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SIMULATION OF MICRO-CUTTING IN THE PROCESS OF FINISHING ANTI-FRICTION NON-ABRASIVE TREATMENT

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Abstract. The influence of the shapes and sizes of microroughnesses on the creation of favorable conditions for micro-cutting of antifriction material by modeling the contact interaction of microroughnesses with the treated surface during the finishing antifriction non-abrasive treatment (FANT) is studied in the work. It is shown that the formation of the anti-friction coating FANT depends on the conditions of contact interaction of the tool with the treated surface, and the shape and size of the microroughness determine the quality of the resulting coating. In the study of FANT at the stage of micro-cutting, a similarity and dimension theory method was used, according to which cutters made of gray cast iron SCh20 were made, the geometry of the cutting part of which simulated a separate microroughness of the surface of the workpiece with different front cutting angles. As a contacting surface and coating material used brass L63. The micro cutting process is considered as a low-temperature process of deep plastic deformations with a predominance of a simple shear of the processed material in the chip formation zone according to the free orthogonal cutting scheme. A scheme for the interaction of microroughness with the treated surface is constructed with the friction-mechanical method FANT. It has been established that the cutting blade of a cast-iron micro-cutter wears out intensively in the process of interacting with a brass surface, and the process of changing the geometry of the tip of the cutter occurs in accordance with the principle of adaptability of the entire system of the cutter - the part according to which the minimum of micro-cutting energy is realized. It is proved that with a decrease in the cutting front angle, the blunting radius of the cutting edge increases, and the actual cutting depth and the volume of microchips decrease. Reducing the cutting front angle contributes to the strain hardening of the rubbed material, which reduces the chip formation process of the antifriction material. In order to intensify micro-cutting and obtain a high-quality FANT coating, single microroughnesses of the treated surface should have a cutting front angle $\gamma \geq 0°$. The obtained experimental data and simulation results made it possible to present contact interaction diagrams of the tool with the surface being machined for various angles during FANT at the stage of microcuts, and also to establish the basic laws of their parameters. An analysis of the characteristic microcutting patterns in FANT by the friction-mechanical method made it possible to recommend the parameters of the initial surface microrelief, thereby creating favorable conditions for micro-cutting of the antifriction material and to improve the quality of the formation of the antifriction coating.

Keywords: finishing anti-friction non-abrasive treatment, anti-friction coating, micro-cutting, simulation, contact interaction, microroughness, cutting angle.

Introduction

One of the most important and priority areas of world engineering is the development and widespread use of innovative technologies based on modern achievements of science and technology. Creation of new and improvement of existing technologies should be aimed at improving the quality of work surfaces by obtaining optimal operational properties of machine parts. A significant influence on the formation of these properties is exerted by the intermediate medium through which the interaction of microroughness occurs. Therefore, an important reserve for improving the quality of parts during their manufacture and repair is the modification of their working surfaces by creating and applying anti-friction coatings.

Progressive technologies for applying such coatings include the finishing anti-friction non-abrasive treatment (FANT), which is realized due to the frictional interaction of a copper-containing tool with the surface of the workpiece in the presence of a process fluid, which ensures the transfer of tool material and the formation of an antifriction coating with a thickness of up to 5 μm on the surface of the part, and also harden the surface layer of the base material to a depth of 70–80 μm [1].

The anti-friction coating obtained by FANT helps to reduce running-in time, eliminates scuffing of friction surfaces of parts, increase the bearing capacity of parts and joints, protect friction surfaces from hydrogen wear, reduce the temperature of friction and increase the period of operation of the friction unit when the lubricant is turned off, reduce the friction coefficient, and therefore, reducing fuel consumption by internal combustion engines, etc. [2]–[4].

The quality of application of the anti-friction coating FANT is largely determined by the conditions of contacting the tool with the treated surface and depend on the completeness of the triggering channels of activation of the contacting surfaces [1]. The study of the processes occurring during FANT, the establishment of the basic laws, will improve the quality of the coating, and hence the operational properties of the part. Thus, studies of the contact interaction of surfaces and ongoing processes during FANT seem very relevant.

