UDC 621.952.529.229
MRNTI 55.22.31
DOI 10.56525/QNHZ4176

STUDY OF DIAMOND SMOOTHING PROCESSES DURING SURFACE PLASTIC DEFORMATION OF COATED PARTS

[1]Букаева А., [2]Kikvidze O.G.
[1]Yessenov University, Aktau, Kazakhstan
[2]Akaki Tsereteli State University, Kutaisi, Georgia
e-mail.ru: amina.bukaeva@yu.edu.kz, kikvidze6@mail.ru

Abstract: The article is devoted to the study of diamond ironing as a modern and highly effective method of surface plastic deformation, used to improve the quality and operational properties of machine building parts. The main physical mechanisms of the process are considered: strengthening of surface layers, the formation of residual compression stresses, a decrease in roughness parameters and an increase in wear resistance. Particular attention is paid to the processing of parts with wear-resistant coatings, such as titanium nitride (TiN), which is especially important for tool and machine-building production. The paper presents analytical relationships that allow to determine the optimal process modes, including the compression force and the depth of the strengthened layer. Thermal stress analysis was carried out, the influence of temperature factors on the stability of diamond tools and the preservation of coating properties was shown. Critical temperatures have been established, exceeding which leads to a decrease in processing efficiency. Thus, diamond ironing is a universal and technologically accessible method of hardening and finishing, however, the effectiveness of its application is determined by the optimization of processing modes, taking into account the thermal limitations and design features of the system. The obtained results can be used in the development of technological processes to increase the reliability and durability of mechanical engineering parts and tool production.

Keywords: diamond ironing, surface plastic deformation, roughness, hardening, residual stresses.

Introduction

Modern mechanical engineering and tool manufacturing impose increasing demands on the quality of the surfaces of parts, on which their performance characteristics depend, such as wear resistance, fatigue strength, corrosion resistance and reliability under intense loads. One of the most effective ways to improve the quality of the surface layer is the use of surface plastic deformation methods. These methods provide the formation of a strengthened layer with favorable residual stresses, a decrease in roughness and an increase in hardness, which together contributes to an increase in the durability of products [1-3].

Among the methods of surface plastic deformation, diamond ironing occupies a special place, which is characterized by ease of implementation, the ability to use standard metal-cutting equipment and high efficiency in the processing of parts made of steels and alloys, including coatings such as titanium nitride (TiN). In the process of ironing, not only smoothing of microroughnesses occurs, but also strengthening of the surface layer due to plastic deformations.

Despite the widespread use of diamond ironing, there are still questions related to the choice of optimal processing modes that provide minimal roughness and maximum strengthening effects at an acceptable level of thermal stress. Especially relevant is the study of the influence of the compression force, the geometry of the smoother, the rigidity of the surface plastic deformation system, as well as thermophysical processes in the contact zone of the tool and part.

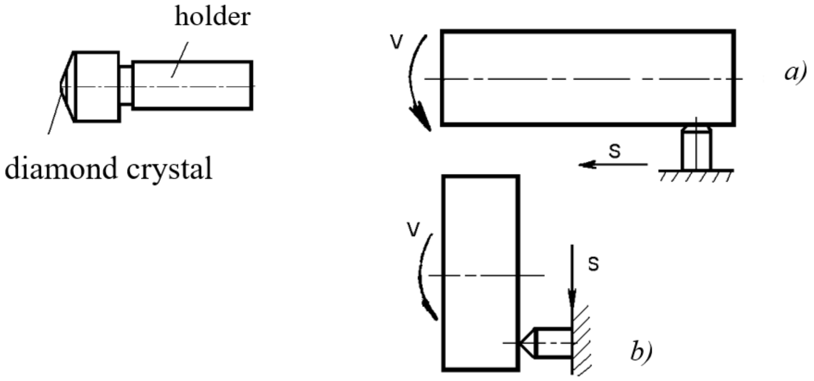
The purpose of this study is to analyze the processes of diamond ironing when processing steels with wear-resistant coatings, to determine the effect of processing parameters on the formation of residual stresses, the depth and hardness of the strengthened layer, as well as to study the thermal stress of the process.

Materials and methods

One of the simplest and most effective ways to improve the quality of surfaces of tools and parts is processing by surface plastic deformation methods, among which diamond ironing plays an important role [3, 4].

