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ORIGINAL ARTICLE

Substantiation of the parameters of the process of plasma-mechanical milling of titanium alloys and alloyed steels

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ABSTRACT – The article is devoted to the development and scientific substantiation of the method of processing high-strength materials using surface plasma heating. A method for determining the parameters of the plasma-mechanical milling process has been formed, which includes: thermal calculations of the plasma arc power; thermal field characteristics in the part material; determination of residual stresses and hardness of the surface layer of the part. The choice of technological parameters of a plasma heating source is grounded. Criteria are formulated to which the source of plasma heating must correspond. Calculations are performed to determine the dependence of the performance of the milling process on titanium alloy Ti-6Al-4V with the achievement of a certain microstructure of the part being cut off under the influence of plasma heating. A new scheme of plasma-mechanical milling is proposed, which provides for arc scanning in a magnetic field in the direction of the minute vector filing cutters and additional cyclical movement across the plasma torch feed vector with an amplitude of approximately equal to width milling. The proposed method of plasma heating a cut off layer allows lowering costs of processing time, and solve the problem of shortening ships' construction time.

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Plasma-mechanical milling; titanium alloy; structural-phase changes; plasma arc

INTRODUCTION

Titanium and its alloys are widely used in engineering due to their high mechanical strength, which is maintained at high temperatures, corrosion resistance, heat resistance, specific strength, low density, and other useful properties. The high cost of titanium and its alloys in many cases is compensated by their greater efficiency, and in some cases, they are the only material from which equipment or structures can be made that can work under these specific conditions. In shipbuilding, they are used for linings and hulls of ships and submarines, welded pipes, propellers and pump parts.

Many properties that give operational advantages to titanium alloy parts have a significant impact on its machinability [1] i.e. relatively quick tool wear, low cutting speed, and as a result, low productivity of the processing process. Productive processing of billets of alloy steels, which are used in large volumes in all industries, is also an urgent task. Reduction deadlines manufacturing products engineering in a lot associated with a raise performance milling planes, edges, chamfers for welding and other parts that are in parts durable titanium ship hull [2]. A significant part of the total volume of milling occurs in extreme conditions - on the scale, with large cross section of cut. Therefore, effective preliminary plasma heating of the cut down leads to a reduction in the cutting work and the time spent on processing, and it allows to improve other technological and economic parameters of the process.

The present study proposed a new innovative scheme of plasma-mechanical milling (PMM), which involves scanning the arc in a magnetic field in the direction of the vector of the cutter's minute feed and additional cyclical movement of the plasma torch across the feed vector, with an amplitude approximately equal to the milling width. The new scheme can facilitate the process of milling, a significant reduction in the strength of the surface layer of the workpiece, improve productivity and speed. However, the thermal processes occurring in materials exposed to a plasma heating is not sufficiently studied, rational ways are offered to regulate power density at the heating spot of the plasma arc, and are not formulated criteria which must conform to the plasma heat source, which determined the purpose and objectives of the study.

Features of heat sources and a variety of technological modes used in various types of plasma-assisted machining has create a wide range of options for heating conditions, which led to the emergence of a significant number of studies devoted to the selection of rational technological parameters. Lamikiz et al. [3] conducted a plasma-assisted milling experiment for Inconel-718. The results showed that the cutting force can be reduced by 25%, the lifetime of the cutter can be extended by about 100%. It indicated the importance and the significant difference caused by preheating with an additional heat source. Leshock et al. [4] developed a plasma heating-assisted system for lathe machines. First, the plasma heating was generated by the surface temperature through the numerical simulation and an infrared radiation thermometer. Then, the simulation analysis showed all operating parameters which influenced the surface temperature. Finally, the operating conditions of plasma-assisted machining were corrected in accordance with the experimental results. Compared

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to traditional machining, the plasma-assisted machining can reduce the cutting force by 30% and extend the lifetime of the cutter by about 40%.

