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Influence of the bi-material interface on the crack propagation through a thin protective layer

Lucie Malíková[a,b,*], Petr Miarka[a,b], Pavel Doubek[b,c], Stanislav Seitl[a,b]

[a]Institute of Physics of Materials Czech Academy of Sciences, v. v. i., Zizkova 513/22, 616 00 Brno, Czech Republic
[b]Brno University of Technology, Faculty of Civil Engineering, Institute of Structural Mechanics, Veveri 331/95, 602 00 Brno, Czech Republic
[c]OMNI-X CZ s.r.o., Samalova 60a, 615 00 Brno, Czech Republic

Abstract

Finite element parametric analysis is performed on a cracked bi-material bar subjected to pure bending in order to investigate the fatigue behaviour of a short crack in the thin protective layer laser-cladded on a steel substrate. Elastic properties of the surface layer are chosen with regard to real combinations of materials when bronze, nickel or cobalt alloys are applied as the surface layers to improve the properties of the basic steel substrate and the influence of their mismatch is analysed. Classical linear elastic fracture mechanics theory is applied, and several conclusions are stated that shall help to select a suitable material of the protective layer. The conclusions can be applied analogically to any other bi-material combination.

Keywords: bi-material; laser cladding; crack; fracture mechanics, fatigue

1. Introduction

Various structural elements that combine often contradictory properties are more and more common in technical practice, see e.g. Bhat et al. (2019) or Khodadad Motarjemi et al. (2002). One of possibilities how to connect various

* Corresponding author. Tel.: +420541147381; fax: +420541240994.
E-mail address: malikova.l@fce.vutbr.cz

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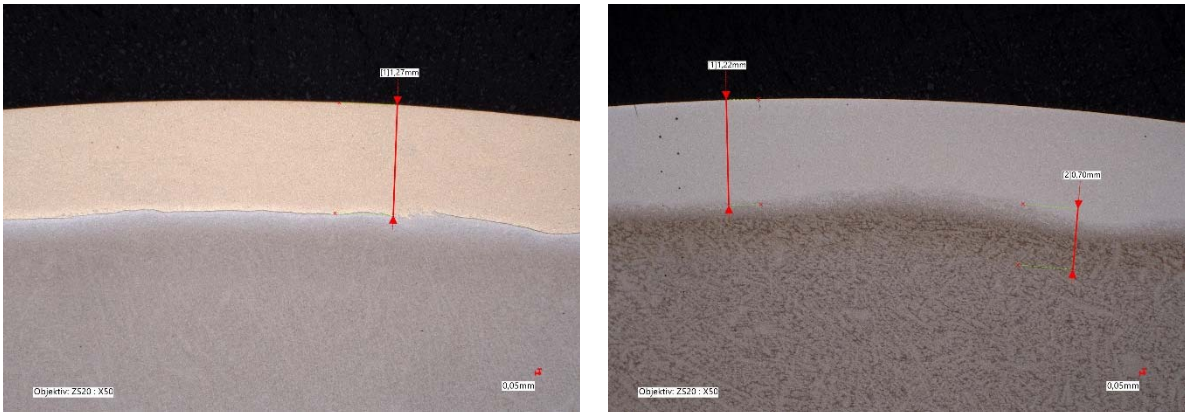
materials is using different layers of materials with different properties. This approach is especially suitable for metallic materials and can be applied either during the design process or additionally during renovation/repair of structures, see e.g. Li et al. (2020). It is usually a base material with the required properties which is supplemented by a relatively thin layer of additional material with better useful and protective properties. The layers of additive material are usually applied to improve the mechanical or chemical properties of the surface (increase hardness, abrasion resistance, slip resistance, surface corrosion resistance, temperature resistance, etc.) and to extend the service life of the component. Saving of production or repair costs are also important aspects.

