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Creation of progressive hole processing processes based on the study of contact phenomena during deforming broaching and finishing antifriction non-abrasive treatment in various technological environments

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Abstract

This work is devoted to the creation of progressive technological processes for processing holes. The relevance of studying this issue is substantiated, technological environments (TE) used in these operations are listed. The purpose of the work performed is to study the influence of TE on contact phenomena and quality parameters of the treated surface during deformation broaching (DB) and finishing antifriction non-abrasive processing (FANT) and the creation on this basis of new technological processes to obtain parts with improved performance. New methods have been developed for studying contact interaction in the case of DB using solid lubricants, as well as for modeling the FANT process. The conditions for the use of liquid lubricants in the DB are described. It has been established that, when them applied, the altitudinal roughness parameters decrease and the surface layer hardens to a considerable depth. It is shown that the use of solid lubricants in DB is mandatory when processing products from hard-to-work materials and alloys. When them applied, significant plastic deformations of the hole can be made. In this case, the surface layer of the workpiece is little different from the original. The change in the altitude parameters of the rough layer, as well as contact pressures using solid lubricants, was studied. Peculiarities of contact phenomena in the case of DB using solid lubricants are revealed. For this case, a functional relationship has been established between the altitude parameters of roughness and the relative contact pressure. An analytical dependence is proposed for their calculation. The boundary conditions for its application are determined. Formation FANT also occurs when using the TE. It was established that solid lubricants during FANT perform a dual function, namely, technological, like solid lubricant during processing, and operational - improve the quality parameters of the processed parts. The combination of DB and FANT operations allows us to develop a new technological process for processing holes of parts such as bushings and sleeves. This process consists in the use of DB as a roughing and finishing operations, and FANT as a finishing operation, which allows to improve the quality indicators of the machined part.

Key words: deforming broaching, finishing antifriction non-abrasive treatment, technological environment, solid lubricants, liquid lubricants, contact phenomena, roughness, hardening, quality of the processed surface

Introduction

The deforming broaching (DB) of products from ductile metals and alloys is always carried out using technological lubricants, which eliminates the setting of the tool with the workpiece material, reduces the energy consumption for the process, and also improves the quality of the processed surface [1].

The technology of finishing anti-friction non-abrasive treatment (FANT), based on the use in the process of friction, setting and selective transfer, also requires the use of a special technological fluid - a technological environment (TE). It moistens the treated surface, loosens the oxide film, plasticizes the surface and creates the conditions for the setting of metals [2].

The most widely used in DB are liquid lubricants, which are used both in finishing and rough operations. When finishing processing, they allow you to get high performance properties of the processed surface of the workpiece. In this case, there is direct contact between the treated surface and the deforming element under liquid lubrication conditions. The treated surface receives hardening and a textured layer to a depth to 0.2 mm, compressing residual stresses that exceed the yield strength of the processed material, low roughness (Ra ≤ 0.1 μm), improved microrelief. All this helps to improve the operational characteristics of the finished part [3].

Literature review

According to work [1], the most common liquid lubricants are oil-based lubricants: sulfofresol, mineral oils of the MR class, as well as oils of plant origin. For the processing of non-ferrous materials, a 10% solution of soap in water is used.

The formation of the antifriction coating FANT on the surface of steel or cast iron is also carried out using a technological envirenment, which includes a number of chemical elements that ensure, under specific conditions, the interaction of materials and the presence of surface self-organization processes [4]. Since in this case the coatings are applied without significant changes in the composition and structure of the tool and the applied coating (the tool material is transferred to the steel (or cast-iron) surface of the part), the role of the TE is primarily to clean the surface of the part from oxides. In this case, the layer of applied anti-friction coating can also play the role of a solid lubricant.

The role of the lubricant during broaching by carbide deforming elements becomes especially significant when deforming parts from hard-to-work materials: chromium-nickel-molybdenum and stainless steels of austenitic class, titanium alloys. In these cases, significant deformation of the hole when broaching with liquid lubricants becomes impossible due to the adhesive setting of the tool with the part. Then use solid lubricants, which are characterized by high shielding properties [1].

This makes it possible to use deformation broaching for such materials as a rough shaping operation, the main purpose of which is to increase the utilization of the material in subsequent machining operations. In this case, the main characteristic of the lubricant used should be not anti-friction, but shielding properties, that is, the ability to exclude direct contact of the tool with the product. A number of solid lubricants meet this requirement, which also provide adhesive properties. They must be firmly fixed on the treated surface and localize large shear deformations in the lubricant layer itself.

A series of solid lubricants based on epoxy resins and solid fillers such as graphite, molybdenum disulfide, boron nitride, etc. have been developed at ISM NAS of Ukraine. They are sometimes modified with organosilicon compounds to improve the shielding properties. This allows you to process up to 10% of the holes in billets made of the following materials during deformation: stainless and heat-resistant alloys, hardened steels 30HGSA, EI643, 30HNMA, 38HMYuA, heat-treated aluminum alloys AK6, D16, tubes made of vanadium and niobium, as well as parts from VT1-0, VT6, VT22 titanium alloys.

