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INCREASING OF THE DURABILITY OF DETAILS WORKING UNDER REPEATABLE-LOADS

The article develops processes of increase the durability of parts operating under repeated loads, by justifying the parameters of surface plastic deformation (SPD) and cold gas-dynamic coating. The influence on the depth of the reinforced surface layer, the nature of the distribution of the stress-strain state of the material and residual compressive stresses, as well as the value of the used plasticity of the metal, the parameters of the SPD process. The hypothesis is substantiated that the main factor in the formation of residual compressive stresses during SPD is the decrease in metal density, which is associated with the use of the plasticity resource. The model of definition of the used resource of plasticity of metals at SPD is developed, that allows to provide qualitative characteristics of a surface layer of details. Methods for shifting the layer with maximum hardening and residual compressive stresses to the surface of the part by using a deformable tool of smaller dimensions in subsequent passes and gas-dynamic coating before SPD.

The vast majority of traditional gas-thermal coating methods occur at significant temperature effects on the surface of the part, which is unacceptable for the surface treated by SPD methods. Cold gas-dynamic spraying provides an allowable temperature regime for the creation of special auxiliary coatings while maintaining the properties of the surface treated by SPD methods.

The technology of gas-dynamic coating includes heating the compressed gas (air), feeding it into the nozzle and forming a supersonic air stream in this nozzle, introducing a powder material into this stream, accelerating this material in the nozzle by a supersonic air flow and directing it to the surface of the workpiece. As a result, a special auxiliary coating is formed on the surface of the product, which provides optimal parameters of the SPD process.

Keywords: *surface plastic deformation, residual compressive stresses, used plasticity resource, cold gas-dynamic coating.*

Introduction. The intensification of production processes leads to a forced increase in the speed of equipment and modes with re-variable load of its parts. As a result, the reliability and durability of machines largely depends on the strength of endurance (fatigue resistance) of the most loaded components and parts. In turn, the durability of parts significantly depends on the characteristics of their surface layer. Such characteristics include: strength (hardness) and ductility of the material, the presence of residual compressive stresses, the microstructure of the material, surface roughness and relief, and so on. One of the ways to increase endurance, as well as other performance characteristics of parts is the use of surface plastic deformation (PPD).

As a result of application of PPD in a surface layer of preparation characteristics of durability and plasticity of material are change, hardness and residual compressive stresses increase, structure and texture of material change. However, it is not always possible to purposefully influence these changes and predict the necessary qualitative characteristics of the surface layer due to the complexity and non-stationarity of PPD processes, as well as their insufficient study. Therefore, the implementation of PPD processes to obtain the necessary characteristics of the product is accompanied by time-consuming experiments. Moreover, their results apply mainly only to the establishment of certain characteristics of specific products made of a specific material.

Analysis of recent research. Studies of the surface layer show that all methods of surface plastic deformation create residual compressive stresses on the surface, different in magnitude and depth of propagation, with the transition at depth to residual tensile stresses (Fig. 1).

The results of fatigue tests of parts after hardening by PPD methods, as a rule, show an increase in the endurance limit (Fig. 2), but an unambiguous connection with the magnitude and depth of the distribution of residual compressive stresses is not given. According to fig. 2 dependences are constructed for types of processing: 1 normalizing heat treatment; 2 - vibrating steel balls with a diameter of 1.0-1.3 mm; 3 - ultrasonic hardening with steel balls with a diameter of 1.0-1.3 mm; 4 - hydro-jet reinforcement with balls with a diameter of 1.6 mm; 5 - shot blasting with steel balls with a diameter of 0.1-0.2 mm

In [2], the results of a study of low-cycle fatigue of smooth samples based on 8-10 cycles / min are presented, which show that all PPD methods give a significant increase in durability, compared with grinding.

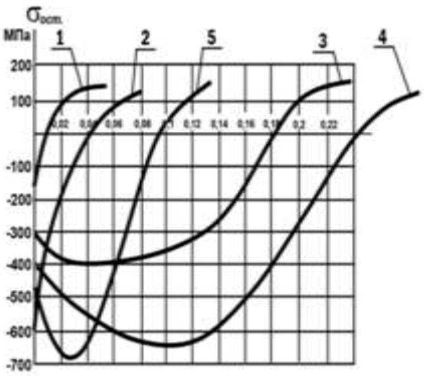


Fig. 1. Distribution of residual stresses in the surface layer of parts made of alloy EP718 with different types of finishing

