of the milling modes, which provide an increase in the initial hardness of the machined surface, were established. Simulation of the process of the thermal friction milling modes and analysis of the achieved hardness of the machined surface were performed.**

***Index Terms*—thermal friction milling, pulse cooling, hardness, welding material, wear, repairing**

I. Introduction

The analysis of the state of repair production of a locomotive and railcar manufacturing facilities has shown that there is a problem of the increasing wear of locomotive and railcar parts, especially the automatic coupling part of the rolling stock [1].

LLP «Electric locomotive assembly factory» produces freight and passenger electric locomotives KZ8A and KZ4A series, as well as repair and restoration of parts and components of the rolling stock. One of the such major components subject to cyclic repair and restoration of parts is the automatic coupling device of the rolling stock.

Fig. 1 shows the body and parts of the automatic coupler.

b)

Figure 1. Body and parts of the coupling device: a - automatic coupler housing and detailing; b - parts prepared for surfacing; 1 - automatic coupler housing; 2 - safety; 3 - lifter; 4 - bolt with lock washers; 5 - shaft lifter; 6 - locking mechanism; 7 – lock.

As a result of the study of the repair technology of parts of the automatic coupling device it was found that there is a problem of the quality assurance associated with machining and surfacing of the worn surfaces parts. It is not always possible to keep the original hardness of the surfacing material after surfacing or after machining [2].

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The welding material (electrode) SURRADUR 400B is used for welding the worn surfaces of the automatic coupling device parts. The hardness of the welding material (electrode) SURRADUR 400B is HB 320-450. Table I lists the chemical composition of SURRADUR 400B.

TABLE I. CHEMICAL COMPOSITION OF SURRADUR 400B

Chemical analysis	Mean values, %
C	0,2
Mn	0,4
Si	0,7
Cr	2,7
Fe	the rest of

Welding is used for the production of the metal coatings, to restore and protect the surfaces of the parts with a layer of the molten metal, because during the operation of the parts, to improve their performance properties the surface of the parts must be hard enough, having a fine-dispersed structure, smoothed shape micro roughness [3]-[5].

Hardness is the most important mechanical property of a cutting tool, which significantly affects cutting performance and wear resistance. Therefore, it has a great importance to accurately determine the hardness of the tool surface.

When analyzing various works, it was found out that in order to increase the performance characteristics of the parts, the process of hardening deformation treatment is effectively used, especially in the finishing operations of the technological process of manufacturing parts [6]-[8]. They are used to increase fatigue strength, hardness of the metal surface layer, to reduce roughness, as well as to create internal compression stresses in the surface layer of the workpiece [6], [7].

The papers [9]-[14] consider machining methods that allow creating macro-relief of the various shapes, including those with increased hardness, on the surface of the part. This method is called a deforming cutting. The main deformation of the undercut layer of the material takes place in the conditional plane of the shear of the process and at the transition of the material through the deforming edge.

Method of the surface hardening of the parts using a special machining operation that combines cutting and plastic deformation of the surface layers of the steel billets. The advantage of this method of hardening is the possibility of the uniform distribution of microhardness over the height of the macro relief, which will maintain the stability of the operational characteristics of the surface during operation, the use of the standard metal-cutting equipment, small radial forces acting on the workpiece during the formation of the hardened layer [9]-[11].

Thus, the purposeful use of the heat release in the cutting zone and mechanical impact of the cutting tool on the formed macro-relief allows to heat the undercut metal layers to hardening temperatures with simultaneous their plastic deformation [11].

An abrasive grinding is the most widespread in the machining of the clad surfaces [15], [16]. In [16] the peculiarities of the abrasive grinding of surfaces restored by cladding, namely the influence of hardness and the grit size of the wheel on the cutting ability coefficient and roughness of the machined surface were established.

As a result, a study of machinability of surfaced surfaces with the grinding wheels of different characteristics, including those made of the new wear-resistant abrasive materials showed the low grinding efficiency of the surfaces by all process indicators [15].

