STATISTICAL ADHESION/COHESION STRENGTH CRITERION FOR COATINGS

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Abstract: *The effect of changing coating length on the cohesive and adhesive failure of the coating on metallic flat substrates is analyzed by uniaxial loading. The criterion for determining the fragmentation length of the coating with mixed (adhesive-cohesive) failure was developed. Calculating the critical length as the intersection point of the two lines (interfacial failure shear stress-length curve and the normal failure stress-length curve) does not always give correct value. The critical length of coating should be evaluated as maximum value within the annular trapezoid. It is established that the kind of probability density function both the adhesion strength and the cohesion one should be considered when determining the critical length of the coating. Verification of the developed criterion was performed on the example of plasma-sprayed coatings. It was noted, the formation of multiple cracks in the plasma-sprayed coating has random character due to microstructural defects, such as pores and microcracks.*

Keywords: COATING, DETACHMENT, MULTIPLE CRACKING, FRACTURE CRITERION, INTERFACE SHEAR STRESS, NORMAL STRESS, PLASMA SPRAYING, TENSILE TESTING

1. Introduction

Coatings are subjected to various kinds of mechanical loading in service. It can cause their destruction. Researchers use various models that allow studying how the load is transferred from the substrate to the coating through the interface for understanding of the destruction processes in the coated materials [1]. Pioneering study of the load transfer through the interface contact has been performed in shear lag model by Cox [2].

The stress state of the substrate–coating system is inhomogeneous due to difference of the elastic properties of the substrate and the coating. Adhesion and cohesion failure occurs in areas where the stress reaches a critical value. The true data on the adhesion and cohesion strength can be obtained only by taking into account the inhomogeneity of the stress state in the coated materials or when we using specimens with coatings, in which the inhomogeneity of stress state can be neglected. However, both in the coated specimens and in the structural elements with coatings there is considerable heterogeneity of the stress state. The feature of the substrate–coating system is the ability to transmit the load both in the coating and in the substrate through the interface. Consider a case where the stress arises in the coating due to load applied to the substrate (Fig. 1).

There are ~~a~~ number of models that are used to study the stress distributions in the coatings and in the interface area. The basis of the classical Cox shear-lag model is the assumption that stresses in the fiber-matrix system are proportional to the difference of the displacement components of this system [2]. The hypothesis regarding that the stresses in the coating–substrate system are proportional to the difference of substrate and coating displacements, led to the development of another models [3–8].

Usually, in the case of the uniaxial loading the periodical multiply cracking in the coating occurs in the direction perpendicular to the load [9]. The cracking space depends on the magnitude of the applied loads and the coating strength.

Some kinds of coatings continue to fulfill their functions even after the cracking, such as: wear-resistant [10], tribological “chameleon” type [11] and thermal barrier [12]. Positive effect from the cracking of the thermal barrier coatings is reported in [13]. Coatings with the previously created cracks have a higher thermal shock resistance than coatings without cracks [14]. Therefore, this paper deals with development of the criterion for defining of the critical coating length at which the delamination and the cracking occur simultaneously. The aim of our study was to perform a consideration on the fracture of plasma-sprayed coating during application of uniaxial load, taking into account the processes of cracking and delamination.

