Mathematical modeling of the stress state in the coating during the electromechanical treatment

A Yu Ivannikov

Baikov Institute of Metallurgy and Material Science, Russian Academy of Sciences, 49, Leninsky ave., 119334 Moscow, Russian Federation

E-mail: ivannikov-a@mail.ru

Abstract. The principal aim of this study is to determine the stress state in the thermal sprayed coating during the electromechanical treatment. The solution is performed using the finite difference method. Lode-Nadai coefficient and Bagmutov parameter are used to describe the stress state in the cross-section of the half-space with coating.

1. Introduction

Post-treatment of thermal sprayed coatings is used to regulate the structure and to improve physical and mechanical properties. Traditionally, re-melting and machining are used for post-processing [1]. Re-melting is not advisable for nanostructured materials. Therefore, for the post-treatment of nanostructured thermal sprayed coatings, it is necessary to use modern post-treatment methods, which allow saving the rapidly quenched structure. Electromechanical treatment (EMT) is one such method [2-4]. During the EMT, the combined effect of resistive heating and plastic deformation of the thermal sprayed coating is realized. Series of experiments and preliminary mathematical modeling are required for determining the processing modes.

Mathematical modeling is a promising way to determine effective modes of post-treatment. There are various methods of mathematical modeling, for example, finite element method [5,6], finite difference method [7, 8], etc. The main problem, solved during the simulation, is the determination of the temperature field, stress-strain state, etc. Analysis of the results of mathematical modeling makes it possible to evaluate structural and phase transformations in alloys, predict the formation of cracks, etc. At present, various stress state criteria are used to assess the probability of product failure. In this work, two criteria, the Lode-Nadai coefficient and the Bagmutov parameter, are adopted. These criteria make it possible to describe the entire range of stress states from triaxial tension to full compression. Having information about the type of stress state, the probability of coating failure can be predicted. Therefore, in this study, the stress state of the half-space with the coating is calculated, which makes it possible to determine the areas in the coating, where conditions can be formed for the destruction of the coating during the EMT process.

The purpose of this study is to analyze the stress state in the thermal sprayed coatings during the electromechanical treatment.

2. Method of the Solution

The numerical modeling of temperature, strain-stress state, etc. was presented in the paper [9]. The solution was performed using the finite difference method. In this study, the results of the strain-stress state are used for the calculation of the stress state. The Lode-Nadai coefficient and the Bagmutov
parameter are used for the analysis of the stress state of the half-space with the coating. The half-space with the coating is the model of the specimen with thermal sprayed coating.

![Diagram of cross-sections in the half space with coating for analysis of the parameters of the stress state](image)

**Figure 1.** Cross-sections in the half space with coating for analysis of the parameters of the stress state

The Lode-Nadai coefficient is calculated using equation:

\[
\nu = \frac{2}{\pi} \arctg \left( \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{\sigma_1 + \sigma_2 + \sigma_3}} \right)
\]

where \(\sigma_1, \sigma_2, \sigma_3\) are general stresses.

The Bagmutov parameter is calculated using equation:

\[
\nu' = \frac{2}{\pi} \arctg \left( \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{\sigma_1 + \sigma_2 + \sigma_3}} \right)
\]

### 3. Results and Discussion

During the calculation, the following results are obtained.

Figure 2 shows the longitudinal cross-section C-C of the half-space with the coating. Four characteristic areas are identified.
Figure 2. Cross-sections C-C in the half space with coating

The first area is formed at the border of the trailing edge of the stamp. In this area, the maximum temperature field is found [3]. The stress state parameters have the values \( \mu_\sigma \approx 0.75..0.5 \) and \( \nu_\sigma \approx 1..0.75 \). The stress state is close to triaxial tension. The ratio of stress intensity to yield strength is \( \sigma_i/\sigma_{0.2} = 1..1.18 \). The combination of these parameters indicates the possibility of developing brittle fractures in this area.

In the second zone, the parameters are as follows: \( \mu_\sigma \approx 0.75..0.5 \) and \( \nu_\sigma \approx 0.25..0.5 \); ratio \( \sigma_i/\sigma_{0.2} = 0.12..0.26 \). According to the classification of the stress state, two tensile and one compressive stress are formed there. The ratio of stress intensity to yield strength is less than unity, and the possibility of crack development in this area is low.

The third zone is formed below the second zone. The parameters are as follows: \( \mu_\sigma \approx -0.75..0.5 \) and \( \nu_\sigma \approx 0..0.3 \). The value of these parameters indicates one tensile and two compressive stresses, the stress intensity is two times less than the yield stress. The possibility of crack development in this area is low.

The fourth zone is formed before the stamp. The parameters are as follows: \( \mu_\sigma \approx 0.75..0.5 \) and \( \nu_\sigma \approx -0.3..0.5 \). The value of these parameters indicates two tensile and one compressive stress. The stress intensity is two times less than the yield stress. The possibility of crack development in this area is low.

Figure 3 shows the transverse cross-section B-B, which is located behind the stamp in the area of action of significant temperature field. A high level of tensile stresses is determined by overheating of the surface and the lack of pressure from the stamp. Therefore, there is zone 1 with the ratio of intensity and yield strength more than 1.

Figure 4 shows the stress state analysis in the transverse cross-section under the stamp. In the first zone, there are two compressive stresses, and the ratio is \( \sigma_i/\sigma_{0.2} = 0.92..1.05 \). The zone 2 is located below zone 1. In zone 2 there are two tensile and one compressive stress, and \( \sigma_i/\sigma_{0.2} = 0.39..0.52 \). Zone 4 is formed to the left and right of the contact area of the coating and the stamp.
Figure 3. Cross-sections B-B in the half space with coating

Figure 4. Cross-sections A-A in the half space with coating
4. Conclusion
Stress state analysis for the half-space with coating has been completed. Coating and half-space have different physical-mechanical properties. The considered method can be used to analyze hazardous zone during the EMT of the thermal spray coatings.

Zone with triaxial tension and a value of stress intensity favorable for the development of brittle fracture is formed behind the stamp. It means that during the EMT the cracks in the coatings can be obtained. Therefore, the effect of the modes of the EMT on the stress state of the thermal spray coating can be calculated before a test.

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