In addition to the experimental tests, processing simulations using the finite element methods are widely used to study the behavior of various materials under the processing conditions. This computational tool has two main advantages: it allows predicting thermomechanical reactions that are difficult to measure experimentally, and it can be used to reduce the number of the experimental tests performed by eliminating certain parameters that cause undesirable reactions [16]. Also, a gap in the research on simulation of machining with coolant supply is related to the additional degree of the parameterization difficulty and verification of this kind of the simulation, with most of the models available in the literature operating in dry conditions. But the authors [17] have developed new modeling strategies adopted by the researchers to develop coolant-fed machining models, which will help in future work.

It has been shown in [18], [19] that the results of the carbide tool hardness studies based on the finite element method (FEM) are quite reliable. The values of the carbide tool hardness are then calculated by the traditional method. It is found that the hardness values of the traditional method of modeling are similar in the values. Based on the finite element modeling and experimental determination of hardness, the results show that the values correspond to experimental data with a relative error of only 4.72% on the surface and 3.57% in the center of the workpiece.

Thus, the use of computer simulation once again confirms the positive results of the research.

To increase the initial hardness of the welding material after surfacing by machining, thermal friction treatment methods are proposed – a traditional thermal friction milling and a thermal friction milling with pulse cooling.

The main purpose of this study is to determine a more acceptable method from the above-mentioned, which will increase the initial hardness of the deposited surface.

II. THE MAIN PART

We choose the factors of planning matrix: x_1 - speed of the tool rotation, (rpm), x_2 - feed, (mm/min), x_3 - depth of the cutting, (mm), we choose the hardness of the workpiece surface after the treatment, μ_m as the response function Y.

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

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

When planning experiments for simplification, the so-called coded values of the considered factors are used [20]-[22].

The levels of variation are written in a simplified way: the upper level corresponds to +1, the lower - 1, and the main 0 (Table II).

TABLE II. LEVELS OF VARIATION

Levels	x_1	x_2	x_3
Basic level x_{io}	2500	375	3
Variation Interval I_i	500	175	2
Levels	x_1	x_2	x_3
Lower level -1	2000	200	1
Upper level +1	3000	550	5

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

The experimental study of surface hardness at different methods of the thermal friction milling were carried out in the laboratory base of the department "Technological equipment, mechanical engineering and standardization" of Saginov Karaganda Technical University. Samples were prepared for milling, deposited with surfacing material (electrode) SURRADUR 400B.

The surfacing of the samples was carried out by arc surfacing using a Speed MIG 450 DW welding machine.

To investigate the process of traditional thermal friction milling using smooth friction milling cutter the following milling modes were used: n_m =1000-3000 rpm; S = 80-300 mm/min; t = 0.5-2.5 mm. Smooth friction cutter Ø285 mm.

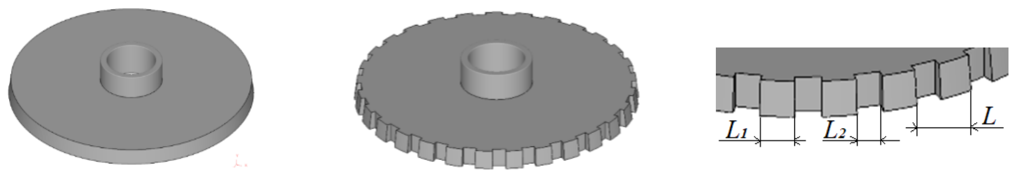
TABLE III. PLANNING MATRIX

Experience number	x_0	x_1	x_2	x_3	Y
1	+	+	+	+	Y_1
2	+	-	+	+	Y_2
3	+	+	-	+	Y_3
4	+	-	-	+	Y_4
5	+	+	+	-	Y_5
6	+	-	+	-	Y_6
7	+	+	-	-	Y_7
8	+	-	-	-	Y_8

And to study the process of thermal friction milling with impulse cooling using the friction cutter with notches the following milling modes were used: n_m =1000-3000 rpm; S = 80-300 mm/min; t = 0.5-2.5 mm.

