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EVALUATION OF THE QUALITY PARAMETERS OF THE SURFACE LAYER OF PARTS AFTER MACHINING WITH PLASMA HEATING

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Abstract: This study aims to improve the technology for processing parts from hard-to-work materials, to study and substantiate the parameters of the plasma-assisted machining processing of surfaces of alloy steel parts to increase processing productivity and ensure the necessary quality of surface layers. Theoretical studies consist in determining the parameters of the thermal field of a workpiece during milling and turning with plasma heating. Experimental studies are based on a study of the interrelationship of the main indicators of machining with factors of preliminary plasma heating allowance.

KEYWORDS: plasma-assisted machining, microhardness, microstructure, plasma arc

1 Introduction

The problem and its connection with scientific and practical tasks. The development of mechanical engineering requires scientists and engineers to search for new, highly efficient methods of processing structural materials, creating reliable technological processes and their most efficient application under production conditions.

Modern structural materials are advancing rapidly in strength, viscosity, and other characteristics. However, the tool materials used in production often cannot handle high-performance machining of workpieces. This is due to extreme cutting conditions required, such as cutting on the crust of an item, on high-strength surfacing, or with large cross-sections. These factors exacerbate the difficulties of the cutting process. To improve efficiency, a technique is being developed that temporarily reduces the strength of the material being machined and changes the mechanisms of contact processes occurring on the tool's working surfaces. This method and other technological operations aim to intensify the cutting process [6 – 9, 15, 18].

Plasma-assisted machining (PAM) is a process that has been around since the middle of the last century and is still being researched in scientific laboratories to discover new opportunities and prospects. PAM is a complex process with many controlled parameters, making it challenging to apply efficiently without prior research to determine its rational modes [1-5, 13, 22]. During PAM, mechanical energy and low-temperature plasma energy are used together to

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enhance the efficiency of the cutting process when manufacturing machine parts from modern, difficult-to-machine materials [10-14, 18-25].

During plasma heating, the thermal cycle of the surface layers of the workpiece causes structural-phase transformations that substantially decrease their physical and mechanical properties. However, this can significantly increase machining productivity while ensuring that the cutting tool maintains the necessary durability. This has been supported by research studies [13-15].

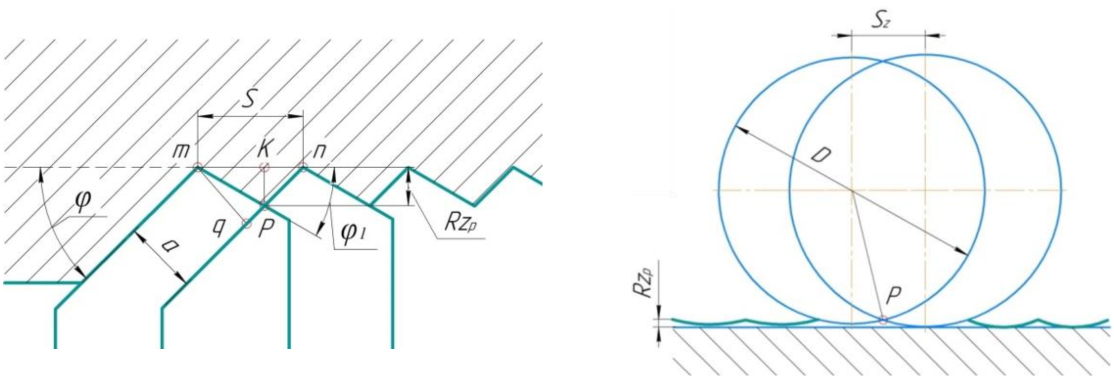
The high efficiency of the PAM makes relevant further developments aimed at finding new ways to use plasma arc for surface heating and softening of the allowance, which would significantly increase the productivity of machining difficult-to-machine materials, provided that the quality of the surface layers of the machined items is ensured [8-11, 24].