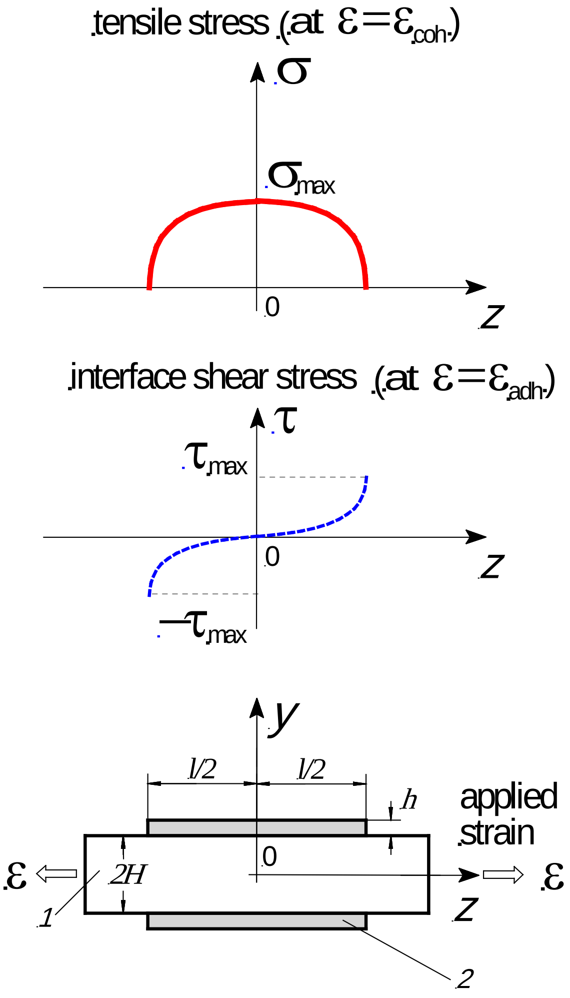


Fig. 1. *Model of the coated specimen (1 - substrate, 2 - coating)*

2. Theory

In the theoretical coating–substrate model the maximum shear stress occurs at the coating end [4]. In accordance with the equations for determining the distribution of normal stresses in the coating and shear stresses in the interface, given in [4], the strains at which the cracking $\varepsilon_{coh}(l)$ and delamination $\varepsilon_{adh}(l)$ of the coating are occurred, is given by the model as

$$\varepsilon_{coh}(l) = \sigma_{\max} \cdot h \cdot \left(1/(E_c h) + 1/(E_s H)\right)\left(1 - \frac{1}{\cosh(k\,l/2)}\right)^{-1}, \quad (1)$$

$$\varepsilon_{adh}(l) = \frac{\tau_{\max}}{k} \cdot \left(1/(E_c h) + 1/(E_s H)\right) \cdot \frac{\cosh(k\,l/2)}{\sinh(k\,l/2)}, \quad (2)$$

where $\sigma_{\max}$ is the maximum critical normal stresses in the coating at $z = 0$; $\tau_{\max}$ is the maximum critical interface shear stress at $z = \pm l/2$; E_s and E_c are the elastic modulus of the substrate and coating, respectively; G_s and G_c are shear modulus of the substrate and coating, respectively; $2H$ and h are thickness of the substrate and coating, respectively; l is the coating length and constants k and L are given by

$$k = \sqrt{L \cdot \left(1/(E_c h) + 1/(E_s H)\right)}; \quad (3)$$

$$L = 2\left(\frac{G_s}{H} \cdot \frac{G_c}{h}\right) \Big/ \left(\frac{G_s}{H} + \frac{G_c}{h}\right). \quad (4)$$

Equations 1 and 2 are plotted in Fig. 2. The coating will crack if $\varepsilon_{coh}(l) < \varepsilon_{adh}(l)$. If $\varepsilon_{coh}(l) > \varepsilon_{adh}(l)$ then the coating will detach from the substrate.

As it is seen from Fig. 2 the value of the critical length l_{cr}, at which the coating cracking process turns into the delamination, is determined by the point of intersection of two curves. The critical length of the coating l_{cr} is determined by the relationship:

$$\varepsilon_{coh}(l_{cr}) = \varepsilon_{adh}(l_{cr}). \quad (5)$$

Transform relationship (5) to the following form:

$$\frac{k}{\tau_{\max}\left(1/(E_c h) + 1/(E_s H)\right)} \tanh(k\,l_{cr}/2) = = \frac{1}{\sigma_{\max} h\left(1/(E_c h) + 1/(E_s H)\right)}\left(1 - \frac{1}{\cosh(k\,l_{cr}/2)}\right).$$

