FATIGUE BEHAVIOUR OF A SHORT CRACK IN A THIN PROTECTIVE LAYER LASER-CLADDED ON A STEEL SUBSTRATE

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Abstract. *Fatigue behaviour of a short crack in a thin protective laser-cladded layer has been investigated. A two-dimensional finite element model of a steel bar with two thin cracked layers on its both sides was created. Propagation of a crack under pure tension and pure bending was studied via linear elastic fracture mechanics concept considering various Young's modulus of the surface layers. The effect of the elastic mismatch between both materials is demonstrated considering the critical stress intensity factor range of 20 to 25 MPa·m*$^{1/2}$ *as it is typical for aluminium alloys. It is shown that more compliant materials enhance the critical crack length that causes the unstable crack growth and therefore also the lifetime of the component with laser-cladded protective layers.*

Keywords

Bi-material, laser cladding, fracture mechanics, crack behaviour.

1. Introduction

Combinations of two different materials in structural elements are really common in engineering applications [1][2]. By this connection, material properties of both can be used to achieve best possible results. One way to produce an element made of different materials is to use them in layers of various thicknesses. Therefore, the outer materials are commonly the ones with better resistance to unhostile conditions, to protect the inner material from corrosion or/and mechanical damage. This material can be considered as a protection layer and it could significantly influence the length of the service life of the component, see e.g. [3]. Typical use of thin layered material is in combination of two metal materials. Additive layer could therefore be added not only during the manufacturing process, but also in the sphere of renovations and repairs.

In production, several methods of joining metal materials are used. Nowadays, one of the popular ones, basing on its modern characteristic is the laser cladding technology [4]. The base of this technology is to create an equal layer of a metal, very precisely bonded to the base material. A metallic powder or wire is fed into the melt pool that is generated by a laser beam scanning the surface. This creates metallurgical connection with almost perfect adhesion between the two materials. Thanks to the development of laser technologies, results of laser cladding prove this technology to be one of the most precise there is. Few of advantages of this method worth mentioning are: a lower heat distortion due to low energy input, reduced dilation, low porosity levels and higher speed, comparing to the traditional ways of cladding. The materials used on surface have similar or even better properties than the original ones. Materials, that are commonly applied through laser cladding are tool steel, stainless steel types (Fe, Cr, Ni), cobalt, copper, nickel, or aluminium alloys. The application of this method coming from mentioned properties corresponds to reparation of welded structures, surface cladding, and partly manufacturing. Many industries including engineering, constructions, automotive or medical benefit from it, i.e. in making of drilling tools, agricultural machinery, hydraulic cylinders, shafts, rotors, turbines, etc. Many of those mentioned are exposed to cyclic loading, which could lead to the fatigue damage.

In order to investigate the crack propagation, mentioning of the influence of different elastic material properties ahead and behind the interface on stress distribution is important, see e.g. [5] or [6]. Surface layers made of material with various Young's modulus are therefore considered in this study and their effect on the fracture parameters is investigated, particularly the stress intensity factor range is studied in dependence on the crack length for two types of loading (pure tension and pure bending).

2. Theory and application

This paper focuses on an analysis of fatigue behaviour of a steel specimen with laser cladded metal layers. The crack is located in the thin protective layers and the whole specimen is exposed to a cyclic loading of a defined manner. Single-parameter linear elastic fracture mechanics concept is used for the study. This work is devoted to numerical simulations that shall be later compared to results of experimental tests.

The numerical calculations in this analysis were made using FEM (Finite element method) software, particularly Ansys Mechanical APDL was utilized [7]. The geometry of the model was suggested in accordance with the real specimens prepared for upcoming experimental testing. Experimental specimens, visible in Fig. 1, consists of a steel cylinder with an aluminium bronze and/or a hard chrome layer. These are to be compared with numerical results in further stages of research.

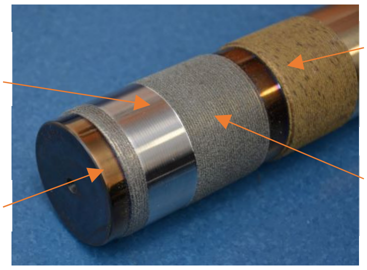

Fig. 1: Real cylindrical specimen consisting of a steel substrate coated with a hard chrome layer and/or an aluminium bronze layer.