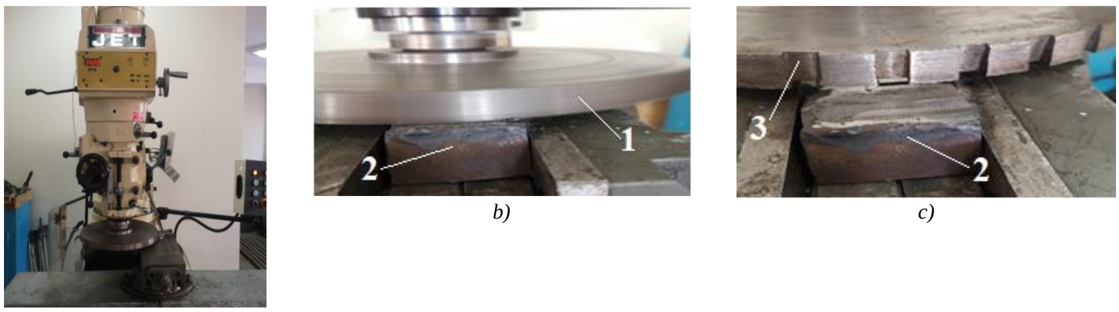
Friction milling cutter with geometrical parameters: Ø285 mm; heating zone L_1 = 26 mm; cooling zone L_2 = 6 mm, respectively step L = 32 mm. Geometry of the friction milling cutter was chosen according to recommendations [23], [24].

Fig. 2 shows the friction cutter and the geometry of the friction cutter with notches. Fig. 3 shows the machining process of the thermal friction milling methods.



a) b) c)

Figure 2. Friction cutters and notched friction cutter geometry: a - smooth friction cutter; b - friction cutter with notches; c - geometry of the friction cutter with notches; L_1- zone of heating; L_2- zone of cooling; L- zone step.



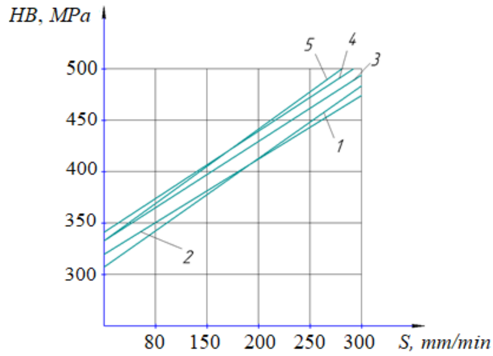
b) c)

a)

Figure 3. Machining processes by friction milling methods: a - vertical milling machine model JTM-1050 VSE JET; b - smooth friction milling process; c - notched friction milling process; 1 - smooth milling machine; 2 - cladding specimens; 3 - notched friction milling machine.

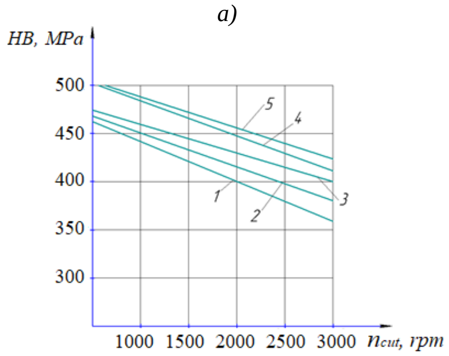
The influence of milling modes on the hardness of the machined surface after welding was investigated experimentally. The hardness of machined surfaces was measured using TDM-2 electronic small-sized dynamic hardness tester

Fig. 4 shows plots of the influence of milling modes of the smooth friction milling cutter on the hardness of the machined surface after welding.



