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Numerical Study of the Stress Condition in the Coatings Surface Layers Obtained by Electro-Spark Alloying of Hard Alloys

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Abstract

The paper considers numerical influence of elastic and strength characteristics on stress condition and strength of hard-alloy materials with coatings of high-melting compound, obtained by electro-spark alloying under the influence of temperature and power factors using the finite element method.

Keywords: model, stress condition, material, coating, elastic and strength characteristics, finite element method

1. Introduction

Recently triboengineering and tooling industry commonly use composite materials with surface gradient of physical and mechanical properties. Effectiveness of material surface hardening largely depends on the right choice of surface gradient parameters influencing the strength and durability of machine parts. Science and technology now know numerous surface hardening methods of metal surfaces. Among these methods electro-spark alloying (ESA) method is of particular interest enhancing the cutting tool efficiency [1 – 3].

However, despite the positive ESA effect on wear resistance of the surface layer, its disadvantages limit the application of this method to a wide variety of parts and materials. These disadvantages include the formation of cracks and chips due to the formation of tensile stresses resulting in the alloyed layer formation. Moreover, in the ESA process with a specific alloying time, as a rule, observed the fraction of the surface layer (cathode mass decrease) that imposes strict requirements for processing modes selection.

In this regard, the aim of the work was the numerical study of elastic and strength characteristics of ESA coatings to further optimize the formation technology.

2. Problem statement

Strength of the material is an important characteristic that determines the ability of a material to resist the micro- and macro-fracture. In case of insufficient article strength there is a high probability of fraction by brittle chipping and spalling or as a result of plastic deformation and subsequent section. The article strength characteristics largely determine its reliability. Material with coatings deterioration requires creation of special models of composites based on the study of elastic and strength characteristics of the materials coated with the help of computer simulation, including the use of high performance computing systems.

Mechanical strength of surface gradient material (SGM) is determined by many parameters. For example, it depends on the coating or effective layer thickness, the gradient of physical and mechanical properties, thermal and power factors. In general, stress condition SGM models can be represented as:

$$\sigma = f(P, T, t_i, gradE, grad\alpha),$$

where P – load acting on the material, T – temperature, t_i – thickness of coating layers or the effective layer, $grad\,E$ – surface gradient of elastic characteristics, $grad\alpha$ – surface gradient of thermal characteristics.

Essential baseline data in the study of compositions strength are elastic characteristics (modulus of elasticity, Poisson's ratio, etc.) of its structural components. In accordance with the accepted model for the materials strength study was adopted the following study model of stress condition [4], which is discussed below.

Rectangular coordinate system is chosen so that the origin lies at the point of load application, the x axis is directed from the surface depthward the material's volume, and the y axis – along the surface of the considered area perpendicular to the x axis (Figure 1).

Since articles dimensions are sufficiently large compared to the contact zone size, this zone voltage is weakly dependent on the configuration of articles themselves away from the precise method of fastening and bearing articles [5]. Therefore, we can assume that the studied area has limited dimensions: $0 \leq x \leq$ B, -A $\leq y \leq$ A (2A, B $\approx 10 \div 20$ mm).