There are known works when the authors noted the effect of reducing the work of deformation of the processed material under plasma arc heating. However, this was mainly explained by a temporary thermal decrease in the strength of the heated layer [3-11]. Hence, Chen and Tsai [12] has adopted plasma heating to soften parts of the materials and aimed to explore the heating of nickel base alloy. However, there are other facts that influence the improvement of workability due to the specific properties of the plasma arc, which are not fully investigated.

Novak et al. [13] and Amin et al. [14] confirm the hypothesis of Shaterin et al. [6] on the effect on the workability of materials in the stress-strain state of the allowance under the influence of plasma heating in combination with the thermal factor. In the work of Korotkih [1, 5], the idea is to put forward improvement of the alloyed steels machinability at the end of milling process by ensuring that the cutter's tooth cuts into the soft austenitic structure. Multiple PMM schemas are described. These schemes are not optimal in terms of heat input to the treatment area. Therefore, it is important to further refine the methodology of thermal calculations, a comprehensive analysis of structural changes in the layer of material (allowance) is relevant in order to increase the performance of the plasma-mechanical milling of the material with altered properties.

RESEARCH METHODOLOGY

Plasma-Assisted Machining

Plasma-assisted machining (PAM) is a consistent sequential impact on the material of the workpiece by the plasma arc and the cutting edge of the tool. A system of structural transformations and thermal stresses arises in the surface layers of the workpiece when heated by a plasma arc. It leads to a decrease in the strength of the processed material, a change in the friction parameters on the contact surfaces of the workpiece and cutting tool [4, 15, 16].The temperature field created in the layers of the allowance plasma arc moving over the surface of the workpiece has large temperature gradients, the heating process is characterized by high rates of temperature change [17].

The theoretical part of this work, related to thermal calculations, suggested solving the problem of schematizing a heating source during plasma-mechanical milling. It is generally accepted that for this case, it would be fair to consider the source of heating acting under boundary conditions of the second kind with a flat nature of the heated surface closer to the actual thermal situation of heating the workpiece. In the case of heating the metal to be treated with a plasma arc scanning across the velocity vector of the plasma torch, the temperature field of the workpiece can be found using two-dimensional and one-dimensional thermal fast-moving sources.

Naturally, the assumptions made regarding the boundary conditions of the shape of the heat source and the distribution law of its intensity, as well as the idealization of the configuration and size of the workpiece (half-space or unlimited plate) lead to a discrepancy between the calculated and experimental data. However, the mathematical solution of the problem in analytical or numerical form allows us to assess the impact on the PAM process and outline ways of its optimization.

Structural Transformations

As part of the next stage of the study, it is necessary to evaluate the structural transformations in the cut layer when heated by the scanning plasma arc, their depth, in order to determine the distance from the heating source to the cutting tool. The diagrams of temperature changes obtained from the results of theoretical and experimental studies of thermal fields from the effects of a flat fast-moving source show that during plasma heating of a part, the depth of structural transformations depends on the power of the heating source, cooling rate and thermal physical properties of the material.

According to recommendations [18], it is possible to determine the maximum penetration depth of the maximum temperature:

$$X = \frac{0{,}484q}{V \times C_{\theta} \times \rho \times \theta_{\mathrm{m}}} \tag{1}$$

where q is a specific intensity of the source, V is the speed of its movement, C_θ is the heat capacity, ρ is the density of the workpiece material and θ_m is the specified maximum temperature.

At a distance from the heating source, the temperature of the stock is leveled and can be estimated by the surface temperature of the workpiece. Temperature value for a point lying on the surface:

$$\theta = \theta_{\max} \times \theta^{*} \tag{2}$$

where θ^* is the maximum dimensionless temperature and θ_{max} is the reheat temperature, $\theta_{max} = \theta_{fusing}$;

$$\theta^{*} = \sqrt{\mu} - \sqrt{\mu - 1} \tag{3}$$

where μ is relative coefficient of increment of nondimensional time per thermal cycle ; $\mu = \frac{L}{l_S}$ where L is the distance from a point on the surface to the front of the heating source.

$$\theta^* = \sqrt{\frac{L}{l_S}} - \sqrt{\frac{L-l_S}{l_S}} \tag{4}$$

where l_S is the length of the heat source along its motion vector.