1 – t_1 = 0,5 mm; 2 – t_2 = 1,0 mm; 3 – t_3 = 1,5 mm; 4 – t_4 = 2,0 mm; 5 – t_5 = 2,5 mm.

a)



1 – S_1 = 80mm/min; 2 – S_2 = 150mm/min; 3 – S_3 = 200 mm/min; 4 – S_4 = 250mm/min; 5 – S_5 = 300 mm/min.

b)

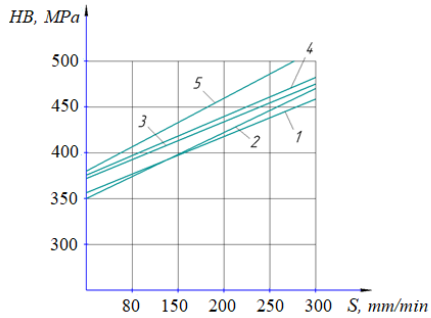
Figure 4. Graphs of the influence of the milling modes of the smooth friction milling cutter on hardness: a - effect of depth of the cut at different feed rates on hardness; b - effect of feed at different cutting speeds on hardness.

Fig. 5 shows plots of the influence of pulse-cooling milling modes with the use of a friction cutter with recesses on the hardness of the machined surface after surfacing.

In a traditional thermal friction milling using a smooth friction cutter, the influence of the depth of a cut t and the feed rate S are monotonic (Fig. 4a). As the value of the depth of a cut t and the feed rate S increase, the value of the hardness of the machined surface after surfacing increases. Optimal values of the cutting depth and feed rate we choose S = 300 mm/min and t = 0,5 mm. From the graph (Fig. 4a) we can see that the maximum values of both modes provide a higher hardness of the machined surface after surfacing. However, an excessive increase in the cutting depth value is undesirable, as it leads to higher consumption of the surfacing material. Taking this into account, the cutting depth value t = 0.5 mm was chosen. At this (Fig. 4a, curve 1) hardness of the processed surface makes HB480, that on ≈7 % (HB30) more, than initial hardness (HB450) of the welded surface.

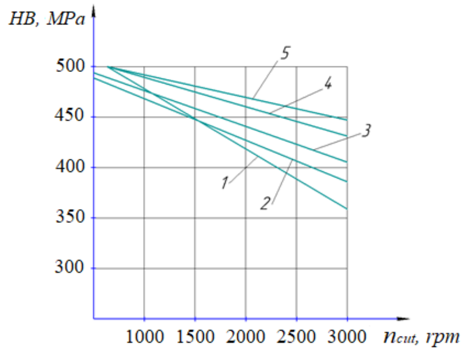
III. Discussion

And an increase in the value of the feed S and cutting speed n_m on the contrary leads to a decrease in the hardness of the machined surface after surfacing (see Fig. 4b). In this case the maximum value of feed S = 300 mm/min and the minimum value of the cutting speed n_m = 1000 rpm will be optimal. In this case also the hardness of the machined surface is HB480 (see Fig. 4b, curve 5).



1 – t_1 = 0,5 mm; 2 – t_2 = 1,0 mm; 3 – t_3 = 1,5 mm; 4 – t_4 = 2,0 mm; 5 – t_5 = 2,5 mm.

a)



1 – S_1 = 80mm/min; 2 – S_2 = 150 mm/min; 3 – S_3 = 200 mm/min; 4 – S_4 = 250mm/min; 5 – S_5 = 300 mm/min.

b)

Figure 5. Diagrams of the effect of pulse-cooled milling modes with the use of a notched friction cutter on hardness: a - effect of depth of a cut at different feed rates on hardness; b - effect of feed at different cutting speeds on hardness.

The results of thermal friction milling with a pulse cooling using a friction-milling cutter with special notches are shown in Figure 5. The graphs show that the character of influence of the milling modes is the same as in traditional thermal friction milling. Increasing the value of a cutting depth t and a feed rate S have a positive effect on the hardness of the machined surface after surfacing (see Fig. 5a). And an increase in the feed value S and cutting speed n_m have a negative effect on the value of hardness of the machined surface after surfacing (see Fig. 5a). We choose the optimal values of milling modes: S = 300 mm/min; t = 0.5 mm; n_m = 1000 rpm.