Research and publication analysis. The surface roughness and the surface layer material condition determine the machined surface's quality. The micro-unevenness's height and shape characterize the machined surface's roughness. The state of the surface layer material is characterized by its strain hardening, microstructure, magnitude and sign of residual stresses and the depth of their occurrence [1, 5, 16, 19, 27, 29]. An analysis of the literature data on turning and milling made it possible to identify specific factors that affect the change in the height of micro-unevenness, microstructure and residual stresses in the surface layer of the workpiece [18, 20, 22, 26, 28, 30, 31].

Fig. 1 shows the calculated micro-profile of the machined surface during turning (a) and milling using cylindrical milling cutters (b). To simplify the picture, the cutter without an intermediate blade is shown. During sharpening, the height of the calculated unevenness Rz_p equals the height *pk* of triangle *mnp*:

$$Rz_p = mn \cdot \sin \varphi_1 \tag{1}$$

$$Rz_P = \frac{S \cdot sin\,\varphi \cdot sin\,\varphi_1}{sin(\varphi + \varphi_1)} \tag{2}$$



(a) turning (b) milling using cylindrical milling cutters

Fig. 1 Theoretical microprofile of the machined surface during turning (a) and milling with cylindrical cutters (b)

This formula is suitable for calculating Rz_p when boring, drilling, countersinking, planning and milling using end mills. When milling, the height of the calculated unevenness is determined by the position of point *p* of the intersection of two circles spaced at a distance equal to feed S_z to the tooth of the milling cutter:

$$Rz_P \approx S_Z^2/4D \tag{3}$$

The calculated unevenness of the surface during turning decreases as the feed and angles in the plan view decrease, while the radius of the intermediate blade increases. If the cutter auxiliary angle in the plan view is made equal to zero, while the length of the auxiliary blade is made 20-30 % longer than the feed per revolution, then the calculated unevenness will not be formed [16].

In addition to the above factors, the height of the unevenness is affected by all those factors that change the magnitude of plastic deformation of the material and the friction conditions on the contact surfaces of the tool. These can include the mechanical properties of the material being processed, the cutting speed, and the properties of the coolant used.

With an increase in the hardness and strength of the material being machined and a decrease in its plasticity, the magnitude of plastic deformation decreases, leading to a decrease in the height of the unevenness.

Residual stresses that occur in the surface layer and its strain hardening are a consequence of the force field created by the forces of cutting, heating of the material of the workpiece and structural transformations. When cutting using a metal tool (sharpening, milling, drilling), residual stresses are generated mainly by the force field. Temperature importance is secondary. When machining brittle materials, the residual stresses are compressive, while when machining ductile metals, they are most often tensile. In high-temperature machining mode (grinding), residual stresses are always tensile and occur due to the high temperature of the surface layer.

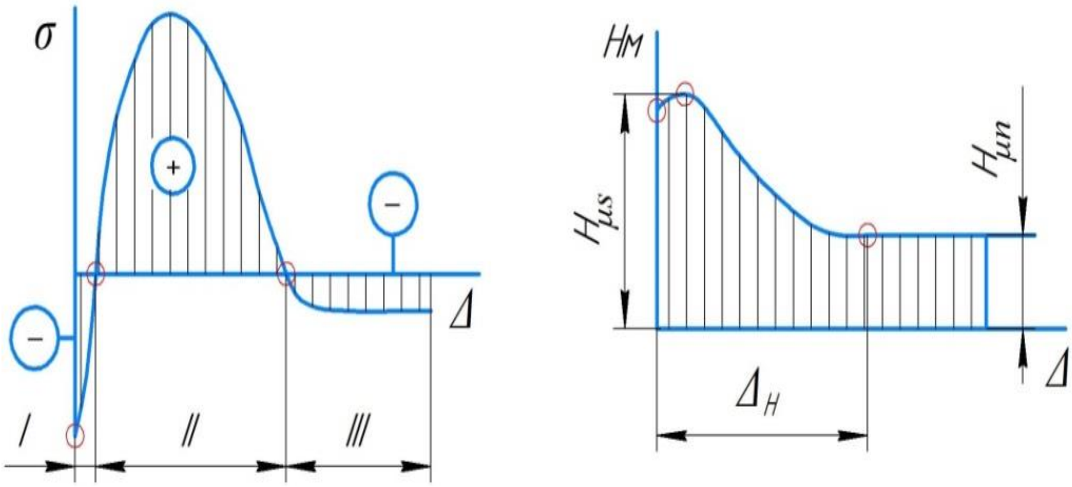


Fig. 2 Distribution diagram of changes in residual stresses in response to the distance *Δ* from the surface being machined