Substituting Eq. (3) into Eq. (4), we obtain the expression for calculating the surface temperature at any distance L from the source:

$$\theta = \theta_{\max} \times \left(\sqrt{\frac{L}{l_S}} - \sqrt{\frac{L-l_S}{l_S}} \right) \tag{5}$$

The last expression allows us to solve the inverse problem i.e. to determine the distance L from the cutter to the plasma torch, depending on the rational temperature of the workpiece at the time of cutting.

Plasma-mechanical milling of alloy steels has specific differences from PAM of titanium alloys. As already mentioned, in the case of steel alloys, it is necessary to transfer the allowance to the state of supercooled austenite due to heating, whereas for titanium alloys a thermal decrease in the strength of the metal is sufficient. It is known that steel billets, heated to temperature Ac_3, during the subsequent cooling, pass successively a series of stages of decomposition of supercooled austenite. The result is a very complex metal structure, consisting of upper and lower bainite, martensite and residual austenite. Bainite is a biphasic mixture of ferrite and cementite crystals. Ferrite has low strength and high ductility. With a small number of cementite inclusions, plastic deformation develops relatively freely and the material properties are characterized by low hardness. If, as a result of heat treatment, particles of cementite become larger, then some volumes of ferrite are released for the movement of dislocations, and the ability of steel to plastic deformation increases, and plasticity increases. This fact is of great importance from the point of view of the loss of material strength since it is known that when a moving dislocation encounters insurmountable inclusions for it, it passes through them, leaving each time dislocation loops around the inclusions. The more loops are accumulated, the more hardening occurs [19].

Plasma heating ($\theta > 500$°C) leads metal layers of pearlite-martensitic classes to undergo a high-temperature tempering below temperatures corresponding to the Ac_1 point of the onset of the austenitic transformation. Austenitic steels and alloys do not undergo phase transformations upon heating, which suggests the absence of structural changes under conditions of plasma heating [19]. If at slow heating, the removal of internal stresses and coagulation of carbide particles occurs in the range of 300 to 400 °C, then at high-speed heating [21], which is heated by the plasma arc at PMM, the temperature of these transformations shifts upwards on the temperature scale. At these temperatures (500 to 700 °C), the tendency of hardness decreases, as well as other indicators of strength (σ_B is the ultimate tension, $\sigma_{0,2}$ is the proof stress at 0.2 percent set), then as indicators of plasticity (Ψ is the percent elongation, δ is the percentage reduction) increase (see Figure 1). With increasing tempering temperature coarsen q cementite particles, as discussed above, can lead to increased plasticity of the material (see Figure 2).

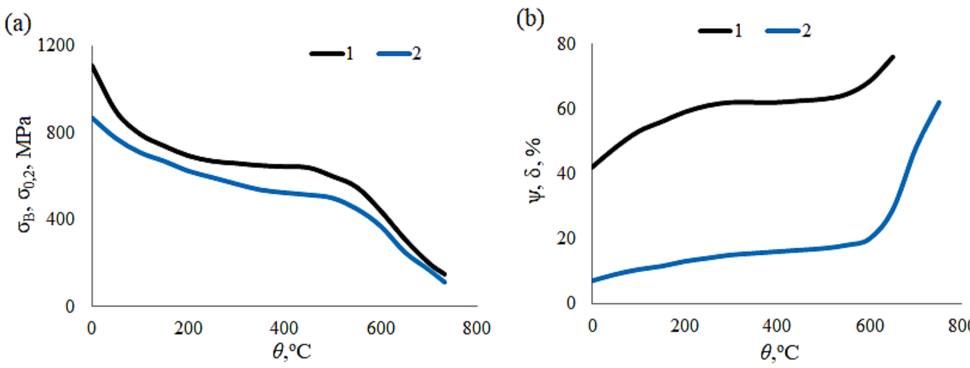

Figure 1. The change in the mechanical properties of steel 55NiCrMoV5 with surface plasma heating: (a) strength indicators ($1 - \sigma_B$; $2 - \sigma_{0,2}$) and (b) plasticity indicators ($1 - \Psi$; $2 - \delta$)

