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Justification of the microcutting scheme in the friction-mechanical method of applying anti-friction coatings

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Abstract

A review of modern approaches to substantiating the patterns of anti-friction coating formation during friction-mechanical application has made it possible to establish the importance of ensuring favourable conditions for microcutting of anti-friction material. Creating these conditions requires studying the interaction scheme of microirregularities in the contact zone between the tool and the part. From the point of view of cutting mechanics, a scheme of interaction of a single micro-irregularity, which is a model – a cutter made of 200 gray cast iron, with a contact surface made of anti-friction material – brass L63, was constructed, which made it possible to establish physical changes in the tool and machined surface system. The value of the front cutting angle has been theoretically established to ensure maximum efficiency of the microcutting process and filling of microcavities between microirregularities. The use of a model experiment, the method of similarity and dimensions made it possible to confirm the main theoretical regularities obtained using characteristic microcutting diagrams. It has been shown that the process of changing the geometry of the micro-irregularity vertex occurs in accordance with the principle of adaptability of the entire 'tool-part' system, according to which the minimum micro-cutting energy is realised. The results obtained are an important reserve for improving the quality of anti-friction coating application by the friction-mechanical method.

Keywords: anti-friction coating, final anti-friction non-abrasive treatment, microcutting, micro-irregularity interaction diagram, cutting angle, microchips, microcutter

Introduction

Numerous studies have shown that in order to increase reliability and service life, it is necessary to ensure that the working surface of a part has a protective coating in accordance with its intended use and operating conditions [1, 2, etc.].

Among the simplest, most effective and environmentally friendly methods of obtaining coatings, it is worth highlighting a group of technologies for finishing anti-friction non-abrasive treatment (FANT), which is implemented through the frictional interaction of the processing tool with the surface of the part being processed [3]. It has been proven that the use of FANT technology improves the characteristics of the working surface: it reduces the running-in time and friction coefficient and increases the load-bearing capacity of the part and connection [4].

The quality of FANT antifriction coating formation is determined by the conditions of contact between the tool and the machined surface and depends on the completeness of physical contact and activation of contact surfaces [5]. Among the main channels of activation, in the performance of which depends on the formation of quality antifriction coating, should be highlighted as follows: mechanical, chemical, thermal and channel associated with plastic deformation. These channels are closely connected with each other and are simultaneously involved in the formation of antifriction coating during friction-mechanical contact.

A number of factors affecting the final results of FANT should also be considered [6]:

- the adhesive tendency between the applied material and the surface to be treated;

- structural and phase composition of the treated surface;
- initial quality of the treated surface;
- friction and wear conditions.

However, in our opinion, a number of processes accompanying FANT require clarification and deeper study.

In particular, there is no consensus on the values of the initial roughness of the treated surface, which determines the conditions of contact with the antifriction material. At the same time, the surface roughness obtained by FANT is one of the main criteria of coating quality [6, 7, etc.].

Thus, studies of the contact interaction of surfaces and the processes occurring during FANT seem to be very relevant. Establishment of the basic regularities of the processes at this process will allow to increase the quality of the coating, and hence the operational properties of the part.

Literature review

There are a number of approaches that allow us to understand the mechanism of formation of antifriction coating at the friction-mechanical method of FANT implementation [8, 9, etc.]. The authors of the presented works agree that it is necessary to create a number of conditions and achieve certain criteria to obtain a high-quality antifriction coating. Such mandatory conditions and criteria should include: the conditions of micro-cutting and plastic contact; the criterion of seizure and achievement of optimal modes of coating application.

Considering the stages of the process of frictional transfer of antifriction material the authors of works [8, 9] note the presence of:

- plastic pushing away of the initial material, carried out by the microroughnesses of the surface, on which the coating is applied, passing to destruction by micro-cutting;
- adhesion of the particles formed as a result of micro-cutting with the surface to which the transfer takes place.