Fig. 2 shows a distribution diagram of the change in residual stresses in response to distance *Δ* from the machined surface when machining most ductile materials. In a very thin layer with a thickness of 0.001÷0.004 mm (Zone *I*), compressive stresses are at play. In Zone *II*, whose length depends on the cutting mode and the front angle of the tool, tensile stresses are at play. The length of Zone *II* 10 times or more exceeds the length of Zone *I*, by the nature and magnitude of stresses in Zone *II* and is therefore determines the state of the surface layer. In Zone *III* that balances the action of the residual stresses of the first two zones, the stresses are compressive. The presence of tensile stresses in the surface layer significantly impairs its quality since this reduces the fatigue strength. If the residual stresses exceed the ultimate strength of the material of the workpiece, this can lead to the formation of surface cracks.

The magnitude and the depth of occurrence of residual stresses depend on the front angle of the tool, its feed (the thickness of the layer to be cut), cutting speed and degree of the tool's wear.

Degree of strain hardening ΔH_M of the surface layer is understood as the ratio of the difference between maximum micro-hardness $H_{\mu s}$ of the strain-hardened layer and micro-hardness $H_{\mu н}$ of the non-strain-hardened material to $H_{\mu n}$:

$$\Delta H_M = [(H_{мн} - H_{мс}) / H_{мс}]\ 100\% \qquad (4)$$

The strain hardening of a surface layer is mainly associated with the strain and strengthening of the ferritic phase of the material being machined. The degree of strain hardening and thickness Δh of the strain-hardened layer are directly dependent on the degree of strain of the cut layer and the cutting forces involved.

Since the special literature contains virtually no structured information on the features of changes in the quality parameters of the surface layers of the workpiece during the PAM, it was considered appropriate to supplement the missing information in this area. The purpose of this paper is, therefore, to try and improve the process of machining workpieces made from difficult-to-machine materials, viz to research and scientifically substantiate the parameters of the process of plasma-assisted machining of surfaces of workpieces made from alloy steels in order to enhance the productivity of machining and ensure the required quality of surface layers of the machined items.

The above purpose of the paper necessitated the study of the features of contact processes in the cutting zone, including the influence of the parameters of the cutting part of the tool and the PAM modes on the roughness, residual stresses and microstructure of the surface layers of the workpiece.

2 Experimental studies of the influence of PAM parameters

Next, we will consider the obtained data regarding the influence of the PAM parameters on the microstructure and strain hardening of the surface layers of the workpiece, as well as on the roughness and residual stresses of those layers.

Heating the workpiece with a plasma arc causes four main phenomena: a decrease in the strength of the metal being machined; the emergence of a system of structural transformations and thermal stresses in the surface layers of the workpiece; melting of the part of the metal to be cut, and change in the friction parameters on the contact surfaces of the heated metal of the workpiece and the cutting tool [11, 17, 22].

2.1 Microstructure and strain hardening of the surface layers of the metal

The main feature of plasma heating is its localized nature combined with the high power of the heat source. Thermal processes in the workpiece are characterized by high heating and cooling rates, significant temperature gradients, and the very temperatures on the heated surface can reach the machined material melting (and even evaporation) point. Under such conditions, structural changes occur in the surface layers of the workpiece, and thermal stresses develop, thus creating a defective layer.

Cracks, changes in the chemical composition of the metal, as well as unfavourable distribution of residual stresses can occur in the defective layer. The most dangerous defect of the machined surface after the PAM is cracks that can reach considerable depth causing the need to increase the allowance for the subsequent machining of the workpiece and reducing the strength of the item as a whole. Cracks can occur most often when machining brittle metals, such as the steel of grade GX120Mn12, cast iron or high-strength surfacing alloys.