Schema of the geometry is visible in Fig. 2. For purposes of the study, a simplified 2D numerical model was created. Protective layers with cracks were modelled on both top and bottom sides of the specimen, which can be understood as a compact surface layer of the cylindrical specimen. Symmetry of the geometry was used to create only one half of the studied specimen, replacing the remaining one with appropriate boundary conditions. Finite element mesh was finer in the vicinity of the studied cracks, as can be seen in Fig. 3. Quadrilateral 2D elements (called PLANE183) were chosen. Material properties of the specimen were defined by the Poisson's ratio of 0.3 and by the Young's modulus, constant for the steel specimen, and different for the surface layers in the range from 100 to 300 GPa. The specimen was loaded via two different manners: via pure tension and pure bending (realized by means of the couple-moment), see Fig. 2.

The range of the values of the Young's modulus of the cladded layers was chosen with regard to elastic properties of real materials that are commonly used in praxis, i.e. hardchrome (E ~ 100 GPa), aluminium bronze (E ~ 115 GPa), high-strength copper beryllium alloys (E ~ 130 GPa) and/or cobalt alloys (E ~ 210 GPa).

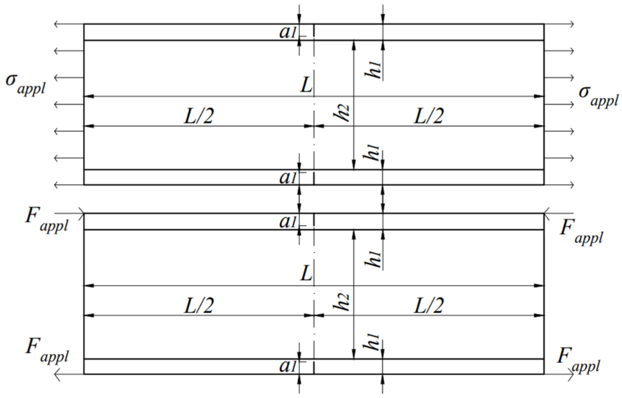

Fig. 2: Schema of the geometry of the investigated specimens loaded via pure tension (top) and pure bending (bottom).

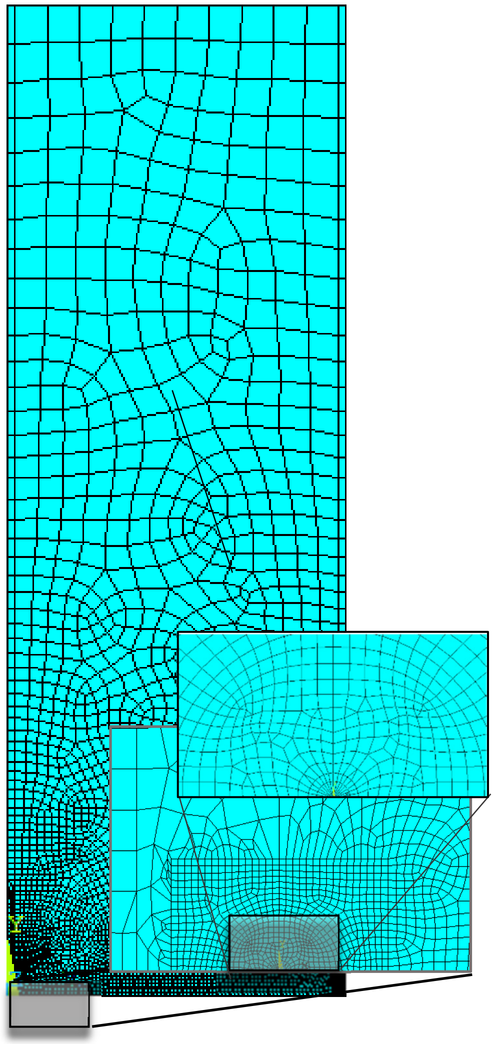

Fig. 3: FE mesh of the steel bar with two symmetrical cracks in the thin protective layers.

The values of the material properties and geometry dimensions are specified in Tab. 1. The value of the applied tensile stress has been chosen regarding the real loading of the cylindrical specimens in technical practice. Similarly, the value of the applied forces (that realize the pure bending loading) corresponds to the same value of the stress at the specimen surface, i.e. 800 MPa.

Tab.1: Material and geometrical parameters of the numerical model.

Parameter	Value	Unit
Young's modulus of the cladded layers, 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 layers, h_1	1	mm
Thickness of the steel substrate, h_2	40	mm
Relative crack length, a/h_1	0.03 ÷ 0.92	-
Bar specimen length, L	$6(2h_1 + h_2)$	mm
Applied tensile load, σ_{appl}	800	MPa
Applied force in the couple-moment, F_{appl}	5.595	kN

The stress intensity factor range was investigated for a range of crack lengths located in the thin laser-cladded layers. The results obtained can be found in the following section.