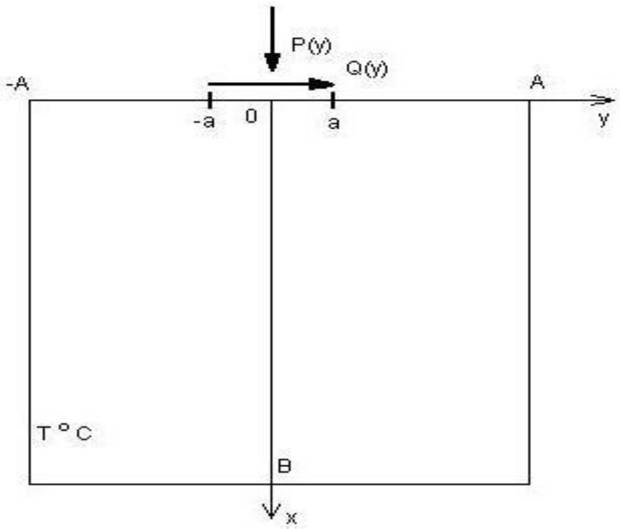


Figure 1. Design scheme

Surface gradient materials of instrumental purpose are subjected to friction and compression. Therefore, determining in the zone of contact of the material are compressive P(*y*) and shear load Q(*y*) load. Since, in case tensile stresses occur in the surface layers the mechanical properties of materials with coating are adjusted, hard alloys basically have low tensile strength, in calculation of value P(*y*), Q (*y*) they were as 30, 50 and 70 % of the ultimate strength of the tensile base material and shear, respectively. It is known, that during operation temperature fields occur in the material, resulting in thermal stresses, which may play a crucial role in the material fraction. It is therefore considered that the study area is evenly heated to temperatures of 100 °C, 200 °C and 400 °C.

Problem is solved in a two-dimensional formulation of the elasticity theory. Stress tensor components $\sigma_z = \tau_{xz} = \tau_{yz} = 0$. Deformation tensor components $\gamma_{xz} = \gamma_{yz} = 0$. Then the stress tensor will be in the form of $\sigma = \begin{bmatrix} \sigma_x & \tau_{xy} \\ \tau_{xy} & \sigma_y \end{bmatrix}$, the components of which satisfy the equations of equilibrium:

$$\begin{cases} \dfrac{\partial \sigma_x}{\partial x} + \dfrac{\partial \tau_{xy}}{\partial y} = 0, \\ \dfrac{\partial \sigma_y}{\partial y} + \dfrac{\partial \tau_{xy}}{\partial x} = 0. \end{cases}$$

Appropriate deformations ε_x, ε_y, γ_{xy} shall satisfy the compatibility equation:

$$\frac{\partial^2 \varepsilon_x}{\partial y^2} + \frac{\partial^2 \varepsilon_y}{\partial x^2} = \frac{\partial^2 \gamma_{xy}}{\partial x \partial y}.$$

Moreover, deformations are associated with movements of geometric ratios (Cauchy)

$$\varepsilon_x = \frac{\partial u_x}{\partial x}, \quad \varepsilon_x = \frac{\partial u_y}{\partial y}, \quad \gamma_{xy} = \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}.$$

Then Hooke's law, involving stress and strain for plate stress case will be as follows:

$$\begin{cases} \varepsilon_x = \dfrac{1}{E(x)}\left[\sigma_x - \nu(x)\sigma_y\right], \\ \varepsilon_y = \dfrac{1}{E(x)}\left[\sigma_y - \nu(x)\sigma_x\right], \\ \gamma_{xy} = \dfrac{2\left[1+\nu(x)\right]}{E(x)}\tau_{xy}, \end{cases}$$

where $E(x)$, $\nu(x)$ – normal elasticity module gradients and Poisson's ratio, respectively, along the x axis from the surface depthward the material's volume.

In setting objectives, it is necessary to set boundary conditions. For the considered area they will have the following form (Figure 1):
when $x = 0$, $-a \le y \le a$ (contact area): $\sigma = P(y)$, $\tau = Q(y)$;
when $x = 0$, $-A \le y \le -a$, $a \le y \le A$ (free surface): $\sigma = \tau = 0$;
when $x = B$, $-A \le y \le A$: $u_x = 0$, $\tau_x = 0$; when $0 \le x \le B$, $y = -A$; A: $u_y = 0$, $\tau_y = 0$;

The last two boundary conditions are so-called conditions of sliding along a rigid wall.

3. The calculating algorithm for stress condition and strength study

Fracture mechanisms analysis of instrument materials shows that in accordance with the principles of continuum mechanics the material state at the point of a possible fracture is fully determined by the level of operating voltages. Since the limiting state occurrence is determined by the crack criterion, closely related to the shear stresses and their distribution criterion due to normal tensile stresses, the general criterion of instrument materials strength should take into account the effect of both these fraction mechanisms.