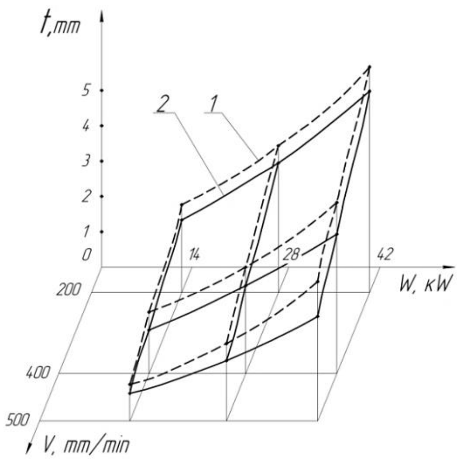

Figure 2. The depth of structural transformations in the surface layer when heated by a scanning plasma arc (t – depth of structural transformations, W – thermal power, V – speed of the source): 1 – steel 55NiCrMoV5; 2 – titanium alloy Ti-6Al-4V

Thus, these data indicate that the plasma heating of the allowance material in terms of PMM can significantly change the state of its structure, which can lead to a significant change in material properties and favorable direction, alleviate conditions of the milling. The choice of rational heating modes for PMM titanium alloys is of the same practical interest as the heating of steel. The phenomena occurring in the surface layers of the alloy Ti-6Al-4V during plasma heating may have specific features compared to those described above for alloyed steel.

The alloy Ti-6Al-4V pertains to the most applicable (α + β) – alloys that are considered to be heat-resistant for a relatively low tendency to soften [22]. But even with these alloys, the strength at 300°C is 20 to 30% lower than at 20°C, and with further temperature increase, the strength drops even faster. The composition of Ti-6Al-4V includes 5 to 6% Al and 3.5 to 4.5% V, which is a stabilizer β - phase, lowers the point of transformation of homogeneous β - solid solution to 700°C and increases the plasticity of the material.

A large number of research papers are devoted to cutting preheated titanium alloys, the authors of which point to the positive effect of heating, citing data on a decrease in strength, ductility and a drop in hardness of the heated layer, which can be calculated from an empirical relationship [17]:

$$HB = 450 - 0.34 \cdot \theta \tag{6}$$

where θ is the heating temperature in °C.

The authors indicate that the ratio between the «hot» hardnesses of the materials of the tool and the workpiece [1, 6–9, 17] has a decisive influence on the nature and intensity of tool wear. However, there is almost no information about possible structural changes in the material of the workpiece under the influence of high-temperature heating.

RESULTS AND DISCUSSION

It is known that with an increase in the ambient temperature, titanium begins to exhibit its high chemical activity towards the gas components of air, which are stabilizers of the α phase and cause phase changes in the heated metal. However, conducted experiments on the heating surface of the workpiece made from Ti-6Al-4V and subsequent analysis of the chart changes microhardness of the surface layers has shown that these changes apply to the depth about 0.07 to 0.15 mm.

If we compare the properties of allotropic modifications of titanium (α - and β - phases), then it should be noted that the layer of material (allowance), having a structure with a predominance of the β - phase, should have greater plasticity and lower strength [20]. Theoretical calculations show the possibility of heating the allowance to the temperature of formation of the homogeneous β-solid solution (882.5 °C). A high cooling rate of the allowance heated by the plasma arc is achieved (about 300 degrees per second) under the conditions of PMM. For titanium alloys (Ti-6Al-4V), after plasma heating and cooling, a β-structure can be fixed, which makes it possible to provide a plasticity margin for this allowance layer. This reduces the amount of work on the deformation of the shear layer and allows you to increase processing performance. The lower layers of the allowance, which experienced less heating and having θ = 300 °C by the time of milling, have better workability as a result of thermal softening. The tempera-ture of the worked surface after PMM should not exceed 500 °C since it will be satu-rated with gases and deterioration.

