Experimental quality improvement of the application of antifriction coating

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Abstract. The paper presents studies aimed at improving the quality of the application of antifriction coatings by finish antifriction non-abrasive treatment (FANT). It is proved that one of the conditions for the formation of a high-quality anti-friction coating is the targeted formation of favorable shapes and sizes of microroughnesses in the operations preceding the coating. The effectiveness of the use of turning when substantiating the creation of the necessary shapes and sizes of microroughness is justified. A procedure for applying an antifriction coating by a friction-mechanical method is proposed, which allows multiple studies on one specimen. For the adopted processing scheme by using the developed devices and methods, the relationship between the geometrical parameters of the micro-relief and the quality parameters of the coating is established, this make it possible to improve the quality of the application of antifriction coatings by FANT.

1. Introduction

The priority of improving the work or contact surfaces quality of different machine parts is to develop antifriction coatings. To ensure a high quality surface layer, it is necessary to orient a perspective direction using combined processes, which gives the advantages of surface modification and coating application \cite{1,2}. From the various methods of obtaining antifriction coatings, those with optimal values of hardness and modulus of elasticity and high antifriction properties are preferred to ensure a favorable internal stresses and maximum adhesion characteristics of the coating with the base material \cite{3}. This kind of coating could be obtained by friction rubbing ductile metals by finishing antifriction non-abrasive treatment (FANT) \cite{4,5}. This process is characterized by environmental cleanliness, reduction the running-in time of the parts, elimination of scratches on friction surfaces, increasing the bearing capacity of the parts and joints, protecting the friction surface from hydrogen wear, reduction the friction temperature and prolonging the friction unit operation time when turning off the lubrication supply. Additionally, it reduces the friction coefficient of the processed surface. However, the use of traditional FANT technologies neither provides sufficient adhesion of the coating with the base material nor strengthening the surface of the parts. Therefore it improves the wear resistance during a long time operation. The quality of FANT can be improved by applying new schemes of process implementation, including the use of the surface plastic deformation methods \cite{6}.

Roughness of the substrate influences the practical adhesion of the coatings, especially for coatings with high residual stresses \cite{7,8}. Roughness plays a critical role in determining how the coating
interacts with its environment. Rough surfaces usually wear more quickly and have higher friction coefficients than smooth surfaces [9].

Podogornik et al. [10] concluded that polishing of the substrate prior to coating deposition lowers the friction and increases the critical load of material transfer. However, a post-polishing of a ground and coated surfaces gives the same or even better galling properties as compared to the finest substrate polishing. Siu and Li [11] found that wear resistance was greatest when a coating thickness of 1 μm was used and when the substrate surface roughness (Ra) was 0.1 μm or below.

Others studies [12-14] have proved that the formation of high-quality antifriction coating by FANT depends on an interaction of four channels of contact surfaces activation: mechanical, chemical, thermal, and plastic deformation factor. Coating roughness, thickness and continuity are the criteria that can be taken to estimate the quality of the obtained antifriction coating.

At the same time, the authors of [15,16] took the surface roughness obtained by FANT as the main criterion for assessing the quality of the coating, while [17] considered that the quality of the coating significantly depends on the base material and the initial surface roughness.

Garkunov [18] found that in order to ensure high quality of the coating and improving the process productivity (the least number of tool passes) the parameter Ra (the arithmetic mean roughness) should have values not lower than 1.25 μm. In this case, sharp shapes of micro-asperities are formed on the part surface, and the tool wear leads to form a continuous coating. When Ra <0.3 μm the penetration of the tool material into the valleys is hampered by the fact that the process of a tool micro-cutting with a part is replaced by plastic press back, as a result the tool wear rate decreases, a gradual cold-work hardening of the tool material takes place to a considerable depth, the separation of individual particles and their transfer to the part become more difficult. The coating in this case is not continuous, which indicates a low quality surface.

In works [15,17] it has been indicated that to ensure the quality of the copper layer over the entire height of the micro-asperities, their maximum height Rmax after pretreatment should be no more than 15 μm. While 0.08 μm <Ra <1.5 μm must be indicated for stable formation of the antifriction layer. Moreover, in the contact zone (friction block – treated surface) micro-cutting process must take place.

