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Significance and Mechanism of the Crack Initiation Process during Very High Cycle Fatigue of Duplex Stainless Steel

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Abstract

In the very high cycle fatigue (VHCF) regime, fatigue damage starts by the formation of slip bands within the softer austenite phase. By high energy X-ray diffraction it was shown that local austenite plasticity due to elastic/plastic anisotropy results in the gradual formation of residual stresses within the ferrite grains. Consequently, cracks are initiated either transgranularly or intergranularly at austenite/ferrite phase boundaries or ferrite/ferrite grain boundaries in the vicinity of the austenite slip bands. By means of ultrasonic fatigue testing of miniature specimens in combination with (i) in-situ observation, (ii) electron back-scatter diffraction, (iii) synchrotron computer tomography, and (vi) high-energy X-ray diffraction, the fatigue crack initiation process and the interactions of the cracks with the first microstructural barriers were quantified. By implementing the results in a numerical modeling approach, the experimental observation that the first barrier seems to limit the VHCF life was supported.

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Keywords: duplex steel, VHCF; short cracks; modeling; barrier strength

1. Introduction

Austenitic-ferritic duplex steels are increasingly used for structural components, where a high corrosion fatigue resistance is required, e.g., off-shore applications, chemical reactors or bio-waste incineration. The fatigue behavior

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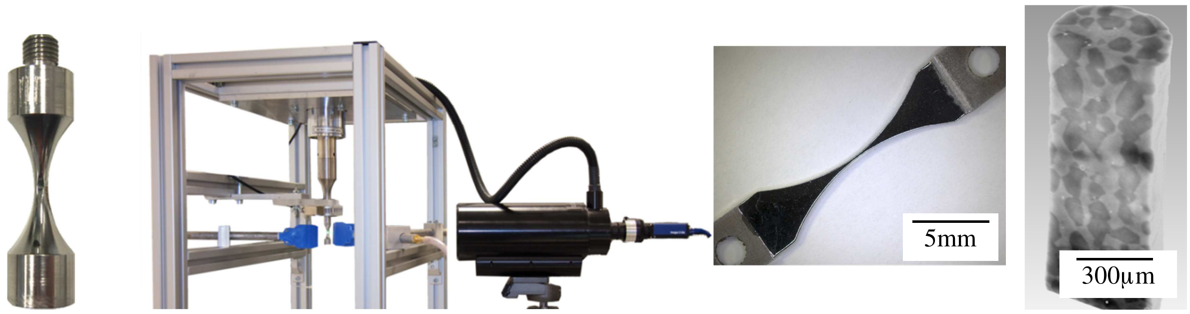
of this material depends strongly on the individual strength and morphology of the two phases austenite and ferrite, which can be altered separately. By means of an embrittling heat treatment, the ferrite phase disintegrates into a Fe-rich α matrix and Cr-rich α' precipitates by spinodal decomposition [1]. Alloying with nitrogen leads to a pronounced increase in the austenite strength due to the higher N solubility (super duplex steel) [1]. The fatigue behavior of the duplex steel family was subject of numerous studies focusing on the low-cycle (LCF) and the high-cycle fatigue (HCF) regime (e.g. [2,3]). For low-N lean duplex steel it was found that the early stage of fatigue damage is dominated by extensive slip band formation, for LCF in both ferrite and austenite, for HCF within the softer austenite phase mainly [4]. Cracks initiate intergranularly at ferrite-ferrite grain boundaries and ferrite-austenite phase boundaries or transgranularly either along austenite or ferrite slip bands [5]. Once being initiated, fatigue cracks interact with the grain and phase boundaries, resulting in a pronounced microstructure-depending oscillation of the crack propagation rates *da/dN*, as it was observed, e.g., in [6]. There is evidence from the literature [7], that microstructurally short fatigue cracks play a decisive role even in the VHCF regime. The quantitative analysis and numerical simulation of such cracks is subject of the present paper.

