Investigation and prediction of adhesion strength of plasma coatings by mathematical modeling of deposition parameters

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Abstract. In this paper, studies were conducted in the field of adhesive strength of plasma coatings and the surface of the part. The propagation of a crack front in a plasma coating material with composite inclusions is simulated. It was proposed to consider the possibility of introducing into the composition of the material sputtering additional composite inclusions that have a greater plasticity and a size greater than the size of the particles in the coating.

1. Introduction

About half of parts delivered for refurbishing can be used again with repair cost of only 15-30% from new part price. This makes gas-thermal treatment refurbishing methods economically beneficial. It is worth noting that only 5-9% of damaged parts are non-reparable [1-3].

Plasma coating is one of the promising methods to repair worn out parts. Gas-thermal treatment, particularly plasma coating, allows implementing various materials in coating composition. Metals, ceramics, cermets are used [2]. Any other deposition methods have a limited choice of materials [3].

However, plasma coatings have a notable drawback limiting their applications – poor adhesion with substrate. Consequently, coating durability needs to be substantially enhanced. Considering this, theoretical and practical investigations of part durability increase by plasma coatings are of high interest [4].

The goal of this work is to study adhesion between plasma coatings and part surfaces. To accomplish mathematical modeling of crack propagation in composite plasma coatings.

2. Coating durability study

The main figure of merit in analytical studies of plasma coating durability is an amount of mechanical stresses. These stresses should not exceed cohesion forces between grains in a coating itself, and also adhesion between a coating and a part surface.

To evaluate stresses and material quality in coating and part contact zone, as well as in complementary part contact zone, surface interactions need to be modeled. It is enough to include only static mechanical load on a coating (figure 1). Dynamic load is increased by tangential friction force [5].

Based on schematics of 2 bodies in contact (figure 1) and previous works [6], let’s outline that 2 protrusions in contact experience elastic deformation under certain load threshold. After that, deformation is plastic. Here, surface roughness of harder material is introduced into softer material,
and deformation of harder body is much less comparing to softer body. Hence, surface roughness of a harder body is of priority consideration [7].

![Figure 1. Schematics of 2 surfaces in contact](image)

Roughness height distribution, defining plasma coating surface microprofile, is described by Gaussian distribution [8]:

$$\Phi(Z) = \int \phi(\xi) d\xi$$  \hspace{1cm} (1)

where: $\Phi$ – distribution function; $Z$ – coordinate of relative convergence; $\phi$ – density function; $\xi$ – current coordinate (defines surface roughness class).

In plasma coating, a load is perceived through separate grains. This load is limited by elastic deformation threshold of particular grains. Complementary part hardness is also influencing coating grain deformation. Plastic deformation is typically minor due to large number of boundaries and weak bonds between grains. This is a consequence of high coating material porosity. Therefore, resultant contact stress should not exceed at least cohesional bond strength between coating grains. Only fulfilling this condition allows expecting sufficient coated part lifetime.

### 3. Study of two-phase material durability

Considering two-phase (composite) material, one notes that different fraction grains in a coating and part surface all possess different thermo-elastic properties. Hence, taking into account weak cohesion between grains and poor adhesion with substrate, different fraction grains can be a reason of cracks [9].

An amount of fragile inclusions in plasma coating is a main factor influencing crack propagation. If destruction propagates freely from grain to grain, the whole composite system will breakdown after fragile component collapses. But if fragile components will be isolated by crack-resistant grains, they will collapse independently in series, which makes such system more durable (figure 2).

![Figure 2. Crack propagation model in a material with inhomogeneous components](image)
From previous works [10] it is known that coatings are most sensitive to stretching stress described by:

\[ \frac{dP}{d\varepsilon} = 0 \]  

(2)

where: \( P \) – coating load; \( \varepsilon \) – amount of deformation.

Further we use a behavior of two-phase composite material. In this case the 1st phase is composite inclusions, the 2nd – coating base material. With small deformations (figure 3a) within elastic limit, with \( \varepsilon_1 = \varepsilon_2 \) a stress in two-phase material can be expressed as:

\[ \sigma = V_1 E_1 \varepsilon_1 + V_2 E_2 \varepsilon_2 \]  

(3)

where: \( V_1 \) and \( V_2 \) – relative phase volume; \( E_1 \) and \( E_2 \) – elastic modulus.

For further plasma coating wear and tear study, as well as for crack propagation study and evaluation of stress and deformation tensor dependencies, Hooke’s law is a core of mathematical model. It describes equations with different constants, for example, technical modulus \( E \). This modulus can be expressed with Lame coefficients [11], which are of use for part plasma coating:

\[ E = \frac{\mu(3\lambda + 2\mu)}{\lambda + \mu} \]  

(4)

where: \( \lambda \) and \( \mu \) are Lame coefficients.

The phase with smaller threshold deformation starts to degrade with increased load. Considering \( \varepsilon_1 > \varepsilon_2 \) as well as equation (4), we get:

\[ \sigma = V_1 \frac{\mu(3\lambda_1 + 2\mu_1)}{\lambda_1 + \mu_1} \varepsilon_1 + V_2 \varepsilon_2 \]  

(5)

Under such stress phase 2 will collapse and stress will be redistributed on phase 1. Phase 1 collapse conditions are given as:

\[ \sigma_1 V_1 < V_1 \frac{\mu(3\lambda_1 + 2\mu_1)}{\lambda_1 + \mu_1} \varepsilon_1 + V_2 \varepsilon_2 \]  

(6)

In this case breakdown zone will be limited to an area in direct contact with the first collapse zone. So, a breakdown propagation is isolated. This is called a singular collapse (figure 3b).

In case if \( \sigma_1 > \sigma_2 \), or \( V_1 < V_2 \), fragile phase 2 will continue to hold increasing load till breakdown stress is reached:

\[ \sigma_1 V_1 > V_1 \frac{\mu(3\lambda_1 + 2\mu_1)}{\lambda_1 + \mu_1} \varepsilon_1 + V_2 \varepsilon_2 \]  

(7)

Fragile phase 2 will keep degrading with this. Such phenomenon is called a multiple collapse (figure 3c).
4. Results and discussions
After analysis of before mentioned equations we can conclude that in case if $e_1 > e_2$ and $V_1 > V_2$, there will be a singular collapse. For $e_1 > e_2$ and $V_1 < V_2$ a multiple collapse will take place.

Interpreting coating properties with studied composite properties, one can see that with 100% elastic phase 1 content a multiple collapse of material will occur, i.e., coating has higher hardness.

This coating condition is typical for thermally deposited monolythic metal.

When fragile phase 2 content is 100%, a singular material collapse will take place as a result of crack propagation. This is a typical situation for composite coatings.

Introduction of an additional phase with higher plasticity and bigger grain size can potentially sufficiently increase a coating durability [12].

5. Conclusion
A study on plasma coating adhesion with part surface is done. A mathematical model of crack propagation in plasma coating with composite inclusions is developed. It is concluded that addition of material with higher plasticity and bigger grain size is needed to enhance a cohesion and adhesion of a composite coating. To validate this theory, a set of experiments based on metallic substrate coatings with composite materials of different composition is needed. Plasma deposition process variability, as well as process technological and kinematic parameters are to be addressed during outlined experiments.

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