In order to obtain a high-quality coating by friction rubbing of copper, Kuzmenko [19] performed optimization of the initial surface roughness. The author analyzed the change in the average deviation of the asperities values (∆=Rap=Rap, where Rap and Rave are the specimen roughness after and before rubbing, respectively) of the specimen, on the basis that the higher the ∆ value, the higher the surface roughness. Moreover, the greater the difference between the surface and the ideally smoother one, the greater the possibility of its deformation and the continuous copper layer is obtained at Ra = 3.4 μm value.

In the work of Shepelenko et al. [20], the surface roughness was determined before and after FANT coating with additional tool vibration. It was established that at initial surface roughness of the specimen (Ra = 12.5 μm) and coating porosity increased by approximately 3 to 4 times compared with the coating porosity obtained on specimens with initial roughness of Ra = 0.63 μm.

Litvinov et al. [21] found that at the initial roughness of the steel specimen with parameters of 0.16 μm <Ra <0.32 μm, the optimal conditions could be achieved for implementation of the selective transfer mode in a pair of copper alloy-steel in glycerin, and repeated deformation of the specimen surface layer made of copper alloy by more rigid micro-roughness of steel specimen plays a significant role in the formation of the copper coating.

To obtain a high-quality coating by FANT on surfaces having a surface roughness of Ra = 40-320 μm, Garkunov [22] succeeded through treating the peripheral portion of a brass roller freely rotating around the axis that makes 75°-80° with the part axis. In this case, the roller gets rotation due to friction against the part, rubbing the workpiece. On its working surface, reciprocal micro-reliefs are formed, which easily penetrate the valleys of the asperities and perform rubbing along them.

It should be noted that very contradictory information was presented on the influence of the initial surface roughness on the formation of a high-quality coating by FANT process [23,24]. Thus, Prikhodko [23] indicated that the surface roughness of specimens (prepared for FANT Ra=0.25 – 0.32
µm) remains practically unchanged after FANT. While Chelyubeev [24] experimentally established that FANT reduces the surface roughness parameter of specimens from Ra = 0.25 µm to Ra = 0.13 µm, due to peaks smoothening during treatment and filling the valleys of the micro-asperities with brass particles.

Based on literature survey analyses, it should be noted that almost all researchers used only one average roughness parameter (Ra) for determining the influence of machined surface initial roughness on the formation of an antifriction coating. So, there is no consensus about the optimal value of this parameter. The authors of works [18-20,23,24] indicated that high-quality antifriction coating formed at initial surface roughness (Ra) ranged from 0.08 µm to 3.4 µm, while in work of Garkunov [22] the roughness was found much higher.

In our opinion, the influence of the initial roughness of the previously machined surface on the formation of antifriction coating FANT is not sufficiently studied. In addition using only one parameter Ra (average roughness deviation) does not give a complete picture of the surface micro-relief, which largely depends on the processing type. Therefore, when turning (most often used before applying antifriction coating), the shape and dimensions of the machined surface residual peaks and valleys are largely determined by the cutting tool geometry in terms of plan approach angles and its cutting feed ratio. Based on the above mentioned, it can be concluded that it is necessary to conduct special studies on the influence of the asperities shape and dimensions on the formation of an antifriction coating obtained by FANT.

So the aim of this work is to study the influence of the micro-roughness shape and dimensions, obtained in previous operations, on obtaining high-quality antifriction coating by FANT method.

2. Materials and research methodology

Experimental studies of applying a metal layers coating by FANT were carried out on a disc-shape gray cast iron (CЧ 20) specimens (see Table 1), which is the basis for special modified cast iron liners of internal combustion engines. As seen in Table 1, copper (М1), brass (Л63) and bronze (ОЦС 5-5-5) were used as a rubbing material for antifriction coating. The choice of these materials for coating is due to the fact that it is these copper-containing materials that best realize the selective transfer during friction [5]. To study the effect of the shape and dimensions of the micro-roughness of the base surface on the antifriction layer formation process on the disc surface, regular micro-reliefs were previously created.