Microscopic analysis of the particles contained in the contact zone ‘friction rod - machined surface’ showed the presence of chip microparticles, which indicates that the process of micro-cutting [8].

Realisation of the specified conditions of micro-cutting is associated with certain requirements to the microroughness of the contacting surfaces, which can be described by the following dependence [9]:

$$\frac{2h_i}{r} = 1 - \frac{2\tau_n}{\sigma_T} \leq 0{,}02 \,, \tag{1}$$

where h_i – is the height of a single microroughness;

r – is the radius of rounding of the top of a single microroughness;

τ_n – is the tangential component of the adhesive bond strength;

σ_T – is the yield strength of the brass rod.

The model of applying FANT anti-friction coating is discussed in detail in the works of German researchers [10], where it is stated that at the initial moment of tribointeraction, the process of microcutting of copper alloy prevails. The authors note the following processes occurring on contact surfaces:

- the Rebinder effect with adsorption plasticisation and an increase in the positive strength gradient during shear in the friction zone;
- transfer of more plastic metal to a harder substrate due to microadhesion;
- the Kirkendall effect (diffusive) with selective dissolution of alloying elements due to the potential difference;
- deposition of copper particles and ions by an electrochemical process activated tribochemically;
- formation of organometallic compounds with a surface-active environment and catalytic effect of copper.

Analysis of experimental data and theoretical description of the coating formation process has revealed tool wear and material transfer, which is characteristic of microcutting with surface roughness of the workpiece. However, there is no consensus on the optimal value of this roughness parameter. Thus, the authors of works [11, 12] indicate the formation of a high-quality anti-friction coating at an initial surface roughness value of Ra from 0.08 μm to 3.4 μm, and in some cases significantly higher [13].

In our opinion, the process of coating formation by the FANT friction-mechanical method is quite complex and requires in-depth research. Analysis of the literature on this issue reveals different approaches to explaining the mechanism of coating formation. At the same time, despite different approaches and views, the authors agree on the importance of ensuring the necessary conditions for microcutting of anti-friction material. Creating these conditions requires research into the interaction of micro-irregularities to better ensure microcutting of anti-friction material.

Purpose

The aim of the work is to clarify the scheme of interaction of micro-irregularities at the micro-cutting stage using the friction-mechanical method of applying anti-friction coatings.

Research Methodology

The theoretical and experimental studies of micro-cutting are based on the method of the theory of similarity and dimensionality [14], in accordance with which the miro cutters made of 200 gray cast iron (Fig. 1), the geometry of the cutting part of which modelled a separate microroughness of the surface of the processed workpiece, were manufactured.

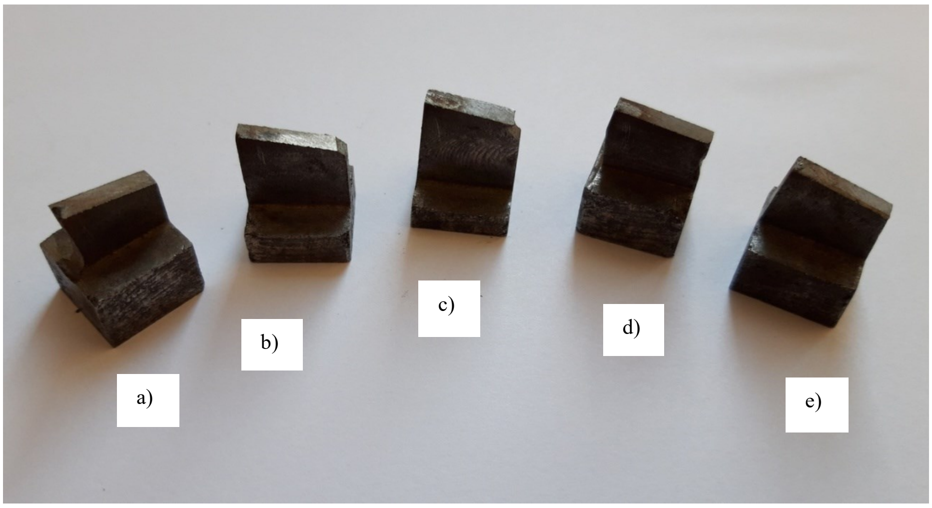


Fig. 1. Micro-cutters from the value of the front cutting angle γ: a) +5°; b) 0°; c) -5°; d) -10°; e) -15°

The interaction scheme of contacting surfaces during the model experiment is shown in Fig. 2.

