Scanning electron microscopy and computer modelling of microstructural changes in the vicinity of propagating short fatigue cracks in austenitic stainless steels

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Abstract. The present paper deals with the in-situ observation of local fatigue damage processes by using a conventional servohydraulic testing machine and a new developed piezo-driven miniature testing system in the scanning electron microscope in combination with electron backscatter diffraction to correlate crack initiation and propagation with local microstructural features. In the case of metastable austenitic 304L steel it is shown and supported by finite element calculations that fatigue-induced strain localization causes the formation of \( \alpha' \) martensite. Martensite nuclei lying parallel to the slip planes in the austenite grains and twin boundaries can be considered as crack-initiation sites. Fatigue crack propagation causes an increasing martensite transformation rate ahead of the crack tip leading to the occurrence of crack closure effects. As shown in an earlier study, crack closure in the case of short cracks follows a transient regime, i.e. immediately after crack initiation the crack stays open almost during the complete fatigue cycles. The development of a short crack model based on the boundary element method aims to the prediction of crack initiation and short fatigue crack propagation rates.

1. Introduction

More than 90% of the fatigue life of structural stainless steel components loaded by high numbers of cycles is determined by crack initiation and short crack growth. During this phase of the fatigue damage process the material can not be considered as a homogeneous structure. The variation in grain geometry and crystallographic orientation causes an inhomogeneous distribution of mechanical stresses due to elastic anisotropy (cf. Fig. 1 and [1, 2]). As a consequence of ongoing cyclic loading, stress/strain localization leads to plastic deformation and in the case of metastable austenitic steels to a transformation from \( \gamma \) austenite to \( \varepsilon \) and \( \alpha' \) martensite. Eventually, accumulation of plastic strain and transformation-induced martensite results in fatigue crack initiation and crack propagation which during the early stage of the fatigue damage process is strongly influenced by the microstructure, like grain size and orientation distribution (cf. [2]). Due to a 2.57% volume increase and the higher...
strength of the martensite laths [3] there is an intrinsic crack tip shielding effect, i.e., the transformed plastic zone ahead of the crack tip may retard the crack propagation rate by (i) transformation-induced crack closure and (ii) by a higher yield strength (cf. [4, 5]).

Since the effect of martensitic transformation has a significant impact on the strength properties not only of metastable austenitic steels but also of TRIP steels (transformation-induced plasticity) being frequently used in the automotive industry, there is a strong need to implement it into modeling concepts relating the microstructure with the applied fatigue loading conditions.

Fig. 1: Plastic strain localization (grains 1 and 3) in AISI 304L steel: (a) SEM micrograph (after fatigue loading) and corresponding inhomogeneous stress distribution, with stress maxima at the grain boundaries of grains 1 and 3 (FE calculation based on an elastic anisotropic material model and EBSD data)

2. Experimental
Fully reversed ($R = -1$) fatigue tests were applied to AISI304L metastable austenitic steel (0.03C, 18.1Cr, 8.8Ni, 1.9Mn, in wt%) under stress control and a stress amplitude slightly above the $10^7$ cycle fatigue limit of $\Delta \sigma / 2 = 230$MPa. Experiments were carried out (i) in-situ in a scanning electron microscope (SEM) using a self-designed piezo-driven miniature testing system shown in Fig. 2, and (ii) in a MTS servohydraulic testing machine. To correlate fatigue damage and martensite transformation phenomena with the microstructure, fatigue experiments were accompanied by automated electron backscatter diffraction (EBSD) measurements of crystallographic orientations.

Fig. 2: In-situ fatigue testing system for integration into a SEM: (a) piezo actuator and specimen stage, (b) 70° tilt stage for EBSD measurements during fatigue testing

3. Influence of Martensite Formation during Early Fatigue Crack Propagation
Even small-strain fatigue loading is sufficient to create slip markings in many grains. This is due to the low friction stress in face-centred cubic stainless steels. The origin of the slip markings are grains of high elastic anisotropy stresses (cf. Fig. 1) and high Schmid factors (close to 0.5). The slip markings act as nuclei for the austenite martensite formation as is clearly revealed by EBSD measurements. Here, only $\alpha'$ martensite having the Kurdjumov-Sachs orientation relationship with the parent
austenite phase, i.e. \((\overline{1}1\overline{1}), \parallel (101)_a\) and \([\overline{1}0\overline{1}], \parallel [\overline{1}1\overline{1}]_a\) is detected. The metastable hexagonal \(\varepsilon\) martensite is assumed to vanish after a short transition period.

