

STRESS RAISING IN LASER CLAD COMPONENTS DEPENDING ON GEOMETRY AND DEFECTS

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Abstract

The fatigue life of laser clad components is basically determined by stress raisers, which are here studied by Finite Element Analysis. Cylindrical and square section bars are compared for axial, bending and torsional load conditions, which induces the macro-stress field with corresponding stress peaks. Defects from laser cladding such as pores, cracks or the surface roughness superimpose additional stress raising action on this stress field. The geometrical position and orientation of the defects has strong impact on the induced maximum stress level. For surface pores it is demonstrated by the fractography that their occurrence within a critical azimuthal range can initiate fatigue cracking. The different conditions of sample geometry, load situations, materials and defects are compared and discussed. In particular, advanced illustration methods are applied for improved and generalized documentation and explanation of the trends, both qualitatively and quantitatively. Guidelines are presented, in particular emphasizing critical defects and situations, such as surface pores that are difficult to detect because of inclusions, or pores just underneath the surface that generate particularly high stress.

Keywords: laser cladding, defect, geometry, fatigue cracking, stress raiser

1 Introduction

Fatigue cracking of laser clad components takes place from locations of maximum stress. These locations depend on the macroscopic stress load of a certain component under specific load plus local stress raisers, particularly by defects like pores or cracks. A literature survey on defects and fatigue cracking of laser cladding was written by Md. M. Alam [1]. The present study compares four different basic laser clad components and their load case as well as different defects and their location and orientation. Comparison between the different stress raisers is illustrated by various documentation methods. Experimental results from fatigue fractography confirm their origin from stress raisers like pores. While part of the results have already been published,[1-3] we here particularly present results on the fatigue crack propagation dependent on various defects and their locations.

2 Methodology

Four basic laser clad component geometries with corresponding load conditions are studied, namely (i) a cylindrical rod for axial load, (ii) a cylindrical rod for four-point bending load, (iii) a rectangular bar for four-point bending load and (iv) a cylindrical rod for torsional load. The circular rods are laser-clad at the entire surface while the rectangular bar is laser-clad at one side. After laser-cladding, for optimized parameters, the clad surfaces are smoothened by machining off a layer. Visual inspection is carried out for the detection of surface defects, particularly pores. The clad components are fatigue tested, to develop SN-diagrams, also in comparison with non-clad base material samples. Stress analysis by the Finite Element Method, FEM, is carried out to calculate the stress field for the respective load condition of the components, called the macro-field. In addition, local stress analysis of defects is performed, which is an additive stress raiser to the macro-field in its respective location. For certain situations the crack propagation is also calculated by FEA. Fractography by microscopic analysis of the fracture surfaces of the samples after fatigue testing provides additional information. Occasionally, cross sections of the laser clads are made, to study the metallurgy and defects, accompanied by other kinds of analysis, including residual stress measurement. Finally, the main trends are interpreted, categorized and visualized in graphical charts.

2.1 Laser cladding

Laser cladding was carried out at the Technology Centre KETEK Ltd. in Kokkola, Finland, with the parameters shown in **Table 1**. A diode-pumped Nd:YAG-laser was used. A 1.5 mm thick clad layer was made, machined off then to 0.75 mm. More details can be found in [2,3].

Table 1. Parameters used for laser cladding

Parameter	Value / Unit
Laser beam power (cw)	3.25 kW
Beam diameter	6 mm
Traverse speed	1.1 m/min
Powder feeding rate	30 g/min
Shielding gas type	Ar
Gas flow rate	16 l/min
Lateral clad layer displacement	2 mm

2.2 Fatigue testing

The fatigue testing was carried out at different locations of the Finnish partners. The four different loading situations described above were tested, i.e. axial, bending (cylindrical rod and rectangular bar) and torsional fatigue load. Details about the fatigue testing set-up and first results can be found in [1-3]. As example, **Fig. 1(a)** shows a cracked cylindrical rod after four-point bending fatigue testing. Beside the primary crack also a secondary crack can be seen. A cross section of the milled laser clad is shown in **Fig. 1(b)** where the vertical crack (here the secondary crack, denominated E) through the clad layer into the substrate can be seen. Note the wavy interface clad-substrate from the overlapping clad-layers. The crack surface of the rod can be seen in **Fig. 1(c)**. The fatigue testing was stopped after a certain crack propagation and drop in force and strain and the sample was cut through afterwards. In this case it was found that the crack was initiated from a surface pore that was filled with an oxide inclusion, see **Figs. 1(d)-(f)**, which is described in detail in [3].