Purpose

The study of the influence of solid lubricants on contact phenomena and the quality parameters of the treated surface during the DB and FANT and the creation on this basis of new technological processes for processing holes to obtain parts with improved performance.

This will reveal the features of the processes flow and establish their influence on the quality indicators of the treated surface. In turn, research will expand the scope of DB and FANT due to the creation of new technological processes for processing hard-to-work materials and the intensification of the FANT process.

Research methodology

The experiments were carried out on bushings made of 12H18N10T steel with dimensions: hole diameter d_0 = 35 mm, wall thickness t_0 = 35 mm, length l_0 = 250 mm. The initial surface roughness of the hole after boring is Ra = 3–4 μm. And also on bushings made of titanium alloy VT1-0 with dimensions: d_0 = 35 mm, t_0 = 4; 7; 9 mm, l_0 = 250 mm and d_0 = 19 mm, t_0 = 4; 7; 9 mm, l_0 = 150 mm.

The broaching was carried out on a horizontally broaching machine mod. 7B520 and at a special stand developed at the ISM NAS of Ukraine, which allows flashing a workpiece with a force of up to 100 kN. When broaching billets of steel 12H18N10T, solid lubricant ASM-6 was used, which included varnish F-9-K, molybdenum disulfide MoS_2 and toluene. It was previously established that this lubricant can withstand contact pressures of about 2.5 GPa and very significant hole deformations (up to 15%) without breaking. When broaching the VT1-0 titanium alloy preforms, a solid lubricant based on diane epoxy resin with anhydride hardener and filler – colloidal graphite, modified by introducing organosilicon compounds and a highly dispersed carbon filler [5] was used. The specified grease withstands without destruction contact pressure up to 3.2 GPa, which allows for very significant deformation during the expansion of the hole.

The roughness was measured by the parameter Ra along the generatrix of the hole after each deformation cycle, that is, after each missed deforming element, and surface profilograms were taken before and after processing. The measurement was carried out on a "Talysurf-5M-120" profilometer-profilograph and on a VEI-Caliber mod. 201. After each broaching cycle, a portion of the machined sleeve 10–15 mm long was cut off, with which the solid lubricant was removed with acetone, and roughness was measured. In some cases, the study of the roughness and conditions of contact interaction was carried out using transverse sections on the "Micron-gamma" devices, designed by the National Aviation University of Ukraine. Vickers hardness of the samples was measured on a HPO-250 hardness tester, and microhardness was measured on a PMT-3 instrument at loads of 50 and 200 grams. The FANT process was studied by modeling it by the interaction of the peaks of microprotrusions in the form of cutters from cast iron SCh20 and a sample from brass L63. In this case, a brass sample in the form of a plate was fixed on the working table of the milling machine, and a cast-iron micro-cutter was installed in a special device, the geometry of the cutting part of which simulated a separate microroughness of the surface. The front angle of the cutter γ varied from +50 ÷ –150°, and the cutting depth from 0.1 to 0.6 mm. The load on the sample was provided by the vertical feed mechanism of the machine and was controlled by an indicator head. In this case, the force P_e was measured with a special dynamometer. The thickness of the cut was insignificant and comparable with the radius of blunting of the cutting edge, that is, the contact interaction corresponded to the actual conditions of the interaction of the microprotrusion with a brass tool. Glycerin was used as TE. Measurement of the wear of the cutter, as well as the adhesion area of brass L63 on the rear surface of the cutter and its continuity, were performed on a ZEISS EVO 50XVP electron microscope.

Results

In fig. 1, the quality parameters of a surface treated by deforming broaching of steel sleeves 12H18N10T using solid lubricant based on molybdenum disulfide are given.

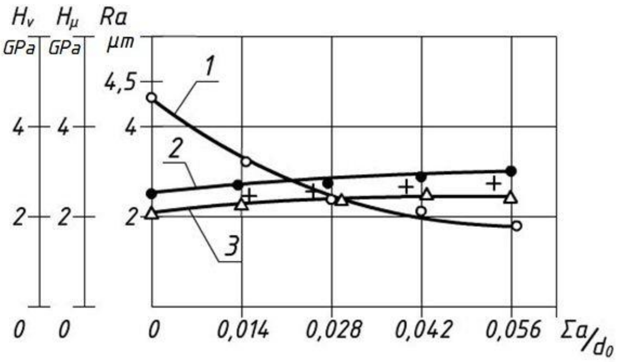


Fig. 1. The dependence of roughness (*Ra*), hardness *HV*, microhardness $H_{\mu 50}$ on the total deformation when machining bushings made of steel 12H18N10T: when using solid lubricant ASM-6: 1 – *Ra*, 2 – $H_{\mu 50}$ (● – on the surface, + – at a depth of 0.5 mm), 3 – *HV*

As can be seen, the altitude parameters of roughness decrease with an increase in the total expansion deformation, however, the decrease does not occur as intensively as with the use of liquid lubricants [6], which, apparently, indicates a decrease in shear deformations in the surface layer. The roughness profile of the machined surface of the sleeve made of 12H18N10T steel previously bored and stretched using solid lubricants (Fig. 2, a) also remains almost unchanged. The supporting surface also changes slightly at the midline level (Fig. 2, b).