2. Experimental

Cylindrical specimens of austenitic ferritic steel (Fe-22Cr-5Ni-3Mo-2Mn-0.2N, according to German standard 1.4462) was fatigued using ultrasonic testing systems (BOKU Vienna) at f=20kHz under fully-reversed loading (stress ratio R=-1). After a grain-coarsening heat treatment (resulting in 50% ferrite grains of 41μm and 50% austenite grains of 33μm diameter, resp.) and machining, the specimens were electropolished and given a shallow notch to force crack initiation within the observation area of an optical microscope (Questar QM100), cf. Fig. 1a and b). Additionally, specimens with a diameter of approx. 350μm (Fig. 1c) were prepared for synchrotron tomography (phase contrast (PCT), e.g., Fig. 1d, and diffraction contrast (DCT)). These techniques allow the 3D measurement of phase and crystal orientation distributions in addition to the 2D measurements that are carried out by electron back-scatter diffraction (EBSD). The results are used as input data for finite element modeling of VHCF damage.



a b c d

Fig. 1. Ultrasonic fatigue testing: (a) shallow-notched specimen, (b) test setup with long distance microscope and piezo actuator, (c) miniature specimen and (d) longitudinal section through a synchrotron PCT 3D phase mapping (light: α ferrite, dark: γ austenite).

3. Results and Discussion

Fatigue testing of duplex steel specimens in the VHCF regime (up to 10^9 cycles) revealed the existence of a real fatigue limit of a value of $\sigma_{FL}\approx$330MPa. In general, fatigue failure was initiated at the specimen surface (except few specimens that contained large non-metallic inclusions (Al_2O_3) that cause subsurface crack initiation). Even the run-out specimens exhibited indications of fatigue damage in the form of pronounced slip markings (extrusions and intrusions as shown by focused ion beam milling (FIB)), mainly limited to the austenite grains (cf. Fig. 2a). The height of these slip markings were periodically measured by confocal laser scanning microscopy (CLSM). Obviously, slip activity is limited to about 10^4 cycles only. Afterwards, strain hardening leads to the activation of parallel slip systems. Therefore, a gradual increase in the slip band density can be observed throughout the fatigue life, as it is demonstrated by the micrograph series in Fig. 2a. This result was supported by (i) in-situ observation of the slip-band formation during ultrasonic loading and (ii) periodical X-ray diffraction that allowed the determination of the dislocation density (Fig. 2b).

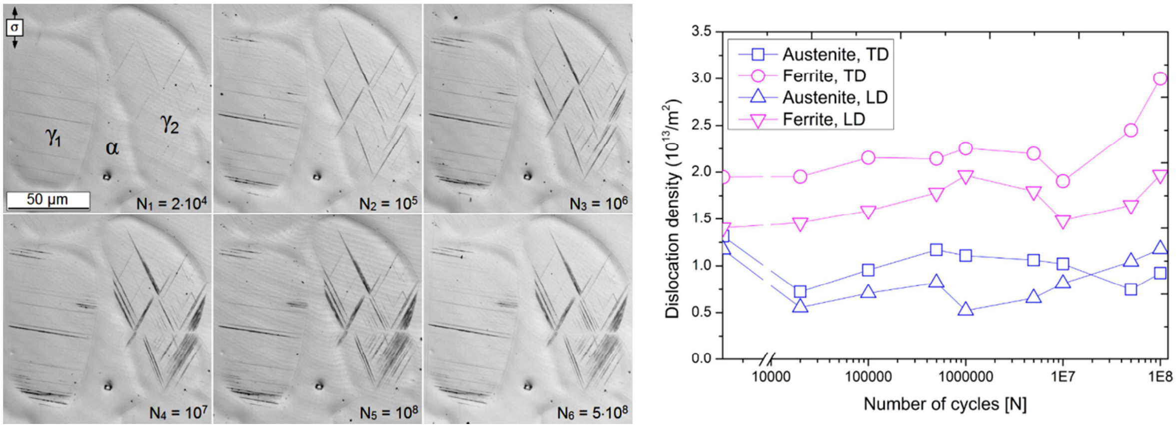


Fig. 2. VHCF of duplex steel: (a) formation and gradual density increase of slip bands in austenite grains; (b) change in dislocation density in ferrite and austenite grains (LD: loading direction, TD: transversal direction, evaluated by means of modified Wilkinson plot).