There exist various methods of applying surface layers. One of the modern, and nowadays widely applicable methods is laser cladding technology, more details can be found in a review paper by Zhu et al. (2021). The method is suitable for creating functional surfaces with specific properties as well as for carrying out quality repairs of damaged components due to manufacturing errors, accidents, or operational wear. During the laser cladding process, a metal powder or wire is fed to a laser beam. This powder/wire is then melted together with the base material and a deposition layer is created on the surface of the structure. A strong metallurgical bond creates between the new metallic surface layer and the material of the substrate, see Fig. 1. The advantage of the laser cladding consists in an excellent adhesion between the surface layer and the original structure, a small heat-affected zone, a lower dilution rate and a high variability in functional layers, see for instance the webpage of Laser Therm (2021). The technology is used on highly stressed components or their functional parts such as forming tools, shear edges, leading edges of turbine blades, pins, stops, etc. The cladded layers can also help against chemical effects or high temperatures which leads to reduction of lifetime of components. It can be expected that some older ecologically disadvantageous technologies will be substituted by laser cladding or similar procedures.



(a) (b)

Fig. 1. 50× zoomed steel core with (a) aluminium bronze layer; (b) hard chrome layer.

When fracture behaviour of layered components shall be investigated, it shall be considered that the bi-material interface represents a sharp change of elastic properties between the individual layers. Therefore, also the stress distribution ahead of a crack tip is affected and influences the crack behaviour near the interface. Whereas the Poisson's ratio has rather negligible effect (documented by Aslantas and Tasgetiren (2002) or Delalde and Erdogan (1983)), the Young's moduli mismatch is more significant (see the works by Chiang (1991) or Menčík (1996)). The fracture behaviour of a steel substrate with a cladded metal layer containing a fatigue crack is investigated within this paper.

2. Description of the problem

It is considered that a crack exists in a laser-cladded layer and the whole specimen is subjected to a cyclic loading, i.e. a fatigue crack propagation is assessed via the stress intensity factor range ΔK_{I}, for more details see the book by Anderson (2005). So far, different loading arrangements have been used in fatigue testing, including compression, tension and bending test. The analysis has been performed based on the real specimens prepared for the future experimental campaign, see Fig. 2. One (Fig. 2a) or two (Fig 2b) thin layers can be cladded on the steel substrate in dependence on the request on the total protective layer thickness. It should be noted that machining of the surface (and sometimes also annealing) is necessary after laser cladding.

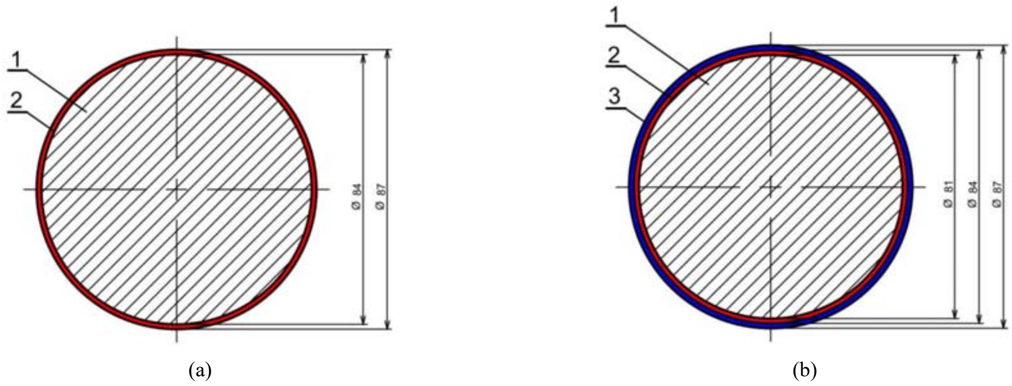


Fig. 2. Cylindric specimens for experimental campaign made of a steel substrate (numbered as 1) and (a) one thin laser-cladded layer (numbered as 2); (b) two thin laser-cladded layers (numbered as 3).

Real specimens of a steel cylinder coated with a hard chrome layer and/or an aluminium bronze layer can be seen in Fig. 3. These are going to be subjected to experimental tests to obtain results for comparison with numerical simulations.