Literature Review

It has been proved [5]–[7] that the application of metal coatings by the friction-mechanical FANT method is accompanied by micro-cutting of antifriction material (for example, brass, copper and bronze) by microroughness tops of the processed material. In this case, the antifriction material will fill in microroughnesses in the form of microchips and will largely determine the formation and quality of applying the antifriction coating.

It should be noted that during FANT there are a number of processes accompanying micro-cutting: adhesion sticking, grasping of particles formed as a result of micro-cutting with the surface onto which the transfer and subsequent micro-smoothing take place, etc. Despite the fact that these processes exist in close contact in narrow temporal, geometric, mechanical limits, it is at the stage of micro-cutting that the foundations for the formation of a high-quality coating are laid.

The importance of the role of micro-cutting of antifriction material by the microroughnesses of contacting surfaces during the formation of an antifriction coating was shown in [5]–[7]. Despite the difference in approaches to the interpretation of the mechanism of coating formation by the friction-mechanical FANT method, the authors of these works agree on the need to create favorable conditions for micro-cutting, the fulfillment of which is associated with certain requirements for the microroughness of the contacting surfaces.

It was shown in [8] that micro-cutting of antifriction material occurs due to plastic deformation in near-surface volumes, and an increase in temperature in the contact zone leads to a decrease in the yield strength of the material.

It was established in [9] that the wear of the tool and the transfer of its material occurs due to micro-cutting by the surface roughness of the workpiece at high pressure of the tool, accompanied by the introduction of microprotrusions of the surface roughness of the workpiece into the surface of a softer material which forms coatings.

It is obvious that the creation of conditions for micro-cutting requires the provision of the necessary initial surface roughness. It was noted in [10] that obtaining a high-quality coating on a surface with a coarse regular microrelief is complicated by the peculiarities of filling inter-crest cavities with antifriction material. Moreover, the shape of the protrusions and depressions of the microrelief is determined by the forming part of the tip of the incisor, which can be: sharp, blunt, partly with a radius and straight segments, only with a radius. The dimensions of the protrusions and troughs of the microrelief, their area depend on the size of the cutter angles in the plan φ, φ_1, radius r and the feed rate S of the cutter. Since the protrusions of microroughnesses regardless of the shape of the working part of the cutter in the plan always have a wedge-shaped shape with a sharp edge, each they can be considered as a separate cutting wedge, and the space between them can be considered as grooves for the location of the chips, which is formed as a result of micro-cutting during the interaction of the tool from antifriction material with the base surface.

The formation of the FANT antifriction coating largely depends on the conditions of contact interaction of the tool with the surface being treated, and the shape and size of the microroughness determine the quality of the coating obtained, its continuity and adhesive strength [10]. In our opinion, studies of the contact interaction of microroughness of the treated surface with the tool will determine the optimal conditions for the micro-cutting process and subsequent fixing of the coating on the surface to be treated, which is an important reserve to improve the quality of the application of FANT anti-friction coating.

In this regard, it seems advisable to conduct special studies of the influence of the shapes and sizes of microroughnesses on the course of micro-cutting during the FANT process. Carrying out such studies is possible by modeling the contact interaction of antifriction material with microroughness peaks during FANT at the stage of micro-cutting.

The aim of the work is to study the influence of the shapes and sizes of microroughnesses on the creation of favorable conditions for micro-cutting by simulation the FANT process.

Research Methodology

Contact interaction of surfaces was simulated on special samples of gray cast iron SCh20 and brass L63. When studying the micro-cutting process, the method of the theory of similarity and dimensions was used [11], according to which cast-iron cutters were made, the geometry of the cutting part of which simulated a separate microroughness of the surface of the workpiece. Moreover, the rake angle of this microroughness varied within $\gamma = +5°…–15°$. As a test sample, interacting with a single microroughness, a plate made of brass L63 was used. A diagram of the interaction of contacting surfaces during a simulated experiment is shown in Fig. 1.

