CRACK INITIATION CRITERIA FOR SINGULAR STRESS CONCENTRATIONS
Part IV: Applications To Fracture Of Coated Structures

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The influence of through crack in the protective surface layer on damage of coated structure is investigated. The coated structure is modeled as a particular case of a bi-material body consisting of thin surface layer on the substrate. The problem is studied under the assumptions corresponding to small scale yielding conditions and calculations are performed by the finite element method. Specific attention is devoted to the case of a through coating crack with its tip at the interface between coating and the substrate. To estimate how the coating crack with its tip at the interface influences the substrate failure the general approach described in [1, 2, 3] (Part I, II, III of this contribution) is applied. An approximate approach based on calculations of crack mouth opening displacement for thin protective layers is suggested and developed. It is concluded that in the case of a stiffer coating on a more compliant substrate, the through coating cracks represent dangerous stress concentrators and, as a consequence of elastic mismatch of both materials, the critical applied stress for substrate failure decreases. Traditional approaches may have underestimated this effect and estimations of the service life of coated structures neglecting this phenomenon could lead to non-conservative values, with unexpected failures.

Key words : *fracture mechanics, bi-material body, thin layers, fracture of coated structures*

1. Introduction

There has been increased interest in the use of protective coatings on mechanical components in variety of industrial applications, see e.g. [4]. Coatings are frequently used to increase the resistance of substrate against corrosion, wear, fatigue or to serve as protection for metallic components at high temperatures, but they are not used for their loading bearing contribution. Two extreme cases are: soft compliant coating on a stiff substrate, and hard brittle coating on a compliant structure. Principal failure modes of coatings are cracking and delamination. To this end a great deal of work has been done over past decades to extend fracture mechanics to predict behaviour of cracks on, or near, the vicinity of an interface between two dissimilar materials and a number of papers have recently been published on the problem, e.g. [5–7]. The problem of crack propagation from the coating surface towards the coating – substrate interface has been studied e.g. in [8].

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From the point of fracture mechanics there are generally two basic problems connected with coated structures. The first one is associated with the integrity of protective coatings themselves (including an interfacial delamination). If the coating fails, it may cease to provide its protective function and the intended purpose of the coating is not achieved. The second problem, analysed in this paper, is related to the integrity of the whole coating-substrate system and is connected with the passage of coating cracks across the interface into substrate [9]. It is assumed here that cracking has already occurred through the film thickness, with the crack terminating at the coating – surface interface. This case is typical for brittle fracture of hard coating. Consequently a propagation of the crack existing in the coating and ending at the interface through the substrate may lead to final failure of the whole structure.

Basically, a structure with a protective layer can be modelled as a bi-material body (coating – substrate) and everything written in [1, 2, 3] (denotes here as Parts I, II and III of the contribution) is here generally valid. As the surface layer thickness is usually small compared to the thickness of the body, there are some special features of the problem solution following from this fact.

In practice there are many factors which can contribute to coatings failure. These are mainly surface scratches created at the outer surface of the coating. When coated structures are subjected to external loads (or to thermal or moistures cycling, etc.) coating surface cracks initiate in the vicinity of scratches and rapidly propagate through the entire thickness of the coating. Finally there are arrested at the interface between the coating and the substrate. The existence of cracks in the coating with their crack tips at the interface represents a singular stress concentrator and can, in some cases, cause the failure of the whole structure. The question whether and how the through coating crack will grow any further is of paramount importance when studying the potential failure of coated structures.

Depending on the character and magnitude of the load a single crack can appear in the coating or more often a whole system of cracks can be generated. Typically, in the case of uniaxial external stress or under mechanical or thermal cycles, a roughly periodic array of coating cracks perpendicular to the loading direction can be developed [10]. The distance d between individual cracks depends on the applied stress and on the coating strength.

In this contribution, the existence of coating cracks ending at the interface is assumed. The integrity of the system coating – substrate is analyzed as a function of their elastic mismatch. Special attention is devoted to thin coatings (i.e. protective films or foils). Only the failure mode caused by crack propagation from the interface into the substrate is considered, i.e., it is assumed that the coating remains attached to the substrate. The problem is studied under the assumptions of linear elastic fracture mechanics (LEFM) and the corresponding calculations are performed by the finite element method.

