Numerical solution of stress-strain state during electromechanical treatment of plasma sprayed coatings

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Abstract. The principal aim of this study was to determine the distribution patterns of the stress-strain state at different times. The solution was performed using the finite difference method. The main results were presented depending on the time of action of the alternating electric current during the electromechanical treatment of the plasma sprayed coating.

1. Introduction

The electromechanical treatment is the modern method of the post-treatment of the plasma sprayed coating. This approach is based on the simultaneous resistive heating of the surface and the deformation of the plasma sprayed coating by the electrode. The plasma sprayed coating was densified after the EMT due to deformation and welding of the boundaries of the splats. The nanostructured crystal size was formed after the EMT because of high value of the cooling rates during the post-process; it was confirmed by the decrease of the crystal size and the increase of the microstrain [1, 2]. The cohesive strength of the plasma sprayed coatings increased after the EMT because of the resistive welding and the formation of the nanostructured crystal phases [3, 4]. The wear resistance of the plasma sprayed coatings increased, too. For this reason, the postprocessing of the plasma sprayed coatings by means of the concentrated energy fluxing during the EMT has great potential.

The numerical modeling of temperature, strain-stress state, etc. is the practical approach to determine the most effective modes of post-treatments. Also this approach was used for explanation of the structured transformation. For this reason, the papers [5-8] presented investigation process of the post-treatment of the coatings by means of the concentrated energy fluxing. The solution of this problem concerning stress and strain state is needed to ensure the determination of the effective modes of the post-treatment. By the way, the parameters of the strained condition of the two layers of the half-space, which are modelling the coatings and substrate, needs to be calculated.

The purpose of this study is to calculate strain-stress state and to determine the main parameters of the strained condition during the EMT process.

2. Method of the Solution

The solution of the thermo-force contact problem in the elastic-plastic formulation was performed. The high-temperature exposure and the intense contact pressure were also taken into account. The main boundary conditions were presented in the paper [9]. In this study, the solution was performed using the finite difference method.
An explicit finite-difference scheme was used for the approximate solution. The differential equation of equilibrium in the form of Dugamell-Neumann was approximated by a system of algebraic equations:

\[
\begin{align*}
\left(1 + \frac{1}{1 - 2\mu_i^n, k}\right)u_{i+1,j,k}^n + u_{i-1,j,k}^n - 2\cdot u_{i,j,k}^n &+ \\
\frac{u_{i,j,k+1}^n + u_{i,j,k-1}^n - 2\cdot u_{i,j,k}^n + u_{i,j+1,k}^n + u_{i,j-1,k}^n - 2\cdot u_{i,j,k}^n}{h_x^2} &+ \\
\frac{1}{1 - 2\mu_i^n, j,k}\left[v_{i+1,j,k}^n - v_{i-1,j,k}^n - v_{i,j,k+1}^n + v_{i,j,k-1}^n\right] &+ \\
\frac{w_{i+1,j,k}^n - w_{i,j,k-1}^n + w_{i,j,k+1}^n - w_{i,j-1,k}^n}{4\cdot h_x \cdot h_y} &+ \\
2\left(1 + \mu_i^n, j,k\right)\left[\frac{\alpha_{i+1,j,k}^n - \alpha_{i,j,k}^n}{2\cdot h_x} + \frac{\alpha_{i,j+1,k}^n - \alpha_{i,j,k}^n}{2\cdot h_y}\right] &= 0,
\end{align*}
\]

where all variables are assigned corresponding finite-difference indices: \(n\) – for the nodes of the time grid (\(n=0, 1, \ldots, Nt\); \(Nt\) – the number of steps in time); \(i, j, k\) – for the nodes of the spatial grid on the coordinate axes \(x, y, z\); \(i=1, 2, \ldots, Ni\); \(j=1, 2, \ldots, Nj\); \(k=1, 2, \ldots, Nk\) (\(Ni, Nj, Nk\) – the number of points of the finite-difference grid in the direction of the \(x, y, z\) coordinate axes, respectively).