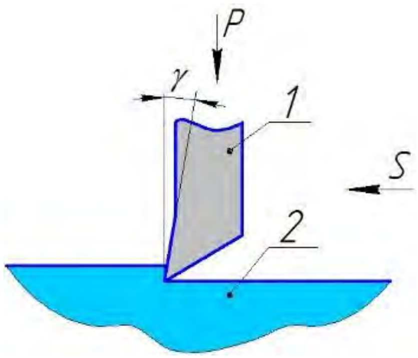


Fig. 1. The scheme of contacting surfaces when simulation micro-cutting at FANT by the friction-mechanical method:
1 – micro-cutter from cast iron SCh20;
2 – plate made of brass L63

The FANT process was simulated at the micro-cutting stage using a technique and a device developed by the authors [10] on a milling machine. The geometry of the contacting surfaces was studied using the standard technique using MIM-7 and “Altami” metallographic microscopes and a ZEISSEVO 50XVP scanning electron microscope. The geometry of the contacting surfaces was evaluated using a MahrXR20 profilograph, a PC-based device. The coating continuity and its tendency to stick to the back surface of the micro-cutter were determined based on the results of metallographic analysis of the surface using digital image processing on a PC.

To obtain a quantitative assessment of micro-cutting, simulation of chip formation was carried out at various cutting front angles γ using the DEFORM-3D software package.

Results

Let us consider the micro cutting process under the friction-mechanical FANT method as a low-temperature process of deep plastic deformations with a predominance of a simple shear of the processed material in the chip formation zone according to the free orthogonal cutting scheme. The micro-cutting scheme during the formation of an antifriction coating by the friction-mechanical method FANT is presented in Fig. 2.

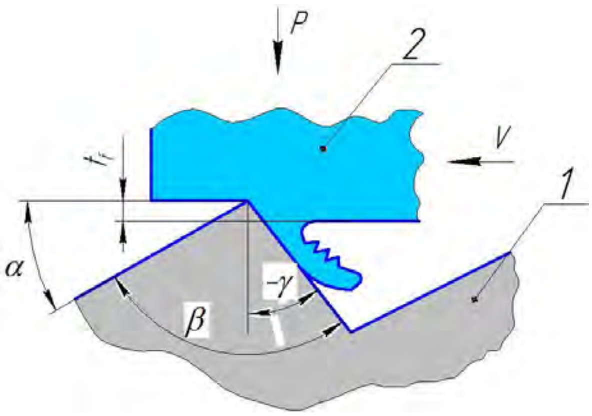


Fig. 2. The scheme of the micro-cutting process during the formation of an antifriction coating by the friction-mechanical method FANT: 1 – the processed surface; 2 – anti-friction block

Suppose that a separate microprotrusion of the surface of the base 1 acts as a cutting wedge, and the antifriction block 2 is the object from which the metal layer is cut off. According to the presented scheme (Fig. 2), the micro-cutting process is ensured by pressing the anti-friction block against the work surface of the base with effort P and its movement V across microroughnesses. In this case, the thickness of the shear layer t_f will be determined by the penetration depth of the cutting wedge into the antifriction material, which depends on the effort P, the plastic properties of the antifriction material and the rake angle γ of the cutting wedge.

Let us consider the contact interaction of a single microroughness formed during the processing of a surface from brass L63 with a cutter from cast iron SCh20. At the beginning, the micro-cutting process is carried out with a sharpened cutter, the initial radius of the cutting edge of which is r = 0.008…0.015 mm. It is significantly less than the thickness of the removal t_r. The interaction diagram of such a cutter with the surface of a brass sample is shown in Fig. 3.

As follows from Fig. 3, the contour of the cutting wedge consists of the following parts: *AB* is the rectilinear part of the contour of the front surface, sharpened with a rake angle $\gamma > 0$; *BC* – a rounded portion of the front surface in which $\gamma > 0$; *CD* – the rounded part of the contour of the rear surface, in which the rear angle $\alpha > 0$.The length of this section is practically determined by the process of plastic recovery since the amount of elastic recovery of the processed material $d_{el} << d_{pl}$. Thus, the front surface of the cutting wedge consists of two parts $L = AB + BC$, and its rear surface of length L_1 consists of three parts $L_1 = CD + DE + EF$. Point C corresponds to the section of the front and back surfaces of the wedge.