To estimate the failure stress of the substrate in the case of thin protective layers, a simplified approach has been suggested. The procedure is based on calculations of crack mouth opening displacement ($CMOD$). An example showing the application of the suggested approach is presented. It is concluded that the resistance of the substrate to damage significantly decreases for cases of hard coatings on a more compliant substrate. Traditional approaches may have underestimated the effect and estimations of the service life of coated structures neglecting this fact could lead to non-conservative values and thus cause unexpected failures.

2. Problem description

The problem solved in this study is illustrated in Fig.1, which shows a surface layer bonded to a thick substrate. The surface layer thickness is small in comparison with the thickness of the substrate. Both the layer and the substrate are assumed to be isotropic and linear elastic and the layer is perfectly bonded to the substrate. In the presented paper it is assumed that cracking has already occurred through the layer thickness. The analysed configuration corresponds to a crack oriented normal to the layer – substrate interface and terminating at the interface. Fundamental problem solved here is to find stability conditions of the system, i.e. decide whether, under given conditions, the crack stays arrested at the interface or propagates through it into the substrate, and to estimate corresponding critical stress σ_{crit}.

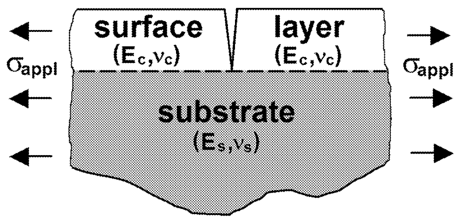

Fig.1: Surface layer with a through crack bonded to a massive substrate

In the case of a crack perpendicular to the interface and loaded parallel to the interface only one stress singularity exists and the stress field around the crack tip can be described by the expression:

$$\sigma_{ij} = H_1\, r^{-p}\, f_{ij}(\theta,\alpha,\beta)\ , \tag{1}$$

where $f_{ij}(\theta,\alpha,\beta)$ is a known function, p is the corresponding stress singularity exponent and H_1 generalized stress intensity factor (GSIF), see Part III for details. To formulate stability conditions and to estimate the critical stress for the crack propagation into the substrate, the procedures described in Part I and III can be used, namely the criterion based on average stress ahead of the crack tip for brittle fracture [11] and criterion based on a plastic zone size ahead of a crack tip for cyclic loading [12]. Regardless of the surface coating thickness a structure with cracked protective layer can be modeled as a bi-material body with a crack perpendicular to and terminating at the interface, Part III, Fig. 8, where M1 (M2) represents material of the coating (of the substrate).

Note that protective films are typically deposited at elevated temperatures and consequently are in a state of residual stress at operating temperatures. The problem of residual stresses in the case of thin films is discussed in [8, 13, 14]. The residual stresses are not considered here but can be easily treated as a part of applied loading.

The calculation of the critical applied stress $\sigma_{\mathrm{appl}} = \sigma_{\mathrm{crit}}$ for a crack terminating at the interface between two different materials is described in Part III. Note that the key point of suggested numerical procedure is the estimation of the value of general stress intensity factor $H_{\mathrm{I}}(\sigma_{\mathrm{appl}})$. The estimation of GSIF is generally not straightforward and needs some experiences. Especially, the application of direct method for the H_{I} estimation needs very fine finite element mesh and the results may be sometimes confusing, see [15, 16]. This fact complicates estimations of expected service life of the coated system.

3. Thin surface layers

In most cases the coating thickness is usually small compared to the thickness of the body (substrate) and the through coating cracks can be treated as edge surface cracks. In the following an approximate approach is suggested which makes it possible to estimate the critical stress for substrate failure in the case of thin protective layers (foils or films) without calculation of the $H_{\mathrm{I}}(\sigma_{\mathrm{appl}})$ values. The approach is based on estimation of a crack opening at the surface of the coated structure and its application is simple and straightforward. Note that plane strain conditions are considered in next text.