The most effective and fastest growing numerical method in the deformable body mechanics, composite and fracture mechanics is the finite element method (FEM) [6]. The basis of this method is the partition of the study area into separate elements of a simple geometric configuration (rectangular or triangular shape). Elements connection is implemented in the nodes, in which met the conditions of equilibrium and motion continuity.

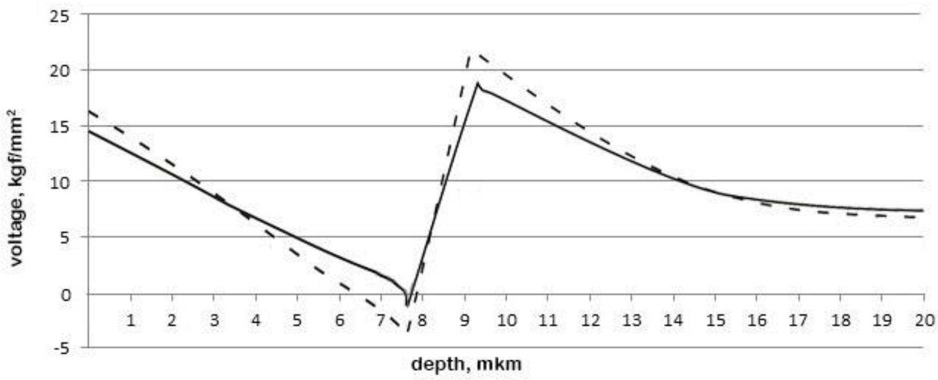
Due to the fact that the coating and surface hardened layers' thickness is much smaller the size of the study area, the calculation of the stress condition was carried out in two stages. The first stage carries out calculation of the stress state at the macro level, the area material was considered isotropic (Figure 1). The second stage, having identified the area with high levels of stress at the surface, calculates the stress condition at the meso-level. At this stage the test material was considered isotropic along the y axis and heterogeneous along the x axis, but the layer material retains effective characteristics of real materials. As the boundary conditions used voltages obtained in the previous stage.

On each direction were considered materials with different coatings, were evaluated their strength. Numerical calculation of the stress state problem was solved using FEM. The basis of this method is the partition of the study area into separate elements of a simple shape (rectangular and triangular shape). Elements connection is implemented in the nodes, in which fully met the conditions of equilibrium and motion continuity. FEM is effective in gradient materials study due to that any finite element may have its own elastic characteristics. Further, having constructed the stress condition, estimated the strength of the base material by Lebedeva-Pisarenko criterion, and the coating material – by the largest tangential stresses criterion [7]. If one of the materials stress exceeds the critical voltage, the material will fracture.

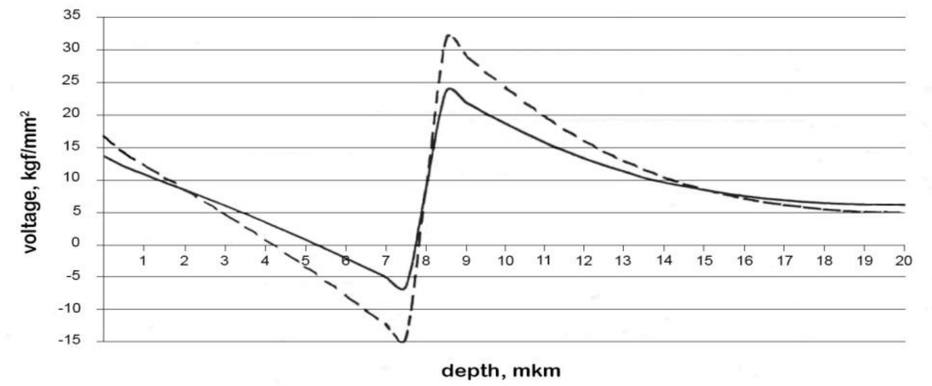
4. Analysis and results

For the selected load configuration, the parameter determining stress condition is the stress tensor component. The following compositions were considered: as the basis material – hard alloys VK6 (WC – 94%, Co – 6%), as the coating material – high-melting compounds (TiC, TiN). Figure 2 (a, b, c, d, e, f, g, h, i) shows the stresses in the surface layer from the surface depthward the alloy VK6. It is seen that on the coating surface there are high tensile stresses gradually decreasing to the interface. Dependence is expressed by a sawtooth curve, while the maximum stress observed at the coating surface and at the interface "coating – base" that can promote the coatings spalling.