Let us consider this scheme in more detail. According to the data [9], the workpiece material deposited onto the cutting wedge at point C is divided into two flows, one of which moves along the tool's front surface, and the second layer, of thickness d, is deformed by the back surface of the cutting wedge. In this case, the real cut surface passes through point C and the actual cut depth does not coincide with the nominal thickness t_r of the surface cut.

In our case, point C is the dividing point of the entire layer to be removed with a thickness of t_r, namely, to the layer of material that goes into microchips with the actual cutting depth t_f and to the layer that is processed by surface plastic deformation by the radius portion of the back surface. Its value $d \leq r$, meaning $t_r \sim t_f + r$, where r – the blunting radius of the tip of the cutter, which changes during operation.

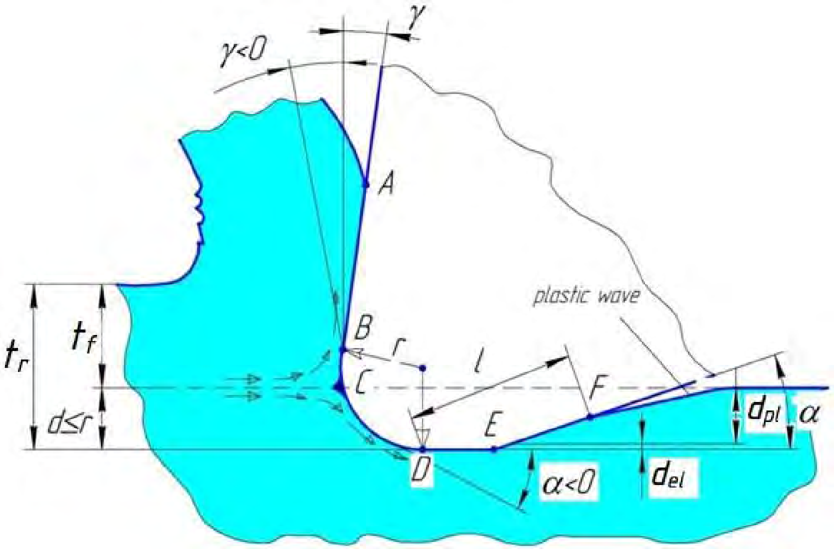


Fig. 3. The scheme of interaction of a single microroughness with the treated surface during FANT

In the zone of chip formation, plastic deformation of the material occurs, which is preceded by elastic deformation. It leads to the lowering of the layer of material that is below the surface cut. After passing the micro-cutter, the load is removed, and this layer is elastically restored, returning to its original state, which leads to its interaction with the back surface of the micro-cutter. The amount of elastic recovery d_{el} determines the length of the elastic contact along the rear surface of the cutting wedge.

Modeling of the FANT process showed that the cutting blade of a cast-iron micro-cutter wears out intensively in the process of interaction with a brass surface, and this happens already at the very beginning of its work. The process of changing the geometry of the tip of the cutter occurs in accordance with the principle of adaptability of the entire system of the cutter – the part according to which the minimum energy of micro-cutting is realized. The quantitative bluntness value showed the influence of the front angle γ on the bluntness radius r of the cutting edge of the SCh20 cast iron micro cutter. The calculation of the ratio of the blunting radius r to the actual cutting depth t_f for various angles γ showed that with decreasing front angle γ the blunting radius r increases (Fig. 4).