The shape and dimensions of the machined surface micro-roughness are determined, first of all, by the single point tool (SPT) geometry and its cutting feed ratio. Therefore, in order to obtain the microroughnesses of the surface of the studied samples with different sizes and shapes of protrusions and troughs, we initially selected the values of the main (φ) and auxiliary (φ₁) angles of the cutter in plan, its radius (r) and the transverse feed (S) of the cutter.

It is known that oils and oxide films on the part surfaces prevent the adhesion of metals during friction [25]. Therefore, the surfaces which will be applied with antifriction metal coating must be degreased and cleaned from the oxide films. Based on this, 12% HCl solution in glycerin was used as catalyst, which was applied with a brush on the investigated specimen surface during friction rubbing by FANT. The process of applying an anti-friction coating was carried out using the developed device mounted on a mode milling machine 676P, the working area and diagram of which are shown in figure 1 a, b [26].

The studied specimen 1 in the form of a disk with a ground supporting end was rigidly fixed by using bolt 2 on the milling machine table 3. The device 4 with the head 5, on which the anti-friction block 6 is fixed, was motionlessly mounted with a mandrel 7 in the vertical machine headstock 8. To fix the pressing force of the anti-friction block to the treated surface, a magnetic stand with an indicator head 9 was used.
Table 1. Chemical compositions of gray cast iron СЧ 20, copper М1, brass Л63, and bronze ОЦС 5-5-5 materials in %.

|                   | С    | Si  | Mn  | S   | P   | Fe    |
|-------------------|------|-----|-----|-----|-----|-------|
| Gray cast iron (СЧ 20) | 3.3-3.5 | 1.4-2.4 | 0.7-1 | Up to 0.15 | Up to 0.2 | Around 93 |
| Copper (М1)        | Fe   | Ni  | S   | As  | Pb  | Zn    | O     | Sb  | Bi  | Sn  | Cu+Ag |
|                   | Up to 0.005 | Up to 0.002 | Up to 0.004 | Up to 0.002 | Up to 0.005 | Up to 0.004 | Up to 0.002 | Up to 0.002 | Up to 0.002 | min
| Brass (Л63)       | Fe   | P   | Cu  | Pb  | Zn  | Sb   | Bi    | Impurity |
|                   | Up to 0.2 | Up to 0.01 | 62-65 | Up to 0.07 | 34.22-37.5 | Up to 0.005 | Up to 0.002 | 0.5 |
| Bronze (ОЦС 5-5-5) | Sn   | Zn  | Pb  | Cu  |     |      |       |         |
|                   | 4.0-6.0 | 4.0-6.0 | 4.0-6.0 | remain |      |      |       |         |

![Figure 1](image1.png)

**Figure 1.** Developed device for applying anti-friction coatings by FANT: a - the device working area; b - anti-friction coating scheme [26]

Before coating application, the machine table was installed relative to the axis of the head, so that the direction of the table longitudinal movement ensured the orientation of the antifriction block to the center of the specimen. The end face of the antifriction block was pressed against the outer edge of the disc investigated surface. The load on the antifriction block was provided by a vertical feed mechanism (P) of the milling machine table and controlled with the indicator head 9.

Antifriction coating was applied to the machined surface, surface-active medium, through manually longitudinal movement of the milling machine table. In this case, moving under load, the antifriction block left a trace in the form of a path on the investigated surface, the path width corresponds to the width of the contact end of the antifriction block.

For coating under other conditions (change the load on the antifriction block, base material, and coatings, etc.), it is enough to rotate the specimen relative to the axis at a certain angle, which will
provide a new area for the coating and then repeat the operation. This technique provides multiple use of one specimen while maintaining the information obtained from previous experiments.

Coating was carried out on a previously machined surface by using turning SPT with main plan approach angle (ϕ) and auxiliary plan approach angle (ϕ₁) = 45° at different feeds, providing a micro-relief pitch (t = 0.05, 0.10, 0.15 and 0.175 mm), and also taking into account the recommendations set forth in [26]. The pressing force of the anti-friction block to the treated surface (P) was 82.4 N, 164.6 N and 245.2 N, which corresponds to a nominal contact area of the tool with the work surface (a × b = 18 mm²) of contact pressure (q - 4.6 MPa, 9.2 MPa; 13.6 MPa).