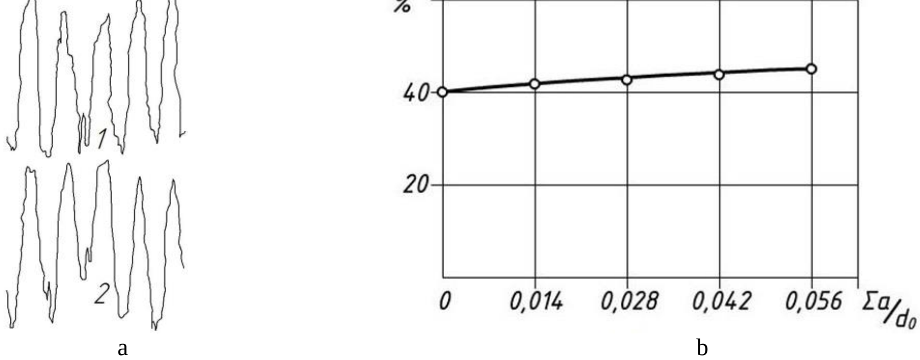


Fig. 2. The profile of the initial and processed surface (a) and the reference length of the profile at the midline level (b): 1 – the initial surface after boring, 2 – the surface after 4 cycles of deformation

After boring, the initial area of the supporting surface was 40%, and after 4 cycles of deformation, it increased by only 6–7%. This is also confirmed by the results of measuring the hardness of the treated surface (Fig. 1, curve 3), the microhardness of the surface and the microhardness of the material at a certain depth from the treated surface (Fig. 1, curve 2).

Similar results were obtained during the deformation of VT1-0 titanium alloy billets with applied hole deformations of up to 6% (Fig. 3). When processing these blanks, solid lubricant was also used, the composition of which is given in work [7].

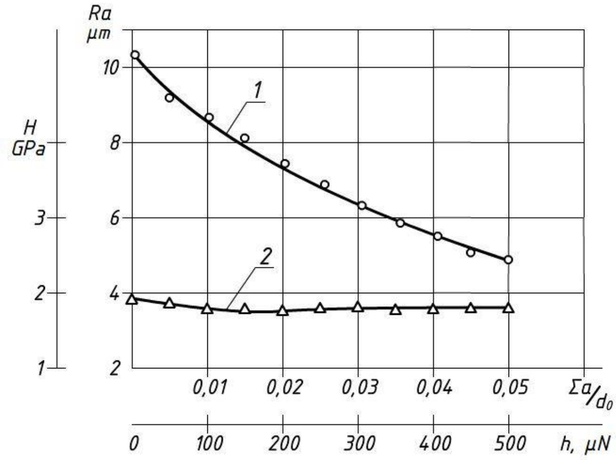


Fig. 3. The dependence of roughness (1) and microhardness (2) on the total deformation when processing bushings from titanium alloy VT1-0 with t_0/d_0=0,21 using solid lubricant based on diane epoxy resin ED-5 with colloidal graphite as a filler and modified organosilicon compounds

In this case, there are also no noticeable shear deformations in the surface layer, which is confirmed by the data shown in Fig. 3. It follows from them that the altitude parameter Ra decreases slightly after each cycle, which is due to the influence of mainly circumferential deformation of the hole. Therefore, the change in microhardness along the wall thickness is almost imperceptible. This is qualitatively different from the known nature of the change in this indicator when using liquid lubricants, which cause the formation of texture and the creation of a significant gradient of changes in hardening along the wall thickness [6].

The indicated features of the deformation of the surface layer when using solid lubricants are confirmed by photographs of the thin sections of the contact zone obtained on "Micron-gamma" device. It allows you to get not only a real picture of the interaction of the tool with the treated surface, but also to determine the height of microroughnesses using a scale ruler (1 division - 10 μm). As can be seen (Fig. 4), a layer of solid lubricant is present between the contacting surfaces, which, due to its screening properties, localizes shear deformations in itself. Microgeometry of the treated surface layer differs little from the original. That is, as indicated above, its change is caused mainly by the influence of the circumferential deformation of the hole – $\Sigma a/d_0$.

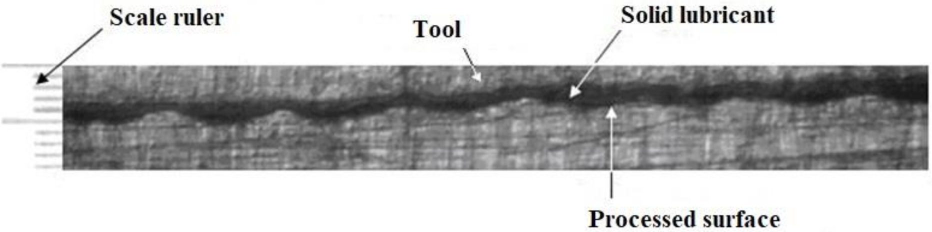


Fig. 4. Contact of the tool with the processed surface when using solid lubricant

Some differences in roughness values (Figs. 1 and 2) are due to its different initial values. For relative roughness $R_a/R_{a\ init}$, the experimental points for different materials lie practically on the same curve (Fig. 5), which apparently indicates close shielding properties of the applied solid lubricants.