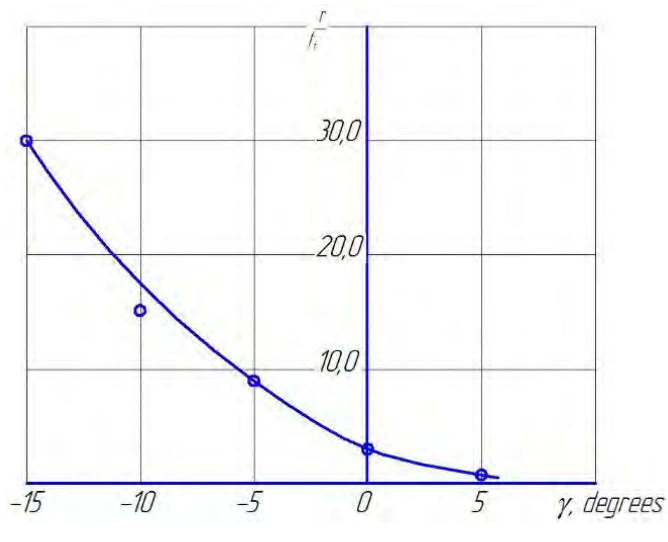


Fig. 4. Dependence of the ratio of the blunting radius of the cutting edge of the cutter r to the actual cutting depth t_f on the cutting front angle γ when simulation with a cast iron cutter SCh20 when machining brass L63

A similar calculation of the ratio of the blunting radius **r** of the cutting edge of the cutter to the total cutting depth t_r also showed a significant effect of the angle γ on the blunting radius **r** of the cutting edge of the cutter (Fig. 5), from which it follows that minimal wear occurs at an angle of $\gamma = +5°$. With a value of γ from +5° to 0°, this wear increases, and then at negative angles γ its intensity decreases, which is due to a small (very close to 0 at $\gamma = –10°…–15°$) actual cutting depth t_f.

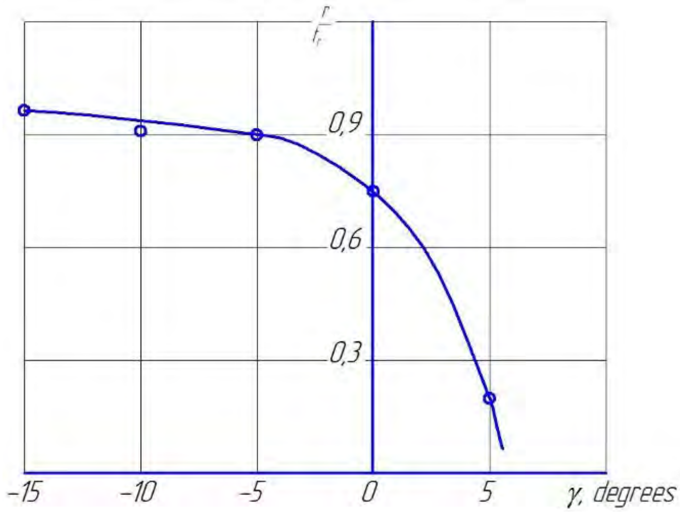
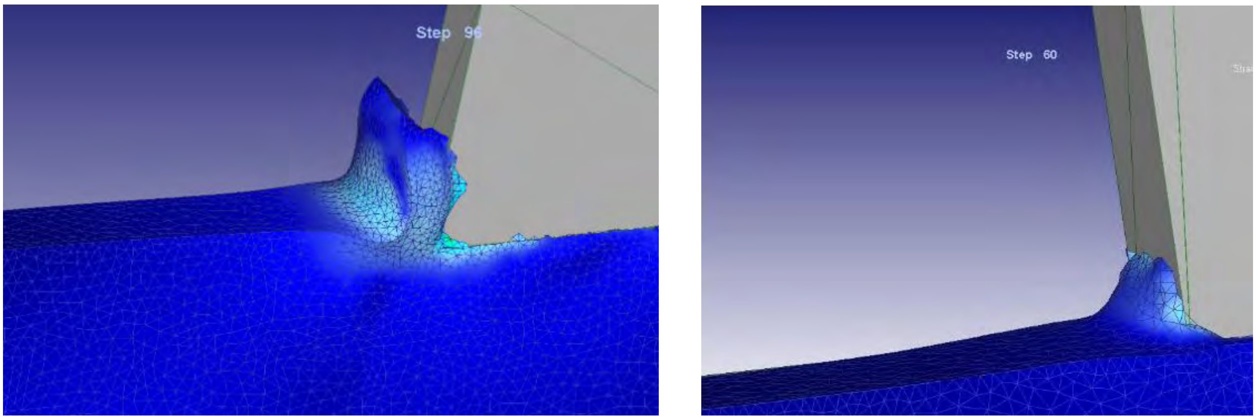