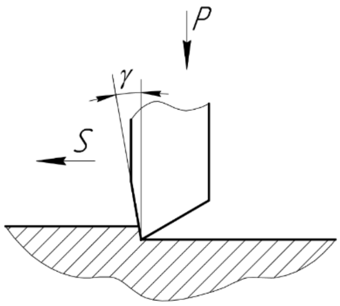


Fig. 2. Surface contact diagram in microcutting modelling: *P* – micro-cutter force; *S* – microcutter feed

Simulation of the microcutting process during the application of anti-friction coatings using a friction-mechanical method was performed using the proposed device (Fig. 3).

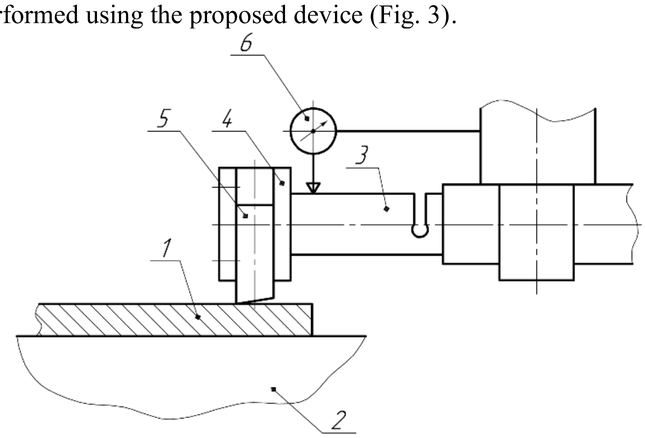


Fig. 3. Microcutting research setup: 1 – sample made of anti-friction material; 2 – machine table; 3 – microcutter mounting device; 4 – mounting head; 5 – replaceable microcutter; 6 – indicator head

In accordance with the diagram presented (see Fig. 3), the test sample 1 made of anti-friction material was rigidly fixed on the work table 2 of the milling machine. Device 3 with head 4, to which a replaceable micro-cutter 5 made of 200 gray cast iron is attached. A magnetic stand with indicator head 6 is provided to fix the pressure of the anti-friction sample against the surface being machined on the machine. Microcutter 5, which simulates a separate micro-irregularity, was pressed against the outer edge of sample 1. The load on microcutter 5 was provided by the vertical feed mechanism of the machine table, which was controlled by indicator head 6. The simulated microcutter, moving under load, cuts off a layer of the sample made of anti-friction metal (brass), thereby imitating the microcutting process in the friction-mechanical method of applying anti-friction coatings.

Results

To clarify the main patterns that occur when a single micro-irregularity interacts, let us consider in detail the interaction scheme of a 200 gray cast iron with the surface of a sample made of anti-friction material (Fig. 4).

The cutting wedge contour consists of the following parts:

AB – a straight part of the front surface contour, sharpened with a front angle $\gamma > 0$;

BC – a rounded part of the front surface, in which $\gamma < 0$;

CD – a rounded part of the rear surface contour, in which the rear angle $\alpha < 0$;

DE – part of the contour of the rear surface, formed as a result of its wear;

EF – part of the straight 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 restoration, since the value of elastic restoration of the processed material $d_{el} << d_{pl}$.