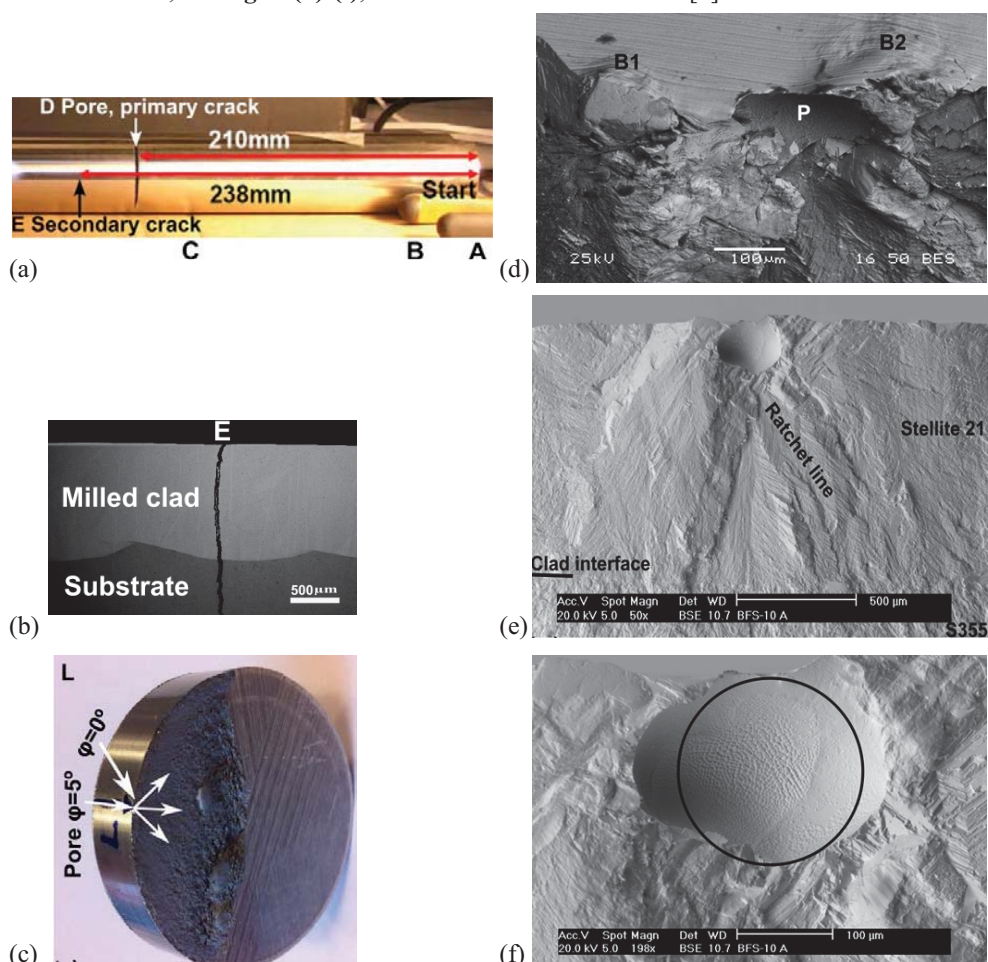


Fig. 1. (a) 2 cracks at round rod (here non-clad, for comparison) after four-point bending fatigue testing, (b) secondary crack through the clad layer, (c) fracture surface of the rod with pore location as crack initiation, (d)-(f) surface pore and crack surface with ratchet lines.[3]

2.3 FE stress analysis

Stress analysis was carried out at different levels, by Finite Element Analysis, FEA. The static stress field, the macro-field, was calculated for the maximum load of the four cases. For a variety of defect geometries (pores, surface pores, hot cracks, etc.) the stress raiser or stress concentration factor K was calculated locally around the defect. Moreover, the stress raisers were superimposed to the calculated macro-field to study the influence of different locations and orientations of defects in the component. In addition, the crack propagation was calculated (simplified in two dimensions) by FEA, based on the stress intensity K_I at the tip of the crack, leading to the direction and speed of the fatigue crack propagation but also indicating its preferred location of initiation, from maximum stress raisers. In particular, the stress propagation was computed for different locations of initiation, for different sizes and orientations of initiation defects and for different interaction when propagating in the vicinity of defects. Details of the stress analysis method, i.e. the FEA can be found in [1-3]. From the stress analysis, better interpretation of the experimental results has been expected.

Although the study tries to distinguish between the stress field induced by the load including defect stress raisers and the residual stress field as a different mechanism to be optimized, the residual stress field was measured for a few samples and will here be presented.

3 Results and discussion

3.1 Macro stress field depending on load

The calculated macro-stress field for the four cases studied is shown in **Fig. 2**.