In the process of solidifying and subsequent cooling of the workpiece sections that melted under the effect of the plasma arc, several zones of structurally altered, pre-stressed metal are formed (Fig. 3). Adjacent to the heated surface is Zone ***2*** of disoriented dendrites, in which deep cracks appear. Under this zone, Layer ***3*** with columnar dendrites is situated, and further down is Area ***1***, in which micro-cracks occur.

Metallographic studies of the layers adjacent to the machined metal surface show that under rational cutting and heating modes the PAM process of steels (including heat-treated ones) not only significantly increases the productivity of operations, but also makes it possible to obtain, as a rule, a required quality of the surface layer of the workpieces.

During high-temperature heating of heat-resistant alloys, as studies showed, the appearance is possible of a near-surface layer 0.2...0.6 mm deep with an altered fine-grained structure, which, however, does not compromise the quality of the surface machined.

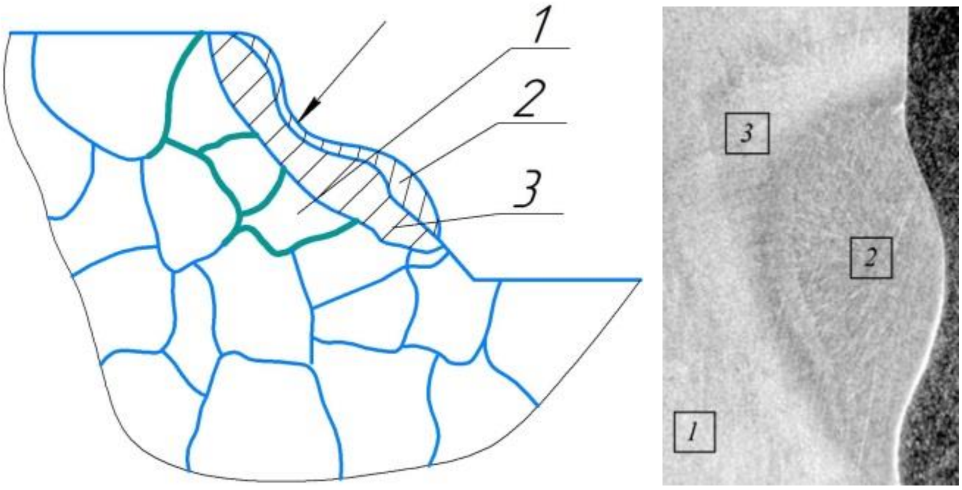


Fig. 3 Theoretical microprofile of the surface being machined

Workpieces made of high-strength and heat-resistant alloyed cast irons with low thermal conductivity and high brittleness are more difficult to machine using plasma heating. Studies showed that high-performance PAM of annealed chromium and heat-resistant cast irons is quite feasible if plasma heating is carried out more evenly and not as intensively as during machining of steel workpieces.

The chemical composition of the surface layers of the workpieces made of the GX120Mn12, 30CrNiMo8 and GX19NiCrMo4 steels, as shown by studies performed using the Camebax MV-1 micro-analyser, remains unchanged.

Plastic deformation during the PAM process increases, as during conventional cutting, the hardness of the metal of the surface layers of the workpiece in comparison with the original hardness of the workpiece material. This can be seen from Fig. 4, which shows the response of micro-hardness H to the depth of the surface layer of the 25CrMo4 steel workpieces (cutting mode: t = 18 mm; S = 2,5 mm/rev; V = 15 m/min), where curve 1 is turning without heating; curve 2 is PAM at I = 250 A; U = 180 V; curve 3 is PAM at I = 400 A; U = 180 V. A feature of the PAM process (Fig.4) is that as the arc power increases, the micro-hardness increases as well. This is due to the hardening of the machined surface by a reflected flow of incandescent gases coming out of the heating spot area.