Fig. 3. Real specimens of a steel cylinder coated with a hard chrome layer and/or an aluminium bronze layer.

Note that also other material combinations are considered regarding the real structures used in industrial applications. The particular possibilities are presented in Tabs. 1 and 2.

Table 1. Material of the substrate and its parameters.

Wr.-Nr.	ČSN	Description	E [GPa]	ν [-]
1.2344	19 554	Tool steel	215	0.27 ÷ 0.30
1.2738	~ 15 142	Structural steel	212	0.27 ÷ 0.30

Table 2. Material of the laser-cladded layer and its parameters.

Designation	Description	E [GPa]	ν [-]
-	Hard chrome	104	0.22
Ampco 18	Aluminium bronze	117	0.32
Ampco 21	Aluminium bronze	110	~ 0.32
C17200	High strength copper beryllium alloy	131	0.30 ÷ 0.33
Stellite	Cobalt alloy	210 ÷ 214	0.27 ÷ 0.30

Within this paper, a simplified numerical model regarding the geometry of the real specimens has been created to perform finite-element (FE) simulations, the ANSYS software was used. In Fig. 4, the schema (a) as well as the particular FE mesh of the half-specimen model (b) and a detail of the refined FE mesh around the crack tip (c) can be seen. The symmetry boundary conditions could be applied, therefore only one half of the full specimen was sufficient to be modelled. Quadrilateral 8-node elements PLANE183 were used. The specimen was subjected to a pure tension. Thus, the crack is subjected to the pure loading mode I (opening mode).

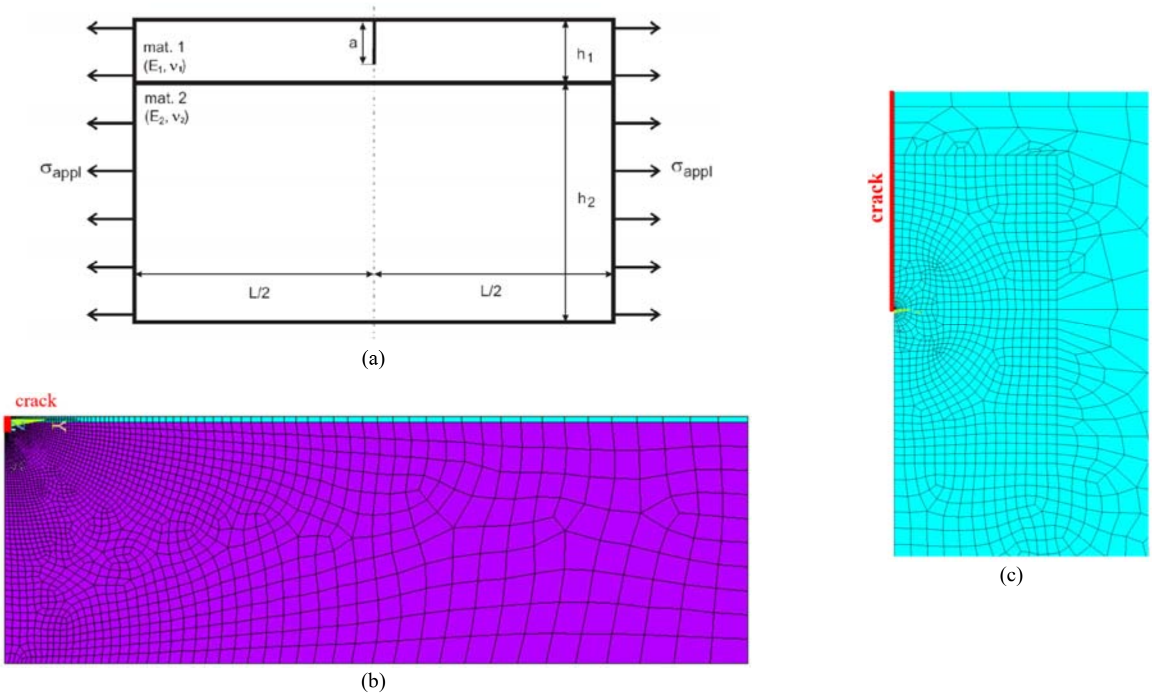


Fig. 4. Simplified numerical model: (a) schema and dimensions; (b) FE mesh of the right half of the specimen with the crack in the upper left corner; (c) detail of the refined FE mesh around the crack tip.