Diamond ironing consists in treatment of pre-polished and polished surface with rounded diamond cutters (radius 2-3 mm). The surface layer is compacted to a depth of 0.3-0.5 mm.

Diamond ironing machine and ironing schemes are shown in Figure 1.



a - cylinders, b – planes

Figure 1 - Diamond ironing machine and ironing schemes

As a tool for ironing, tips from natural or synthetic diamond with a working surface in the form of a sphere, cylinder or cone are used. Smoothing by kinematics (Figure 1 *a, b*) in most cases is similar to turning. The process proceeds under sliding friction conditions. With a certain force of pressing diamond to the treated surface, plastic deformations develop in the contact zone. In this case, intensive smoothing of the initial roughness occurs, the hardness of the surface layer increases, and favorable residual compression stresses are formed in it.

Surfaces of steel parts, cemented and nitrided, having hard coatings, as well as parts made of bronze and other alloys, can be easily smoothed. This process is carried out on lathes or boring machines and does not require special equipment.

A diamond smoothing tool with a spherical working surface is made with sphere radii from 0.5 to 4.0 mm through 0.5 mm from natural crystalline diamonds, as well as synthetic diamonds, which are polycrystals up to 5.0...6.0 mm in size. Diamond ironing can be performed by tool with rigid and elastic contact of deforming element with processed surface.

The surface of the part is treated by introducing a diamond smoother at a certain depth, depending on a number of factors. High sensitivity to the value of tension at rigid rounding of the smoother leads to certain limitations of the rigidity of the system of surface plastic deformation and the value of the run-out of the treated surface. Tools with rigid fastening should be worked on machines with increased rigidity with a minimum spindle runout (not more than 0.015 mm). It is recommended to use ironing with this tool for processing high-precision parts and perform it in one installation with preliminary treatment for ironing [4].

When processing with elastic contact of the deforming element of the surface, the necessary deformation force is set by means of a spring. In this case, the deformation force is kept almost constant during the treatment, since in the presence of even a relatively large beat of the treated surface, changes in radial forces will be insignificant.

Research results

As a result of diamond smoothing of tool steel with TiN coating, residual stresses arise in the surface layer. As is known, the sign and magnitude of residual stresses have a significant effect on the performance of the articles. This also applies to, depending on the physical and mechanical properties of the processed material and processing modes, the depth of the strengthened layer during surface plastic deformation by smoothing with diamond tools. can vary within a wide range - from 0.2 to 25 mm, and the hardness of the surface layer can be increased by 40-50% compared to the initial one [5].

The optimal value of the smoothing force F_N can be determined by the formula:

$$F_N = c \cdot 3 \cdot \sigma_b \cdot \left(\frac{D_d \cdot R_{sf}}{D_d + R_{sf}}\right)^2 \tag{1}$$

where: F_N – smoothing force, $F_N = 182$ H

c – factor considering processing conditions, $c = 0{,}008$

$D_{д}$ – part diameter.

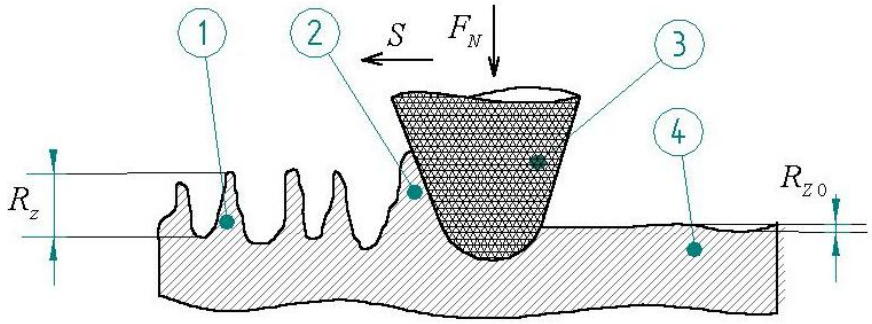


Figure 2 - Diagram of deformation of the surface layer during diamond ironing (in the feed direction)
1 - microroughness of the initial surface; 2 - influx;
3 - ironing machine; 4 - surface after ironing.