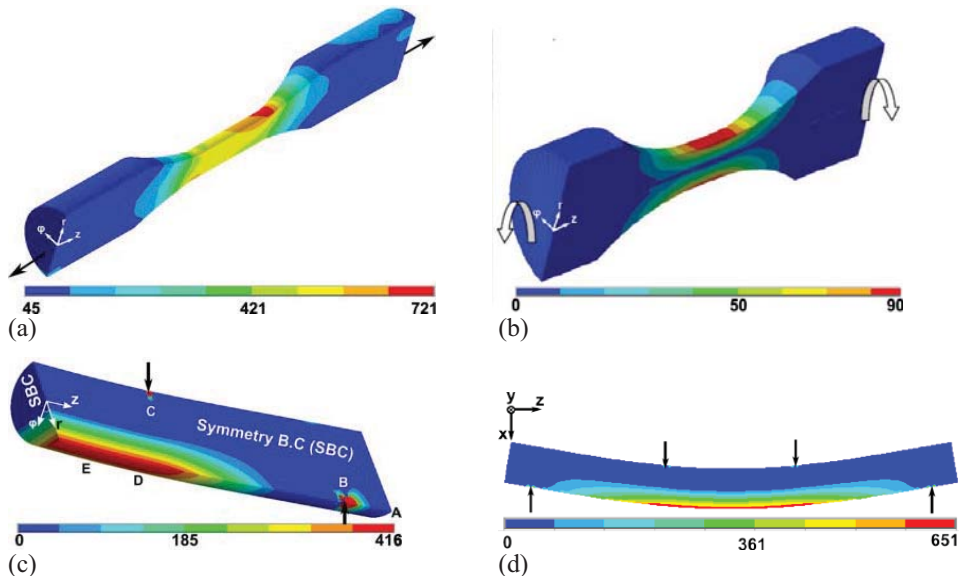


Fig. 2. Calculated 1st principle macro stress field (in MPa, long section) for (a) axial fatigue loading of a cylindrical laser clad rod, (b) torsional loading (cylindrical), (c) 4-point bend load (cylindrical, here quarter-rod), (d) 4-point bend load (rectangular bar, bottom-clad).[2]

For the axial and torsional load a ‘dog-bone’-geometry was used, following the standards. For axial loading, the representative cylindrical central part shows an almost constant stress value. Torsional load leads to a central (red) peak around the cylinder, rapidly decaying radially inwards, as shear stress slices. For bending load a long area of rather constant maximum stress is obtained at the lower surface, strongly decreasing upwards. This macro field (note: it is the amplitude of the cyclic fatigue load) is the starting condition for the loaded laser-clad component, so far without any imperfections at the surface or in the material. Fatigue cracking is expected to initiate from the respective peak stress location. The material plays here a minor role [2] because the E-modulus of the thin clad and the base material match well.

3.2 Residual stress

As mentioned above, residual stress is present, as a superimposing field, but the central part of the study are the generation of peak stress by the load, geometry, defects and their locations. For some samples the residual stress was measured. **Figure 3** shows the measured residual stress (hole drilling method) for the two material combinations studied, at three locations along the laser clad (and then milled) bars, with and without post weld heat treatment (PWHT). Positive tensile stress was measured almost throughout. Therefore residual stress is a critical (superimposing) contribution that will be further studied and improved.

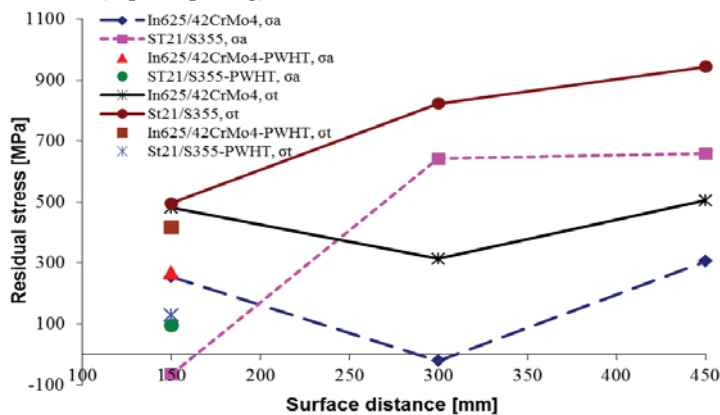


Fig.3. Residual stress components measured at different locations along the clad (and milled) bar, for the two material combinations with and without post-weld-heat-treatment (PWHT)