Quality assessment of the coating was carried out after one pass of antifriction block on a treated surface. The thickness of the antifriction coating was determined by the micrometric measurement of specimen method before and after FANT, while Coating continuity was determined based on the results of metallographic analysis by using digital image processing methods on a personal computer. Micro-relief roughness was studied before and after FANT by using the profilograph–profilometer (Taly surf-5). Studies of the topography, coating structure and base surface were performed on the metallographic microscope (MIM-7) and (Altami), and also on an electron microscope-microprobe (Camscan-4DW).

3. Results and Discussion
In practice, before applying the antifriction film coating, turning is widely used, which ensures the formation of a regular microrelief with a regular alternation of residual protrusions and troughs of micro-roughnesses. Therefore, the shape and dimension of the micro-roughnesses are influenced by the cutting tool geometry, cutting variables, process rigidity (machine - tool - workpiece), etc. Of these factors, the cutting edge geometry (in terms of the main and auxiliary plan approach angles, nose radius) and cutting feed ratio have the greatest influence on the shape and dimension of micro-asperities, which can be changed depending on the requirements of antifriction coating.

According to the purpose of our work, the influence of the shapes and dimensions of the surface micro-roughnesses, previously obtained by turning operation, on the formation of antifriction metal layer when the antifriction block is moved relative to the direction of the created micro-roughnesses was carried out.

The shape and dimensions of the micro-roughnesses supplement the micro-relief surface characteristic formed by turning operation. Thus, the shape of the residual protrusions and troughs was determined by the forming shape of the SPT nose, which can be: sharp (a), blunt (b), partially with radius and straight segments (b), and only with radius (g) as shown in figure 2. The dimensions and areas of the protrusions and troughs depend on the SPT main and auxiliary plan approach angles (ϕ, ϕ₁) respectively, width (b) of radius (r), and cutting feed ratio (S). So, to calculate the area of the troughs between adjacent protrusions, in addition to the cutting feed ratio (S), it is enough to know the depth of the troughs (H).

Troughs depth (H) for two cases has been calculated by using the following equations [27]:

SPT with sharp nose:

\[ H = \frac{\tan \phi \times \tan \phi_1}{\tan \phi + \tan \phi_1}, \text{mm} \]  \hspace{1cm} (1)

Micro-profile formed only with radius:

\[ H = r - \sqrt{r^2 - \frac{S^2}{4}} \quad \text{or} \quad H = \frac{S^2}{2r}, \text{mm} \]  \hspace{1cm} (2)

Where: H– Valleys depth of the micro-roughnesses, mm;
S – Cutting feed ratio, mm/rev;
ϕ, ϕ₁ – Main and auxiliary plan approach angles, respectively;
r – Troughs radii of the micro-roughnesses.
Figure 2. The shape of the residual protrusions and troughs of the machined surface after turning with inserted SPT: a) sharp nose; b) blunt nose; c) partially with radius and straight line segments nose; d) nose only with radius

From equations (1, 2) it could be noted that the smaller the troughs of \((S, \varphi \text{ and } \varphi_1)\) and the larger the radius \((r)\), the smaller the depth of the trough \((H)\) will be and vice versa.

Analysis of the micro-roughnesses scheme on the prior coating operation (figure 2) and the physics of the FANT process allowed us to observe the following:

Since the residual peaks, regardless of the shape of the SPT cutting part, always have a wedge-shape with a sharp edge, each of them can be considered as a separate cutting wedge;

The spaces between the residual peaks and troughs should be considered as grooves for chip placement, which are formed during the interaction of the antifriction tool material with the base surface.