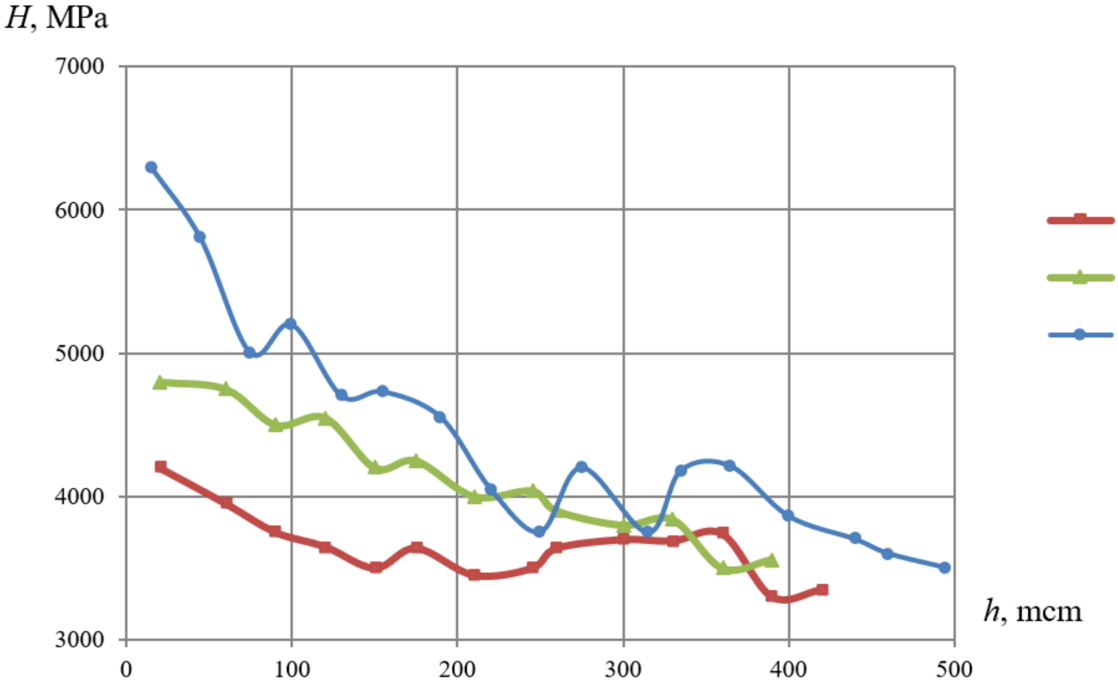


Fig. 4 Response of micro-hardness *H* to the depth of the surface layer of the 25CrMo4 steel workpieces

2.2 Surface roughness and residual stresses

Studies showed that during roughing and semi-finishing sharpening using plasma heating the roughness of the machined surface is virtually no different from the one obtained in the same mode of cutting without heating the workpiece using a plasma arc. Residual stresses in the layer adjacent to the machined surface are formed during the PMO as a result of temperature and mechanical deformations occurring in the metal under the effect of the thermal cycle and the cutting process.

N.N. Davydenkov's methods were used to determine the tangential residual stresses in the surface layers of the workpieces after the PAM. The distribution of residual stresses along the depth of the surface layer is shown in Fig. 5, where curve 1 is turning without heating, the workpiece material is the 34NiCrMoV14-5 steel (cutting mode: $t = 4$ mm; $S = 0.43$ mm/rev; $V = 29$ m/min; the cutter material is HS345); 2 – the same, but with heating ($I = 175$ A; U=120 V); 3 – turning of the workpieces made of the 34NiCrMoV14-5 steel (cutting mode: $t = 2$ mm; $S = 0.195$ mm/rev; $V = 68$ m/min; $I = 100$ A; $U = 120$ V; the cutter material is HS345); 4 – planning of the GX120Mn12 steel workpieces (cutting mode: $t = 6$ mm, $S = 1.4$ mm/double pass; $V = 14$ m/min; $I = 200$ A; $U = 100$ V; the cutter material is HS345); 5- turning of the workpieces made of the 40NiCr6 steel (cutting mode: $t = 3$ mm; $S = 0.4$ mm/rev; $V = 140$ m/min; $I = 110$ A; $U = 125$ V; the cutter material is HS345); 6 – turning of the workpieces made of the X12CrMo9-1 steel (cutting mode: $t = 5$ mm; $S = 1.6$ mm/rev; $V = 100$ m/min; $I = 230$ A; $U = 130$ V; the cutter material is HS345). An analysis of the experimental data (Fig. 5) indicates the complex nature of the effect of plasma heating of the workpieces on the residual stresses. This manifests itself most substantially at cutting speeds below 30 m/min, where plasma heating leads to residual compressive stresses. The magnitude of those stresses depends on the specific energy (E) of the heat source and the cross section of the cut. At $t{\cdot}s = 5{\cdot}1$ mm^2 and $15{\cdot}2$ mm^2, when $E \geq 10$ and $E \geq 100$ J/kg, respectively, residual compressive stresses σ_τ = - (200 ... 600) MPa spread to a depth of 0,05...0,1 mm, further evolving into balancing tensile stresses. At more significant PAM speeds of workpieces made of 40NiCr6 and X12CrMo9-1 steels, surface residual tensile stresses σ_τ =