At the value of longitudinal feed $s = 0.08$ mm/vol [6], the obtained R_{Z0} roughness is calculated by the following formula:

$$R_{Z0} = R_{sf} - \sqrt{{R_{sf}}^2 - \frac{s^2}{4}} \tag{2}$$

where: $R_{Z0} = 2.35$ мкм

The roughness parameters also depend on the number of working strokes z of the smoother. As z increases to 2... 3, the roughness parameter decreases to a lesser extent. At z ≥ 4, overblown of the surface layer is possible.

The depth of the riveted layer according to the relationship [7] is determined by the formula:

$$\frac{2 \cdot \delta}{d} = 1 - \frac{\sigma_b}{\sigma_p} \tag{3}$$

where: d – part diameter;

σ_p – strength after hardening;

σ_b – core strength;

δ – depth of the riveted layer;

$\sigma_b = 750$ MPa, $\sigma_b = 877$ MPa.

The increase in surface strength is 17% higher than the initial strength [8] for 12Kh2N4A steel.

Therefore, the thickness of the hardened layer:

$$\delta = \left(1 - \frac{\sigma_b}{\sigma_p}\right) \cdot \frac{d}{2} \tag{4}$$

The use of surface plastic deformation processes, especially with diamond tools, shows that the main technological characteristics of the quality, as well as the wear resistance of tools, depend on the thermal stress in the deformation site and contact temperatures. The thermal factor is the main reason for the decrease in the strength and wear resistance of the diamond-ironing tool and the wear-resistant coating, since diamond loses its properties as a tool material already at a temperature of 700-800 °C, and a thin film coating of titanium nitride at a temperature of 550-600 °C. Therefore, the thermal intensity of the process, with which the formation of the physic mechanical properties of the hardened surface is directly related, determines the processing efficiency.

In the analytical study, the thermophysical problem was solved by methods of heat sources. For this, the temperature field in the workpiece and the temperature field in the tool were determined. Temperatures at common points of contact of the product with the tool were compared.

As a result of analytical research, relations were obtained in the form of equality of contact temperatures at the same point, but calculated separately from the side of the product and the tool. Another equation was defined in the form of a balance between the total amount of heat released in the deformation site and the amount of heat consumed to heat the part and the tool.

To calculate the temperature in the center of contact of the diamond-ironing tool with the product, the formula is obtained:

$$\Theta = \frac{q_i \cdot R}{\lambda_i} \cdot \sqrt{\frac{\pi}{k_R}}, \tag{5}$$

where q_i – point source power, J/s;

l_i – thermal conductivity coefficient of diamond-ironing tool material, W/m °C;

k_R– factor characterizing processing conditions;

$$k_R = \sqrt{k_l k_b} \tag{6}$$

where: k_l, k_b – coefficients characterizing the intensity of heat release.

Temperature regime in the machined part for the central part of the contact in the event of an unsteady process:

$$\Theta_0 = \frac{q_0}{4c\rho(\pi\omega)^{3/2}} \int_0^r \frac{exp\left[-\frac{V^2(t-t_i)^2}{4\omega T}\right]}{T^{3/2}} dt_i, \tag{7}$$

where: q_0 – maximum heat release intensity, W/m^3;

ω – thermal diffusivity, m^2/s;

t, t_i – processing time, s;

$c\rho$ – specific heat per unit volume, J/m^3°C;

V – velocity of fast-moving point source, m/s.

Since the heat source is normally spherical for the product, its total thermal power can be represented as:

$$Q_0 = q_0 \frac{\pi^{3/2} R^3}{2k_R^{3/2}}. \tag{8}$$

For a tool, the source is normal-circular and its thermal power is defined as:

$$Q_1 = q_i \frac{\pi R^2}{k_R}. \tag{9}$$

Total process thermal power:

$$Q = P_V V. \tag{10}$$

Obtained, ratio for determination of tangential component of radial force:

$$P_V = \frac{\tau_s \pi k R^2}{2}\left(\left(\frac{2}{k} - 1\right)\varepsilon^2 + 1\right) \tag{11}$$

where: τ_s – shear strength of the material;
$k = \mu_n/\mu$ – ratio of friction coefficients of coating and base;
$\varepsilon = R_0/R$ – the hardness factor of the treated material is in the range of ε = 0,45...0,55.

It is known that the radius of the imprint during the force interaction of two spherical bodies is determined by the formula:

$$R = \sqrt[3]{\frac{3Pr_u}{4}\left(\frac{1-\sigma_1^2}{E_1} + \frac{1-\sigma_2^2}{E_2}\right)} \tag{12}$$

where: P – radial force during machining, H;
r_u – indenter radius, m;
E_1, E_2 – modulus of elasticity of tool material and workpiece material, respectively;
σ_1, σ_2 – Poisson ratios of tool and part materials, respectively.