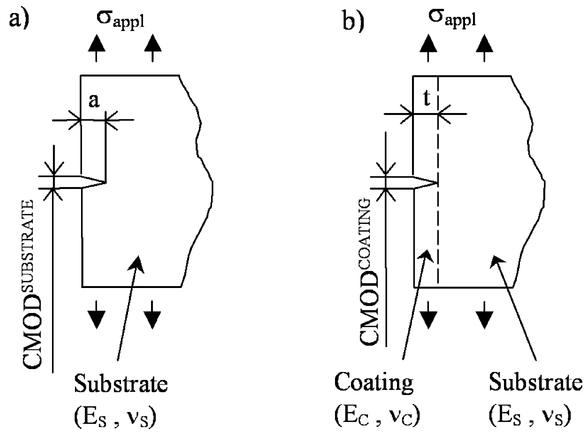

Fig.2: Surface crack in homogeneous material and through coating crack in thin protective surface

3.1. Thin foils – approximate approach

For an edge surface crack in a semi-infinite homogeneous plate, see Fig. 2a, the value of the stress intensity factor K_{I} is given by the approximate expression $K_{\mathrm{I}} = 1.12\,\sigma_{\mathrm{appl}}\sqrt{\pi\,\alpha}$ and the crack will not propagate into the substrate if $K_{\mathrm{I}}(\sigma_{\mathrm{appl}}) < K_{\mathrm{IC}}$, or, identically, if $\sigma_{\mathrm{appl}} < \sigma_{\mathrm{crit}}^{\mathrm{hom}} = K_{\mathrm{IC}}/(1.12\sqrt{\pi\,\alpha})$ where K_{IC} is the fracture toughness of the material considered. Note that in the case of coated structure, the stress distribution around the through coating crack differs from those in a homogeneous body due to the elastic mismatch of the coating and the substrate and above expressions cannot be used.

In the following the influence of the elastic mismatch of coating (E_{C}, ν_{C}) and substrate (E_{S}, ν_{S}) on the critical value σ_{crit} of applied stress for a through coating crack under assumption corresponding to brittle fracture is discussed. Consequently, the value of the critical stress, σ_{crit}, depends on the composite parameters α, β, of both materials (see Part II for definition of α and β).

Following the considerations of Part I, a through coating crack stays arrested at the interface if $H_{\mathrm{I}}(\sigma_{\mathrm{appl}}) < H_{\mathrm{IC}}$ (the corresponding generalized fracture toughness) or equivalently, if $\sigma_{\mathrm{appl}} < \sigma_{\mathrm{crit}}$. The corresponding critical stress σ_{crit} depends on K_{IC} of the substrate and elastic mismatch of the coating and the substrate, i.e., $\sigma_{\mathrm{crit}} = \sigma_{\mathrm{crit}}(K_{\mathrm{IC}}, \alpha, \beta)$. The application of procedures presented in Parts I, II, III demands the estimation of GSIF $H_{\mathrm{I}}(\sigma_{\mathrm{appl}})$ and this fact complicates its use.

In the case of thin coatings the crack mouth opening displacement (*CMOD*) can be considered as a controlling variable L (see Part I for its meaning) for a crack growth. Consequently, it can be supposed that for $\sigma_{\rm appl} = \sigma_{\rm crit}$ it is

$$CMOD^{\rm hom}_{\rm crit}(K_{\rm IC}) \equiv CMOD^{\rm substrate}_{\rm crit}(K_{\rm IC}) = CMOD^{\rm coating}_{\rm crit}(\sigma_{\rm crit}, \alpha, \beta)\ . \qquad (2)$$

The value of *CMOD* can be expressed directly by means of corresponding $K_{\rm I}$ and $H_{\rm I}$ values. In homogeneous substrate the critical value of *CMOD* is given by, e.g. [17]

$$CMOD^{\rm substrate}_{\rm crit}(K_{\rm IC}) = \frac{2\,(1-\nu_{\rm S}^2)}{E_{\rm S}}\, K_{\rm IC} \sqrt{\frac{2\,t}{\pi}} \qquad (3)$$

for a crack length a corresponding to the coating thickness, $a = t$. For the cracked coated structure, see Fig. 2b, the dependence of *CMOD* on applied stress can be calculated by the finite element method (or other numerical method) and the relation

$$CMOD^{\rm coating} = CMOD^{\rm coating}(\sigma_{\rm appl}, \alpha, \beta) \qquad (4)$$

can be found. By applying eqs. (2–4) the value $\sigma_{\rm appl} = \sigma_{\rm crit}$ is then estimated. As an example the suggested procedure is used in the next part to estimate the influence of elastic mismatch between surface layer and substrate on critical fracture stress of coated body.

3.2. Example : failure of the coated structure due to brittle fracture

3.2.1. Single crack

The structure considered in this study consists of a massive substrate covered by a thin protective coating (see Fig. 2b). The interface between the coating and the substrate is of a welded type. The system is loaded by external stress $\sigma_{\rm appl}$ directed parallel to the interface. Due to the symmetry the crack is loaded by normal mode I. First, a single coating crack with its tip at the interface is supposed.