20 ... 600 MPa occur. At a depth of 0,1...0,4 mm from the surface, those stresses become compressive. With a decrease in the cross section of the cut, the probability of compressive stresses appearing on the surface of the machined workpiece increases.+

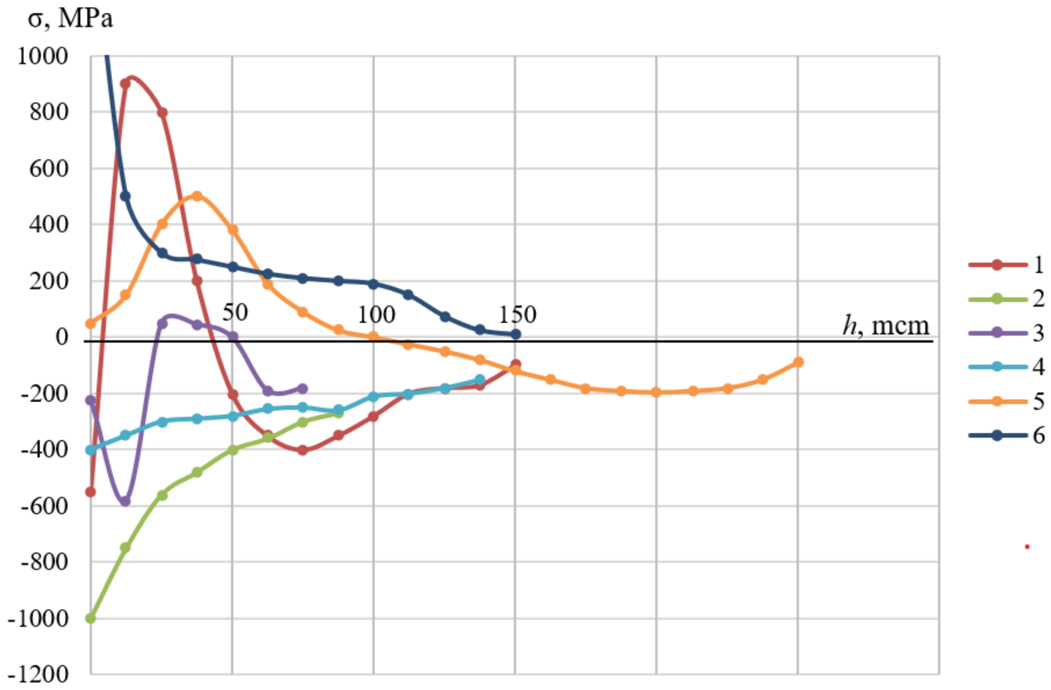


Fig. 5 Distribution of residual stresses along the depth of the surface layer

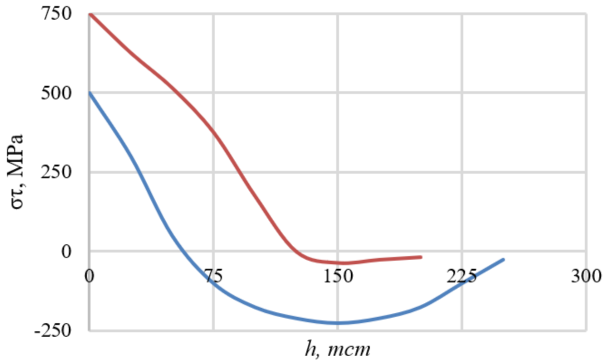


Fig. 6 Distribution of residual stresses in the surface layers of sheet workpieces after milling, under plasma heating, of the edges using a cylindrical milling cutter