The system of equations in the balance problem is represented by relations:

$$\begin{cases} P_V V = q_i \frac{\pi R^2}{k_R} + q_0 \frac{\pi^{3/2} R^3}{2k_R^{3/2}}; \\ \frac{q_i R}{\lambda_i}\sqrt{\frac{\pi}{k_R}} = \Theta_0 , \end{cases} \tag{13}$$

Hence, the temperature regime in the processed part for the central part of the contact in an unsteady process is determined by the formula:

$$\Theta_0 = \frac{Q_0}{2\times 4c\rho(\pi\omega)^{3/2}} \int_0^x \frac{exp\left[-\frac{V^2(t-t_i)^2}{4\omega T}\right]}{T^{3/2}} dt_i;$$

Total processing time is determined by the formula:

$$T = t - t_i + \frac{R^2}{4\omega k} \tag{14}$$

As a result of the system solution (13), it was obtained:

$$q_i = \frac{P_V V \lambda_i \sqrt{k_R A}}{2\pi^{1/2} R \left(1 + \frac{\pi^{1/2} R A \lambda_i}{2k_R^{1/2}} \right)}; \tag{15}$$

$$q_0 = \frac{2P_V V k_R^{3/2}}{\pi^{3/2} R^3} - \frac{P_V V k_R \lambda_i A}{\pi R^2 \left(1 + \frac{R\pi^{1/2} A \lambda_И}{2k_R^{1/2}} \right)}, \tag{16}$$

Total work on surface plastic deformation:

$$A = \frac{1}{4c\rho(\pi\omega)^{3/2}} \int_0^x \frac{exp\left[-\frac{V^2 (t - t_И)^2}{4\omega T} \right]}{T^{3/2}} dt_i \tag{17}$$

The calculation results were performed using the numerical Chebyshev method in the Turbo Basic programming language. Analysis of the obtained dependencies shows that with the parameters of surface plastic deformation treatment used in practice, the processing speed and the concentration coefficient of the heat source have a decisive effect on contact temperatures: with an increase in the speed or concentration coefficient, the temperature increases sharply. This allows us to conclude that the thermal intensity of the process of diamond ironing of parts with TiN coatings is considered as one of the technological limitations when calculating the optimal modes of diamond ironing.

Discussion

The results obtained confirm the high efficiency of diamond ironing when processing parts from tool steels with hard coatings. It was revealed that the process parameters significantly depend on the rigidity of the surface plastic deformation system: when using a tool with rigid fastening, higher accuracy and minimal roughness are ensured, but the sensitivity to spindle beating increases. In turn, the elastic contact of the deforming element makes it possible to compensate for force fluctuations and ensure processing stability, which is consistent with the data of other studies [8-10].

The calculated values of the depth of the strengthened layer and the increase in hardness are consistent with the known patterns of surface plastic deformation. At the same time, it was noted that the thermal stress of the process plays a key role in maintaining the operational properties of the tool and coating. When critical temperatures are exceeded, the wear resistance of the diamond tip and TiN coating decreases, which requires optimization of processing modes.

Thus, diamond ironing can be considered as an effective method of improving the quality and durability of parts, however, its use should be accompanied by taking into account the rigidity of the system and thermal limitations, which determines the direction of further research.

Conclusion

Diamond ironing provides reduction of roughness, hardening and formation of residual compression stresses in surface layer of parts. It is shown that the rigid fastening of the tool requires high system rigidity and minimal spindle runout, while the elastic contact allows you to stabilize the force and increase the versatility of the process. It was found that the depth of the strengthened layer reaches 2.5 mm, and the hardness increases to 50% compared to the original. Analysis of thermal processes confirmed the need to limit the contact temperature in order to avoid reducing the wear resistance of the tool and coating.