3.3 Defects as stress raisers

Figure 4 shows a variety of possible defects from laser cladding, and examples for different locations and orientations of these defects, both for the as-clad surface and when machining off a layer to a smooth surface. From the geometrical nature of the defects it can be distinguished between 0-dimensional defects like pores or inclusions, 1-dimensional defects like the ripples from the as-clad surface or the wavy interface clad-substrate, and defects extended in two dimensions like lack-of-fusion or hot cracks. Photographs of different laser clad defects obtained can be seen in **Fig. 5(a)–(i)**. **Figure 5(j),(k)** shows the calculated stress field (note: different scale) at a spherical pore, when located just underneath the surface or as surface pore, i.e. representative also for the cracking shown in **Fig. 1**. More calculated stress fields for laser clad defects as stress raisers and comprehensive analysis can be found in [2,3]. One conclusion is that a pore just underneath the surface is the strongest stress raiser. Moreover, a central location as in **Figs. 1,4** is the most critical azimuthal location.

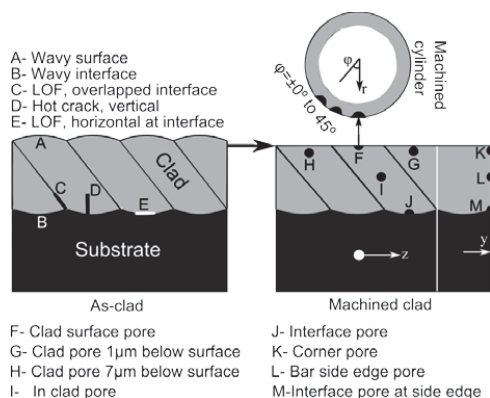


Fig. 4. Illustration of the laser clad layer cross section (left as-clad and right after machining) with the variety of possible defects and their positions

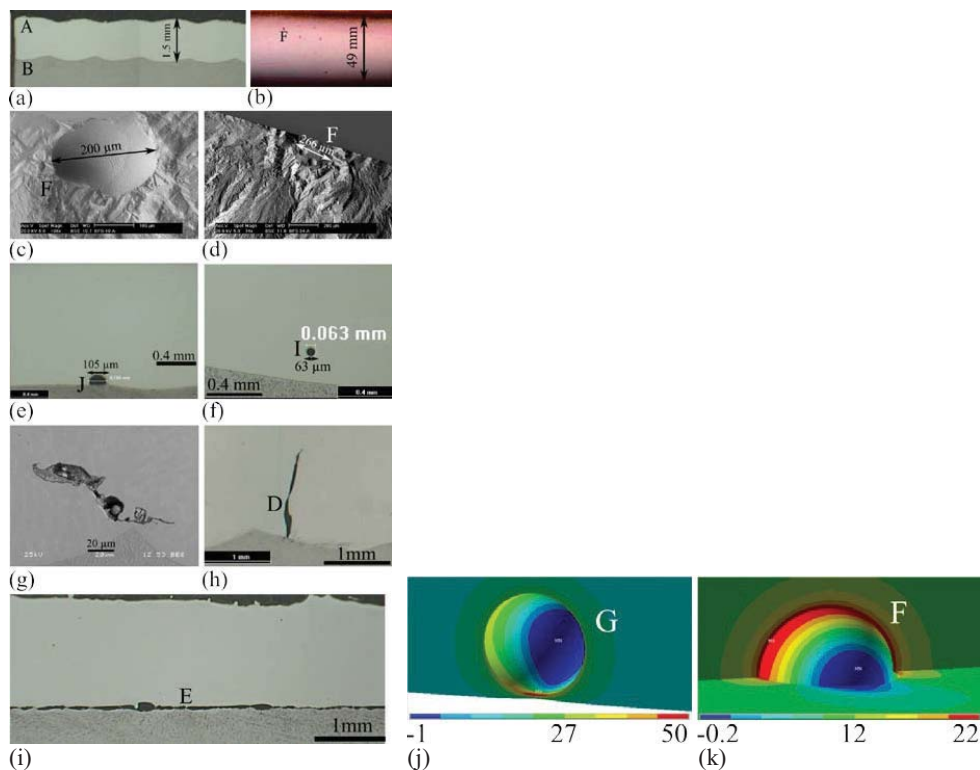


Fig. 5. Photographs of laser cladding defects; (a) as-clad wavy surface A and interface B, (b) detection of surface pores F by dye penetration test, (c) surface pore F, (d) surface pore F with oxide inclusion, (e) semi-spherical interface pore J between clad layer and base material, (f) spherical pore I in-clad, (g) irregular inclusion near the interface, (h) hot crack D, (i) interface lack-of-fusion E; (j) local 1st principle stress field (in MPa) calculated for a spherical pore just underneath the surface, G, and (k) the calculated stress field for a surface pore, F, centrally cut-off [2]

The trends of the two overlapping mechanisms, namely the macro-field and the stress raiser defects are visualized in a quantitative manner in **Fig. 6** and in a qualitative manner in **Fig. 7**. In [1-3] the trends are explained and discussed and recommendations are given. Sometimes the size of the defect is of importance, but more often its location or orientation.