Fig. 5. Dependence of the ratio of the blunting radius of the cutting edge of the cutter **r** to the total cutting depth t_r from the front cutting angle γ when simulation with a cast iron cutter SCh20 when machining brass L63

The efficiency of the micro-cutting process at the positive cutting front angles γ is also confirmed by the chip formation simulation data using the DEFORM-3D software package (Fig. 6).



a b

Fig. 6. Dependence of the ratio of the blunting radius of the cutting edge of the cutter **r** to the total cutting depth t_r from the front cutting angle γ when simulation with a cast iron cutter SCh20 when machining brass L63

The simulation results using the DEFORM-3D software package (Fig. 6) indicate that at an angle of $\gamma = +5°$ the largest thickness of the cut-off layer is observed and the chip descent vector preserves the direction of the front surface with an angle of $\gamma = +5°$ (Fig. 6, *a*). At $\gamma = 0°$, the thickness of the cut-off layer decreases noticeably, and the chip descent vector preserves the direction of the front surface with an angle $\gamma = 0°$. The smallest thickness of the cut-off layer is observed at an angle $\gamma = –5°$ (Fig. 6, *b*) and the chip descent vector preserves the direction of the front surfaces with an angle $\gamma = –5°$.

It should be recognized that simulation of the chip formation using the DEFORM-3D software package allows you to get only a quantitative estimate that does not take into account the mechanics of the process. Obtaining a high-quality picture taking into account the physics of the micro-cutting process is possible only through experimental studies (Figs. 7, 8).

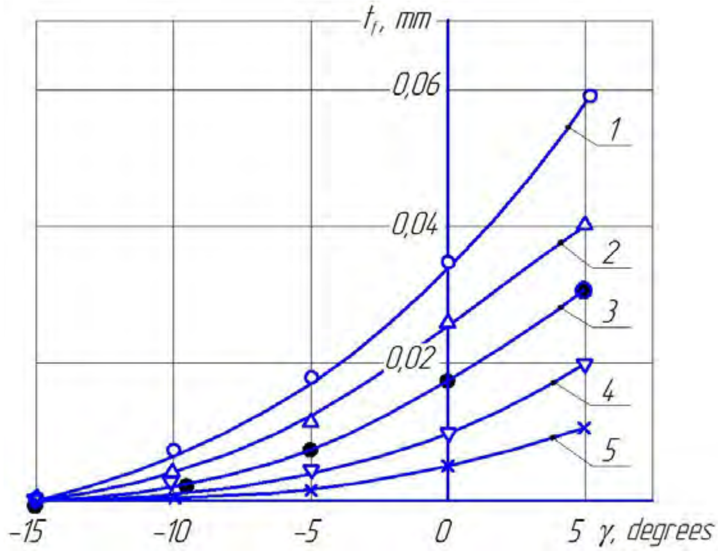


Fig. 7. Dependence of the actual depth of micro-cutting t_f on the cutting front angle γ when simulation of micro-cutting by micro-cutter made of cast iron SCh20 with brass surface L63 at nominal thicknesses of micro-cutting t_{nom}, mm: 1 – 0.6; 2 – 0.4; 3 – 0.3; 4 – 0.2; 5 – 0.1

It follows from Fig. 7 that the actual cutting thickness decreases with the decrease of γ from +5° to –5° in proportion to the angle γ, and then monotonically decreases to 0 at a value of $\gamma = -15°$. This is explained by the intense formation of the wear radius of the cutting edge (Fig. 3). Therefore, to intensify the phase of the chip formation FANT (micro-cutting), individual microroughnesses of the treated surface should interact with the brass surface having an angle $\gamma \geq 0°$.