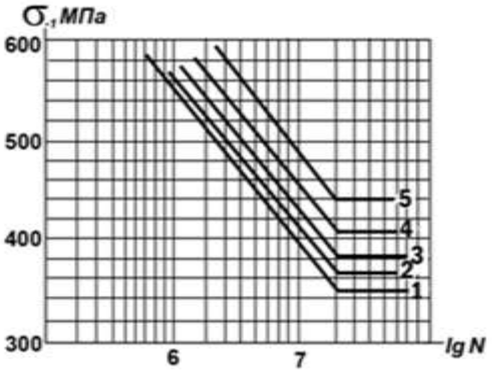


Fig. 2. Fatigue strength curves of EP718 alloy parts for different types of finishing

During PPD, surfaces with a rather small roughness and a large radius of depressions and irregularities are formed, which also has a favorable effect on fatigue resistance. However, this effect is always manifested in combination with other quality parameters of the surface layer. Therefore, for parts operating under cyclic loads, the previously noted parameters have a more significant effect on durability than roughness. This is explained by the fact that the depressions of the bumps have an effect on the resistance to fatigue until there is a fatigue crack. In addition, after hardening of the PPD, a fatigue crack often arises beneath the surface at a certain depth. And the period of development of such a crack is influenced by deformation hardening and residual compressive stresses.

At insignificant degrees (3-10%) and depth (10-20 μm) of hardening, there is an increase in the quality characteristics of the material, due to the reduction of the volume defects of the lattice, the process of polygonization, the formation of a favorable microstructure of the material. At the same time the residual plasticity of material decreases, sensitivity to overloads and formation of cracks increases.

Thus, the most generalizing, for the formation of the service properties of the products, are the characteristics of strength and ductility of the material, as well as the level of residual compressive stresses in the surface layer of the product treated with PPD. Especially important is the information about the magnitude and nature of the distribution in the surface layer of the accumulated deformation and the residual plasticity. These characteristics and determine, to a large extent, the performance characteristics of the product.

The analysis of the influence of PPD on fatigue resistance shows that the main obstacles in the purposeful development of PPD processes are the lack of knowledge about the nature of the distribution of the stress-strain state of the material and its deformability in the zone of plastic hardening.

The purpose of research is to increase the durability of parts operating under repeated loads, by developing, based on the assessment of the deformability of metals, reasonable parameters of the combined technological processes of surface plastic deformation

Presenting main material. To study the VAT of the plastic zone when pressing the ball into the workpiece, the method of coordinate dividing grids was used, based on the use of a technique based on the theory of R-functions. The nature of the distribution of isolines of the intensity of deformation in the area of the impression is shown in (Fig. 3), obtained by measuring the coordinate fissile grid, coincides with that obtained by measuring the hardness. Fig. 4 shows a diagram of the residual stresses on the depth of the surface layer of the part of the alloy EP718 after turboabrasive treatment in a mixture of abrasive and steel balls with a diameter of 0.1-0.2 mm. Studies have shown that as a result of repeated sequential compression of the tool, which is observed in PPD, there is a shift of metal particles in different directions, which leads to a change in the sign of the components of deformation and stress.

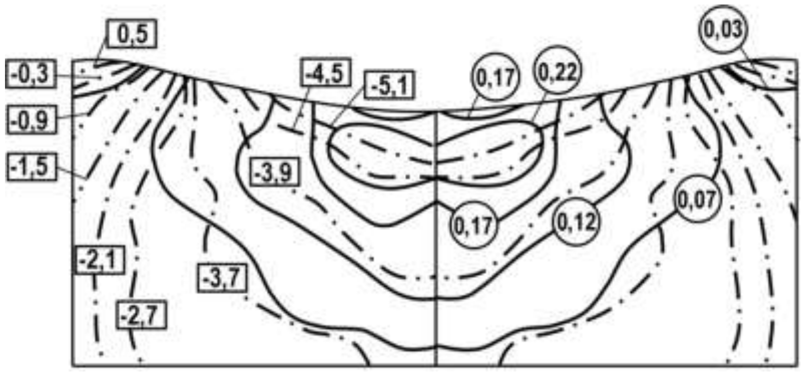


Fig. 3. Distribution of isolines of intensity of deformations $\varepsilon_u = const$ (○)and index$\eta = const$ (□)on depth *h*of a zone of a plastic imprint

