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Crack behaviour at the interface of a surface layer applied on a steel substrate by laser cladding

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Abstract. An influence of the bi-material interface between a steel substrate and a thin protective layer applied through laser cladding was investigated. A range of elastic properties and thicknesses of the layer were considered to cover the behaviour of a short crack in the selected materials such as bronze, nickel or cobalt alloys. The special case of the crack terminating directly at the interface was investigated, which is connected to the necessity of application of generalized approaches of linear elastic fracture mechanics. The results contribute to better understanding of fracture response of selected materials and to a more reliable decision on choosing a proper material of the protective layer.

1. Introduction
In technical practice, structural elements which are formed by combining layers of different metallic materials are used, see e.g. [1, 2]. These combinations of materials are created based on the required function either during the design of the structural component or during its renovation and repair [3].

There is a relatively large number of methods of applying surface layers. One of the modern, widely applicable methods is laser cladding technology, a review on this technology can be found in [4]. The principle of laser cladding is that the metal powder or wire is fed to a laser beam, where this material is melted together with the base material of the part and a deposition layer is formed on the surface of the part. A metallurgical bond is formed between the deposition layer and the base material, guaranteeing excellent adhesion between the cladding layer and the part [5]. With the right choice of material combinations, laser cladding technology can replace some older technologies effectively as they are often problematic from an ecological point of view.

In this work, fracture behaviour of a crack terminating at the bi-material interface between the base steel material and a laser-cladded layer of selected materials is investigated.

2. Generalized fracture mechanics
The goal of the paper was to estimate the value of the critical stress that is needed for penetration of the crack terminating directly at the interface to the material of substrate, see [6–9]. It is well known that a crack with its tip at a bi-material interface represents a general stress concentrator, which means that the stress singularity is greater or lower than 0.5 in dependence on the mutual elastic mismatch of both materials. The stress tensor components near the crack tip can be expressed via the following equation:

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$$\sigma_{ij} = \frac{H_{\mathrm{I}}}{\sqrt{2\pi}} r^{-p} f_{ij}(p, \alpha, \beta) \tag{1}$$

The equation (1) shows the dependence between the stress s_{ij}, generalized stress intensity factor H_{I}, radial distance measured from the crack tip *r*, stress singularity exponent *p* and known function f_{ij} that is dependent besides other things on the bi-material parameters *a* and *b*, see [10]. These constants depend on the elastic properties (Young's modulus *E* and Poisson's ratio *n*) of the materials on both sides of the interface as well as on the stress/strain conditions. For the case of the plane strain state, their values can be calculated as (note that index 1 represents the surface layer and index 2 denotes the material of the substrate):

$$\alpha = \frac{\frac{E_1}{E_2}\cdot\frac{1+\nu_1}{1+\nu_2} - 1}{4(1-\nu_1)} \quad , \quad \beta = \frac{E_1}{E_2} \cdot \frac{1-\nu_2^2}{1-\nu_1^2} \tag{2}$$

The stress singularity exponent needs to be calculated as $p = 1 - l$, where *l* is the eigenvalue and for a crack perpendicular to the interface can be determined from the characteristic equation, see [10] for more details:

$$\lambda^2(-4\alpha^2 + 4\alpha\beta) + 2\alpha^2 - 2\alpha\beta + 2\alpha - \beta + 1 + (-2\alpha^2 + 2\alpha\beta - 2\alpha + 2\beta)\cos(\lambda\pi) = 0 \tag{3}$$

The generalized stress intensity factor (GSIF) can be calculated via direct method when the numerical solution of the problem is found. Then, its value can be determined for example from the development of the opening stress ahead of the crack tip. Using equation (1) enables the extrapolation of the dependence $H_{\mathrm{I}} = H_{\mathrm{I}}(r)$ to the location $r = 0$ where the final value of the GSIF can be found.

Finally, when the critical load leading to crack propagation through the interface shall be calculated, a critical value of the GSIF needs to be estimated by means of selected fracture criteria, see the following subsections.

2.1. Mean tangential stress value criterion

According to this criterion, the stability condition for a crack is related to the average stress calculated across a distance *d* ahead of the crack tip, more details can be found for instance in [11]. Mathematically written:

$$H_{\mathrm{IC}} = K_{\mathrm{IC}} \frac{2d^{\lambda-1/2}}{2-\lambda+g_{\mathrm{R}}} \tag{4}$$

The meaning of the symbols is as follows: H_{IC} represents the critical value of the GSIF, K_{IC} represents the fracture toughness of the material, *d* is the distance ahead of the crack tip, where the criterion is applied, *l* is the eigenvalue and g_{R} is a known function of the parameters *a* and *b* as they are defined in equation (2), see e.g. [12].