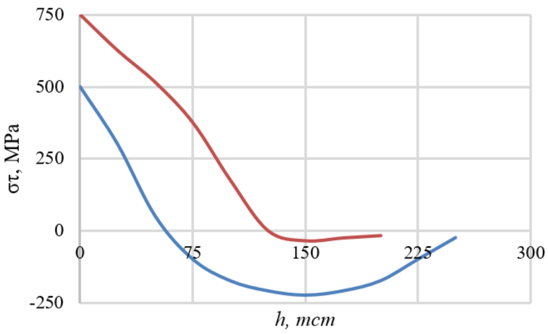


Fig. 7 Distribution of residual stresses in the surface layers of the 34NiCrMoV14-5 steel sheet workpieces after milling using end cutter under plasma heating

Fig. 6 shows the distribution of residual stresses in the surface layers of sheet workpieces after milling, under plasma heating, of the edges using a cylindrical milling cutter (cutting mode: t = 5 mm; V = 200 m/min; I = 200 A; U = 140 V), where curve 1 – workpiece from the

9310H steel (Sz = 0,3 mm/tooth); curve 2 – workpiece from the 45Mn17Al3 steel (*Sz* = 0,2 mm/tooth). And Fig. 7 contains information on the distribution of residual stresses in the surface layers of the 34NiCrMoV14-5 steel sheet workpieces after milling using end cutter under plasma heating (cutting mode: *t* = 5 mm; *Sz* = 0.17 mm/tooth; *V* = 237 m/min; *I* = 170 A; *U* = 140 V), where curve 1 is in a sample obtained at a distance of 60 mm from the edge of the workpiece, and curve 2 is in a sample 10 mm wide from the edge of the workpiece. Tensile stresses at the edges of the sheets intended for welding are desirable because they reduce the magnitude of welding stresses. During end milling using plasma heating, as during machining of workpieces without heating, the residual stresses appear to be compressive (Fig.6 and Fig. 7). The decrease in the magnitude of the latter in the incision area of the milling cutter teeth is apparently due to the effect of the tensile stresses arising as a result of the thermal heating cycle.

3 Results and discussion

Since the PAM is used for roughing operations in modern technological processes, while further machining of workpieces is carried out by conventional methods (without plasma heating), it is important to find out what is the PMA-related technological process heredity of the residual stresses that occur after finishing. Of interest are studies, in which stresses were measured in the near-surface layers of the material of the shafts with a diameter of 550 mm and a length of 1000 mm made of the 25CrMo4 steel. Initially, the stresses were studied after turning under plasma heating, and then after finishing. The measurement results presented in Figure 8 show that the PAM modes have an effect on the magnitude and distribution of residual stresses in the surface layers of the metal.

A conventional method of machining without heating during rough sharpening (*t* = 18 mm; *S* = 2.5 mm/pass; *V* = 15 m/min.) and subsequent finishing sharpening (*t* = 0.4 mm; *S* = 0.06 mm/pass; *V* = 100 m/min.) led to the appearance of residual stresses, whose distribution is described by Curves 1 and 2 (see Fig. 8). Finishing machining without heating increases the residual tensile stresses on the surface of the workpiece, while at a depth of about 30 μm the stresses reverse sign. If roughing of the workpiece is performed using plasma heating in the same cutting modes (*I* = 400 A; *U* = 180 V), the initial distribution of residual stresses (Curve 3) differs substantially from the one when cutting without heating (Curve 1).

Finishing after the PAM performed under the same conditions as in the first variant of the process, leads to the distribution of residual stresses by a similar pattern (Curve 4), but the values of tensile stresses near the machined surface appear to be substantially smaller (4...5 times), which should have a positive impact on the performance of the machined items. The use of roughing operations with plasma heating while appropriately selecting cutting modes and plasma arc parameters therefore opens up the prospect of improving the subsequent performance of machined items by forming a favorable picture of the residual stress distribution.