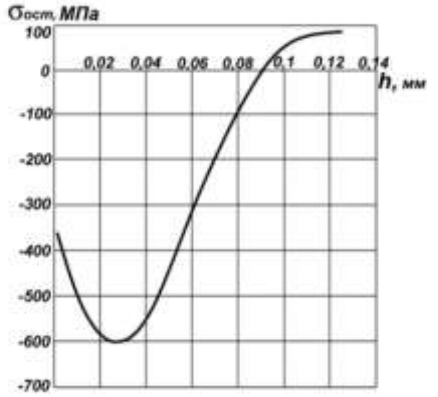


Fig. 4. Plot of residual stresses σ_{ocm} on the depth h of the surface layer of the part of the alloy EP718 after turbo abrasive processing

Indicator of stress $\eta = I_1(T_\sigma)/\sqrt{3I_2(D_\sigma)}$, where $I_1(T_\sigma)$ i $I_2(D_\sigma)$ – the first invariant of the tensor and the second invariant of the stress deviator varies from the values corresponding to the comprehensive compression (η=-5…-3) on the axis of symmetry of the imprint, to the offset-tensile ($\eta \geq 0$) at the edge of the imprint, at the formation of the plastic roller. When the tool is pressed in the area between the prints, the value ofηincreases due to the decrease of the hydrostatic support from the side of the prints. In the center of the newly formed imprint it isη = -2…-4, and at its boundaryη = 0…1.

Thus, in PPD there is a complex multi-stage deformation, which is accompanied by the formation of inflows at the boundary of plastic impressions, followed by their compression.

As can be seen from Fig. 3, the nature of the deformed state in the area of the imprint is quite uneven. The intensity of deformation near the surface is only 50-80% of the maximum. The greatest deformation is observed in the center of the imprint at depth ≈ 0.1*d* (from the imprint surface), where the *d*-diameter of the imprint. The maximum intensity of deformation in the area of the imprint is approximately$\varepsilon_u^{\max}$ ≈(0.4..0.5)*d/D*, and the depth of the plastic zone$h_{пл}$=(1.4…1.6)*d*, where*d*and*D* – the diameter of the imprint and the ball, respectively.

Thus, if it is necessary to form a thin strongly strengthened layer, it is necessary to apply balls of small diameter, appointing many transition process with the maximum relative depth of an imprint. If it is necessary to form a deep, moderately strengthened layer, it is necessary to appoint a little transient process of PPD balls of relatively larger sizes.

The marked nature of the distribution of the deformed state along the depth of the surface layer is observed in many transient deformations.

The stress intensity of the material of the surface layer of the workpiece during PPD, and taking into account the unity of the flow curve, as well as the intensity of deformation, can be determined by measuring the hardness (microhardness). The increase in hardness is associated with the fragmentation of crystals into fragments and blocks, the curvature of the crystal lattice at their boundaries, the increase of dislocations and vacancies.

However, at a certain stage of PPD plastic hardening is accompanied by even more intense plastic loosening of the material, which is also accompanied by a drop in hardness (microhardness) (Fig. 5).

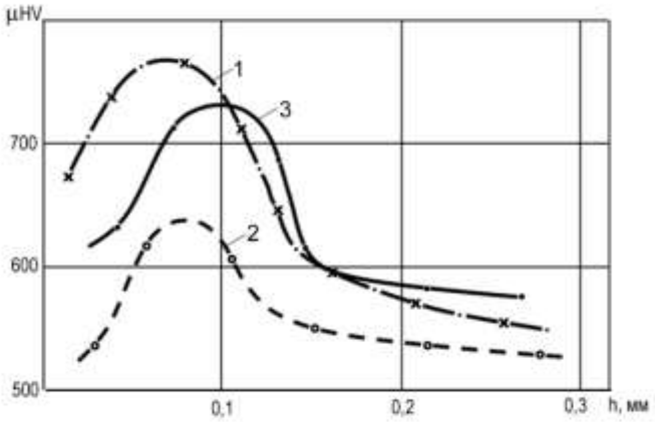


Fig. 5. The nature of the distribution of microhardness μHV along the depth of the surface layer while rolling the rod with EP718 balls: 1 - 2 pass with compression $\Delta h = 0{,}04\text{мм}$; 2 - 15 passages, $\Delta h = 0{,}04\text{мм}$; 3 - 1 pass, $\Delta h = 0{,}07\text{мм}$.

According to the data (Fig. 5) and the calibration graph of the alloy EP718, the maximum value of the intensity of deformation, for curves 1 and 3, was observed at a depth of 0.1 mm and corresponds to 820 and 750 units of μHV, respectively. It is no longer possible to determine the accumulated deformation by the results of curve 2.

Thus, the hardness measurement can be used to determine the VAT of the material of the surface layer of the workpiece in the initial stages of the PPD process and to determine the factors shifting the region of maximum deformation to the workpiece surface, as well as a criterion that would regulate the processing process .