When these bushings were deformed, normal contact pressures were determined. Their change depending on the deformation is shown in Fig. 6.

An analysis of the results showed that the existing models for determining the roughness of the treated surface after deforming broaching, given in [8], are not suitable for describing the process of changing the roughness during broaching using solid lubricants.

One of these models, used for low-cycle deformation, is built on the basis of a cone or prism precipitation scheme. In this case, the relationship between the altitude parameters of the rough layer and the total contact pressure Σq accumulated during each deformation cycle was analytically established [8].

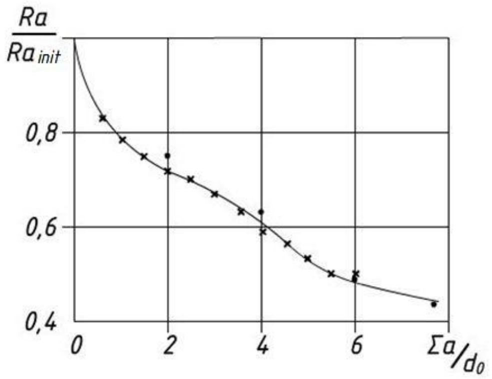


Fig. 5. The dependence of the parameter $R_a/R_{a\ init}$ when processing bushings: × – from titanium VT1-0: t_0/d_0=0,21, : a_0/d_0=0,005; ● – from stainless steel 12H18N10T: t_0/d_0=0,22, : a_0/d_0=0,014

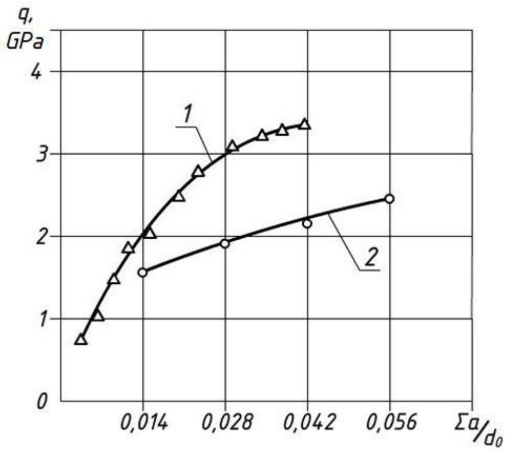


Fig. 6. The dependence of contact pressure on the total deformation during the processing of the bushings: 1 – from titanium VT1-0: t_0/d_0=0,21, a_0/d_0=0,028, l = 0.65 mm; 2 – from stainless steel 12H18N10T: t_0/d_0=0,22, : a_0/d_0=0,014, l = 1.5 mm

Another model of this work was obtained for calculating the change in the altitude parameters of roughness during multi-cycle deformation and takes into account the influence of not only normal loads, but also tangential ones due to friction between contacting surfaces. In this case, the process of reducing the altitude parameters of roughness occurs not only from compression under the action of a normal load, but also from mass transfer caused by the “roll-over” of microroughnesses under the action of the friction force that occurs when using liquid lubricants (Fig. 7). Moreover, with an increase in the number of deformation cycles, the influence of the friction force on the microrelief increases. Along with a decrease in the height of microroughnesses, cavities are filled due to the mass transfer of the material of the microprotrusions from the action of friction.

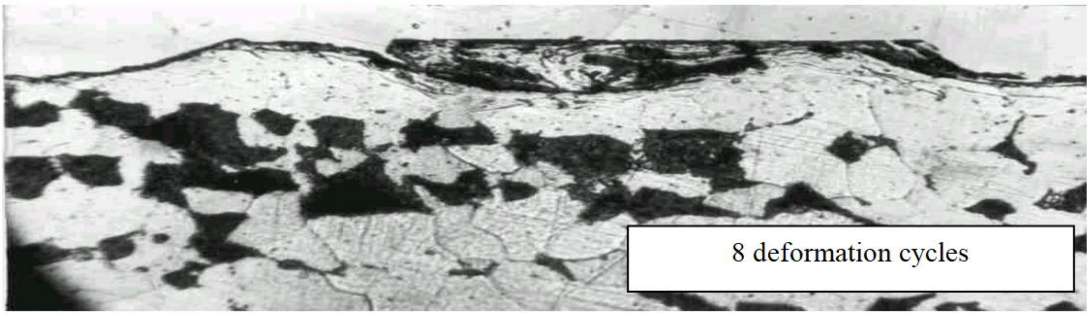


Fig. 7. The nature of the deformation of the microprotrusion of a workpiece made of steel 45 with the number of deformation cycles equal to 8; × 500

When broaching using solid lubricants, the following occurs. In this case, the expansion process occurs in the absence of friction forces on the surface of the workpiece, which are localized in the solid lubricant layer (Fig. 4). Therefore, when using large tension on the deforming element and small angles of the working cone of the tool, when the contact pressures are low and do not exceed the critical contact pressure for a given workpiece material [6], the expansion pattern will be close to the expansion of the pipe by internal pressure.