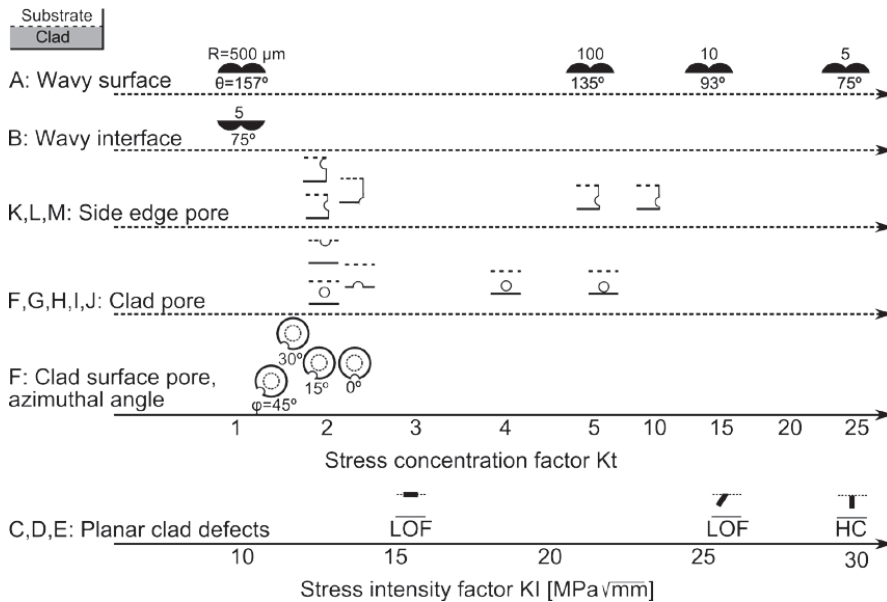


Fig. 6. Stress concentration factor and stress intensity factor for various clad defects and their geometry variations [2]

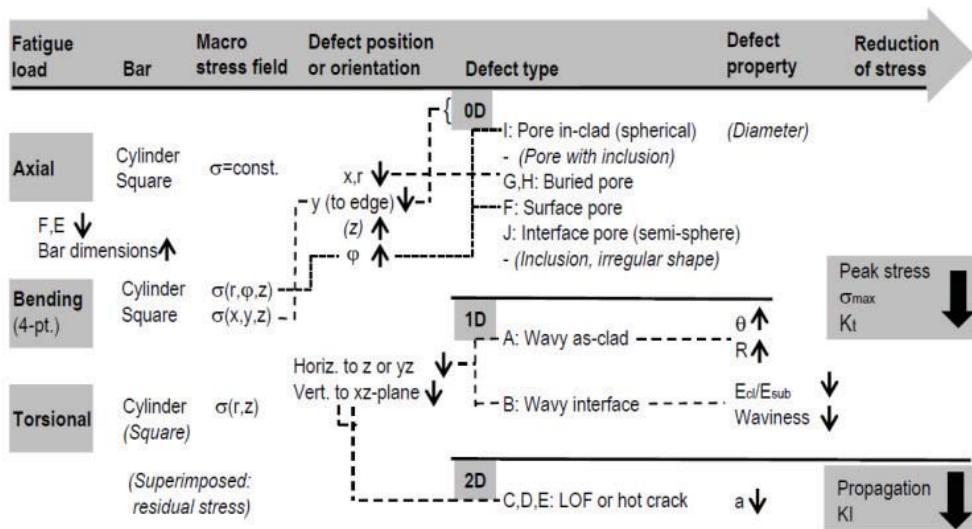


Fig. 7. Tuning Flow Chart, TFC, describing the combination of different stress raisers of laser clad bars under fatigue load; the arrows indicate lowering of the peak stress [2]

3.4 Crack propagation

The initiation and propagation of a fatigue crack from a stress raiser, for local macro-stress, was calculated by the FEM for various conditions, as shown in **Fig. 8**, in particular explained in **Fig. 8(f)**, middle. **Figure 8(a)** shows the significant stress peaks induced by the notches from the long (1D) ripples of as-laser clad surfaces along with an inclined crack (or Lack-of-Fusion) horizontal defect located in the notch of the ripple. **Figure 8(b)** shows a crack that propagated 1.6 mm from a horizontal crack origin at an as-clad surface notch. The stress peak is around the tip of the vertically propagating crack. From **Fig. 8(c)** it can be seen that a horizontal crack just 0.1 mm underneath the surface initiates the cracking but propagates to the surface, while a corresponding inclined crack, **Fig. 8(d)**, propagates in both vertical directions, i.e. the situation is very sensitive to the location and orientation of the defect, often more sensitive than to the size of the defect. **Figure 8(e)** shows that this bidirectional vertical crack propagation can be expected even for a horizontal crack in the clad-substrate interface, and similarly for a tilted crack origin, see **Fig. 8(f)**. Owing to the here applied horizontal stress as the local impact from the macro-field, even horizontally oriented defects rapidly change their direction to vertical.