If it is necessary to determine the degree of deformation accumulated over a certain number of passes or the time of deformation, then by measuring the hardness it should be determined with a limited number of passes or processing time (the smaller the lower the hardening coefficient of the metal). The degree of deformation accumulated during the entire processing process can be defined as the total in terms of passes or processing time (taking into account the gradual reduction due to the strengthening of the metal, if the deformation is carried out at constant load or impact energy).

PPD involves limiting the process in terms of the value of the used resource of plasticity of the metal, a significant depletion of which leads to a decrease in fatigue resistance. The value of the used resource of plasticity of the metal of the surface layer should be calculated using tensor models of damage accumulation, in particular using the criterion [3]:

$$\psi_u = \frac{1}{4}(2N)^{2n}\left[\psi_1^{2n} + 2I(\psi_1\psi_2)^n + \psi_2^{2n}\right] \leq 1 \tag{1}$$

Where *I* – is the invariant parameter, *n*- is the parameter of the damage function, N - is the number of deformation cycles.

For PPD, we take as a basis a complex two-stage deformation in the sequence "simple-complex", using the step function of damage. We get:

$$\psi_u = \left(\frac{\varepsilon_u^{(1)}}{\varepsilon_{-1}}\right)^{2n} + 2\cdot\left(\frac{\varepsilon_u^{(1)}}{\varepsilon_{-1}}\right)^{2n} \cdot \left[a^{(1)}\cdot\beta_{ij}^{(1)} + b^{(1)}\cdot\left(b_{ik}^{(1)}\cdot b_{kj}^{(1)} - \frac{1}{3}\delta_{ij}\right)\right]\cdot\psi_{ij}^{(2)} + \psi_u^{(2)} \tag{2}$$

де

$$\psi_{ij}^{(2)} = \int_{\varepsilon_u^{(1)}}^{\varepsilon_u^{(2)}} [\![\left[A(\square]\varepsilon_u) \cdot \beta_{ij}(\varepsilon_u) + B(\varepsilon_u) \cdot \left(\beta_{ij}(\varepsilon_u) \cdot \beta_{ij}(\varepsilon_u) - \frac{1}{3}\delta_{ij}\right)\right] d\varepsilon_u \qquad (3)$$

where $\varepsilon_u^{(k)}, (k = 1{,}2)$ – accumulated plastic deformation at the end of the k - th stage;

n – parameter of the step model of the damage function;

$b^{(k)}$ – coefficient of tensor nonlinearity: determined by the properties of the material $\left(\left|b^{(k)}\right| \le \sqrt{6}\right)$;

$a^{(k)}$ – determined by the coefficient $b^{(k)}$ and the third invariant of the tensor $\beta_{ij}^{(k)}$.

The constructed model of accumulation of damages (2) allows to define size of the used resource of plasticity at difficult two-stage deformation when at the second stage (displacement of metal by the tool, after its indentation) difficult deformation takes place $\beta_{ij}(\varepsilon_u) \neq const$ .With increasing stages of deformation (number of passes), the total used resource of plasticity is determined by adding the values obtained during the two-stage deformation.

Using model (2), the character of the distribution of the value of the used plasticity resource is obtained ψ_u along the depth of the surface layer of the part, reinforced by PPD methods (Fig. 6).

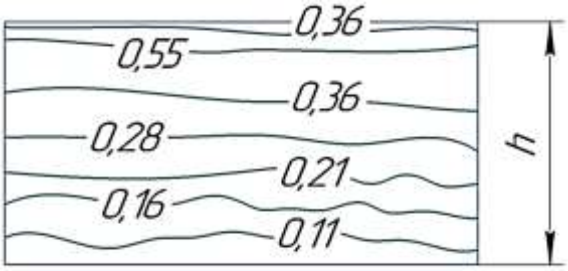
Thus, the maximum used resource of plasticity is under the surface at a depth of approximately 0.1 from the depth of the reinforced layer. By the way, this fact is confirmed by the nature of the destruction of the surface layer, which manifests itself in the form of exfoliation (peeling) of metal particles.

Since plastic loosening of the material occurs during plastic deformation, we conducted a study of changes in the density of steels and alloys under different schemes of stress-strain state. The density of the sample material was determined by triple hydrostatic weighing on analytical balances model VPR-200 with accuracy 10^{-4} .

In fig. Figure 7 shows the average dependence of the relative change in the density of metals $\Delta\rho/\rho_0$ from the value of the used resource of plasticity ψ_u .