Thus, the foregoing leads to the conclusion that the use of plasma heating during face milling provides such a change in the material properties of the stock, which improves the workability of Ti-6Al-4V by cutting (see Figure 3). When assigning heating and cutting modes, it is necessary to take into account that on the treated surface there should be no areas of hardened metal, penetrations and other changes associated with plasma exposure. Qualification workpiece surface quality of the Ti-6Al-4V alloy made when considering the microstructure and hardness of samples after PMM. Analysis of the results showed that the quality matches surface requirements of the treated surfaces of machine parts.

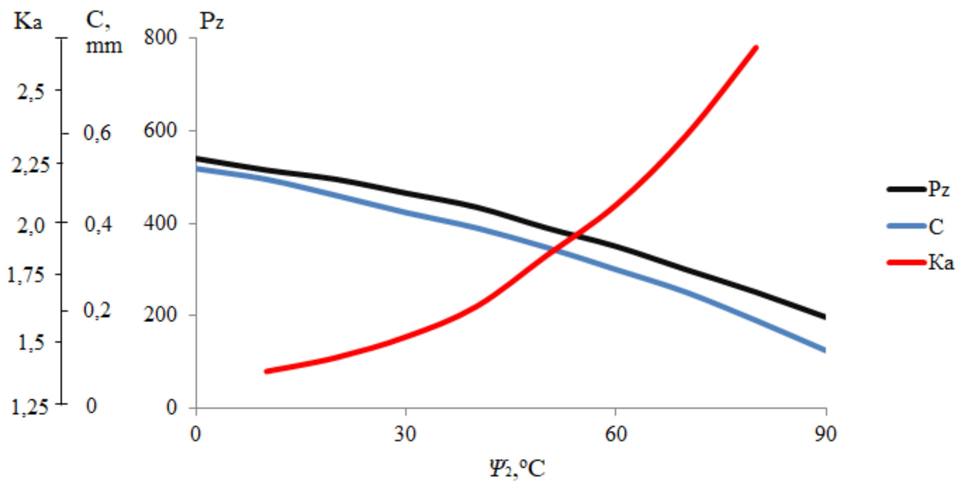

Figure 3. The change in the arc of contact of the cutter shrinkage factor K_a, the length of the contact area of the chip along the front surface C and the cutting force P_Z at PMM of the Ti-6Al-4V alloy (I = 200A, U = 125 V, V = 250 m/min, S_z = 0,2 mm/tooth, t = 5 mm)

The residual stresses in the surface layer after PMM were determined by a mechanical method, based on the removal of the stressed surface layers of the sample by electrochemical etching with simultaneous measurement of its deformations. According to the data obtained using mathematical dependencies, in Davidenkov [20] the values of residual stresses with the corresponding signs were calculated. The sample sizes were chosen from the conditions of the constancy of stresses across the width, a decrease in the relative error of measurements of the sample strain in the etching process, and the adequacy of the deflection along the sample.

In turn, in a study [3], the problem of the plasma jet orientation just ahead of the cutting tool, and the dimensional variation induced by the localized material heating are the reasons for which this technique should be recommended only in roughing operations. Precision finishing cannot be obtained due to thermally induced dimensional variations. The research adopted plasma heating to soften parts of the materials [12]. The temperature variation of the materials was investigated and measured by adjusting the current and feed velocity. But attempts to study and implement the most promising PMM schemes have shown that it is advisable to create the possibility of controlling the heating across the width of the stock, since heating different areas of the contact of the cutter's tooth with the workpiece (input or output) leads to an increase in the cutting tool durability.

With this in mind, we can formulate requirements to the heat source for PMM:

1. Possibility to regulate the heating width from a certain minimum value to a size equal to the milling width.
2. The lack of reflow of the surface layer of the workpiece with sufficient heat input in the stock material.
3. Ensuring the uniform depth of structural transformations.
4. Possibility to achieve the required temperature in the cutting zone at the time of milling.

Magnetically-Deflecting System

The ability to control the density of the heat flux directed to the workpiece provides an application of a magnetically-deflecting system, which causes the plasma arc to scan, according to a periodic law, across the direction of flow with an amplitude equal to half the milling width. A comprehensive analysis of the prototype variants revealed the prerequisites for creating such a PMM scheme that would have broad technological capabilities and meet the criteria specified above. These prerequisites were implemented in the PMM method, developed with the participation of the authors (see Figure 4).