For technological calculations related to forecasting and ensuring the required roughness in case of DB, it is necessary to establish a relationship between the altitude parameters of roughness and contact pressure *q*.

As is known [6], value q is proportional to the hardness of the material being processed. Let us analyze the dependence of the relative roughness $R_a/R_{a\ init}$ on the dimensionless contact pressure *q/HV* (Fig. 8).

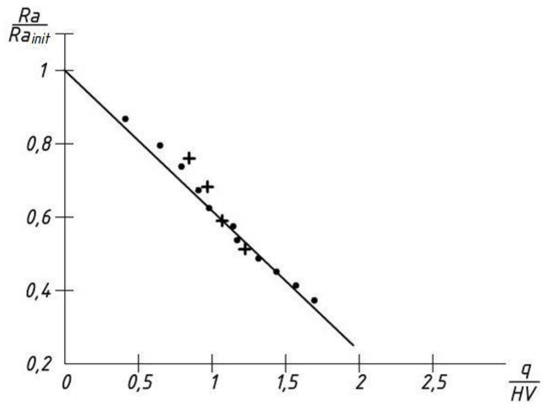


Fig. 8. The dependence of the relative altitude parameter of roughness on the relative contact pressure during the processing of titanium billets VT1-0 (●): t_0/d_0=0,21, a_0/d_0=0,028; from stainless steel 12H18N10T (×): t_0/d_0=0,22, a_0/d_0=0,014

It can be seen that this dependence is almost linear and does not depend on the material being processed and is approximated by the following expression:

$$\frac{Ra}{Ra_{init}} = 1 - 0,36\frac{q}{HV}. \quad (1)$$

In [1,6], based on the analysis of a significant amount of experimental data, empirical calculated dependences are proposed for determining *q* depending on technological factors and properties of the materials being processed.

For this, the axial force of broaching and the contact length *l* are experimentally determined. By the formula (2), the average value of the contact pressure is calculated:

$$q = \frac{Q\cos\eta}{\pi d_0 l \sin(\alpha + \eta)}, \quad (2)$$

where η is the angle of friction, $\eta = arctgf$, *f* is the coefficient of friction, α is the angle of inclination of the generatrix of the working cone of the deforming element.

The friction coefficient for solid lubricants was determined experimentally and was approximated by the dependence:

$$f = C_{fm} q^{-xm}. \quad (3)$$

The values of the coefficients C_{fm} and *xm* for our processing conditions are shown in table 1.

Table 1

The value of the coefficients C_{fm} and *xm* for various processed materials

Lubricant for processed material	C_{fm}
stainless steel 12H18N10T	0,087
titanium alloy VT1-0	0,048

In [10], a calculation scheme was proposed for determining *q* during processing with small tension of substantially thick-walled workpieces with "infinite wall thickness" [6], when $t_0 \geq d_0$. However, it is correct for calculating the contact pressure when its value exceeds the critical pressure [6].

In our case, for technological calculations of the roughness parameters, we need to know the contact pressure, the hardness of the processed material and the initial roughness of the hole surface.

Based on the results obtained in this paper, we can propose a theoretical method for calculating contact pressures when expansion by DB with respect to thin-walled workpieces with large tension, small angles when contact pressure is below critical. Note the relevance of this issue. Large degrees of expansion are used for rough forming operations, and for this processing of workpieces from the above-described difficult-to-handle materials, it is used solid technological lubricants.

Since, as shown above, the roughness of the treated surface depends only on the total degree of deformation of the hole, it is natural to assume that in the case of using solid lubricants, the deformation process will be close to the internal pressure expansion pattern of the pipe. As shown in [8, 9], such a design scheme is acceptable for deformation broaching when determining the fracture deformation of workpieces and their geometric parameters after broaching.

Therefore, we use this model to determine contact pressures for our case. The design scheme is presented in Fig. 9.

Let the hardening of the workpiece material be approximated by the dependence:

$$\sigma_0 = \sigma_T + Ae_0^n, \tag{4}$$

where σ_0 and e_0 are the stress intensity and the intensity of plastic deformations; σ_T - yield strength; A and n are empirical coefficients.