Studies have shown that in the initial stages of deformation, in all types of tests (compression, torsion, tension), for a number of metals is observed insignificant intensity of decrease in relative density. In the alloy EI961 during deposition to values $\psi_u \le 0{,}4$ the density even increased slightly. Titanium alloys VT8 and VT9 in the initial stages are deformed at a relatively low intensity of density reduction. In other steels and alloy EP718 the dependence of the intensity of the decrease in density on ψ_u was close to linear. As the plasticity of metals is exhausted, the relative change in their density is equalized, and at values $\psi_u = 0{,}4$ .the decrease in density for the studied metals was $\Delta\rho/\rho_0 \approx 0{,}6\%$

The decrease in density, and hence the relative increase in the volume of the metal as the resource of plasticity is exhausted, in our opinion, explains the effect of reducing the residual compressive stresses on the surface of the products during PPD. Indeed, the nature of the distribution of residual stresses (Fig. 4) corresponds to the nature of the distribution in the surface layer of the intensity of deformation (Fig. 3), the stress intensity (microhardness, Fig. 5) and the value of the used plasticity resource (Fig. 6). As a result, the zones of the surface layer are the most compressed, in which the maximum deformations accumulate during PPD and the largest relative increase in the volume of the material occurs. In the absence of data on the relative deformation increase in volume for a particular material, at values $\psi_u \ge 0{,}6$ it can be determined by the average dependence 4 (Fig. 7).



The nature of the distribution of the value of the used resource of plasticity ψ_u on the depth of the surface layer of the part, reinforced by PPD methods

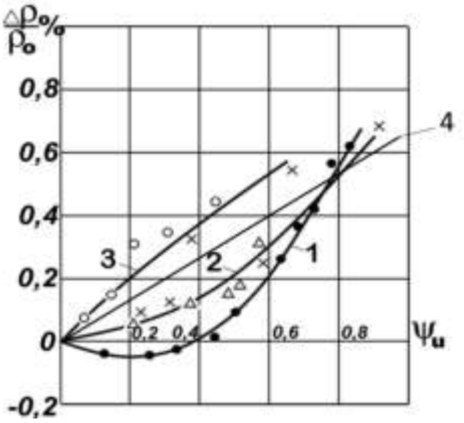


Fig. 7. Dependence of the relative change in the density of metals $\Delta\rho/\rho_0$ from the value of the used resource of plasticity ψ_u : 1 – EI961; 2 – BT9; 3 – ЕП718

To increase fatigue resistance, technological methods should be used that shift the zones with maximum deformation, hardness and residual compressive stresses to the surface of the part. At the same time it is necessary to adhere to restrictions concerning the maximum use of a resource of plasticity of metal.

To shift the zones with maximum residual compressive stresses to the surface of the part, we proposed to use two approaches: to process the surface layer with balls of minimum diameter at the final stages and PPD after cold gas-dynamic application of copper coating on the surface.

The process of rolling cylindrical workpieces by rollers and balls was adopted as the studied PPD process. To implement the process, run-ins were designed, which provide for rolling parts on lathes.

Fig. 8 shows a device for rolling, which involves the use of balls of different diameters. The force on the balls and the depth of their penetration into the material of the part is regulated by a spring.

The rolling device comprises a base 1, which is fixed in the cutter holder of the universal lathe, and levers 2 and 3 that can rotate relative to the base 1 on the axis 4 on the guide column 5 under the action of a spring 6 mounted on the hinge bolt 7. In the levers 2 and 3 housings 8 and 9 with deforming balls 10 with a diameter of 8 mm and 11 with a diameter of 3 mm are installed. The relative depth of indentation of the balls 10 and 11 in the workpiece 12 is provided by the nut 13, as well as changing the diameters of the balls 10, 11.