It was established (Fig. 8) that with a decrease in the angle γ the volume of the removed microchips decreases regardless of the nominal cutting thickness, approaching 0 at a value of $\gamma = -10°\ldots-15°$. Thus, to effectively fill the microcavities with the chip between microprotrusions, it is necessary to create a regular microrelief with $\gamma = 5°$.

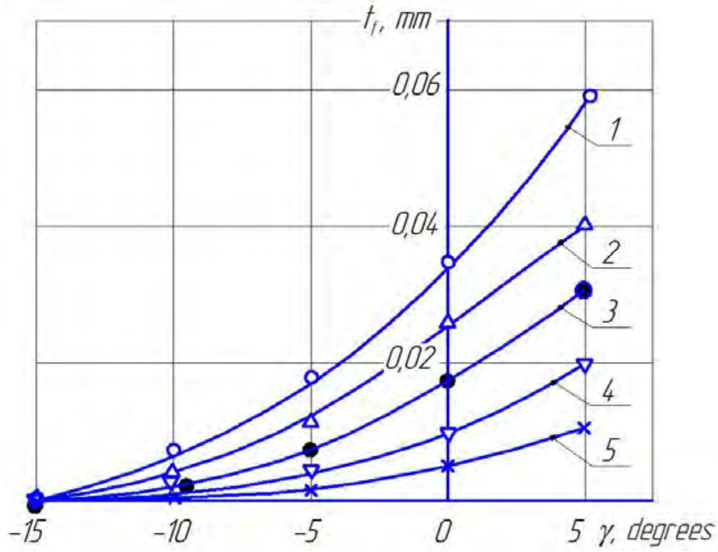


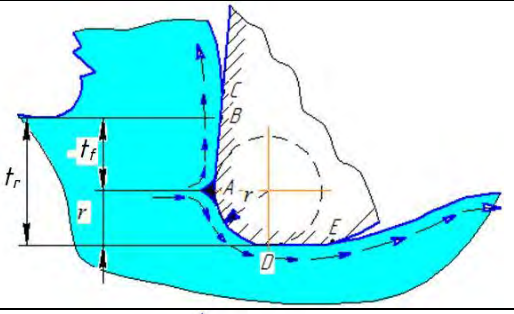
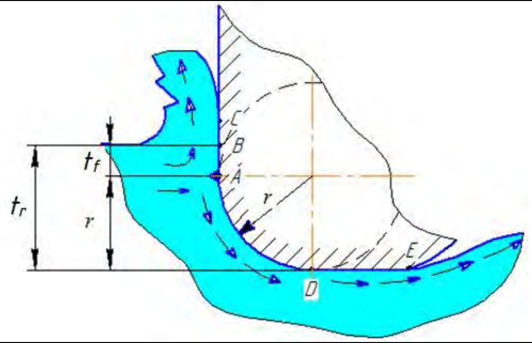
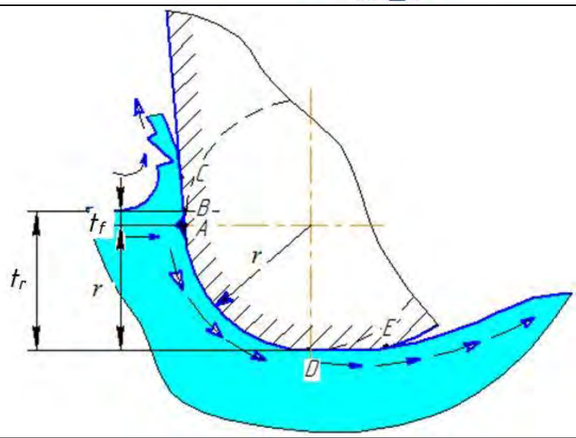
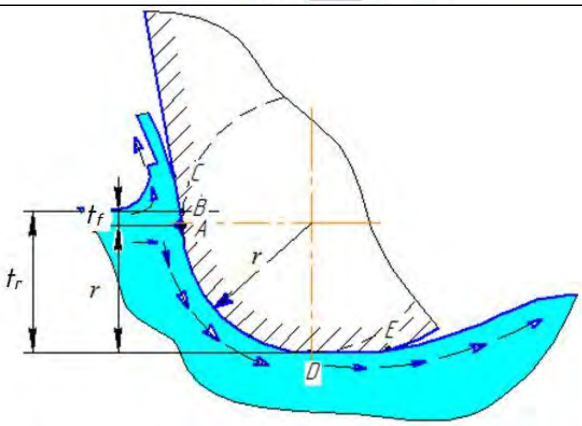
Fig. 8. Dependence of the volume of chips removed from a unit area V on the angle γ when simulation of cutting with a SCh20 cast iron cutter of a sample from brass L63: 1 – t_{nom} = 0.6 mm; 2 – t_{nom} = 0.4 mm