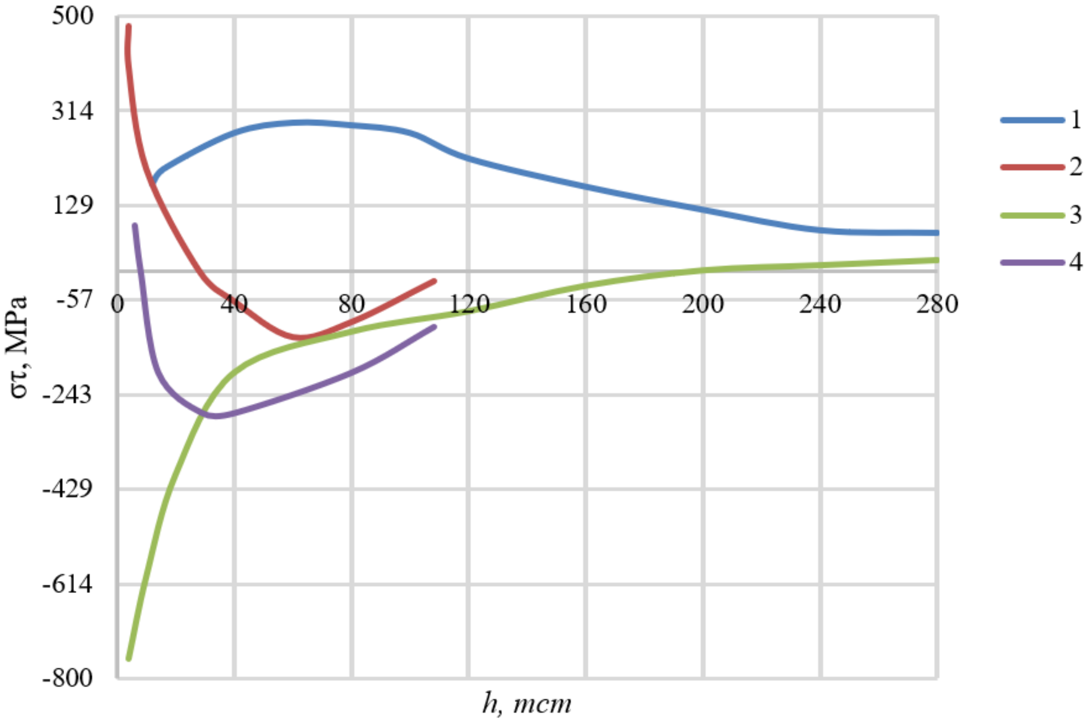


Fig. 8 Distribution of tangential residual stresses in the surface layer of the 25CrMo4 steel samples after rough turning

CONCLUSION

The process of plasma-assisted machining is developed to improve the technology of manufacturing parts from hard-to-machine materials, namely, to increase processing performance and ensure the required quality of the surface layers of machined part. By analyzing the results of computational and experimental studies on the influence of thermal processes, acting on materials under plasma heating, the following conclusions can be drawn:

1. In the process of heating and cooling, the layers of the metal to be cut are subjected to different thermal cycles, resulting in structural changes in some cases or thermal softening in others, and increasing the plasticity of the material being machined. This allows for a significant improvement in machining performance while maintaining the required life of a cutting tool.

2. The effectiveness of a plasma arc as a heating source is highly dependent on the size, speed, and heat output ratio of the heat source. A rational ratio is the one at which the temperature of the heated surface at the rear limit of the heating spot reaches, but does not exceed, the melting point for a given material.

3. Metallographic studies of the surface layer of machined parts show that rational cutting and heating modes can increase the productivity of operations and obtain the specified quality of the surface layer of parts. The roughness of the machined surface does not differ from that obtained with the same cutting mode without heating the workpiece with a plasma arc.

4. Residual stresses in the outer layer are generated during the PAM as a result of thermal and mechanical strains occurring in the metal under the effect of the thermal cycle and the cutting process.

5. The high efficiency of the PAM makes relevant further developments aimed at finding new ways to use plasma arc for surface heating and softening of the allowance, which would

significantly increase the productivity of machining difficult-to-machine materials, provided that the quality of the surface layers of the machined items is ensured.

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