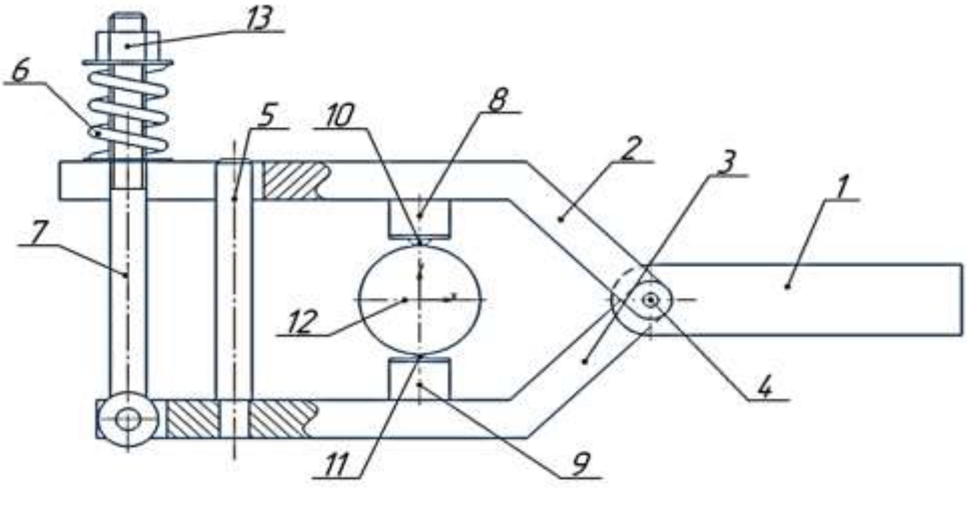


Fig. 8. Type of run-in using balls of different diameters.

The device for strengthening the surfaces of cylindrical metal parts works as follows: the workpiece 12 is mounted in the chuck and the rear head of the universal lathe. The base 1 of the device is installed in the cutter holder of the machine, and the working area of rolling is formed by turning the levers 2 and 3 around the axis 4 with the groove of the guide column 5 and locking the device with a bolt 7 to create a given force spring 6 and nut 13. Housing 8 with deforming ball 10 shifted in the direction of the longitudinal axis of the workpiece by not less than the width of the groove formed on the workpiece by the ball 11. In the housing 8 in the course of rolling is one ball with a diameter of 8 mm, which provides the required depth of hardening surface layer of the workpiece, the ball 11 with a diameter of 3 mm is selected from the condition of the total overlap of the groove formed by the ball 10 and the need to create a balanced system of forces in the deformation zone to ensure stability of the surface hardening process. The size of the smallest balls is selected from the condition of maximum approximation of the zone of the largest residual compressive stresses to the workpiece surface. Adjustment of the amount of compression of the balls 10, 11 is also provided by the nut 13.

Turns on the rotation of the workpiece and the feed movement of the runner along the axis of the caliper by a value 4-5 times smaller than the width of the plastic impression formed by the first ball in the feed. The deformation involves limiting the used plasticity of the metal value $\psi_u \le 0{,}4$, which can be determined in advance using the above mathematical model (2) and finally established provided that the maximum performance of the product.

The next way of forming the maximum residual compressive stresses on the surface of the part is to apply special auxiliary coatings before PPD.

The vast majority of traditional gas-thermal coating methods occur at significant temperature effects on the surface of the part, which is unacceptable for the surface treated by PPD methods. Only gas-dynamic spraying [5] can provide a permissible temperature regime for the creation of special auxiliary coatings while maintaining the properties of the surface treated by PPD methods.

The technology of gas-dynamic coating includes heating of compressed gas (air), its supply to the supersonic nozzle (Fig. 9) and the formation in this nozzle of supersonic air flow, supply to this stream of powder material, acceleration of this material in the nozzle by supersonic air flow and direction it on the surface of the workpiece

The supersonic nozzle with axial supply of material for spraying (Fig. 9) consists of a barrel 3 having a cylindrical hole of constant diameter, in which the left side is cone 5. Cone 5 is made so that it is possible to adjust the gap C between cone 5 and trunk hole. Adjusting the gap C allows you to adjust the pressure and flow rate of the working gas and, accordingly, adjust the parameters and quality of the coating.

To create favorable conditions for the application of quality coating, the following parameters must be observed:
- working gas - air;
- temperature of the working gas - 300-400 ° C;
- working gas pressure 0.5-1 MPa;
- the speed of the spray particles 400-1000 m / s

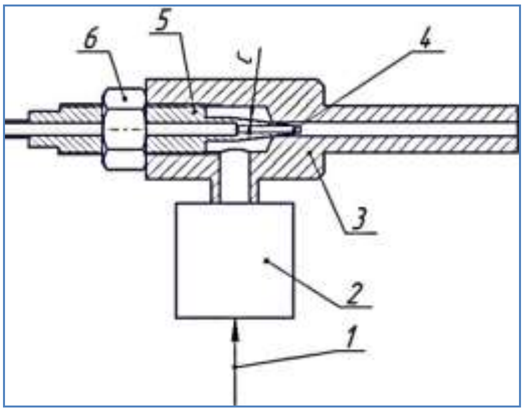


Fig. 9. Supersonic nozzle with axial supply of powder: 1 - supply of compressed gas (air), 2 - gas heater, 3 - barrel, 4 - powder supply channel, 5 - cone with the possibility of adjustable movement, 6 - lock nut.