Corresponding graphs showing the propagating crack length as a function of the crack tip stress intensity KI in comparison between horizontal and tilted crack origins are shown in **Fig. 9(a)-(c)**. As can be expected, the tilted crack origin causes a slightly higher stress intensity factor, which corresponds to faster propagation and shorter fatigue life. **Figure 9(d)** shows the kink angle of the propagating crack as a function of the crack length, for different crack (lack-of-fusion) orientations. An attenuated zig-zag-propagation can be seen.

A crack propagating from the top surface can interact with defects beside the propagation crack, deflecting the crack path and changing its speed. **Figure 10(a)** shows the undisturbed propagation of a crack while **Figs. 10(b)-(d)** show how the crack is deviated when one or two pores are located close to the crack path. Note that the calculations were carried out in two dimensions for the sake of low computation time, i.e. corresponding to cylindrical rather than spherical defects. The basic trends are the same, although quantitatively weaker for spheres, depending also on the in-plane coordinate location.

The crack initiation length at the surface was 10 μm , the pore started 100 μm below the surface, with a diameter of 60 μm . The distance between the two pores was 100 μm , once oriented horizontally, once 45° inclined down from the first pore. Axial loading conditions were applied, inducing horizontal tensile stress.

Figure 11 shows the corresponding length of the propagating crack as a function of the number of cycles. As can be seen, compared to a defect-free sample the lifetime is reduced for one defect and even further for a second defect, in different manner depending on their orientation. Again, for the quantitative values the simplification to two dimensions has to be kept in mind. The defects act as local stress raisers that accelerate the crack propagation. Same as here for round defects (pores) and laser cladding, this was already found earlier for lack-of-fusion (note: a two-dimensional planar defect, therefore 2D-analysis was representative) in laser-arc hybrid welding,[1] where it however was shown that the stress field induced by the defect rapidly decayed in space, keeping the interaction in form of acceleration limited (about 10% reduction of lifetime), while other aspects were more important.