The deformation components were found after determining the components \(u, v, w, w\):

\[
\begin{align*}
\varepsilon_x &= \frac{\partial u}{\partial x}; & \gamma_{xy} &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}; \\
\varepsilon_y &= \frac{\partial v}{\partial y}; & \gamma_{yz} &= \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}; \\
\varepsilon_z &= \frac{\partial w}{\partial z}; & \gamma_{zx} &= \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z},
\end{align*}
\]

The stresses were calculated using physical ratios:
3. Results and Discussion
During the numerical simulation, the following results were obtained.

The main stresses were reallocated. The intensity of the main stress was increased. The characteristic zones of limit states in the coating were identified.

The presence of a non-stationary temperature field in the contact problem under consideration leads to a change in the precipitation of the half-space surface. The value of precipitation of the surface depends on the time and its value. Figure 1 shows the dependence of main stresses in the half-space under non-stationary thermo-force contact loading of a two-layer half-space. Analyzing this relationship, we note, that there is the relationship between the surface precipitation and the maximum temperature in the half-space. Thus, as the temperature increases, the precipitation decreases, and vice versa.

\[
\sigma_x = 2G \left[ \frac{\partial u}{\partial x} + \frac{\mu}{1-2\mu} \cdot \theta - \frac{1+\mu}{1-2\mu} \cdot (\alpha, \Delta T) \right];
\]

\[
\sigma_y = 2G \left[ \frac{\partial v}{\partial y} + \frac{\mu}{1-2\mu} \cdot \theta - \frac{1+\mu}{1-2\mu} \cdot (\alpha, \Delta T) \right];
\]

\[
\sigma_z = 2G \left[ \frac{\partial w}{\partial z} + \frac{\mu}{1-2\mu} \cdot \theta - \frac{1+\mu}{1-2\mu} \cdot (\alpha, \Delta T) \right];
\]

\[
r_{ss} = G \left[ \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right];
\]

\[
r_{sx} = G \left[ \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right];
\]

\[
r_{sz} = G \left[ \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right].
\]
**Figure 1.** Distribution of main stresses in the half-space under non-stationary thermo-force contact loading of a two-layer half-space
Figure 2. Stress intensities and parameters of the stress state in the half-space under non-stationary temperature-force contact loading of a two-layer half-space.
Figure 3. Residual deformations in the half-space: a – homogeneous, b – two-layer

Figure 2 shows the stress intensities and parameters of the stress state in the half-space under non-stationary temperature-force contact loading of a two-layer half-space. Analyzing this relationship, we note, that there is the relationship between the stress intensities, parameters of the stress state, and the
maximum temperature in the half-space. Thus, as the temperature increases, the precipitation of the stress intensifies, parameters of the stress state increase, too.

Figure 3 shows residual deformations for homogeneous and two-layer half-space. Thus, in the case of a two-layer half-space, the value of residual deformation in the surface layer decreases (Fig. 3).

The obtained numerical results of residual deformations are confirmed by experimental results [10]. The investigation shows that the coating after the EMT had wavy structure. Due to the fact that part of the material was squeezed out along the roller's edges under pressure, the wavy structure was formed on the surface of the coating. The main geometric parameters of the wavy structure depend on the frequency of alternating electric current during the EMT.

The results of the numerical modeling obtained in this work allow us to determine the influence of the EMT modes on the stress-strain state in the coating. Therefore, an initial approach has been developed to determine the effective modes of the EMT of the plasma sprayed coating.

4. Conclusion

1. The solution of a non-stationary thermo-force contact problem is carried out. The change in the profile of the half-space surface depending on the size and the position of the temperature field during the EMT is shown.
2. The effect of the elastic properties on the stress-strain state of a two-layer half-space at a thermo-force contact during the EMT of the plasma sprayed coatings is examined.
3. It is determined that the developed model allows to choose the effective modes of the EMT of the plasma sprayed coatings.

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