The initial crack density at small-strain fatigue is very small; interestingly, crack initiation is found to occur not only at the martensite lamellae but also at twin boundaries (cf. [1, 6]). Immediately after initiation, microcracks grow crystallographically along slip planes (stage 1), but after short time they change to normal stress controlled stage 1b growth (cf. [2, 7]), operated by two alternately active \{111\} slip planes. This stage of the crack propagation process strongly involves martensite formation as is shown in Fig. 3. The crack path appears in the EBSD in form of martensite that was formed in the plastic zone ahead of the crack tip. Extension of the plastic zone and hence crack propagation is blocked by the grain boundaries as indicated by the crack propagation rates that show an oscillating behavior. Since cracks are observed to stay open at zero load (Fig. 3b) in combination with martensite formation at the crack tip, transformation-induced crack closure is assumed to be active in such a way, that the crack tip is not shielded but remains open even during a certain part of the compressive half cycle.

![Fig. 3: Crack propagation in AISI304L metastable austenitic steel: (a) barrier effect of the grain boundaries (the lines correlate the crack propagation rate data with the EBSD grain orientation map) and (b) crack opening at \(\sigma = 0\) due to martensite formation at the crack tip](image)

4. Modeling Concept

Microstructural control of short fatigue cracks has been modeled by means of a boundary element (BE) approach (cf. [2, 8]), where slip band cracks and the adjacent plastic zones are meshed by displacement discontinuity elements. This approach allows for calculating the cyclic crack tip slide displacement (\(\Delta CTSD\)) being the direct driving force for crack propagation. During crack advance the distance between the crack tip and the next grain boundary and consequently, \(\Delta CTSD\) decreases. This decrease causes the crack propagation rate \(da/dN\) to slow down. At the same time the stress acting on slip systems of the neighboring grains increases. After reaching a critical stress, the plastic zone extends to the respective grains and \(\Delta CTSD\) and \(da/dN\) increase. Hence, the BE concept is capable to reflect the oscillating propagation behavior of short cracks as a function of local microstructural features.

To implement both the effect of an inhomogeneous stress distribution, as is shown in Fig. 1, and the phenomenon of local plastic strain-induced martensite formation, a second set of BE was introduced to mesh the grain boundaries [9]. Both sets are superimposed as two sub-problems: crack in an infinite plate and crack-free grains.
Fig. 4 shows the application of the modified BE approach to a simple microstructure consisting of three grains of two different Young's moduli $E_0$ and $E_1$. In the case of a homogeneous plate ($E_1 = E_0$), $\Delta CTS$ starts to decrease when approaching the grain boundary. At a normalized crack length of about 0.9, $\Delta CTS$ exhibits a substantial jump since the critical stress for activation of the slip system in the neighboring grain is exceeded. The strong effect of an inhomogeneous distribution of the Young’s modulus (elastic anisotropy) becomes evident for situations, where the crack propagates in an elastically softer ($E_1 = E_0/1.5$) or an elastically harder material ($E_1 = 1.5 E_0$). As compared to the homogeneous materials, there are strong variations in $\Delta CTS$ and the crack propagation rate, respectively.

In future work, the superposition concept will be applied to microstructures that are generated with experimental EBSD data and where effect of the austenite to martensite formation is included.

![Fig. 4: Crack in an elastically inhomogeneous microstructure: (a) geometrical arrangement and (b) crack tip slide displacement vs. normalized crack length for various arrangements of elastically soft and hard grains (dashed line: BE generation only for the crack).](image)

5. Conclusions

Fatigue damage of AISI304L metastable austenitic steel involves the formation of plastic strain-induced martensite, even at macroscopically very low strain amplitudes. Elastic anisotropy causes strain localization and fatigue crack initiation. As soon as a short crack starts to grow the plastic zone around its tip exhibits martensitic transformation. It is shown qualitatively that this transformation has a strong impact on the current crack propagation rate. This can be attributed to both the development of transformation-induced crack closure and a change in the crack growth mechanism itself, i.e. the crack propagates into high-strength martensite instead of soft austenite. A new superposition boundary element approach based on an existing short crack model accounts for crack propagation within an elastically and plastically inhomogeneous microstructure.

References

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