The results show that at milling modes S = 300 mm/min and t = 0.5 mm (Fig. 5a, curve 1) hardness of the processed surface is HB460, which is 1.0% (HB10) higher than the original hardness (HB450) of the clad surface. Moreover, at milling modes S = 300 mm/min and n_m = 1000 rpm the hardness of the processed surface is HB480 (Fig. 5b, curve 5), as well as at traditional thermal friction milling (Fig. 4b, curve 5).

As a result, both methods of the thermal friction milling of the deposited surface achieved positive results in increasing its initial hardness. However, a higher hardness (HB480) of the machined surface was achieved during traditional thermal friction milling with the use of a smooth friction cutter.

A. Verification of the Experimental Data

Each hardness measurement was made at least 3 times. The results of the measuring hardness of the cladding are shown in Table IV.

TABLE IV. HARDNESS VALUES AFTER MILLING

Number of experience	x_0	x_1	x_2	x_3	Y_1	Y_1	Y_1	Y_{av}
1	2	3	4	5	7	8	9	10
1	+	+	+	+	451	451	451	451
2	+	-	+	+	475	475	476	475
3	+	+	-	+	431	432	432	432
4	+	-	-	+	444	443	443	443
5	+	+	+	-	310	310	310	310
6	+	-	+	-	321	321	321	321
7	+	+	-	-	290	290	291	290
8	+	-	-	-	299	300	300	300

To exclude the influence of random errors, not accounted for factors of the experiment, we will use a table of the random numbers, writing out from it consecutively the numbers in the number of experiments carried out. These numbers determine the sequence of experiments [25].

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

$$t = \frac{(y - y_{av})}{\sigma} < t_{table}, \tag{2}$$

where, t – Student's criterion; t_{tab} – Student's criterion taken at significance level α=0.05 and number of degrees of freedom f_1; σ - root mean square error.

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

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

$$S_y^2 = \frac{\sum_i^N (y_i - y_{cp})^2}{N}, \tag{3}$$

where N - the number of experiments.

Before proceeding to determine the model of the experiment in the form of the regression equation, it is necessary to check the reproducibility of the experiment for the object under study. The reproducibility of the experiment is estimated by the Cochran criterion G.

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

$$F = \frac{S_{ad}^2}{S_y^2} < F_{table}. \tag{4}$$

Using the obtained data, we derive the regression equation:

$$Y = 377{,}25 - 6{,}5 \cdot x_1 + 11 \cdot x_2 + 72 \cdot x_3. \tag{5}$$

Having obtained the adequacy of the obtained model (5), let us convert the encoded values of the model into natural values and as a result, we obtain

$$HB = 265{,}18 - 0{,}013 \cdot V + 0{,}063 \cdot S + 36 \cdot t. \tag{6}$$

Assessment of the nature and degree of influence of the factors under consideration shows that the most strongly influencing parameter is the depth of cutting x_3 (t), with its increase the value of hardness increases. The next most effective is feed x_2 (S) and the least influence is given by cutting speed x_1 (V), while increasing this parameter reduces the hardness. The ranking of the factors makes it possible to adjust the considered parameters and build a more rational scheme of technological process [26]-[28].

The calculation error of the obtained model is less than 6 %, which is satisfactory.

Let's check the experimental data obtained during thermal friction milling with a pulsed cooling.

Each hardness measurement after thermofriction milling with the pulsed cooling was performed at least 3 times.

The results of measuring hardness of the cladding are shown in Table V.