The material properties and the dimensions utilized in the numerical model within the parametric study can be found in Tab. 3. 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.

Table 3. Parameters (material, geometry, loading) used within the FE simulations.

Parameter	Value	Unit
Young's modulus of the cladded layer, E_1	100 ÷ 300	GPa
Young's modulus of the steel substrate, E_2	200	GPa
Poisson's ratio of both materials, $\nu_1 = \nu_2$	0.3	-
Thickness of the cladded layer, h_1	1, 2 and 3	mm
Thickness of the steel substrate, h_2	40	mm
Relative crack length, a/h_1	0.03 ÷ 0.98	-
Bar specimen length, L	$6(h_1 + h_2)$	mm
Applied tensile load, σ_{appl}	800	MPa

3. Results and discussion

In Figs. 5, 6 and 7, the dependences of the stress intensity factor range on the crack length for various Young's moduli of the cladded layer with the thickness h_1 = 1, 2 and 3 mm, respectively, are plotted.

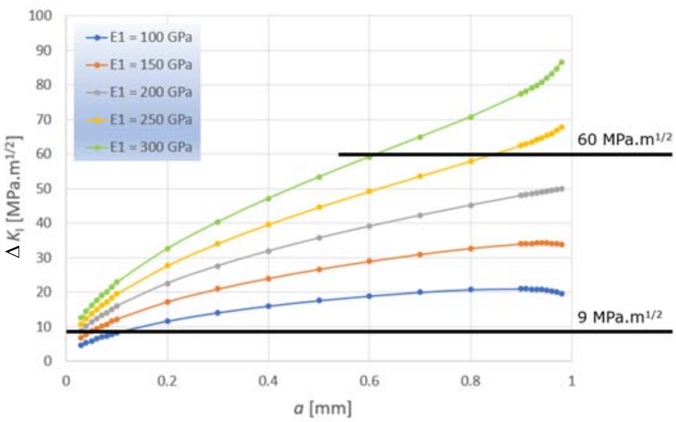


Fig. 5. Dependence of the stress intensity factor range on the crack length for various Young's moduli of the cladded layer with the thickness h_1 = 1 mm.

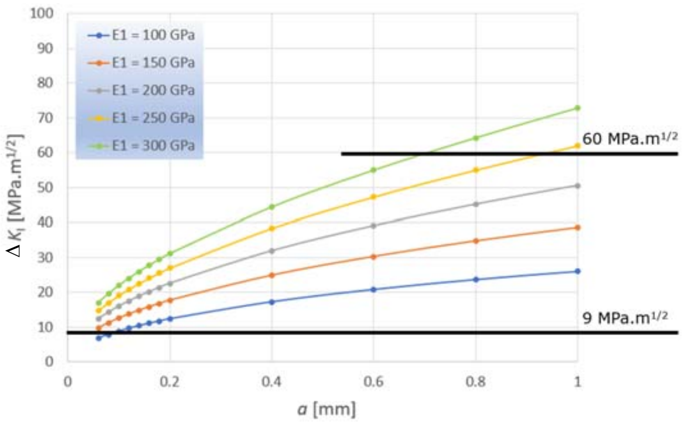


Fig. 6. Dependence of the stress intensity factor range on the crack length for various Young's moduli of the cladded layer with the thickness h_1 = 2 mm.