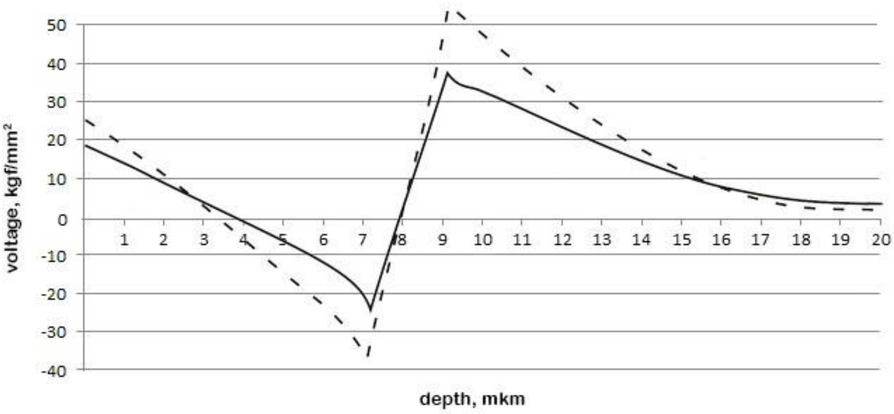
When exposed to combination of power and temperature loads got that the maximum tensile stresses in each coating layer arise mainly from the material's surface. With increasing power loads operating voltage level σ_y at the material's surface with monocoating shifted to tensile stresses area, while in temperature increase there is a curve shift to the area of compressive stresses. As can be seen, even at temperatures of 200 °C and 400 °C at P, Q = 50, 70 % in the coating at the interface base "plate – coating" there are compressive stresses. Figure 2 also shows that in the base plate volume adjacent to the coating there is a high stresses level, which may adversely affect the performance of the base material at high loading conditions.