2.2. Generalized strain energy density factor criterion

A similar equation between the critical value of the GSIF and fracture toughness can be derived also within the idea of the generalized strain energy density criterion, where the minimum value of the strain energy density factor is considered:

$$H_{\mathrm{IC}} = K_{\mathrm{IC}} \cdot d^{p-1/2} \left(\frac{1-2\nu}{(1-p)^2[4(1-2\nu)+(g_{\mathrm{R}}-p)^2]} \right)^{1/2} \tag{5}$$

The meaning of the symbols is as described in the previous sections. It is worthy to note that the elastic and fracture mechanical properties in equations (4) and (5) represent the properties of the material behind the interface.

3. Geometry and material properties considered in the numerical model

A geometry of the numerical model was suggested with regard to the real samples, when a thin surface layer of the thickness between 1 and 3 mm is cladded on a cylindrical steel substrate with the diameter about 82 mm, see figure 1.

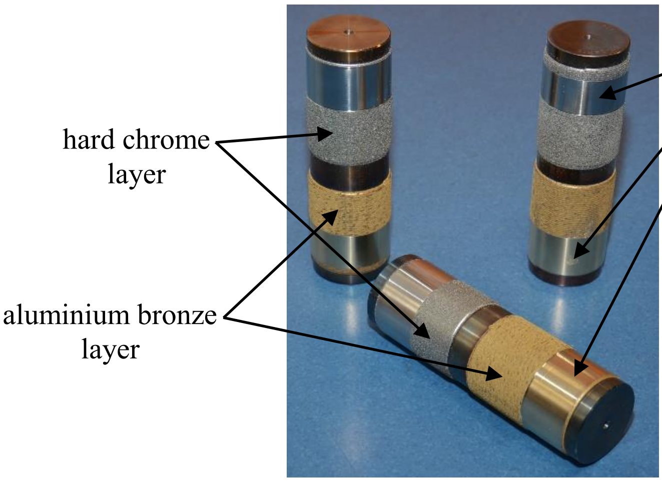


Figure 1. Real samples with laser-cladded surface layers made of hard chrome and aluminium bronze applied on steel cylinders.

Particularly, a simplified bi-material cracked bar under pure tension was modelled according to the schema in figure 2.

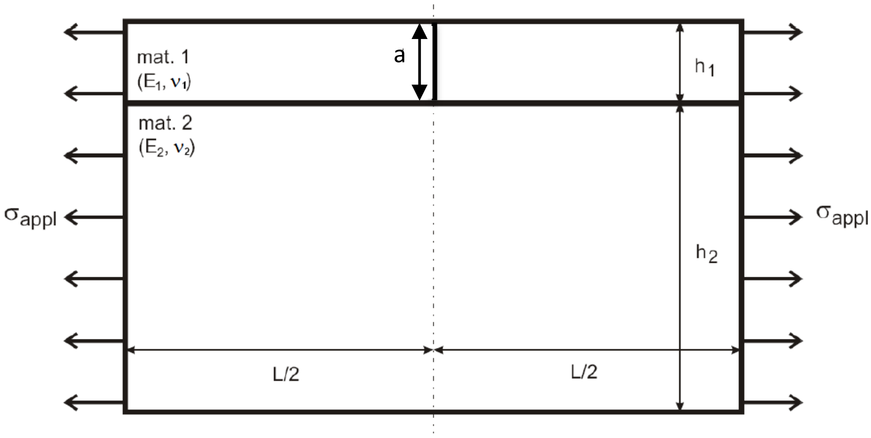


Figure 2. Schema of the bi-material cracked bar under pure tension.

The material properties considered within the parametrical study as well as the dimensions of the numerical model can be found in table 1.

Table 1. Material properties, dimensions and loading applied in the numerical model of the cracked bar under pure tension, see figure 2.

Quantity	Value
h_1	1, 2 and 3 mm
h_2	40 mm
a	h_1
L	$6(h_1+h_2)$
E_1	100 ÷ 300 GPa
E_2	200 GPa
$n_1 = n_2$	0.3
s_{appl}	800 MPa

The values of the Young's modulus of the material of the cladded layer were considered to be 100, 150, 200, 250 and 300 GPa. In the model, quadrilateral 8-node elements 183 were applied and the mesh near the crack tip was refined to emphasize the crack-tip singularity (although its value is different from 0.5 and it holds that $p = 0.43 \div 0.55$ for the studied cases). For calculation of the GSIF via the direct method, always the nodes at the distance of 0.2 to 1 mm from the crack tip were utilized. Values of the stress singularity exponent and GSIF are introduced in table 2.