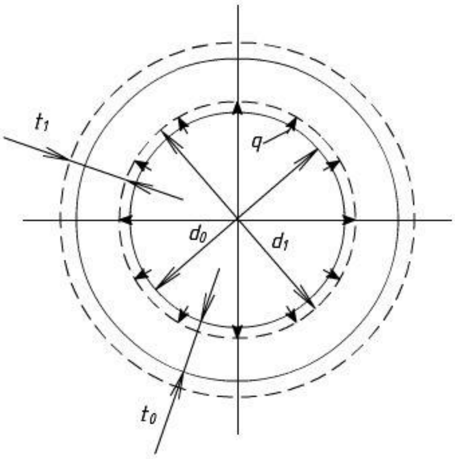


Fig. 9. The calculated expansion scheme

For relatively thin-walled workpieces, average circumferential deformation:

$$e_\varphi = \frac{\sum a}{d_0} = \sum \bar{a} . \tag{5}$$

In the absence of axial tightness

$$e_0 = e_\varphi = \sum \bar{a} . \tag{6}$$

Then

$$\sigma_0 = \sigma_T + A\left(\sum \bar{a}\right)^n . \tag{7}$$

Specific work of plastic deformations (per unit volume):

$$A^* = \sigma_0 e_0 = \sigma_T e_0 + Ae_0^{n+1}. \tag{8}$$

Full work of plastic deformations

$$A = A^* \cdot V_0 , \tag{9}$$

where V_0 is the initial volume of the workpiece, which does not change during deformation:

$$V_0 = \pi d_0 t_0 L_0 , \tag{10}$$

where L_0 is the length of the workpiece.

In view of (10)

$$A = \pi d_0 t_0 L_0 \left[\sigma_T \sum \bar{a} + A\left(\sum \bar{a}\right)^{n+1}\right]. \tag{11}$$

Elementary work on increment diameter $d\left(\sum \bar{a}\right)$

$$dA = \pi d_0 t_0 L_0 \left[\sigma_T d\sum \bar{a} + A(n+1)\left(\sum \bar{a}\right)^n d\left(\sum \bar{a}\right)\right]. \tag{12}$$

On the other hand, it is produced by the current contact pressure q at increment $d\left(\sum \bar{a}\right)$:

$$dA = q\pi d_0 t_0 L_0 d\left(\sum \bar{a}\right). \tag{13}$$

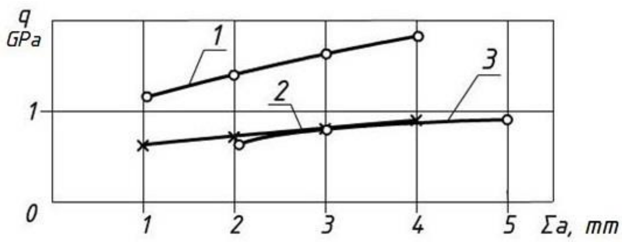
Equating expressions (12) and (13) we obtain

$$q = \frac{t_0}{d_0 + \sum \bar{a}}\left[\sigma_T + A(n+1)\left(\sum \bar{a}\right)^n\right]. \tag{14}$$

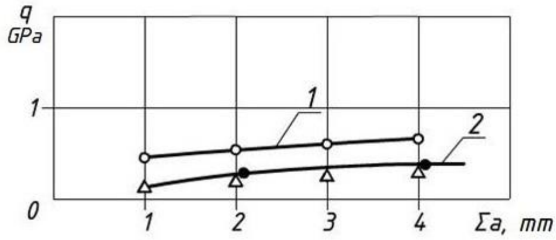
It has been taken into account that the current value of the hole diameter is $d_1 = d_0 + \sum \bar{a}$.

To calculate contact pressures according to dependence (14), it is necessary to know the dimensions of the workpiece and the hardening curve of its material. We define the area of use of formula (14) by comparing the calculated and experimental (according to [6]) *q* values (Fig. 10) for the case of processing workpieces made of steel 20 and steel 45.

For steel 20, the flow curve was approximated by the dependence $\sigma = 220 + 624e^{0,473}$ (MPa), and for steel 45 – $\sigma = 350 + 1180e^{0,5}$ (MPa). As can be seen, good coincidence between the calculated and experimental data (Fig. 10, a, curves 2 and 3 and 10, b, curve 2) is observed at contact pressures below critical values, which, according to the data of [6], lead to the appearance in the deformation zone local zone of plastic deformation in the form of an influx. It causes the appearance of the axial flow of the processed material and large shear deformations (textures). In the presence of critical contact pressures, the calculated contact pressures are much lower than the experimental ones (Fig. 10, a, curves 1 and 2 and Fig. 10, b, curves 1 and 2).



a



b

Fig. 10. The dependence of contact pressures on the total deformation during processing of billets: a) from steel 45: t_0/d_0=0,136, a_0/d_0=0,015: 1 – experiment, 2 – calculation according to (14), 3 – a_0/d_0=0,03 (experiment and calculation according to (14)); b) from steel 20: t_0/d_0=0,65, a_0/d_0=0,015: 1 – experiment, 2 – calculation according to (14) (Δ);a_0/d_0=0,03 (●) – calculation according to (14) and experiment

This is due to the mismatch of the conditions of deformation of the workpiece to the expansion pattern of the pipe with internal pressure. The following conclusion can be drawn from this: the theoretical calculation of contact pressure according to dependence (14) can be performed at contact pressures less than critical. The authors of [6] found that for steel 45 the critical contact pressures are 0.87 GPa, and for steel 20 – 0.78 GPa. At contact pressures equal to and above critical, their calculation must be carried out according to dependence (2) or according to the method described in [10]. The value of *q* depends on the modes of broaching and the size of the workpiece.