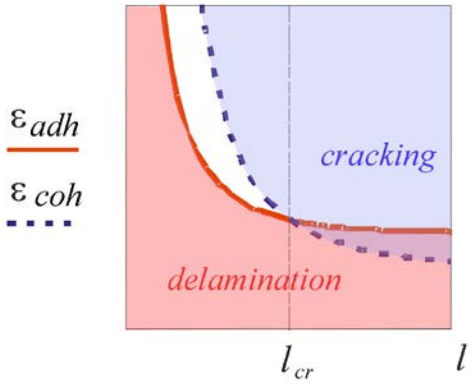


Fig. 2. *$\varepsilon_{coh}(l)$ and $\varepsilon_{adh}(l)$ as functions of coating length l. In the intersection point both delamination and cracking occur*

After appropriate transformations we obtain the equation:

$$\frac{\sigma_{\max} hk}{\tau_{\max}} \tanh(k\,l_{cr}/2) = 1 - \frac{1}{\cosh(k\,l_{cr}/2)}. \quad (6)$$

Introduce the notation

$$\Psi = \sigma_{\max} hk/\tau_{\max}.$$

Equation (6) can be written as follows:

$$\Psi \cdot \tanh(k\,l_{cr}/2) = 1 - \frac{1}{\cosh(k\,l_{cr}/2)}. \quad (7)$$

There are two roots of this equation:

$$l_{cr\,1} = 0$$

and $l_{cr\,2} = \frac{4}{k}\operatorname{artanh}\Psi$ (at $\Psi < 1$). (8)

Decreasing of the coating length l leads to the achievement of the value of the critical length l_{cr}. Cracking of the coating stops at l_{cr} and it starts to detach. In case $\Psi < 1$ cracking occurs, i.e. $l > l_{cr}$. In case $\Psi > 1$, the delamination occurs detaches without cracking, i.e. $l < l_{cr}$. When $\Psi = 1$ delamination and cracking of the coating occur simultaneously.

Strength criteria are usually formulated for micro-homogeneous environments, metals in particular. Strength of metals is determined by averaging over the volume characteristics. At the same time the criteria that are formulated on the basis of hypotheses about the continuity and micro-homogeneity of the environment cannot be used in the case of structurally inhomogeneous coatings. In these cases, the destruction process is dependent by the local defects (micro-cracks, pores, phase inhomogeneities) in the coating structure, and it is not dependent by averaged characteristics. Structure defects become sources of the fracture. In addition, the structural heterogeneities of coatings have a random nature. That is why, the probabilistic methods that describe the fracture of the substrate–coating system, are used to develop the adhesion-cohesion coating fracture criterion.

Experimental data indicate that tensile strength, yield strength, elastic modulus and other mechanical characteristics of the materials have very appreciable scatter. Coating can crack randomly [15–19] and the critical length for the same coating varies.

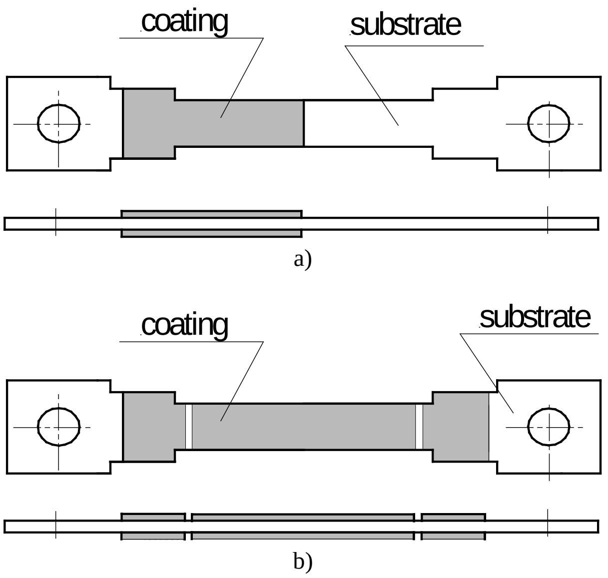
3. *Equipment and materials*

We used plasma-sprayed coatings on stainless steel substrates as model system. Details of the test technique were as follows. Static tensile testing of coated specimens is used in the method. Metal substrate 2.0 mm in thickness and 6.0 mm in width was made according to standards for definition of mechanical properties of metals without coatings. The coating is sprayed up to the half of the working length of the specimen (Fig. 3a) or over the full working length of the specimen (Fig. 3b). Tensile testing was conducted on an *FM*-1000 mechanical testing system.