TABLE V. HARDNESS VALUES AFTER THERMAL FRICTION MILLING WITH IMPULSE COOLING

Number of experience	x_0	x_1	x_2	x_3	x_4	Y_1	Y_2	Y_3	Y_{cp}
1	+	+	+	+	+	460	461	460	460
2	+	-	+	+	+	470	470	470	470
3	+	+	-	+	+	432	432	432	432
4	+	-	-	+	+	445	445	446	445
5	+	+	+	-	+	321	321	320	321
6	+	-	+	-	+	330	330	330	330
7	+	+	-	-	+	310	310	311	310
8	+	-	-	-	+	322	322	322	322
9	+	+	+	+	-	450	450	449	450
10	+	-	+	+	-	470	470	470	470
11	+	+	-	+	-	430	430	429	430
12	+	-	-	+	-	441	440	440	440
13	+	+	+	-	-	310	310	310	310
14	+	-	+	-	-	320	320	320	320
15	+	+	-	-	-	291	290	291	291
16		-	-	-	-	300	300	300	300

To exclude the influence of random errors, not accounted for factors of the experiment, we will use a table of the random numbers, writing out from it consecutively the numbers in the number of experiments carried out. These numbers determine the sequence of experiments [25].

Let's check the experimental data for the presence of gross errors. To determine gross errors, we use Student's t-test (2). Let us calculate the variance of the experiment using the Eq. (3).

Before proceeding to determine the model of the experiment in the form of the regression equation, it is necessary to check the reproducibility of the experiment for the object under study. The reproducibility of the experiment is estimated by the Cochran criterion *G*.

The hypothesis about the adequacy of the model is tested with Fisher's criterion (4). Using the obtained data, we derive the regression equation:

$$Y = 381{,}31-5{,}81\cdot x_1+10{,}06\cdot x_2+68{,}31\cdot x_3+4{,}94\cdot x_4. \tag{7}$$

Having obtained the adequacy of the obtained model (7), let us convert the encoded values of the model into natural values and as a result, we obtain:

$$HB=312{,}75-0{,}012\cdot V+0{,}073\cdot S+22{,}77\cdot t+0{,}224\cdot L_1. \tag{8}$$

Assessment of the nature and degree of the influence of the factors under consideration shows that the most strongly influencing parameter is the depth of cutting x_3 (*t*), with its increase the value of hardness increases. The heating zone x_4 (L_1) turns out to be the next most effective, and the feed x_2 (*S*) and the cutting speed x_1 (*V*) give the least influence, while increasing the cutting speed parameter reduces hardness.

The ranking of factors makes it possible to adjust the considered parameters and build a more rational scheme of technological process [26]-[28]

The calculation error for the obtained model is less than 10%, which is satisfactory.

In general, the error of the obtained models does not exceed 5%.

To compare the results of the experimental data, we study the hardness of the deposited surface after the thermal friction milling using the DEFORM 3D computer program.

IV. Modeling of the Machining Process

In the process of modeling, the methods of scientific research given in the works [29]-[31].

Using the DEFORM 3D software package, determine the hardness of the surface layer during the thermal friction milling with smooth friction milling cutter sand with recessed friction milling cutters.

The hardness values in the software package are determined using the Rockwell scale. To determine Brinell hardness, the Rockwell hardness values must be converted from already defined reference data.

Fig. 6 shows patterns of hardness change as a function of the milling with different discs. The models show that when milling, the hardness of the machined surface increases between 47HRC to 40HRC on average, which ranges from 471 to 373 Brinell units. The hardness does not spread evenly in the subcontact layer of the workpiece. The hardness value also decreases deep into the workpiece (Fig. 6, b).

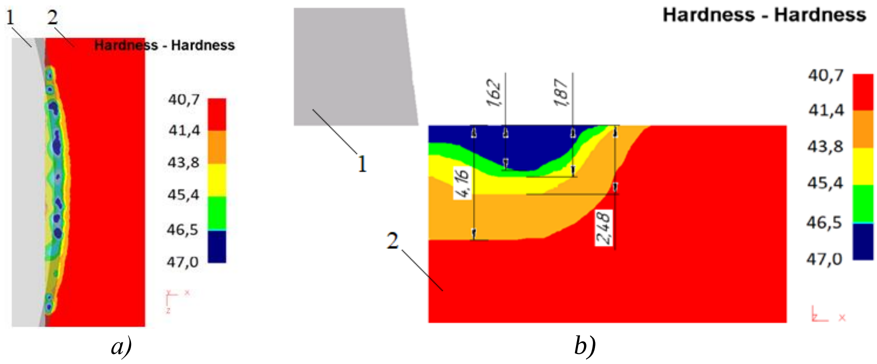


Figure 6. Patterns of hardness change when machining with a smooth friction cutter: a - top view; b - side view; 1 - smooth friction cutter; 2 – workpiece.