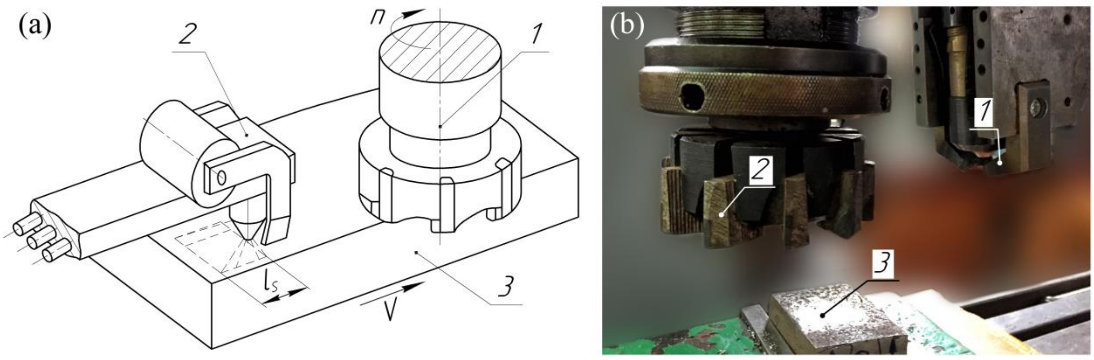

Figure 4. Scheme of face milling with plasma heating (a) and laboratory setup for the implementation of the PMM scheme (b): 1 – milling tool; 2 – plasmatron with a magnetic-deflection system; 3 – workpiece

The new method provided for the surface of the workpiece without flashing over the entire width of the milling and removal of the heated allowance with the face milling cutter according to the associated scheme. Surface melting is avoided by increasing the heating spot by scanning the plasma arc in an alternating magnetic field and additional periodic movement across the feed motion. Single-arc plasma torch for PMM (see Figure 4) was developed based on the above requirements. Preliminary experiments on PMM allowed to specify the technical details of the plasma torch and a manipulator and bring them to the Table 1.

Table 1. Technical characteristics of the plasma torch and manipulator, used in the process PMM

Parameter name	Unit of measurement	Value
Arc current	A	100 to 400
Voltage	V	110 to 140
Voltage a magnetic-deflection system	V	50 to 1000
Nozzle diameter	mm	6
Arc length	mm	35 to 40
The size of the heating spot in the feed direction	mm	5 to 50
Cross scan amplitude	mm	30 to 120
Consumption of plasma gas (air)	m^3/h	2,5 to 3
Cross scan frequency	double way/min	10 to 100
Weight of the plasma torch with a manipulator	kg	14 to 16

Laboratory and industrial tests of the new method showed the possibility of increasing the tool durability at PMM of parts made of alloyed steels and titanium alloys, respectively, by 2.5 and 1.8 times (see Figure 5, 6).