The plasma-sprayed NiAl coating was applied using a plasma torch, with partially imposition of arc and additional cooling of plasma jet by concentric flow of protective gas. Argon was used as the plasma and protective gas. The following plasma spraying conditions were for all powders: current 80–100 A, voltage 50–60 V, gas flow rate 2–3 l/min, powder feed rate 2 kg/h and spray distance 120 mm at 2 mm diameter nozzle. Plasma jet has laminar character of expiration and more extended high temperature area due to equipment design and operating conditions. Before coating deposition substrates were sand blasted. Coatings with thickness of 0.15 and 0.3 mm were sprayed onto substrates.

4. Experimental

In order to study the failure due to applied tensile strain, five tests were preformed for different thickness. The test was ended when the coatings failed by spallation. Experimental studies of tensile specimens with plasma-sprayed coatings show that the crack divides the coating into two equal length segments (Fig. 4). The thicker coatings had a different path of failure than the thinner ones (Fig. 5). Features of the coating's cracking and delamination define four curves characterizing the maximum $\varepsilon_{coh}^{\max}(l)$ and minimum $\varepsilon_{coh}^{\min}(l)$ strains at which cohesion failure occurs as well as the maximum $\varepsilon_{adh}^{\max}(l)$ and minimum $\varepsilon_{adh}^{\min}(l)$ strains at which adhesion failure occurs (Fig. 6.). Area containing the value of the coating critical length is limited to a curved figure which can be approximately represented as a tetragon. Thus, the critical length of the coating is not determined by a single value, but its values form the quadrangular region.



a)

b)

Fig. 3. *Schematic drawing test tensile specimen (dog-bone shape) with coating on two side (a–short length of coating, b– long length of coating)*

Fig. 4. *Multiple cracking of the plasma-sprayed coating with thickness of 150 µm after testing of the tensile specimen. There are a lot of transverse cracks*

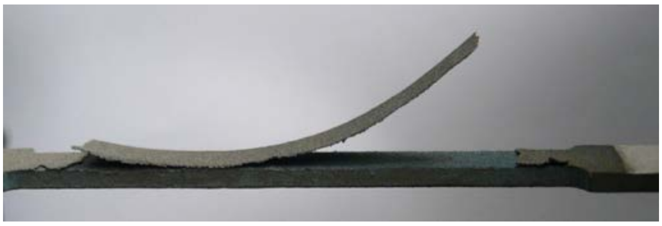


Fig. 5. *Delamination of the plasma-sprayed coating with the thickness of 300 µm*

The critical length of the coating for the normal probability density function coincides with the intersection point of the curves on the Fig. 6.

Figure 7 shows a plot for determining the critical length assuming a uniform probability distribution function for the adhesion and cohesion strength of the coating with thickness of 150 µm. The dashed curves in Fig. 7 show the relations calculated with Eqs. (1) and (2). Figure 7 shows the calculated change of $\varepsilon_{coh}(l)$ and $\varepsilon_{adh}(l)$ as a function of the length of the coating l based on Eqs. (1) and (2) for the assumed values of adhesion strength ($\tau_{\max} = 122$ and 128 MPa) and cohesion strength ($\sigma_{\max} = 258$ and 268 MPa) in comparison with measured ones.