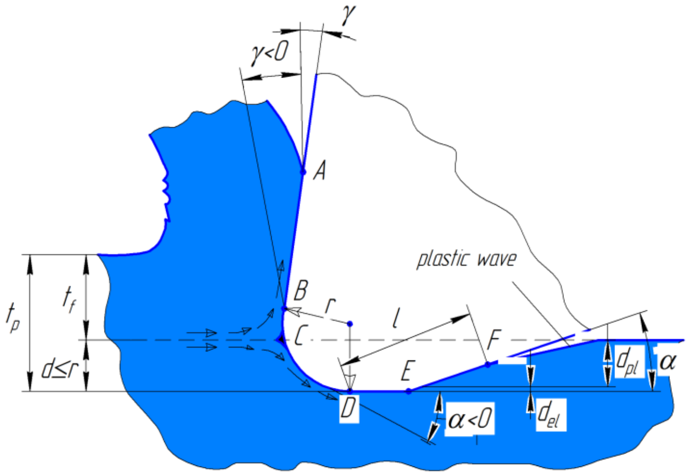


Fig. 4. Schematic representation of the interaction between a single micro-irregularity and the machined surface during micro-cutting

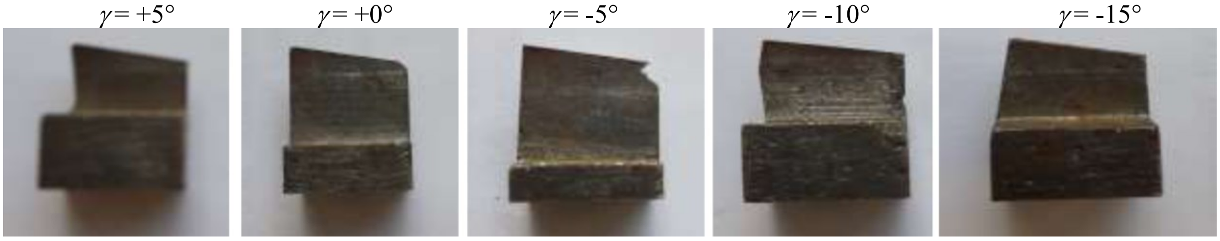
Thus, the front surface of the cutting wedge consists of two parts $L = AB + BC$, and its rear surface with a length of L_1 consists of the following parts $L_1 = CD + DE + EF$. Point *C* corresponds to the section of contact between the material being processed and the front and rear surfaces of the wedge.

The workpiece material flowing onto the cutting wedge at point *C* is divided into two streams, one of which moves along the front surface of the tool, and the second layer, with a thickness of *d*, is deformed by the rear surface of the cutting wedge. In this case, the actual cutting surface passes through point *C*, and the actual cutting depth t_f does not coincide with the nominal thickness t_p of the surface cut. Thus, point *C* will be the dividing point of the entire removed layer with a thickness t_p, namely: the layer of material that goes into microchips, with an actual cutting depth t_f, and the layer that is processed by surface plastic deformation by the radial section of the rear surface. Its value is $d \le r$, i.e. $t_p \sim t_f + r$, where r is the radius of the tool tip blunting, which changes during operation, especially in the initial period of operation.