The wall thickness at which critical contact pressures appear depends on the tension on the element, the angle *α*, as well as the broaching pattern and is determined from the experimentally obtained relationships (15) and (16) for tensile and compression patterns, respectively [11]:

$$t_0/d_0 = 3,39\left(a/d_0\right)^{0,75} \cdot \alpha^{-\left(0,17+14,3\, a/d_0\right)}; \tag{15}$$

$$t_0/d_0 = \left(0,11 + 10,24\, a/d_0\right) \cdot \alpha^{-\left(0,17+11,6\, a/d_0\right)}. \tag{16}$$

They allow us to determine the conditions for using formula (14).

Consider the conditions of contact interaction with FANT. The process of contact interaction of the surface of the workpiece with rubbed material can be divided into two stages: 1) micro cutting of the starting material with the tips of microprotrusions; 2) adhesive adherence and seizure of particles formed as a result of micro-cutting with the surface onto which transfer and subsequent micro-smoothing takes place. In [12], the FANT process was studied at the stage of micro cutting and the role of the latter in the formation of a high-quality antifriction coating. It was established that in order to intensify the FANT process due to micro-cutting, it is necessary to create a regular microrelief of a rough surface with a front cutting angle $\gamma \geq 0°$, and the angle $\gamma = 5°$ is the best option.

In the process, the cutting edge of the microroughness is intensely blunting, the rounding radius increases, which intensifies the next stage of the FANT process – the interaction of the back surface of the tool with the brass surface.

In the contact zone of the processed tool on the back surface there are high contact loads, approximately 3 times higher than the yield strength of brass and approximately equal to its HV hardness. Therefore, a layer of plastically hardened material is created on the back surface of the simulated micro-cutter (microroughness) and a skin of adhesively adhering brass appears (Fig. 11).

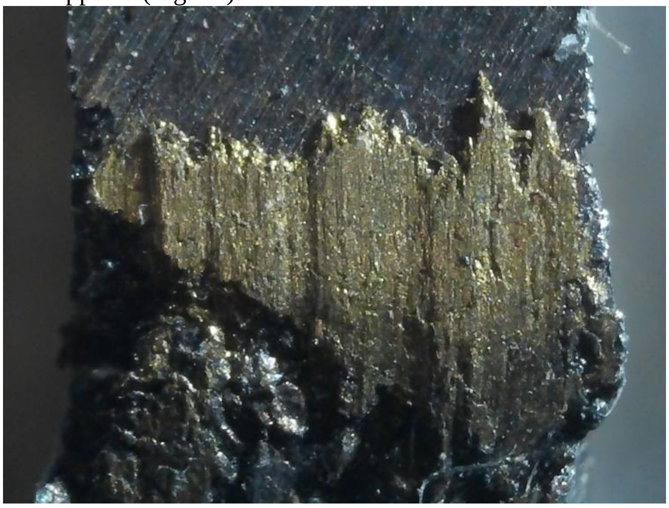


Fig. 11. The sticking of brass L63 on the rear surface of the cutter made of cast iron SCh20 when rubbing

This skin begins to play the role of a third body, that is, solid lubricant, preventing further blunting of the microroughness peaks, and a further increase in the radius of rounding of the cutting edge, which is confirmed by the experimental data shown in Fig. 12.

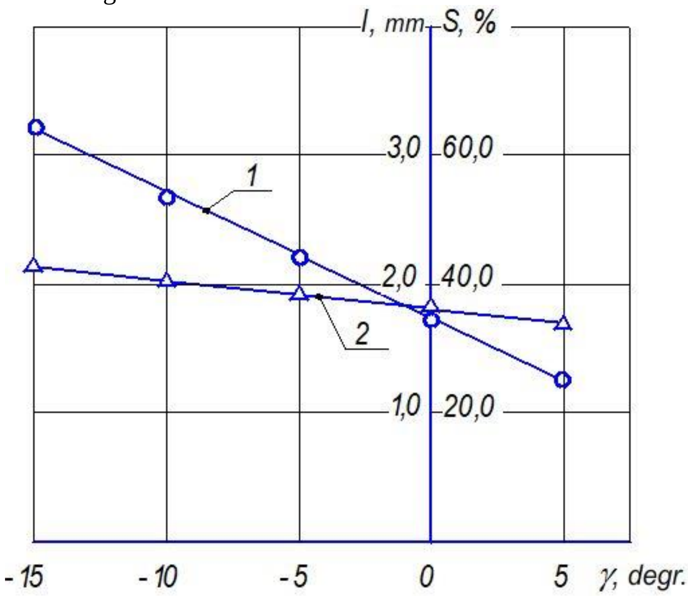


Fig. 12. Dependence of the brass coverage area of the contact surface *S* (curve 1) and the contact length *l* (curve 2) on the angle *γ* when modeling micro-cutting with a SCh20 cast iron cutter with a brass surface L63