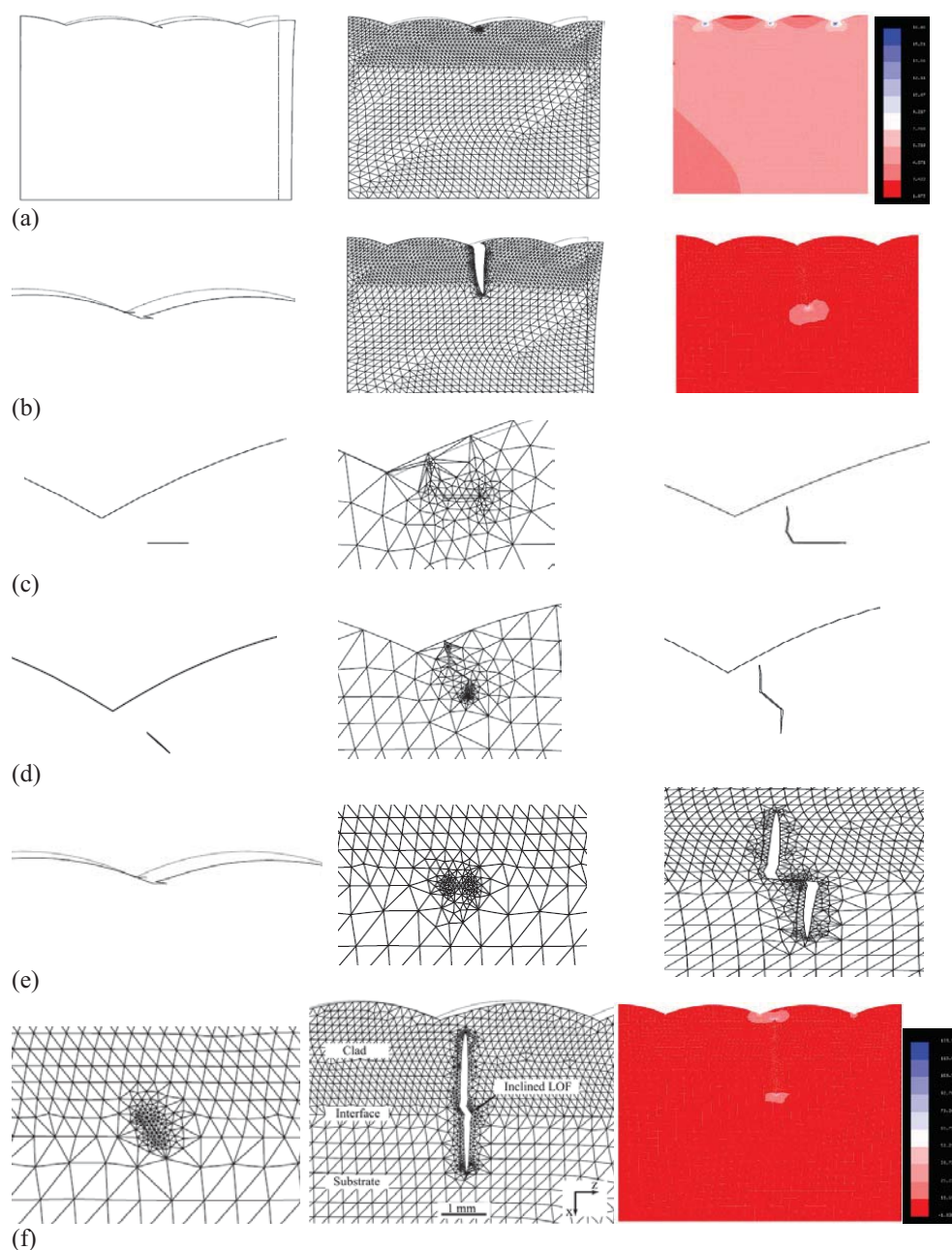


Fig. 8. Local defect (left column), crack initiation path (middle or right) and stress field (right, in colour) by FE-calculation: (a) 0.1 mm short tilted crack at the as-clad surface notch, (b) crack that propagated 1.6 mm from a horizontal 0.1 mm crack, (c) horizontal crack close to the surface and its propagation, (d) inclined crack close to the surface and its propagation, (e) horizontal crack at the clad-substrate interface, (f) inclined crack at clad-substrate interface

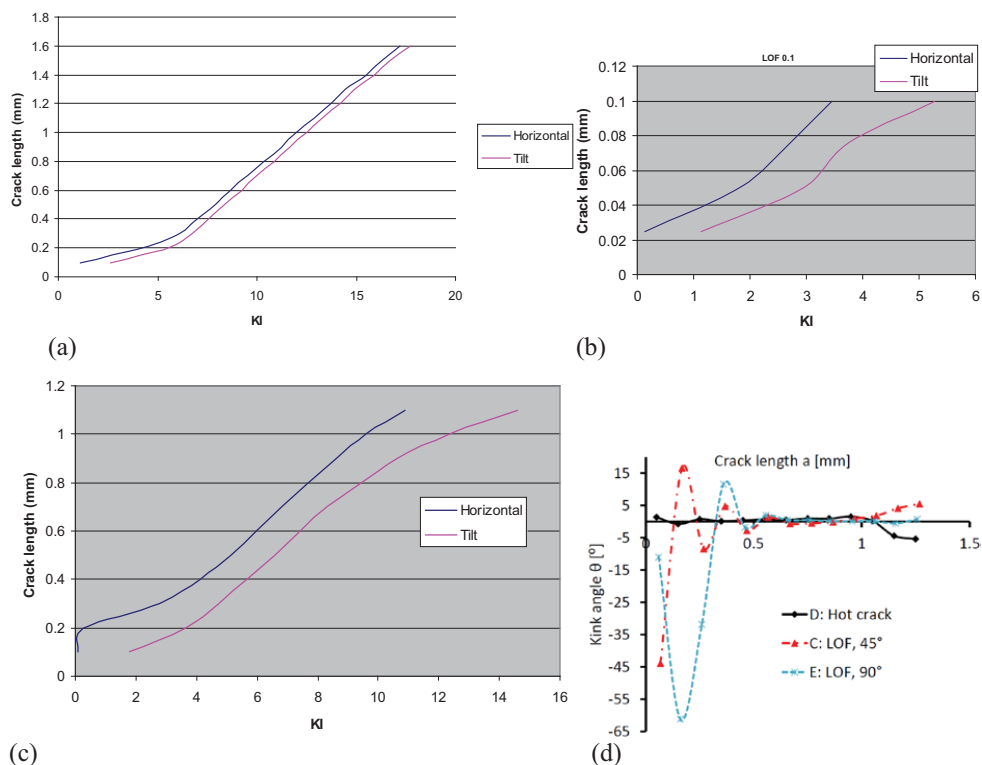


Fig. 9. Crack length propagation as a function of the stress intensity KI at the crack tip, comparing horizontal to tilted crack origins, see also **Fig. 8**: (a) initial crack at an as-clad top notch, (b) initial crack 0.1 mm below the top, (c) initial crack at the solid-liquid interface, (d) kink angle as a function of crack propagation length, for three angle of defect-inclination