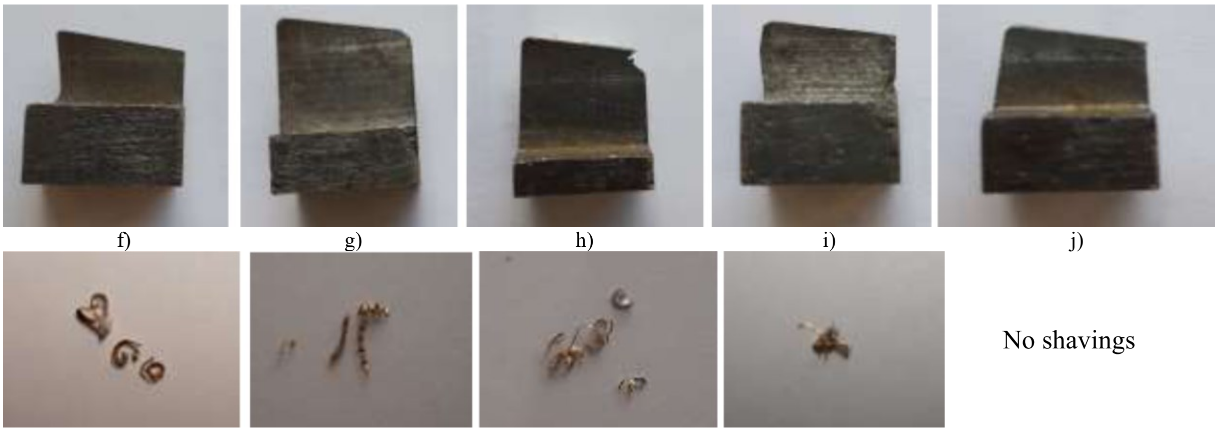
In the chip formation zone, plastic deformation of the material occurs, preceded by elastic deformation. It leads to the lowering of the layer of material located below the surface cut. After the micro-cutter passes, the load is removed, and this layer elastically recovers, returning to its original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

Modeling the FANT process using microcutters (Fig. 5, a-e), each of which should be considered as a separate micro-irregularity, allowed us to establish the following.

$\gamma = +5°$ $\gamma = +0°$ $\gamma = -5°$ $\gamma = -10°$ $\gamma = -15°$



a) b) c) d) e)



k) l) m) n) o)

Fig. 5. View of the cutting part of a micro cutter before processing (a-e) and after processing (f-j), as well as chip formation by different micro cutters (k-o)

The cutting blade of a cast iron micro-cutter wears out intensively during interaction with a brass surface, and this occurs at the very beginning of its operation. The process of changing the geometry of the cutter tip occurs in accordance with the principle of adaptability of the entire "cutter-part" system [7], according to which the minimum energy of microcutting is realized. A detailed examination of microcutters after processing shows the formation of a blunt cutting edge (Fig. 5, f-j). It is also worth noting the patterns of chip formation when using micro-cutters with different cutting angles (Fig. 5, k-n). Moreover, at a front cutting angle of γ = -15°, there are no chips at all (Fig. 5, o).

Photographs of the roots of the chips (Fig. 6, a) also confirm the statement that the greatest thickness of the cut layer is observed at an angle of γ= +5°. At γ = 0°, the thickness of the cut layer decreases significantly (Fig. 6, b), and the smallest thickness of the cut layer is observed at an angle of γ = -5° (Fig. 6, c).

a) b) c)

Fig. 6. Micro-chips obtained during micro-cutting at different front cutting angles γ: a) –γ= +5°; b) – γ= 0°; c) –γ= -5°, increase × 50

To quantitatively assess the effectiveness of microcutting in FANT, the term "volumetric efficiency of microcutting" η, is used, which is determined by the following relationship:

$$\eta = \frac{t_f}{t_p} = \frac{t_f}{t_f + r} . \quad (2)$$

The proposed dependence allows determining the volumetric efficiency of microcutting η (Fig. 7) and proving the effectiveness of microcutting at positive angles γ.

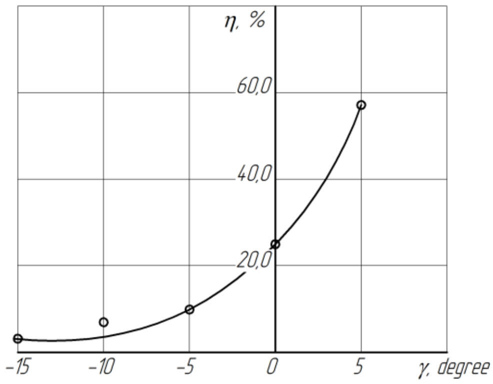


Fig. 7. Dependence of the volumetric efficiency of microcutting η on the angle γ

The experimental data obtained made it possible to present diagrams of the interaction between the tool and the machined surface at different angles γ (Fig. 8).