As follows from the above results, the angle γ has a significant effect on the depth of cut, the radius of curvature of the cutting edge, and therefore will affect the pattern of interaction of the contacting surfaces during micro-cutting.

The obtained experimental data and simulation results made it possible to present contact interaction schemes of the tool with the machined surface for various angles *γ* at FANT at the stage of micro-cutting, as well as establish the basic laws of their parameters (Table 1).

Table 1

Typical micro-cutting patterns at FANT for various angles γ

Angle *γ*, degrees	Micro-cutting process scheme	Established dependencies
5		$t_f = 0.57t_r$ $r = 0.43t_r$
0		$t_f = 0.25t_r$ $r = 0.75t_r$
–5		$t_f = 0.1t_r$ $r = 0.9t_r$
–10		$t_f = 0.083t_r$ $r = 0.917t_r$

Note: t_r – total thickness of the processed layer; t_f – actual cutting depth; *r* – blunting radius of the cutter tip.

The presented analysis of the characteristic micro-cuting schemes during FANT by the friction-mechanical method made it possible to recommend the initial surface microrelief for applying an antifriction coating with the following parameters: φ_1 = 95°; φ = 30° at S = 0.1…0.175 mm/rev (Fig. 9).

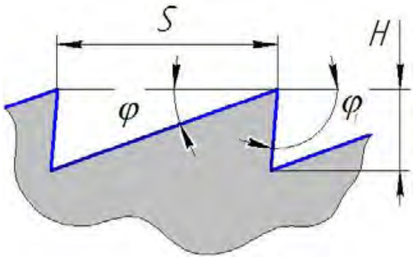


Fig. 9. Recommended shape of the initial surface of the microrelief before applying the FANT coatings by friction-mechanical method

This shape and size of the microrelief will create favorable conditions for micro-cutting of antifriction material with microprotrusions of the initial surface, thereby improving the quality of coating formation by the friction-mechanical FANT method.

Conclusions

Based on the above material, the following main conclusions are formulated:

– at a constant thickness of the processed layer t_r, the micro-cutting scheme remains geometrically similar and depends only on the cutting front angle γ;

– with a decrease in the cutting front angle γ the blunting radius of the cutting edge r increases, the actual cutting depth t_f, and consequently the volume of microchips, decreases;

– the ratio of the blunting radius of the cutting edge r to the total thickness of the processed layer t_r depends only on the cutting front angle γ;

– with an increase in the total thickness of the treated layer t_r, the blunting radius of the cutting edge r increases proportionally, i.e. the dimensionless blunting radius of the cutting edge $\bar{r} = \frac{r}{t_r}$ remains constant and depends only on the cutting front angle γ: $\bar{r} = \bar{r}(\gamma)$;

– a decrease of the cutting front angle γ contributes to the strain hardening of the rubbed material, which significantly affects the micro-cutting process by increasing the tension in the curved section of the rear surface;

– in order to intensify micro-cutting, and therefore to obtain a high-quality FANT coating, single microroughnesses of the treated surface should have a cutting front angle of $\gamma \geq 0°$.

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