Metal powders, alloys or their mechanical mixtures are used as a coating material. By changing the modes, you can change the porosity and thickness of the coating. The powder particles are heated to relatively low temperatures (up to 300 ° C). The surface of the part is heated to 150 ° -200 ° C. The process does not create significant noise and can be automated.

To implement the process of gas-dynamic coating in Vinnytsia National Agrarian University was created special equipment, shown in Fig. 10.

Fig. 10. Gas-dynamic device for coating.

The gas-dynamic coating device consists of two main components: a compressed air heater and a heated compressed air accelerator.

In the body of the compressed air heater there are ceramic disks with holes through which the heating nichrome elements are heated to a temperature of 800 ° C, in contact with them the air is heated to a temperature of 300-500 ° C. Next, the heated air enters the supersonic nozzle (Fig. 9) in the trunk 3. The supersonic nozzle contains a cone 5, which in conjunction with the hole in the trunk 3 forms an annular critical section C. Passing through this section compressed air accelerates to supersonic speed, causing pressure drop at the outlet of the cone 5. As a result, in the hole of the cone 5, the pressure drops below atmospheric, creating the effect of ejection and sucking the spray powder. The powder is accelerated by supersonic air flow and transferred to the surface of the part. In a hot air stream, the powder heats up and, hitting the surface of the part, deforms and forms molecular bonds with it. Thus a continuous coating is formed. Powders of copper, aluminum, bronze, babbitt and other non-ferrous metals, as well as their alloys can be used as the coating material. The size of the powder particles should be in the range of 40-80 µm. Experimental application of aluminum powder on a steel plate, which resulted in the formation of a continuous layer of aluminum coating (Fig. 11).

Fig. 12 shows a diagram of a gas-dynamic application of a continuous coating on a cylindrical part.

Carrying out of operations of PPD for surfaces of the details with the put covering allows to shift as much as possible the strengthened zone to a surface, having increased resistance to fatigue at work of details in the conditions of repeatedly variable loadings. If necessary, the coating can be removed from the surface of the part.

Fig. 11. Gas-dynamic application of aluminum coating on the plate

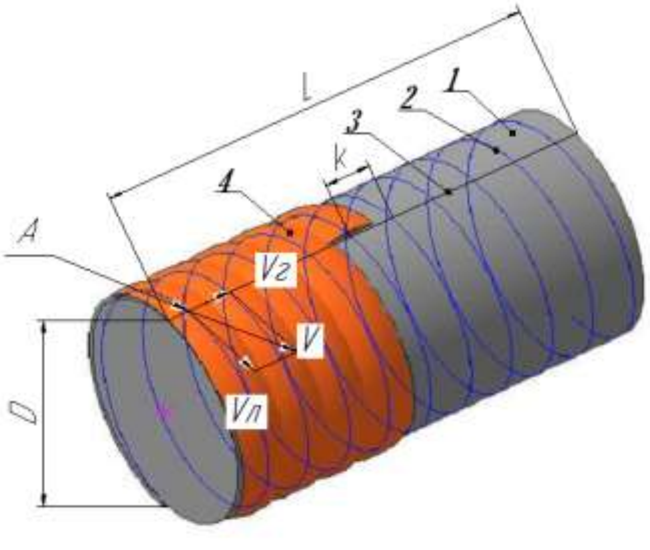


Fig. 12. Scheme of cold gas-dynamic application of a continuous coating on a cylindrical part: 1 - sprayed part; 2 - spiral trajectory of the spray figure; 3 - rectilinear trajectory of the spray device; 4 - coating. Vl - speed of rotation of the part at the point of spraying (A), Vr - speed of movement of the spraying figure (A) along the trajectory of the spraying device. V is the velocity of the sputtering figure along the spiral trajectory. L is the length of the surface to be treated, k is the pitch of the spiral line, D is the diameter of the part

Conclusions. 1. Fatigue resistance of parts operating under re-alternating load depends on the mechanical characteristics of the material of the surface layer: strength, ductility, the level of residual compressive stresses, which can be formed by PPD methods.

2. The model of definition of the used resource of plasticity of metals at PPD that allows to provide qualitative characteristics of a surface layer is developed.

3. The nature of the distribution of the stress-strain state and the used plasticity resource along the depth of the surface layer is established, depending on the parameters of the PPD process.

4. The hypothesis is substantiated that the main factor in the formation of residual compressive stresses in PPD is the decrease in metal density, which is associated with the use of the plasticity resource.

5. Developed methods of displacement of the layer with maximum hardening and residual compressive stresses to the surface of the part by using a deformable tool of smaller dimensions in subsequent passes and gas-dynamic application of a special auxiliary coating before PPD.