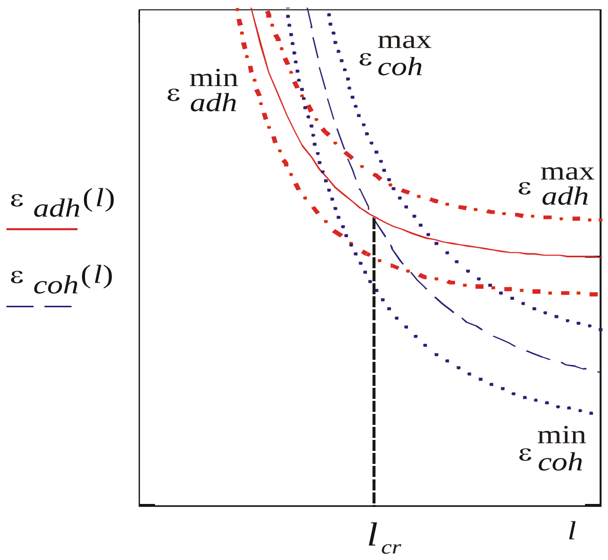


Fig. 6*. The area of the simultaneous delamination and cracking of the coating*

The tensile test technique also can be applied to measure the elastic modulus of the coating. The elastic properties of the coatings were extracted from the tensile response of the coating–substrate system by difference between the pure substrate and coated substrate curves. Elastic properties of the plasma-sprayed coating can be calculated after the stretching of the coated specimen (Fig.3a) [20]. Thus, calculated values of E_c and E_s are 141 and 210 GPa, accordingly. The values of Poisson's ratio of the coating and the substrate used in the calculation are based on values reported in the literature for similar materials ($\mu_c = 0.3$, $\mu_s = 0.28$).

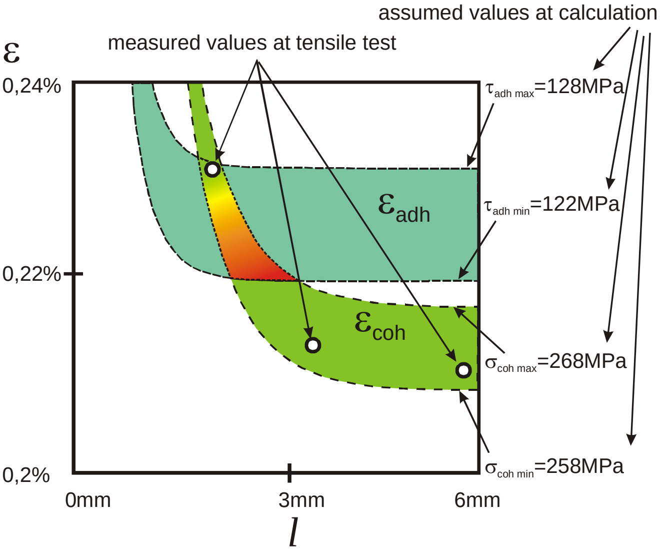


Fig. 7. *Experimental data and theoretical fits of change of $\varepsilon_{coh}(l)$ and $\varepsilon_{adh}(l)$ for a uniform probability density function of the strength as a function of the length of the coating with thickness of 150 µm*

For a uniform probability distribution function of the coating strength, the value of the critical length is shifted towards higher values of the coating length (red area in Fig. 7) in comparison with the value calculated by the formula (8) (yellow area in Fig. 7). Displacement will increase with growing values of the standard deviations for the distributions of strength. This displacement may reach 10% or more of the value of l_{cr}, which is defined by the formula (8), hence the form of the probability density function of strength has to be considered when determining the critical length of the coating.

5. Conclusion

The model describing the formation of the cracks and delamination was presented. It was shown that the crack space can have both constant and random values. The statistical criterion for determining the fragmentation length of the coating with mixed (adhesion-cohesion) failure was developed. Calculating the critical length as the intersection point of the two lines (interfacial failure shear stress-coating length curve and the normal failure stress-coating length curve) does not always give correct value. The critical length of coating should be evaluated as maximum value within the annular trapezoid. It is established that the kind of probability density function both the adhesion strength and the cohesion one should be considered when determining the critical length of the coating.

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