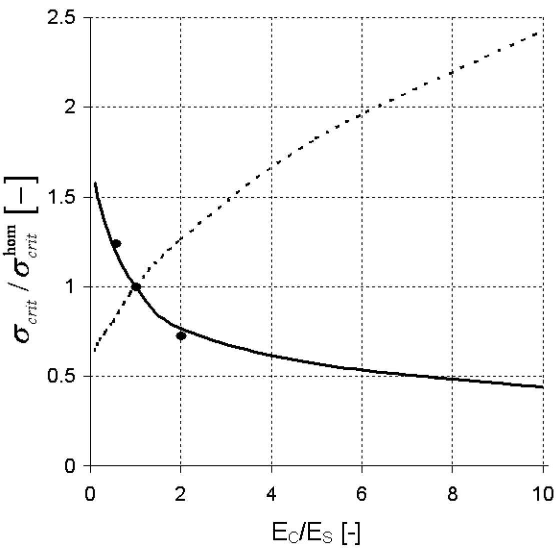

Fig.3: The calculated dependence of the normalized critical stress $\sigma_{\rm crit}$ (solid line) and the normalized $CMOD_{\rm crit}$ (dash line) on the elastic mismatch of coating and substrate; symbols • corresponds to exact solution recalculated from [12]

The procedure suggested has been applied to the estimation of the critical stress value $\sigma_{\rm crit}$ in the case of steel substrate ($E_{\rm S} = 2.1\times10^5$ MPa, $\nu_{\rm S} = 0.3$, $K_{\rm IC} = 50.0\,{\rm MPa\,m}^{1/2}$). The thickness of the protective layer is $t = 100$ mm.

The elastic parameters of the coating have been changed in wide range from $E_{\rm C}/E_{\rm S} = 10$ up to $E_{\rm C}/E_{\rm S} = 0.1$. The influence of Poisson's ratio on results is not very important, so for simplicity it is assumed that $\nu_{\rm C} = \nu_{\rm S}$. The normalized dependence of $CMOD_{\rm crit}/CMOD_{\rm crit}^{\rm hom}$ and $\sigma_{\rm crit}/\sigma_{\rm cirt}^{\rm hom}$ values on the ratio $E_{\rm C}/E_{\rm S}$ are shown in Fig. 3.

The results indicate a relatively strong decrease of the critical applied stress, $\sigma_{\rm crit}$, in cases of stiffer coatings on a more compliant substrate. Such situation corresponds e.g. to the combinations Al_2O_3/steel, where $E_{\rm C}/E_{\rm S} = 1.2$–$2.0$, depending on the porosity and it holds $\sigma_{\rm crit}/\sigma_{\rm crit}^{\rm hom}(E_{\rm C}/E_{\rm S} = 1.2) = 0.92$, $\sigma_{\rm crit}/\sigma_{\rm crit}^{\rm hom}(E_{\rm C}/E_{\rm S} = 2.0) = 0.76$. For combination SiC/steel, where $E_{\rm C}/E_{\rm S} \approx 2.3$, there is $\sigma_{\rm crit}/\sigma_{\rm crit}^{\rm hom}(E_{\rm C}/E_{\rm S} = 2.3) = 0.70$. It follows from the results that the values of the critical substrate failure stress $\sigma_{\rm crit}$, are, due to the elastic mismatch, significantly lower in the case of a coated structure than in a homogeneous case (see Fig. 3).

3.2.2. A periodic array of cracks

The same procedure has been applied to the case of an array of through coating cracks, see Fig. 4. The infinite array of cracks is characterized by the ratio d/t of the distance between cracks d and the thickness of the coating t, see Fig. 4. First, the critical stress and *CMOD*, for the homogeneous material corresponding to the substrate, is calculated as a function of the ratio d/t and then, the case of the through coating cracks is considered. The values of the critical stresses for failure of the substrate depend on the density of through coating cracks and on the elastic mismatch, see Fig. 5. See that approximately, for $d/t > 10$, the critical stresses do not depend on the number of cracks in array and correspond to those shown in Fig. 3 for a single crack. Again, the most dangerous material combination corresponds to cases of stiffer coating on more compliant material, i.e. for $E_{\rm C}/E_{\rm S} > 1$. If the distance d between cracks increases, the critical substrate failure stress $\sigma_{\rm crit}(\alpha, \beta, K_{\rm IC})$ decreases in this cases. This follows from Fig. 5 where the values of the normalized failure stress are given. Note that the most dangerous case corresponds to a single coating crack.