So, the contact length along the rear face l depends on the angle γ, and with increasing γ the value of l increases (Fig. 12, curve 2), which is possibly due to the absence of micro-cutting at $\gamma < -5°$ and an increase tension on the radius section of the rear face. The adhesive interaction of the back surface of the cutter model with brass also increases with decreasing angle γ and reaches its maximum at $\gamma = -15°$. This is evidenced by curve 1 (Fig. 12), which shows the change in the percentage of the area covered with brass, referred to the total contact area. With a further cycle of interaction, an adhesively fixed brass layer plays the role of a technological solid lubricant, and the process of applying an antifriction coating is significantly intensified. The coating layer becomes solid, which indicates an increase in its quality. Subsequently, the formed brass coating increases the quality parameters of the machined part, which improves its durability and is of practical importance.

Thus, a feature of the use of solid lubricants in FANT is that they perform a twofold function, namely, technological – as solid lubricant during processing and operational - increases the quality parameters of the processed part, and therefore its durability and wear resistance.

Our studies of the FANT process [13, 14] showed that the surface layer is significantly hardened. However, the depth of this hardening is negligible. This does not allow the use of the hardening effect when operating the part for a long time. Therefore, it is advisable to combine these two operations, which will allow you to get the processed surface with improved physical, mechanical and geometric characteristics. In this case, the DB will provide a substantial hardening of the surface layer by 30–40% and its bedding to a depth of 0.25 mm, and the FANT process will allow obtaining an equilibrium roughness that coincides with the operational roughness, regardless of the initial roughness.

Given the capabilities of the DB and FANT, the following conclusion can be drawn. To improve the operational properties of a part such as bushings and sleeves, it is necessary to build the technological process of processing according to the following scheme: the first operation is rough shaping using DB, which increases the utilization of metal, bringing the workpiece closer to the size of the part. When processing workpieces from hard-to-work materials, solid lubricant is used according to the recommendations received. In this operation, the bulk of the plastic deformation of the hole is carried out. The next operation is the final deforming broaching of the hole, during which the remainder of the plastic deformation is performed. The treated surface acquires the required macrorelief, roughness, the necessary hardening and the depth of its bedding. Then, given that the antifriction layer has an insignificant thickness $\delta < 5$ μm, we perform the FANT operation, which is the finish and can improve the performance of the treated surface. In this case, the necessary microrelief is provided, obtaining equilibrium roughness, as well as applying solid lubricant from antifriction material.

Conclusions

Analysis of the above material allows us to formulate the following conclusions:

- an analysis of the conditions for the effective use of solid lubricants was performed, and the features of contact phenomena during DB using solid lubricants were revealed.

- a functional relationship has been established between the altitude parameters of roughness and the relative contact pressure during processing using solid lubricants.

- a theoretical dependence has been obtained for calculating contact pressures and it has been established that the field of its effective application is limited by the condition whereby these pressures should not exceed their critical value.

- it was found that in the FANT process, solid lubricants can perform two functions: technological, like solid lubricant during surface treatment of a part, ensuring the quality of the coating, and operational. This improves the quality of machining parts, reduces the wear rate by 2–2.5 times, reduces the running-in time by 2 times and the friction coefficient by 20%.

- a new technological process has been proposed for processing holes of parts such as bushings and sleeves, which consists in combining DB as rough and finishing operations and the FANT finishing operation, which allows to improve the quality indicators of the machined part.

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Створення прогресивних процесів обробки отворів на основі дослідження контактних явищ при деформуючому протягуванні та фінішній антифрикційній безабразивній обробці в умовах різних технологічних середовищ

Виконано дослідження впливу технологічного середовища (ТС) на контактні явища і параметри якості обробленої поверхні при використанні операцій деформуючого протягування (ДПР) і фінішної антифрикційної безабразивної обробки (ФАБО). Описано умови застосування рідинних мастил при ДПР. Розроблені нові методики вивчення контактної взаємодії при ДПР з використанням твердих мастил. Доведено необхідність застосування твердих мастил при обробці виробів з важкооброблюваних матеріалів і сплавів. Досліджено зміну висотних параметрів шорсткості поверхневого шару, а також контактних тисків при використанні твердих мастил. Розкрито особливості контактних явищ при ДПР з використанням твердих мастил. Встановлено функціональний зв'язок між висотними параметрами шорсткості і відносним контактним тиском при ДПР. Показано, що тверді мастила при ФАБО виконують двояку функцію, а саме – технологічну, як тверде мастило при обробці, і експлуатаційну – покращують параметри якості оброблених деталей. Поєднання операцій ДПР і ФАБО дозволило розробити новий технологічний процес обробки отворів деталей типу втулок з покращеними експлуатаційними властивостями.

Ключові слова: деформуюче протягування, фінішна антифрикційна безабразивна обробка, технологічне середовище, тверді мастила, рідкі мастила, контактні явища, шорсткість, зміцнення, якість обробленої поверхні