3. Results and discussion

The stress intensity factor range was investigated in dependence on the crack length for five various combinations of the elastic mismatch between the cladded layers and the steel substrate. Two various types of loading were considered and compared, see Fig. 4

From the dependences plotted in Fig. 4, the following conclusions can be stated:

- It can be seen that the type of loading has only a very low effect on the ΔK_I dependences; especially when the Young's modulus of the protective layers is lower or equal to the Young's modulus of the steel substrate, the stress intensity factor range is the same for both the loading types.
- Considering the threshold stress intensity factor range about 3 to 4 MPa·m$^{1/2}$, which is typical for aluminium alloys [8], it can be seen that even very short cracks in the order of hundredths of millimetres will propagate in the stabile manner under the defined loading which is typical in the real technical conditions.
- On the other hand, a proper choice of the material of the laser-cladded layers can improve the lifetime of the component significantly – the critical value ΔK_{IC} about 20 ÷ 25 MPa·m$^{1/2}$, which is typical for aluminium alloys [9], is plotted as an example in Fig. 4.
- Whereas stiffer materials (with higher E) will fail through the unstable crack propagation at rather low crack lengths (about 0.1 to 0.2 mm), the compliant ones enable the stable fatigue crack propagation up to 0.4 mm (for E = 150 GPa) or even through the whole 1-mm-thick protective layer (for E = 100 GPa).

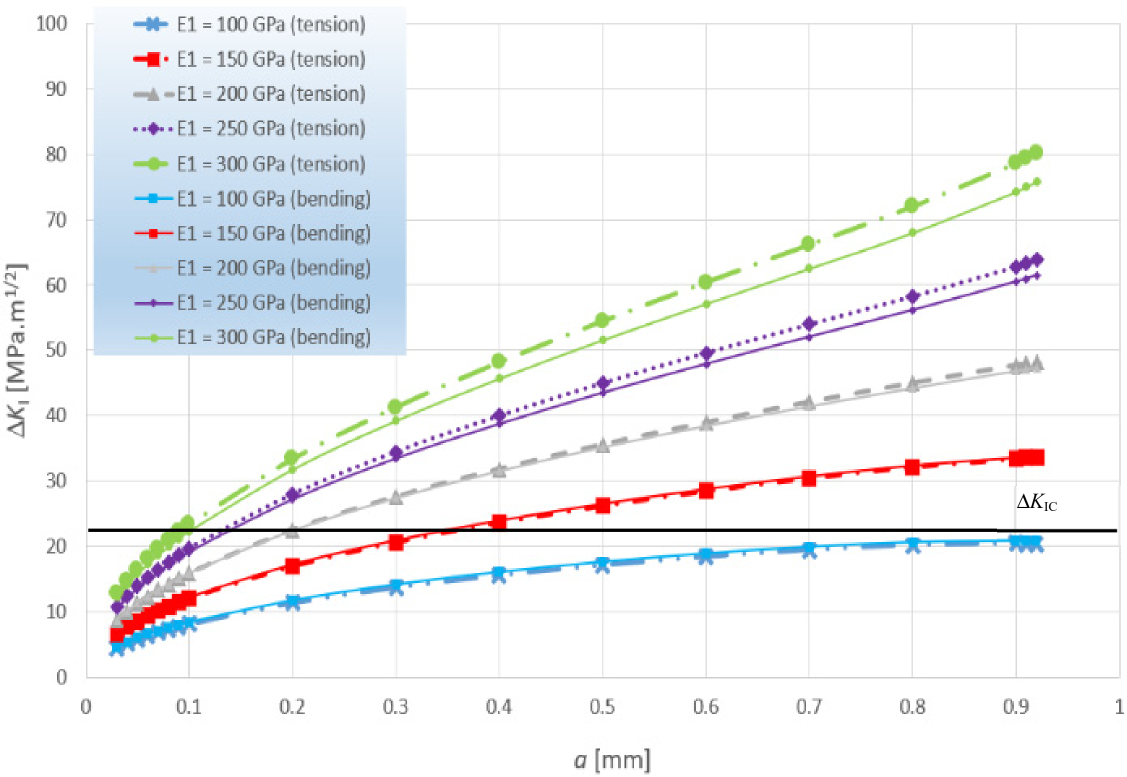

Fig.4: Stress intensity factor range for various Young's modulus of the laser-cladded layers for two types of loading (pure tension and pure bending).

4. Conclusions

Fatigue crack propagation in thin laser-cladded layers applied on a steel substrate has been investigated. Two types of loading (pure tension and pure bending) were modelled via finite element method and the effect of the elastic properties of the protective layers was analysed. It has been found out that more compliant materials of the surface layers cause a higher critical crack length when the unstable crack growth occurs. Therefore, it is very important to know fracture mechanical properties of the materials that can be cladded on the steel substrate and choose the most suitable one.

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