In order to ensure the micro-cutting process of the tool cutting part, which has wedge shape, it must penetrate deeply into the cutting layer. Otherwise only their mutual crushing may exist and the micro-cutting process will not take place. Since the cutting edge will experience heavy loads, the material of this edge must meet a number of requirements, where the hardness and strength are the most important factors. Consequently, when applying an antifriction coating by rubbing, the hardness and strength of the base materials should exceed the mentioned parameters of antifriction materials. The applying process of the antifriction coating by a friction-mechanical method will also be accompanied by the process of cutting the antifriction material. Thus, the antifriction material will fill the pre-formed micro-roughnesses in the form of chips, so the shape and dimension of these roughnesses affect the formation of the coating layer.

The first experiments conducted to answer the following question: is it possible to apply antifriction metal coating on a specimen made of iron СЧ 20 containing graphite at low speed and temperature of the rubbing process? Thus, various antifriction coatings (bronze (ОЦС 5-5-5), brass (Л63), copper (М1)) were successively applied to gray cast iron СЧ 20 specimen, across pre-formed micro-roughness of the base material (figure 3).

After passing the antifriction block on the surface of the specimen, the trace of investigated antifriction materials is formed, regardless of their composition (bronze (ОЦС 5-5-5), brass (Л63), copper (М1)) as shown in figure 3. This phenomenon indicates that particles of antifriction coating material penetrate into the base surface; this confirms possibility of antifriction layer formation on the cast iron base surface at low speed and temperature of the rubbing process.

Subsequent investigations were associated with a quality study of the coating anti-friction application (bronze “ОЦС 5-5-5") by FANT.

Figure 4 shows fragments of the cast iron СЧ 20 specimen surface with an antifriction coating (bronze “ОЦС 5-5-5") obtained with different treatment pitch.
Figure 3. Gray cast iron (СЧ 20) specimen with antifriction coatings; base metal micro-relief pitch \((t = 0.05 \text{ mm})\); SPT cutting edge geometry in terms of \((\varphi = \varphi_1 = 45^\circ)\); contact pressure on the surface \((q = 13.6 \text{ MPa})\); a) bronze (ОЦС 5-5-5); b) brass (Л63); c) copper (М1)

Figure 4. Gray cast iron СЧ 20 specimen surface having HB 1.7 MPa, coated by bronze (ОЦС 5-5-5) with a base metal micro-relief pitch of: a) \(t = 0.05 \text{ mm}\); b) \(t = 0.10 \text{ mm}\); c) \(t = 0.175 \text{ mm}\)

Fragment of the base metal surface with a coating of bronze (ОЦС 5-5-5) also shows a non-uniformity (discreteness) layer shown in figure 5. Under the influence of pressure, the antifriction material penetrates primarily into the cavities-A, and also forms areas in the form of flake spots-B.

Figure 5. Fragment of the coated base: A - coating in the cavity; B - coating in the form of a flake spot

According to metallographic studies (figure 4 and 5), in all cases a discrete anti-friction layer was formed on the specimen surface; therefore the area occupied by the anti-friction material depends on
The discreteness of the coating on the surface of the gray cast iron (CJ 20 base metal can be explained by the presence of free graphite in the base material and its distribution on the surface when the antifriction block is moved. Thus, free graphite creates a shielding film and prevents the antifriction material from being captured by the base material. In addition, it should be noted that the reason for the formation of coating discontinuity is the presence of micro-relief defects of the base surface. The micro-roughnesses of the base surface represent peak alternation with the same pitch and shape, but have different height. In this case, the actual contact of the antifriction block with the base surface will flow only along the tops of the peaks having greater height, as a result, antifriction material will not transfer to the base material over all the entire contact area in the form of a continuous layer.

Table 2. Surface roughness after FANT, Ra (µm)

| Coating thickness, µm | Initial surface roughness, Ra | Surface roughness after FANT, Ra |
|-----------------------|-----------------------------|---------------------------------|
| 1,25                  | 0,63                        | 2,5                             |
| 2,5                   | 0,63                        | 1,25                            |
| 4,6                   | 0,16                        | 0,63                            |

As the value of the surface roughness parameter, the average surface roughness (Ra) was obtained from three measurements.

Analysis data in (Table 2) indicates that in order to obtain a high-quality coating, it is necessary that the initial surface roughness (Ra) is not lower than 1,25 µm. In this case, sharp micro-roughnesses are formed on the surface which intensively worn the tool and as a result, continuous coating is formed. On the other hand, with an average surface roughness (Ra = 2,5 µm) and higher, the process of tool material penetration into the micro-roughnesses troughs is complicated, and the resulting coating is not continuous.