Table 2. Values of the various Young's modulus of the surface layer and corresponding stress singularity exponents and GSIF values for s_{appl} = 800 MPa.

E_1 [GPa]	100	150	200	250	300
E_1/E_2 [-]	0.50	0.75	1.00	1.25	1.50
p [-]	0.43389	0.47133	0.50000	0.52324	0.54279
H_I [MPa·m^p] for h_1 = 1 mm	62.494	55.157	50.340	46.811	44.045
H_I [MPa·m^p] for h_1 = 2 mm	84.963	77.456	71.914	67.474	63.754
H_I [MPa·m^p] for h_1 = 3 mm	104.570	96.266	89.603	84.006	79.186

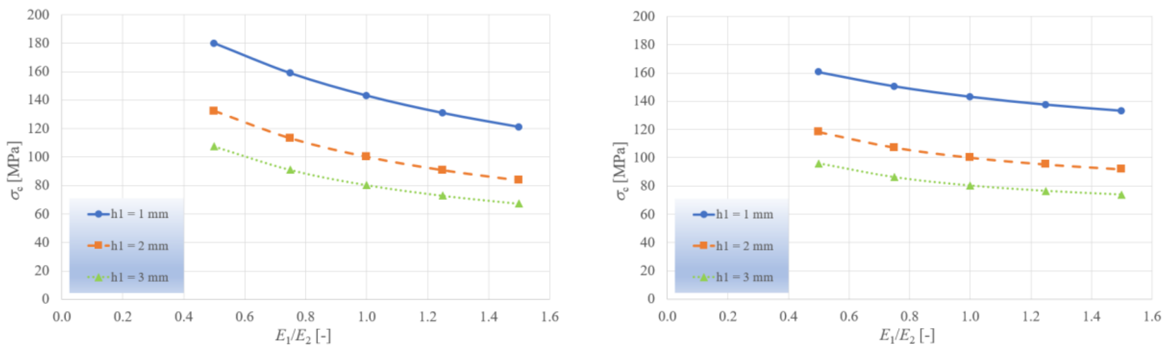
The critical distances that appear in the generalized fracture criteria were considered to be $d = r = 1$ mm in agreement with recommendations published for instance in [13–15].

4. Results and discussion

In figures 3 and 4, the dependences of the critical stress on the elastic mismatch (Young's moduli ratio) can be found for the DK_{Ith} and DK_{IC} value of 9 and 60 MPa·m$^{1/2}$ considered as the material parameters of the steel substrate, respectively. The values of the critical tensile stress are calculated from a simple relation:

$$\sigma_c = \sigma_{appl} \cdot \frac{H_{IC}}{H_I} \tag{6}$$

The plots are printed for the three values of the thickness of the surface layer and both generalized fracture criteria are applied.



(a) (b)

Figure 3. Dependence of the values of the critical stress (when DK_{Ith} = 9 MPa·m$^{1/2}$) on the elastic mismatch for various thicknesses of the surface layer calculated via (a) mean tangential stress value criterion and (b) generalized strain energy density factor criterion.

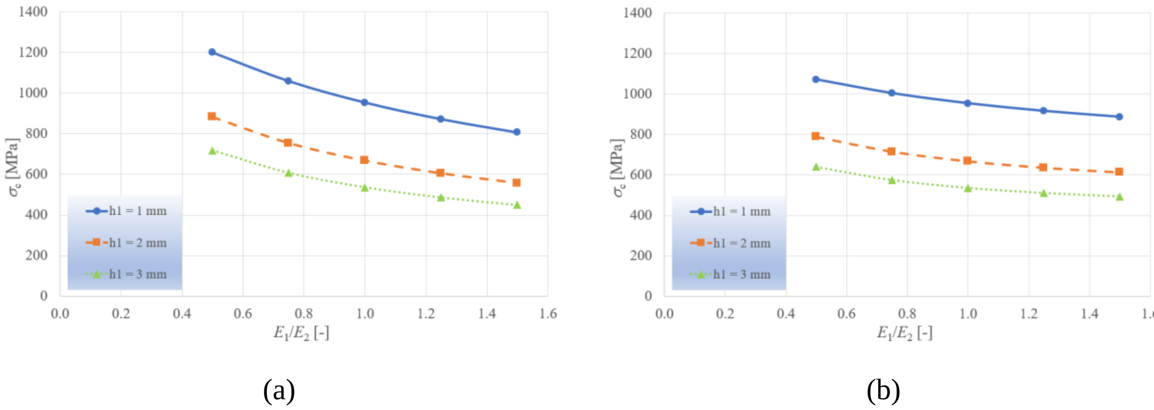


Figure 4. Dependence of the values of the critical stress (when ΔK_{IC} = 60 MPa·m$^{1/2}$) on the elastic mismatch for various thicknesses of the surface layer calculated via (a) mean tangential stress value criterion and (b) generalized strain energy density factor criterion.

