A NUMERICAL ESTIMATION OF THE EFFECT OF A BI-MATERIAL INTERFACE ON CRACK TIP PLASTIC ZONE SIZE AND SHAPE

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Abstract
Fatigue crack propagation in ferrite (bainite) near the austenitic cladding was modelled by means of the elastic-plastic finite element method and the effect of the bi-material interface on the cyclic plastic zone size and shape was investigated. It was demonstrated that cyclic plastic strains in softer austenite are already present at the moment when the cyclic plastic zone around the crack tip in harder ferrite reaches the interface. Crack tip plastic zones under plane stress and plane strain conditions vary in size and shape and are affected by the approaching material interface. The level of dissipated energy in front of the fatigue crack and, therefore, the crack rate increased as the boundary of the cyclic plastic zone reached the material interface.

Keywords: cyclic plastic zone, fatigue crack, bi-material interface, finite element modeling (FEM)

1 Introduction
It was experimentally observed that fatigue crack growth is influenced in a small domain close to the interface between two materials of different yield stress [1–6]. The crack approaching the interface from the softer to the harder material is retarded, whereas the crack approaching the hard/soft interface is accelerated. This phenomenon was also studied numerically in [7–9]. Since many models for fatigue crack growth rate prediction are based on the stress intensity factor and its correction to the actual plastic zone size [10], it is interesting to be aware, how plastic strain ahead of the crack tip is affected by a plastically mismatched interface. In the present study, crack propagation in ferrite (bainite) near the austenite cladding is modelled by means of an elastic-plastic finite element method and the effect of the interface on the cyclic (reversed) plastic zone size is investigated. The results are also compared with a frequently used analytical estimation of the cyclic plastic zone size

\[ r_{pc} = \frac{1}{\alpha \pi} \left( \frac{\Delta K}{2\sigma_y} \right)^2 \]  

(1.)

where:  
- \( r_{pc} \) [m] – cyclic plastic zone radius
- \( \Delta K \) [MPa⋅m\(^{1/2}\)] – stress intensity factor range
- \( \sigma_y \) [MPa] – yield stress
- \( \alpha = 2 \) (plane stress) or \( \alpha = 6 \) (plane strain)
2 Numerical model of the crack tip plastic zone

The numerical model for the plastic zone size estimation is based on an incremental finite element analysis of cyclic plastic strains around the propagating crack. The finite element mesh had to be consequently built and the input material properties and boundary conditions had to be specified. All the simulations were carried out in MSC.Marc 2012 [11].

2.1 Material input

The study deals with fatigue crack propagating perpendicularly to the interface between the 15Kh2MFA steel [12–14] on the cracked side and the austenitic stainless steel layer on the opposite side. This material interface is present in a nuclear power reactor of type VVER-440, in which 15Kh2MFA steel is the base material for the pressure vessel and austenitic cladding serves as the inner layer which protects against corrosion. The cladding was made with automatic strip welding under flux with two layers (Sv 07Kh25N13 + Sv 08Kh18N10G2B austenitic steels) created at four passes to achieve a required total cladding thickness of mm [15]. Although the cladding is non-homogenous and exhibits a certain degree of material anisotropy, it is treated as a homogenous isotropic material for the purpose of the numerical simulation.

The elastic-plastic response of both materials was obtained from common tensile tests and idealised by the bi-linear curves (Fig. 1). 15Kh2MFA steel is harder with a yield stress of $\sigma_y = 499$ MPa, in contrast to softer austenitic cladding with $\sigma_y = 426$ MPa. The cyclic plastic behaviour of both materials was represented by the kinematic hardening rule.

![Fig. 1 Model representation of the elastic-plastic material properties](image)

2.2 Finite element mesh and boundary conditions

With respect to the symmetry, only one half of the CT-specimen is covered by the two-dimensional finite element mesh (Fig. 2). The specimen has a width of 30 mm and a thickness of 5.78 mm. The width of the austenitic layer is 11.29 mm. In the region of the crack propagation and intense cyclic plastic deformation (Fig. 3) linear 4 node quadrilateral elements of the smallest size 10×10 µm are used.

The cyclic loading with a maximum force $F_{\text{max}} = 2050$ N and a stress ratio $R = 0.022$ leads to the stress intensity factor range $\Delta K \approx 30$ MPa\(\cdot\)m\(^{1/2}\) for the crack with the tip at the material interface. A crack tip advance is modelled by the successive release of finite element mesh nodes during cyclic loading. There are two types of consecutive model loading cycles: “active” in which the crack moves along an element edge at the minimum of the cycle and “idle” with a stationary crack and numerically stabilized solution. Crack closing and opening during the loading cycle is simulated by a contact algorithm.
3 Results

The primary goal of all the computations was to obtain the shape, width and height of the cyclic plastic zone at the crack tip approaching the material interface. The zone is formed by particular finite elements in which the change in plastic strain energy per “idle” loading cycle is non-zero. Both a plane stress and plane strain simulation were performed. For a comparison, simulations with no interface were also carried out (the entire specimen is made of 15Kh2MFA steel).