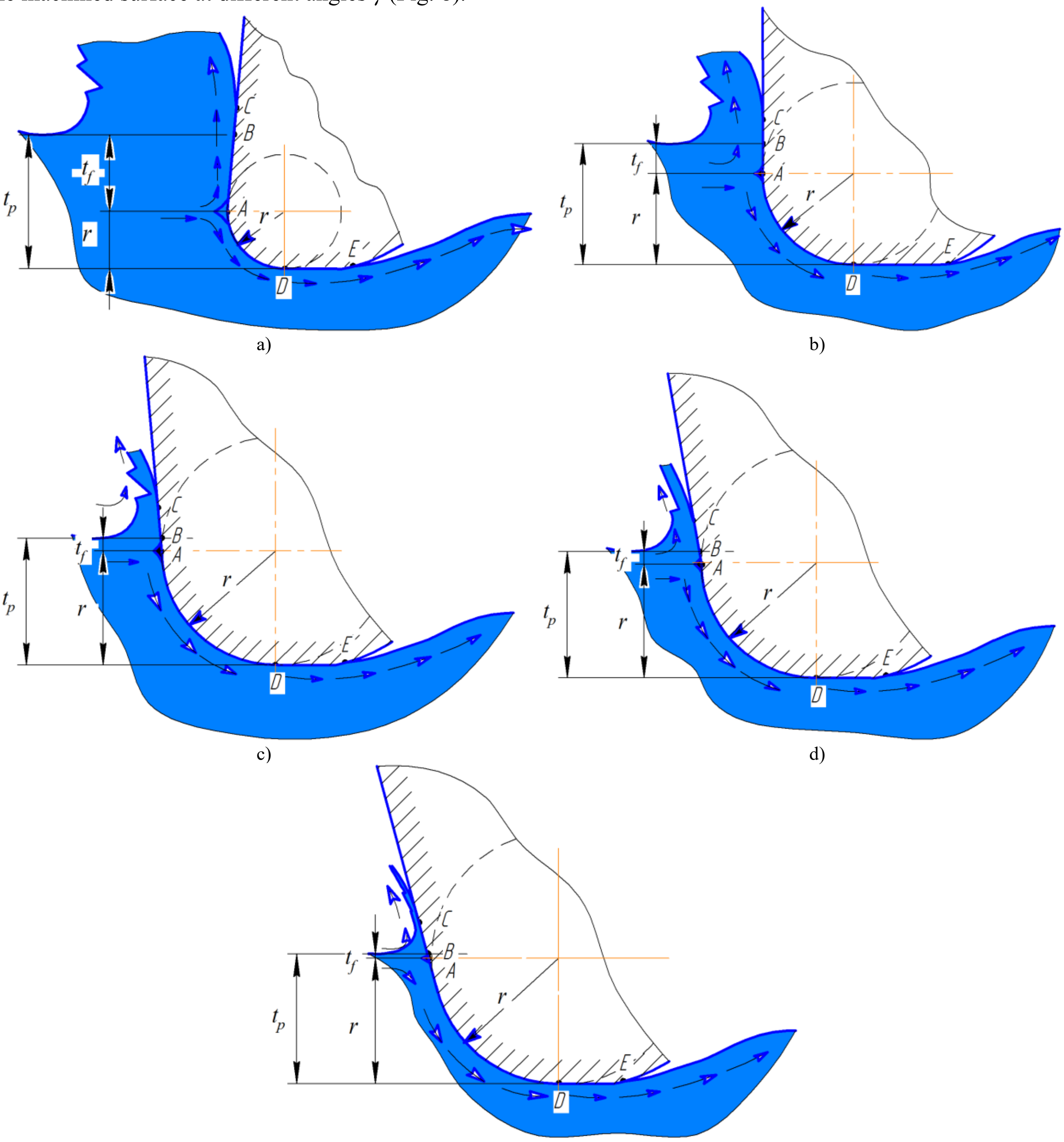


Fig. 8. Characteristic microcutting patterns for FANT at different angles γ: a) –γ= +5°; b) – γ= 0°; c) –γ= -5°; d) –γ = -10°; e) –γ= -15°

Analysis of the proposed microcutting schemes at different front cutting angles (Fig. 8) allowed us to establish the following patterns.