The results plotted in figures 3 and 4 show how the critical stress necessary for crack propagation through the cladded surface layer/steel substrate interface depends on the elastic mismatch between both layer as well as on the thickness of the surface layer. The following conclusions can be stated:

- The critical stress necessary for beginning of the stable fatigue long crack growth (corresponding to ΔK_{Ith} = 9 MPa·m$^{1/2}$) is between the values of 60 and 200 MPa based on the ratio of the elastic moduli, surface layer thickness and fracture criterion applied.
- The values of σ_c necessary for unstable crack growth (corresponding to ΔK_{IC} = 60 MPa·m$^{1/2}$) are much higher, between 400 and 1200 MPa.
- The mean tangential stress value criterion gives slightly higher values of the σ_c values and it is therefore less conservative than the generalized strain energy density fracture criterion.
- For thinner surface layers, it is necessary to apply higher tensile load for stable/unstable crack propagation – this is of course connected to the total crack length ($a = h_1$).
- The more compliant material of the surface layer, the higher critical stress is necessary for the crack to be able to propagate through the interface to the steel substrate.

Considering the dependences discussed above, rather compliant materials of the cladded layer shall be recommended, such as hard chrome (with Young's modulus of ca 104 GPa), aluminium bronze (E ~ 113 GPa) or copper beryllium alloys (elastic modulus about 130 GPa). On the other hand, choice of different cobalt alloys (that are rather tough with E over 200 GPa) as the surface layer could decrease the fracture resistance of the structure assuming the presence of a crack with its tip at the bi-material interface.

5. Conclusions

A numerical study has been performed in order to assess the fracture behaviour of a crack terminating at the bi-material interface between a surface layer cladded on a steel substrate. Various elastic properties as well as various thicknesses of the surface layer were considered and finite element calculation in combination with generalized linear elastic fracture mechanics was performed. The obtained results show that laser cladding of materials with lower elastic modulus (such as hard chrome, aluminium bronze and/or copper beryllium alloys) can improve fracture response of the bi-material structure when a short crack with its tip at the interface is presented. Both generalized fracture criteria applied brings higher values of the critical stress that is necessary for stable/unstable fatigue crack growth to the steel substrate when a more compliant material is cladded on the surface of the specimen.

6. References

[1] Bhat S, Adarsha H, Ravinarayan V and Koushik V P 2019 *Proc. Struct. Integr.* **17** 21
[2] Khodadad Motarjemi A, Koçak M and Ventzke V 2002 *Int. J. Pressure Vessels Piping* **79** 3 181
[3] Li M, Han B, Song L and He Q 2020 *Applied Surface Science* **503** 144226
[4] Zhu L, Xue P, Lan Q, Meng G, Ren Y, Yang Z, Xu P and Liu Z 2021 *Optics & Laser Technology* **138** 106915
[5] Laser cladding – Laser Therm s.r.o. *Homepage – Laser Therm s.r.o.* [28.6.2021] Available online https://www.lasertherm.cz/eng/technologies/laser-technologies/laser-cladding
[6] Klusak J, Krepl O and Profant T 2019 *Theor. Appl. Fract. Mech.* **104** 102341
[7] Krepl O and Klusák J 2017 *Theor. Appl. Fract. Mech.* **90** 85
[8] Krepl O and Klusák J 2018 *Proc. Struct. Integr.* **13** 1279
[9] Nahlik L, Stegnerova K and Hutar P 2018 *Theor. Appl. Fract. Mech.* **93** 247
[10] Lin K Y and Mar J W 1976 *Int. J. Fract.* **12** 4 521
[11] Nahlik L, Knesl Z and Klusak J 2008 *Engng. Mech.* **15** 2 99
[12] Knesl Z, Knapek A and Bednar K 1998 Evaluation of the critical stress in bonded materials with a crack perpendicular to the interface *Surface modification technologies XI* ed T S Sudarshan, M Jeandin and K H Khor (London: The Institute of Materials)
[13] Seweryn A and Lukaszewicz A 2002 *Engng. Fract. Mech.* **69** 13 1487
[14] Sih G C and Ho J W 1991 *Theor. Appl. Fract. Mech.* **16** 3 179
[15] Susmel L and Taylor D 2008 *Engng. Fract. Mech.* **75** 3 534

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