The model shows that the maximum thickness of the hardened layer is 1.62 mm (Fig. 6, b).

In the process of milling with a notched friction milling cutter, the hardness gradually spreading from the contact zone of the workpiece with the tool also decreases (see Fig. 7). During the pulse-cooling milling with a friction cutter with recesses the hardness also increases up to the process with less change in hardness up to 47 HRC which means up to 471 HB.

The maximum thickness of the hardened layer is 0,6 mm (Fig. 7, b).

The decrease in the thickness of the hardened layer can be explained by the fact that during the thermal friction milling with pulse cooling the machined surface is periodically heated [8], [9].

Localization of the hardness change is located exactly under the contact of the disc with the workpiece. The hardness propagation from the disc contact increases, which will lead to greater hardening of the surface after machining.

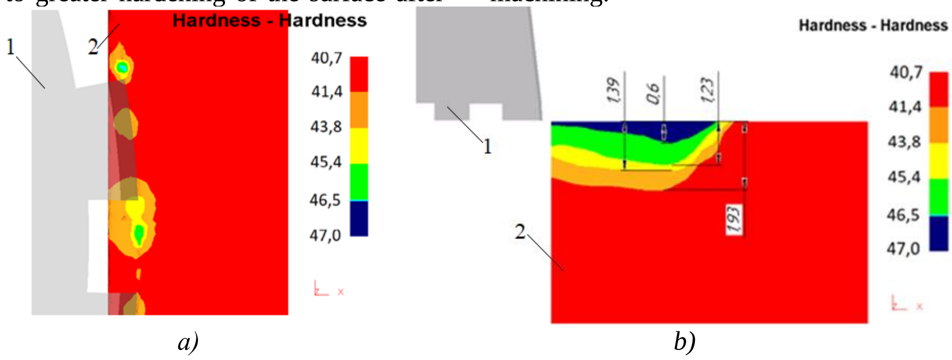


Figure 7. Patterns of hardness change when machining with a notched friction cutter: a - top view; b - side view; 1 - notched friction cutter; 2 – workpiece.

The paper [31] states that the undercut layer of metal undergoes significant plastic deformation, which leads to its hardening and increase in the hardness. It is known that deformation of the material leads to the distortion of its crystal lattice and the appearance of dislocations [32]. According to the hardening theory put forward by I.A. Oding, changes in the crystal lattice entails a change in the size of the resulting distortions of the crystal lattice in a certain volume, which generally increases the density of dislocations and, accordingly, leads to an increase in the strength properties of materials.

Thus, in our case the same effect of surface hardening occurs after the treatment with the thermal friction milling methods.

V. Conclusions

The increase of initial hardness of the machined surface within 1-7% was achieved, which is 10-60 HB accordingly.

It was established that at both milling methods an increase in cutting depth t and feed rate *S* have a positive effect on processed surface hardness after surfacing, and an increase in feed rate *S* and cutting speed *p*fr have a negative effect.

It was also found that during thermal friction milling with smooth friction milling the hardness thickness is 2.5 times greater than during the thermal friction milling with the pulse cooling.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors contributed to the research and article. In particular, Karibek Sherov analyzed the relevance of the research problem and organized the work of the team, as well as for the general outline of the article. Yernat Imanbaev, Isa Kuanov and Nurgul Karsakova are doctoral students and this work is a part of their doctoral research. Medgat Mussayev was responsible for the computer experiments and the final manuscript for submission. Bakhtiyor Mardonov and Lutfiddin Makhmudov collected results and formulated conclusions.

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