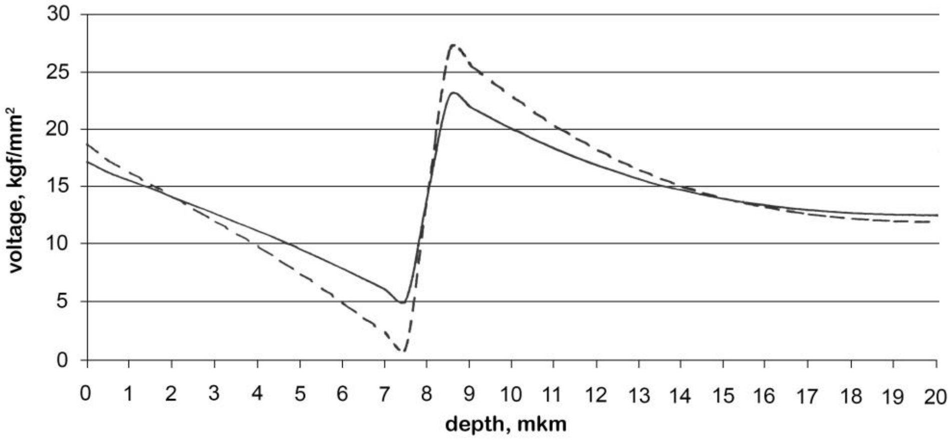
a) P, Q = 30 %, T = 100 °C



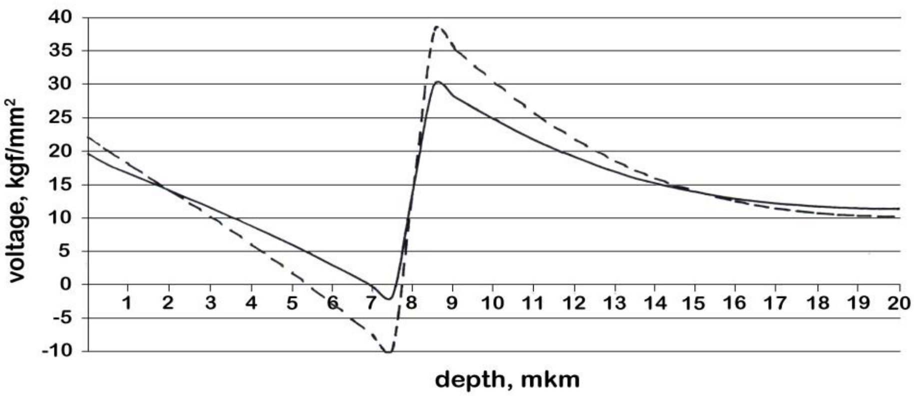
b) P, Q = 30 %, T = 200 °C



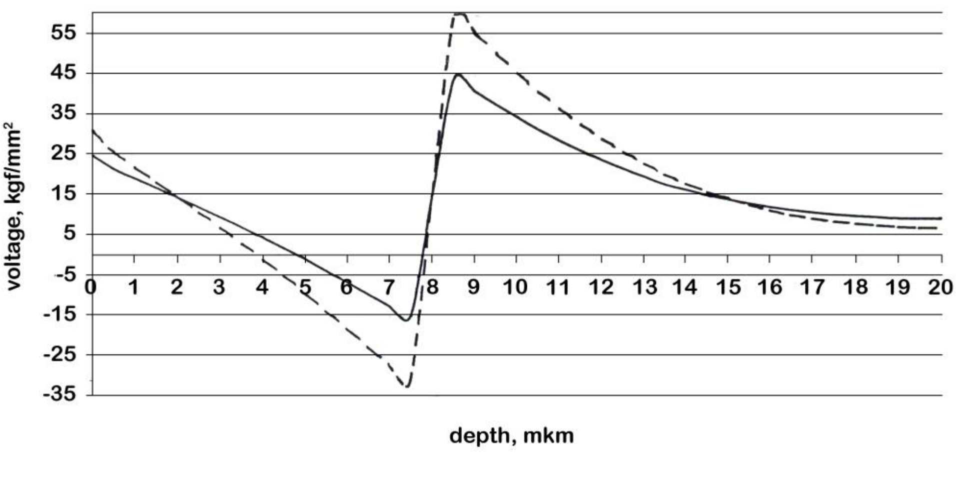
c) P, Q = 30 %, T = 400 °C



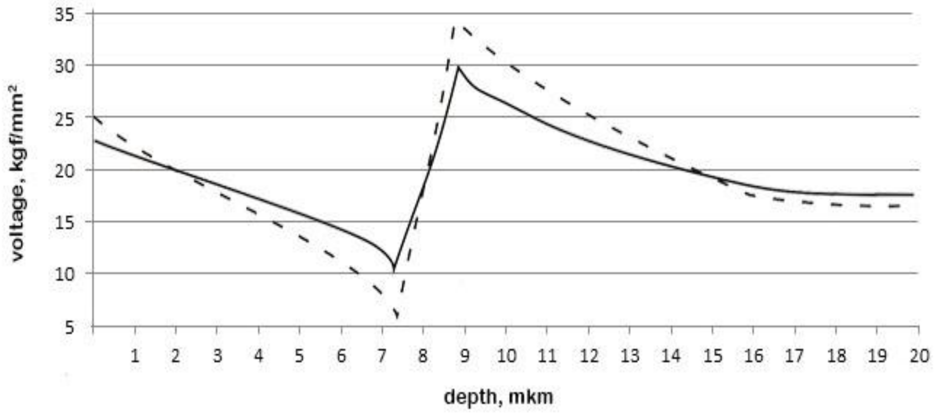
d) *P*, *Q* = 50 %, *T* = 100 °C



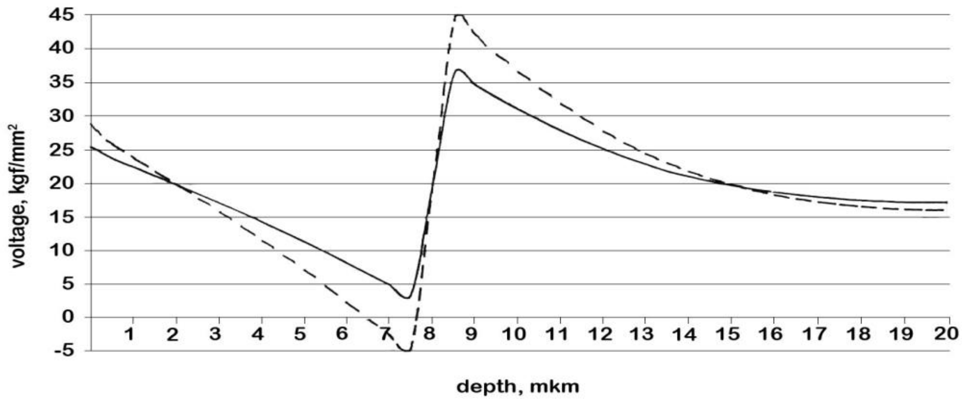
e) *P*, *Q* = 50 %, *T* = 200 °C



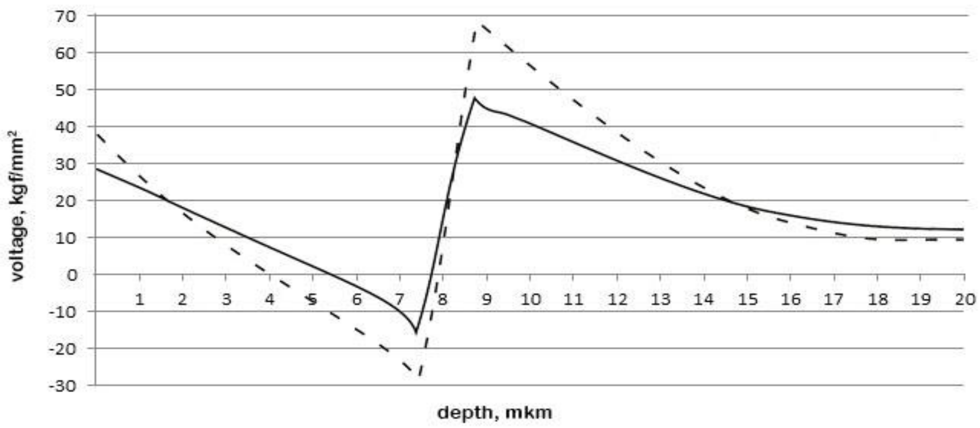
f) *P*, *Q* = 50 %, *T* = 400 °C



g) *P*, *Q* = 70 %, *T* = 100 °C



h) *P*, *Q* = 70 %, *T* = 200 °C



i) *P*, *Q* = 70 %, *T* = 400 °C

Figure 2. The stress distribution σ_y in the material with a multilayer coating from the surface depthward the material's volume (—— VK6+TiC, - - - - - VK6+TiN)

Study of strength showed that almost all materials at high power and temperature loads are practically fractured. This is due to the fact that the coating materials (high-melting compounds) tensile strength is several times less than the tensile strength of hard alloys ($[\sigma^{base}] \approx 3 \ldots 21\ [\sigma^{coat}]$, see, e.g., [8]) Therefore, even with load or 30 % of the $[\sigma^{base}]$ or 100 °C the coating will break down first. And then, depending on the adhesive compound strength with base failure can go either to the base or to the interface.

5. Conclusions

Strength study showed that in almost all cases coating material is fractured first. Studied elastic characteristics of materials used for instrument coating. It is found that the materials stress distribution depends on the thermoelastic and elastic gradient characteristics, gradient layer thickness and loading conditions.

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