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ЖАБЫНЫ БАР БӨЛШЕКТЕРДІҢ БЕТКІ ПЛАСТИКАЛЫҚ ДЕФОРМАЦИЯСЫ КЕЗІНДЕ АЛМАС ТЕГІСТЕУ ПРОЦЕСТЕРІН ЗЕРТТЕУ

[1]А.З. Букаева, [2]О.Г. Киквидзе
[1]Есенов университеті, Ақтау, Қазахстан
[2]Акакия Церетели атындағы мемлекеттік университеті, Грузия, Кутаиси.
e-mail.ru: amina.bukaeva@yu.edu.kz, kikvidze6@mail.ru

Аңдатпа: Мақала машина жасау бөлшектерінің сапасы мен пайдалану қасиеттерін арттыру үшін қолданылатын беттік пластикалық деформациялаудың қазіргі заманғы және тиімділігі жоғары әдісі ретінде алмас тегістеуді зерттеуге арналған. Процестің негізгі физикалық тетіктері қарастырылды: жер үсті қабаттарын нығайту, қысымның қалдық кернеуін қалыптастыру, кедір-бұдырлық параметрлерін төмендету және тозуға төзімділікті арттыру. Титан нитриді (TiN) сияқты тозбайтын жабыны бар бөлшектерді өңдеуге ерекше назар аударылады, бұл әсіресе аспаптық және машина жасау өндірісі үшін өзекті. Жұмыста процестің оңтайлы режимдерін анықтауға мүмкіндік беретін аналитикалық тәуелділіктер келтірілген, оның ішінде нығыздау күші мен нығайтылған қабаттың тереңдігі. Жылу кернеуіне талдау жүргізілді, температуралық факторлардың алмас құралының беріктігіне және жабындардың қасиеттерін сақтауға әсері көрсетілді. Температураның критикалық мәндері белгіленген, олардың артуы өңдеу тиімділігінің төмендеуіне әкеледі. Осылайша, алмасты үтіктеу нығайтудың және мәреге жеткізудің әмбебап және технологиялық қолжетімді әдісі болып табылады, алайда оны қолдану тиімділігі жылу шектеулері мен жүйенің құрылымдық ерекшеліктерін ескере отырып, өңдеу режимдерін оңтайландырумен айқындалады. Алынған нәтижелер машина жасау және аспаптық өндіріс бөлшектерінің сенімділігі мен ұзақтығын арттыру үшін технологиялық процестерді әзірлеу кезінде пайдаланылуы мүмкін.

Түйін сөздер: алмазды тегістеу, беткі пластикалық деформациялау, кедір-бұдырлық, нығайту, қалдық кернеу.

ИССЛЕДОВАНИЕ ПРОЦЕССОВ АЛМАЗНОГО ВЫГЛАЖИВАНИЯ ПРИ ПОВЕРХНОСТНОМ ПЛАСТИЧЕСКОМ ДЕФОРМИРОВАНИИ ДЕТАЛЕЙ С ПОКРЫТИЯМИ

[1]А.З. Букаева, [2]О.Г. Киквидзе
[1]Университет Есенова, Актау Казахстан
[2]Государственный университет им. Акакия Церетели, Грузия, Кутаиси.
e-mail.ru: amina.bukaeva@yu.edu.kz, kikvidze6@mail.ru

Аннотация. Статья посвящена исследованию алмазного выглаживания как современного и высокоэффективного метода поверхностного пластического деформирования, применяемого для повышения качества и эксплуатационных свойств деталей машиностроения. Рассмотрены основные физические механизмы процесса: упрочнение поверхностных слоёв, формирование остаточных напряжений сжатия, снижение параметров шероховатости и увеличение износостойкости. Особое внимание уделено обработке деталей с износостойкими покрытиями, такими как нитрид титана (TiN), что особенно актуально для инструментального и машиностроительного производства. В работе приведены аналитические зависимости, позволяющие определить оптимальные режимы процесса, включая усилие поджатия и глубину упрочнённого слоя. Проведён анализ тепловой напряжённости, показано влияние температурных факторов на стойкость алмазного инструмента и сохранение свойств покрытий. Установлены критические значения температуры, превышение которых приводит к снижению эффективности обработки. Таким образом, алмазное выглаживание является универсальным и технологически доступным методом упрочнения и финишной обработки, однако эффективность его применения определяется оптимизацией режимов обработки с учётом тепловых ограничений и конструктивных особенностей системы. Полученные результаты могут быть использованы при разработке технологических процессов для повышения надёжности и долговечности деталей машиностроения и инструментального производства.

Ключевые слова: алмазное выглаживание, поверхностное пластическое деформирование, шероховатость, упрочнение, остаточные напряжения.