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ПОВЫШЕНИЕ ДОЛГОВЕЧНОСТИ ДЕТАЛЕЙ, РАБОТАЮЩИХ ПРИ ПОВТОРНО-ПЕРЕМЕННЫХ НАГРУЗКАХ

В статье описано разработку процессов по повышению долговечности деталей, работающих при повторно-переменных нагрузках, путем обоснования параметров поверхностного пластического деформирования (ППД) и холодного газодинамического нанесения покрытий. Показано влияние на глубину упрочненного поверхностного слоя, характер распределения в нем напряженно-деформированного состояния материала и остаточных напряжений сжатия, а также величины использованного ресурса пластичности металла, параметров технологического процесса ППД. Обоснованная гипотеза, про то, что основным фактором формирования остаточных напряжений сжатия при ППД является уменьшение плотности металлов, связанное с использованием ресурса пластичности. Разработана модель определения использованного ресурса пластичности металлов при ППД, что позволяет обеспечивать качественные характеристики поверхностного слоя деталей. Разработаны способы смещения слоя с максимальным укреплением и остаточными напряжениями сжатия к поверхности детали путем использования деформируемого инструмента меньших размеров на следующих проходах и газодинамического нанесения покрытия перед проведением ППД.

Подавляющее большинство традиционных газотермических методов нанесения покрытия происходит при значительных температурных воздействиях на поверхность детали, что является недопустимым для поверхности, обработанной методами ППД. Только холодное газодинамическое напыление может обеспечить допустимый температурный режим создания специальных вспомогательных покрытий с сохранением свойств поверхности, обработанной методами ППД.

Технология газодинамического нанесения покрытий включает в себя нагрев сжатого газа (воздуха), подачу его в сверхзвуковое сопло и формирование в этом сопле сверхзвукового воздушного потока, подачу в этот поток порошкового материала, ускорение этого материала в сопле сверхзвуковым потоком воздуха и направление его на поверхность обрабатываемого изделия в результате чего образуется специальное вспомогательное покрытие которое обеспечивает оптимальные параметры процесса ППД.

Ключевые слова: *поверхностное пластическое деформирование, остаточные напряжения сжатия, используемый ресурс пластичности, холодное газодинамическое нанесение покрытия.*

ПІДВИЩЕННЯ ДОВГОВІЧНОСТІ ДЕТАЛЕЙ, ЩО ПРАЦЮЮТЬ ПРИ ПОВТОРНО-ЗМІННИХ НАВАНТАЖЕННЯХ

В статті проведено розробку процесів з підвищення довговічності деталей, що працюють при повторно-змінних навантаженнях, шляхом обґрунтування параметрів поверхневого пластичного деформування (ППД) та холодного газодинамічного нанесення покриттів. Показано вплив на глибину зміцненого поверхневого шару, характер розподілу в ньому напружено-деформованого стану матеріалу і залишкових напружень стиску, а також величини використаного ресурсу пластичності металу, параметрів технологічного процесу ППД. Обґрунтована гіпотеза про те, що основним фактором формування залишкових напружень стиску при ППД є зменшення густини металів, яке пов'язане з використанням ресурсу пластичності. Розроблена модель визначення використаного ресурсу пластичності металів при ППД, що дозволяє забезпечувати якісні характеристики поверхневого шару деталей. Розроблені способи зміщення шару з максимальним зміцненням і залишковими напруженнями стиску до поверхні деталі шляхом використання деформівного інструменту менших розмірів на наступних проходах та газодинамічного нанесення покриття перед проведенням ППД.

Переважна більшість традиційних газотермічних методів нанесення покриття відбувається при значних температурних впливах на поверхню деталі, що є недопустимим для поверхні, обробленої методами ППД. Холодне газодинамічне напилення забезпечує допустимий температурний режим створення спеціальних допоміжних покриттів із збереженням властивостей поверхні, обробленої методами ППД.

Технологія газодинамічного нанесення покриттів включає в себе нагрів стисненого газу (повітря), подачу його в сопло і формування в цьому соплі надзвукового повітряного потоку, внесення в цей потік порошкового матеріалу, прискорення цього матеріалу в соплі надзвуковим потоком повітря і направлення його на поверхню оброблюваного виробу.В результаті чого на поверхні виробу утворюється спеціальне допоміжне покриття, яке забезпечує оптимальні параметри процесу ППД.

Ключові слова: *поверхневе пластичне деформування, залишкові напруження стиску, використаний ресурс пластичності, холодне газодинамічне нанесення покриття.*

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