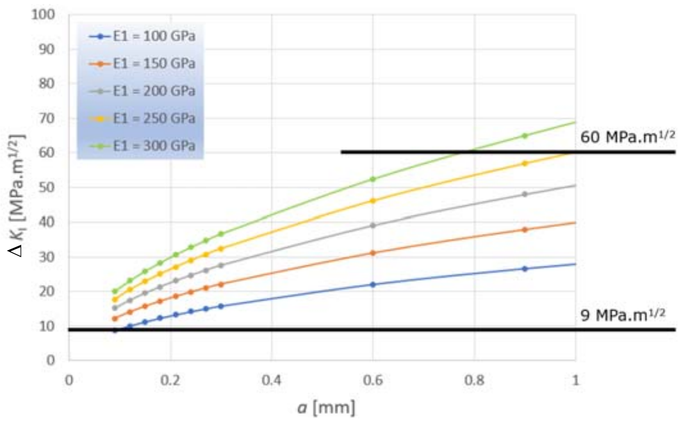


Fig. 7. Dependence of the stress intensity factor range on the crack length for various Young's moduli of the cladded layer with the thickness h_1 = 3 mm.

Based on the results plotted in the figures above, the following statements can be summarized:

- higher Young's modulus values of the protective layer (in comparison to the Young's modulus of the substrate) make the fatigue crack propagation easier/faster;
- all of the materials considered as the protective layer (hard chrome, aluminium bronze, high strength copper beryllium alloy, cobalt alloy) are therefore more compliant than the construction/tool steel (or at least as compliant as the steel);
- note that for the following discussion of the results, common values of the threshold stress intensity factor ΔK_{Ith} and critical value ΔK_{IC} are considered and the presented discussion can be modified for arbitrary values of the material parameters ΔK_{Ith} and ΔK_{IC}.

Considering the threshold values of stress intensity factor ΔK_{Ith} = 9 MPa.m$^{1/2}$, see e.g. for Al in Stanzl et al. (1991), for steel in Suresh (1998) or Pokorný et al. (2017), for high strength steel in Li et al. (2021):

- a crack of the length of 0.03 mm will not propagate in a homogeneous steel at all;
- the more compliant is the protective layer, the longer surface defect can be presented without starting to propagate (if E_1 = 100 GPa, then a_{th} = 0.13 mm);
- a higher protective layer thickness increases slightly the stress intensity factor values for the same crack length (it makes the crack propagation easier/faster).

Considering the critical value ΔK_{IC} = 60 MPa.m$^{1/2}$:

- the unstable crack growth occurs when a_C = 1.4 mm when only the substrate material is considered;
- the compliant surface layer increases the critical crack length necessary for unstable crack growth;
- for instance: if h_1 = 3 mm and E_1 = 150 GPa, a_C = 2.5 mm and for lower Young‘s modulus a_C is even higher.

It should be noted that the results presented within this paper are a part of the project 'Influence of the bi-material interface on initiation and propagation of a short fatigue crack' which started only 4 months ago. These pilot results are going to be complemented by lots of additional studies such as:

- other types of loading can be applied;
- crack entering the substrate material can be modelled and its behaviour can be investigated with regard to the elastic properties of both materials (protective layer and substrate), etc.

A work that is devoted to the analysis of the behaviour of a crack with its tip at the bi-material interface between the cladded layer and the steel substrate has been submitted by Malíková et al. (2021). The final goal is to bring recommendations on the proper material of the surface layer as well as on the choice of its optimal thickness to ensure as high fatigue life of the component as possible.

4. Conclusions

A parametric analysis of fatigue crack propagation in a thin layer cladded on a stell substrate has been performed. Finite element computations have been performed on a cracked plate under pure uniaxial tension. From the results obtained, it can be concluded that protective layers from more compliant materials than the substrate material can be clearly recommended from the point of view of fatigue crack propagation. The compliant surface layer increases both the threshold crack length a_{th} (necessary for starting the fatigue crack propagation) and the critical crack length a_C necessary for unstable crack growth. Unfortunately, the right choice of the suitable thickness of the protective layers can be done only when additional analyses are performed, because a clear conclusion cannot be stated from the results presented.

Acknowledgements

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