3.1 Plane stress simulation

A total of 200 plastic zones for 200 crack lengths of a continuously growing fatigue crack were obtained. Only three snapshots were selected as a typical illustration of the different phases of the crack growth: (i) cyclic plastic strains are only present in the base material in the close vicinity of the crack tip (Fig. 4a), (ii) cyclic plastic strains also occur separately in the softer cladding (Fig. 4b), (iii) cyclic plastic strains are in both materials and form a single zone across the interface (Fig. 4c).

The evolution of the cyclic plastic zone shape is characterized by the maximum width and the height of the continuous zone at the tip (Fig. 5).
Fig. 4 The evolution of the cyclic plastic zones under plane stress. Crack lengths: a) 17.79 mm ($\Delta K = 26.6$ MPa·m$^{1/2}$), b) 17.87 mm ($\Delta K = 26.9$ MPa·m$^{1/2}$), c) 18.57 mm ($\Delta K = 29.5$ MPa·m$^{1/2}$)

Fig. 5 The width and height of the cyclic plastic zone under plane stress for various crack lengths.

3.2 Plane strain simulation
The identical set of plots (as described in chapter 3.1) was made use of for illustration of the results obtained under the plane strain condition (see Figs 6a-c and 7). Since the zones are generally smaller, a longer crack with a smaller distance of the crack tip from the interface was chosen in Fig. 6b.
**Fig. 6** The evolution of the cyclic plastic zones under plane strain. Crack lengths:
a) 17.79 mm ($\Delta K = 26.6$ MPa·m$^{1/2}$), b) 18.47 mm ($\Delta K = 29.1$ MPa·m$^{1/2}$), c) 18.57 mm ($\Delta K = 29.5$ MPa·m$^{1/2}$)

**Fig. 7** The width and height of the cyclic plastic zone under plane strain for various crack lengths

4 Discussion
Determining the exact plastic zone boundary is an ambiguous task since it depends on the used convention. In the presented simulations, the proof stress was used as a starting point for the plastic strain formation. A lower value of the yield stress would lead to a larger resulting zone. Therefore, along with the actual zone size, the strain distribution inside the zone might also be of interest. As can be seen from **Figs. 8a,b**, the majority of the plastic strain energy is stored in an
extremely small fraction of the entire zone volume. The size of this smaller zone roughly corresponds (for both the plane stress and the plane strain) to a simple estimation (1.) based on an ideal elastic-plastic material. Despite this, the cyclic plastic zone size for the evaluation of the effect of the bi-material interface was determined according to the condition of the non-zero plastic strain energy change per cycle.

![Diagram](image)

**Fig. 8** A comparison of the cyclic plastic zone shapes and sizes determined analytically according to eq. (1) and numerically. a) Plane stress, b) plane strain.

The zone under the plane stress condition has an oval shape (Fig. 4a), whereas the plane strain zone is shaped as a butterfly (Fig. 6a) and is generally smaller due to an out-of-plane deformation constraint. This is in agreement with Figs 5 and 7: under the plane stress condition, the width of the zone is larger than the height and the zone is elongated in the direction of the propagation. Under the plane strain condition, the width of the zone is extremely small as compared to its height and, moreover, there is a circular isle in front of the crack tip with no cyclic plastic deformation. Additionally, the initial strains in the cladding occur at different locations: at the axis of the symmetry (plane stress, Fig. 4b) or eccentrically (plane strain, Fig. 6b).

![Diagram](image)

**Fig. 9** The plastic strain energy density change per loading cycle at various distances from the crack tip.
The approaching softer material has no effect on the cyclic plastic zone size (Fig. 5 a 7) or energy distribution within the zone until the boundary of the zone reaches the interface. From that moment, the zone increases in height even in the harder material while the energy at the front of the crack tip is also higher as compared with the case with single material (Fig. 9). From the point of view of the Sih’s energetic criterion [16], an increase in the dissipated strain energy density should lead to an increase in the crack rate.

5 Conclusions
A numerical model for prediction of the cyclic plastic zone around the crack tip approaching the plastically mismatched material interface was proposed. This is based on a detailed FEM analysis of the elastic-plastic strain history in a CT specimen with a moving crack. A total of four simulations under plane stress and plane strain condition and with and without the presence of an interface led to the following conclusions:

1. The shape of the cyclic plastic zone varies based on the stress state: from an oval (plane stress) to a butterfly shape (plane strain). The size of the zones evaluated from most common analytical equation is roughly comparable to the simulated ones defined as the zones, where 90% of all the plastic energy is dissipated.

2. As soon as the crack tip is close enough to the interface, the isolated secondary zone in the softer material begins to form. Its shape is given by the forefront of the primary zone. The effect of the secondary zone on the shape of primary zone is negligible as long as both zones are separated. After their coalescence into a single zone, the plastic strains in the harder material are more complex and the solution without the interface is no longer relevant.

3. The level of dissipated energy in front of the fatigue crack propagating in 15Kh2MFA steel is increased as the boundary of the cyclic plastic zone reaches the material interface with softer austenitic cladding.

References
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