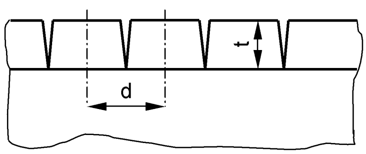

Fig.4: Schematic representation of layered system with a periodic array of through coating cracks; the dotted region represents the unit cell used for numerical modeling

4. Conclusion

The influence of cracked coating surface on the integrity of a coating-substrate system is analysed in this paper. The problem is studied under assumption of linear elastic fracture mechanics and the corresponding calculations have been performed by finite element method. The initial configuration corresponds to a through coating surface crack terminating at the

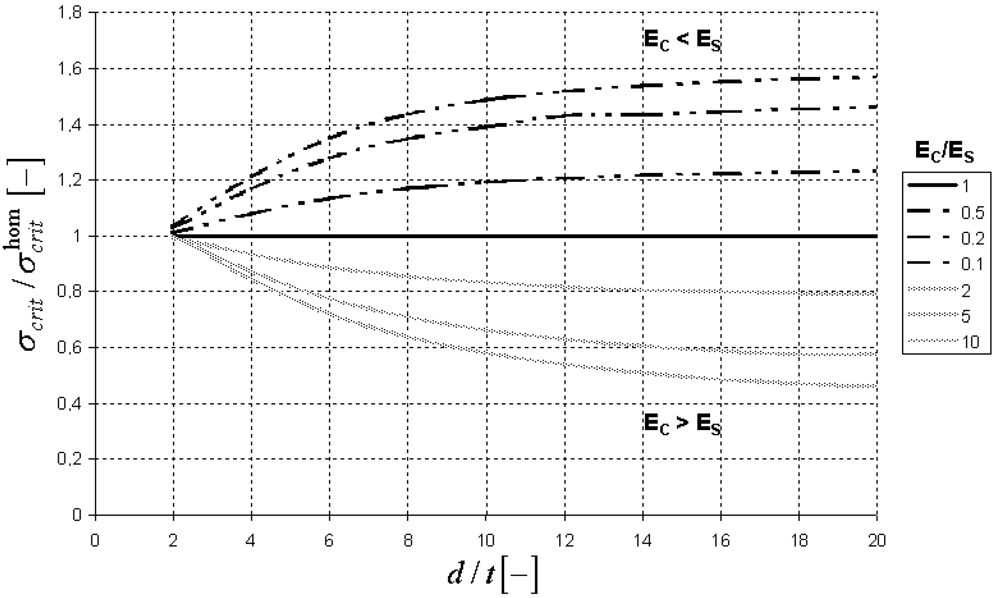

Fig.5: The calculated dependence of the normalized critical stress $\sigma_{\rm crit}/\sigma_{\rm crit}^{\rm hom}$ on the density of through coating cracks d/t; the solid line corresponds to a homogeneous body, dotted lines to a coated structure

surface-substrate interface. As the crack propagation into the substrate may lead to final failure of the whole structure, the question whether and how the through coating crack will grow any further is of paramount importance in praxis. Basically a structure with a protective layer can be modelled as a bi-material body and the problem can be solved by means of procedures suggested in Part I, II, III of this contribution. The key point of corresponding numerical procedures is the estimation of the general stress intensity factor value and this fact complicates estimation of expected service life of the coated system. To avoid it a simplified approach based on calculations of crack mouth opening displacement has been suggested in this paper. The simplified approach is applicable in the case of thin surface layers and its use is straightforward.

It is concluded that (in comparison with homogeneous body) the resistance of the substrate to brittle fracture caused by a through coating crack significantly decreases for cases of stiffer coatings on a compliant substrate. Traditional approaches may have underestimated the effect and estimations of the service life of coated structures neglecting this fact could lead to non-conservative values and thus cause unexpected failures.

The approach has been applied to the case of an array of through coating cracks and it is shown that again the dangerous case corresponds to hard cracked coatings on a compliant substrate. Generally, if the distance d between cracks increases the critical stress for the substrate failure decreases. The most dangerous case corresponds to a single through coated crack.

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