At γ= +5° (Fig. 8, a), the following relationship between the thickness of the anti-friction material cut is observed:

$$t_f = 0,57t_p\,;\; r = 0,43t_p\,. \tag{3}$$

For an angle γ= 0° (Fig. 8, b), the following is characteristic:

$$t_f = 0,25t_p\,;\; r = 0,75t_p\,. \tag{4}$$

For angle γ = -5° (Fig. 8, c), the following is determined:

$$t_f = 0,1t_p\,;\; r = 0,9t_p\,. \tag{5}$$

For an angle γ= -10° (Fig. 8, d), it has been established that:

$$t_f = 0,083t_p\,;\; r = 0,917t_p\,. \tag{6}$$

For angle γ= -15° (Fig. 8, e):

$$t_f = 0,032t_p\,;\ r = 0,968t_p\,. \tag{7}$$

Thus, a series of theoretical and experimental studies has made it possible to establish a scheme of interaction between micro-irregularities at the micro-cutting stage during FANT and to recommend a value for the front angle γ to ensure maximum efficiency of the micro-cutting process and filling of micro-pits between micro-irregularities.

Conclusions

On the basis of theoretical and experimental studies of the micro-cutting process, which is considered as the first stage of FANT, the following conclusions are formulated:

1. Schemes of interaction between the tool and the machined surface at FANT at the micro-cutting stage at different cutting angles have been obtained, which made it possible to study the main regularities of chip formation.

2. Theoretically proved and experimentally confirmed the feasibility of obtaining microrelief with the value of the cutting angle $\gamma \geq 0°$. The most efficient micro-cutting process is carried out at $\gamma = +5°$.

3. It has been established that when micro-irregularities interact with a brass tool, a blunt micro-irregularity tip with a rounding radius is formed almost immediately, which subsequently remains virtually unchanged.

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Шепеленко І.В., Немировський Я.Б., Черновол М.І., Красота М.В., Василенко І.Ф.
Обґрунтування схеми мікрорізання при фрикційно-механічному методі нанесення антифрикційних покриттів

Огляд сучасних підходів до обґрунтування закономірностей формування антифрикційного покриття при фрикційно-механічному їх нанесення дозволив встановити важливість забезпечення сприятливих умов для мікрорізання антифрикційного матеріалу. Створення цих умов вимагає дослідження схеми взаємодіїї мікроонерівностей в зоні контакту «інструмент – деталь». З позиції механіки різання побудована схема взаємодії одиничної мікронерівності, що являє собою модель – різець із чавуну СЧ20, з контактуючою поверхнею з антифрикційного матеріалу – латуні Л63, що дозволило встановити фізичні зміни в системі інструмент і оброблювана поверхня. Теоретично встановлено значення переднього кута різання для забезпечення максимальної ефективності процесу мікрорізання і заповнення мікровпадин між мікронерівностями. Використання модельного експерименту, методу теорії подібності та розмірності дозволило підтвердити основні теоретичні закономірності, отримані за допомогою характерних схем мікрорізання. Показано, що процес зміни геометрії вершини мікронерівності відбувається відповідно до принципу пристосовності всієї системи «інструмент – деталь», відповідно до якого реалізується мінімум енергії мікрорізання. Отримані результати є важливим резервом для підвищення якості нанесення антифрикційного покриття фрикційно-механічним методом.

Ключові слова: антифрикційне покриття, фінішна антифрикційна безабразивна обробка, мікрорізання, схема взаємодії мікронерівностей, кут різання, мікростружка, мікрорізець