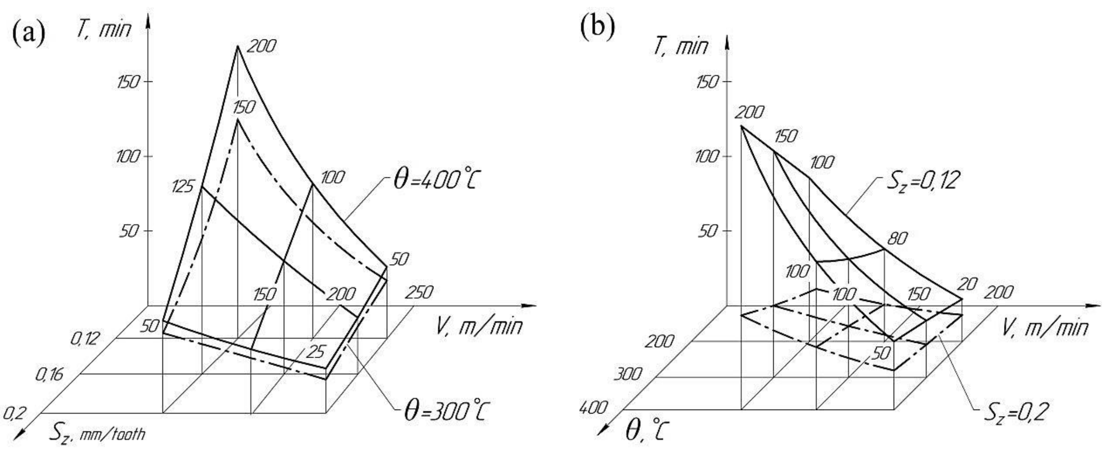

Figure 5. The dependence of the resistance of the cutting blade (T15K6) on the heating parameters (a) and cutting (b) with PMM steel 55NiCrMoV5 (T – the flow time of the thermal cycle, θ – temperature allowance, V – speed of the source, S_z – feed per hob tooth)

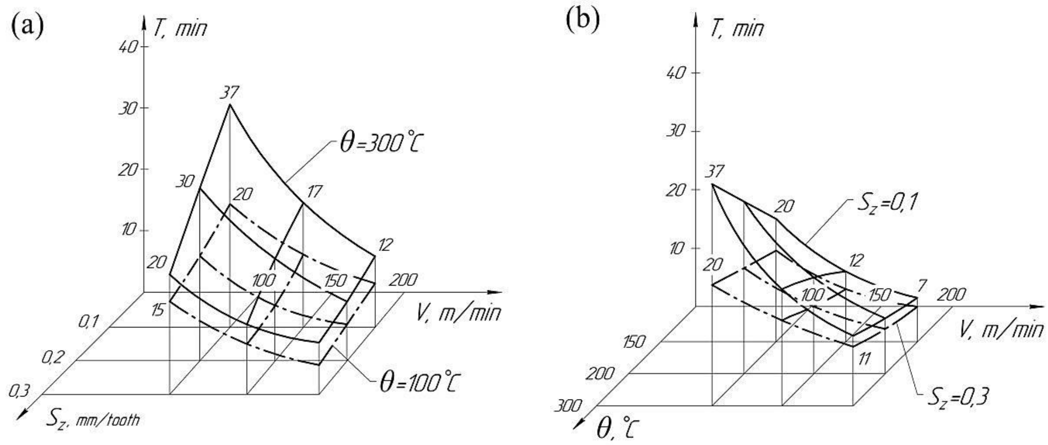

Figure 6. The dependence of the resistance of the cutting blade (VK8) on the heating parameters (a) and cutting (b) with PMM alloy Ti-6Al-4V (T – the flow time of the thermal cycle, θ – temperature allowance, V – speed of the source, S_z – feed per hob tooth)

The results obtained, while implementing the proposed scheme for face milling with plasma heating, have advantages over the known modern analogues [3, 4, 12] and prototypes by the processing productivity and the absence of surface fusion due to heating by scanning a plasma arc in an alternating magnetic field.

CONCLUSIONS

Analysis of the results of calculations and experimental studies of thermal processes occurring in materials under the influence of plasma heating and thermal fields produced are summarized below:

1. Under conditions of laser-mechanical milling, the efficiency of the plasma arc as a heating source depends significantly on the ratio of the dimensions of the heat source, its speed, and thermal power; rationality should be considered such that their ratio at which the temperature of the heated surface at the back of the heating spot reaches, but does not exceed the melting temperature for a given material;
2. In the process of heating and cooling, the layers of the metal being cut off undergo various thermal cycles, as a result of which structural transformations occur in some cases or thermal softening in others, the plasticity of the material being pro-cessed increases.
3. The consequences of plasma heating do not affect the changes in the physicomechanical properties of the finished surface of parts processed in rational modes PMM.
4. It is considered appropriate that the heating source meets the following criteria: no reflow of the treated surface; ensuring a uniform depth of structural changes in the stock material; the ability to control the heating spot to the size of the milling width and more.
5. The possibilities of mass-produced plasma and machine-tool equipment do not hinder the development of a method for laser-mechanical milling, in which, as a result of plasma action, an allowance with a temperature of 300 to 400°C.

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