Based on the obtained values, it could be established the basic law of the variation in the roughness parameter from the technological parameters of FANT (figure 6). The obtained values made it possible to establish the basic laws of variation in the roughness parameter with respect to FANT technological parameters (figure 6).

Where: RaFANT: Surface roughness after FANT, µm.
Ra: Initial surface roughness, µm.

The obtained values made it possible to establish the basic laws of variation in the roughness parameter from the technological parameters of FANT (figure 6). The obtained values made it possible to establish the basic laws of variation in the roughness parameter with respect to FANT technological parameters (figure 6).
confirms the fact of the special importance of the micro-cuts role in the formation of an antifriction coating [14], in addition the effect of rubbing material as a smoothing tool.

The study of the coating continuity dependence on the force parameter (the tool contact pressure ‘anti-friction block’ (q) depending on the micro-relief pitch (t)) allowed the following patterns to be established (figure 7).

**Figure 6.** Dependence of \( \frac{R_{F\text{ANT}}}{R_a} \) during FANT process on the micro-relief peaks pitch of the initial surface (t) with a force of: a) \( P = 82.4 \) N; b) \( P = 164.6 \) N and the number of rubbing cycles: 1 - 2 cycles; 2 - 6 cycles; 3 - 12 cycles.

**Figure 7.** The dependence of the continuity \( F \) of the antifriction coating on the contact pressure \( q \) on the pre-treated surface with a turning tool at a step t: 1 - 0.05 mm; 2 - 0.1 mm; 3 - 0.175 mm.

From figure 7 it can be observed that, the concentration of the antifriction coating on the base surface increases with an increase of both the micro-relief pitch and contact pressure. This means that the coating continuity increases with increasing the contact pressure and the micro-relief pitch of the base material.

Thus, the complex of studies in this work made it possible to establish the influence of the initial surface parameters on the formation of a high-quality antifriction coating, obtained by FANT method. Moreover, these micro-relief parameters before coating can be achieved by turning.

**4. Conclusions**

Based on the obtained results, the following conclusions can be made:

One of the conditions for the formation of high-quality antifriction coating is the purposeful formation of regular micro-reliefs. However, using only one parameter (Ra), does not give a complete picture of...
the surface micro-reliefs. Consequently, it is possible to improve the coating quality by obtaining favorable shapes and dimensions of roughnesses in previous FANT operations.

The required micro-roughnesses shapes and dimensions can be achieved by turning. In this case, the shape of the residual protrusions and troughs are determined by the shape of the SPT cutting nose. The dimensions of the protrusions and troughs, and their area depend on the values of the main and auxiliary plain approach angles (ϕ, ϕi), cutting tool radius (r) and cutting feed ratio (S). Therefore, the necessary shape and dimensions of micro-roughnesses can be successfully achieved by turning, and the shape of the micro-relief protrusions and troughs is determined by the cutting tool nose form. The protrusions and troughs dimensions and their area depend on the values of the cutter tool approach angles in terms of (ϕ, ϕi), tool nose radius (r) and feed ratio (S);

The proposed method and equipment for applying antifriction coating by FANT method due to the progressive motion of the tool, allows multiple studies on specimens with preservation of information, obtained in previous experiments. The use of such a technique made it possible to obtain discrete antifriction coatings on gray cast iron specimens by using bronze, brass and copper as rubbing tools at various contact pressures;

The relationship between the geometric parameters of the micro-relief and the antifriction coating quality parameters was established. It is proved that one of the conditions for the formation of a high-quality anti-friction coating is the purposeful formation of parameters in previous operations. With the adopted treatment scheme, increasing the antifriction coating continuity and thickness can be achieved by increasing the contact loads up to 13.6 MPa, and also with a previously prepared surface for coating by turning by using feed ratio of 0.175 mm/rev, cutting tool geometry of (ϕ = ϕ1 = 45°) and surface roughness Ra = 1.25 µm.

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