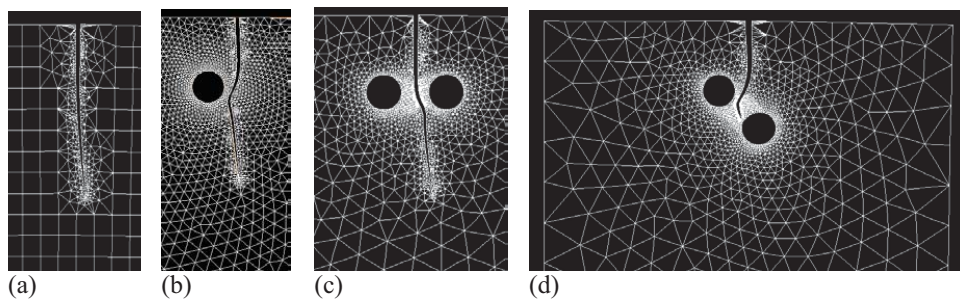


Fig. 10. Calculated crack propagation path from the top surface: (a) without defect, (b) beside a pore in the clad layer, (c) between two pores at same depth in the clad layer, (d) between two pores of different depth (45° orientation)

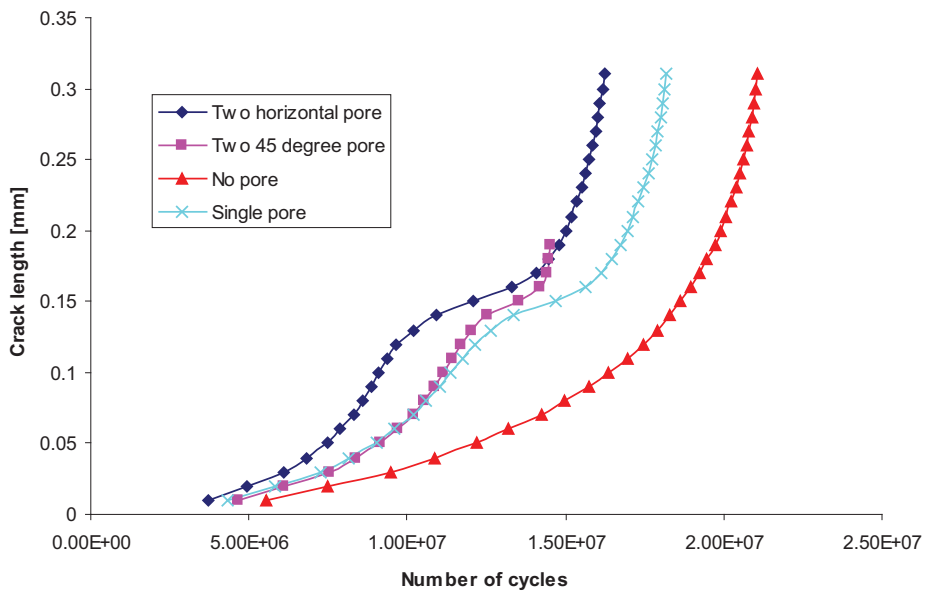


Fig. 11. Calculated crack propagation length as a function of the number of cycles, when comparing the defect-free case with propagation close to pores, as in **Fig. 10**

4 Conclusions

For the theoretical study of stress raising and fatigue life in laser clad components the following conclusions can be drawn:

- (i) The maximum stress in a laser-clad component, which is likely to initiate fatigue cracking, is generated from a superposition of:
 - a. the macro-stress field (from load and component geometry),
 - b. stress raisers by defects (from laser cladding),
 - c. residual stress (generated during laser cladding).
- (ii) Mainly tensile residual stress was measured, which can reduce the fatigue lifetime.
- (iii) For defects, their location and orientation in the macro-field is often more important for their generation of stress raisers than the defect size.
- (iv) Experimental evidence was found where a surface pore has initiated fatigue cracking.
- (v) When a crack propagates in the vicinity of a defect it will be locally deflected and accelerated, in general lowering fatigue life; however, the defect is not wide-ranging.
- (vi) The visualizing maps developed enable to systematically extend existing knowledge and they facilitate the cognition of knowledge, here for stress raisers through defects.

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6 References

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