Since plastic deformation during VHCF is strongly localized, the dislocation density stays at a nearly constant value during the first 50% of fatigue life. Then, plasticity within the ferrite grains seems to increase strongly. This is in agreement with experimental observations, where a strong increase in dislocation density can be observed at (austenite) slip band - phase boundary intersections (Fig. 3a). Once fatigue cracks are initiated, the existence of a fatigue limit seems to depend on the strength of the first microstructural barrier. Fig. 3b shows a crack that initiated at a phase boundary; it propagated during approx. 10^6 cycles through the first grain. Only after overcoming the next boundary, a strong increase in *da/dN* leading to final fracture was measured.

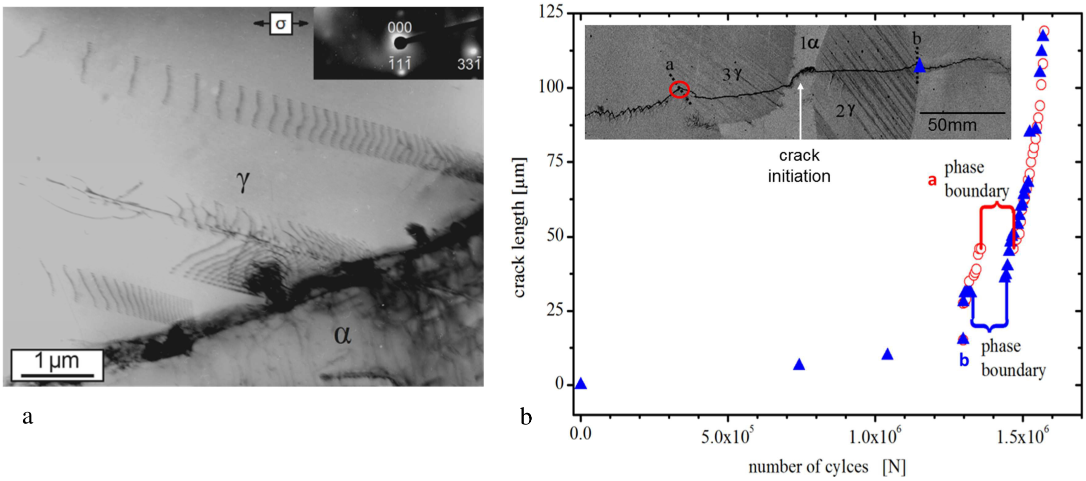


Fig. 3. Barrier effect of phase boundaries in austenitic ferritic duplex steel: (a) dislocation pile up at an austenite ferrite phase boundary and (b) microcrack length vs. number of cycles for two crack tips interacting with phase boundaries.

Based on the EBSD and DCT data, the duplex steel microstructure can be represented by means of a finite element mesh. Applying an elastically anisotropic material model including crystal plasticity, the experimentally found locations of stress/strain concentration and crack initiation were predicted (cf. Fig. 4). Implementing the model of Tanaka and Mura [8] and Chan [9] yields the following equation for the number of cycles N_i required for initiation of a crack of length a (with λ representing cyclic irreversibilty ($0<\lambda<1$), d being the grain size, h the slip band spacing, ν the Poisson ratio and $\Delta\gamma$ the cyclic shear strain).

$$\frac{a}{N_i} = \frac{2\lambda}{9\pi \cdot d \cdot h^2 \cdot (1-\upsilon)} \Delta\gamma^2 \qquad (1)$$

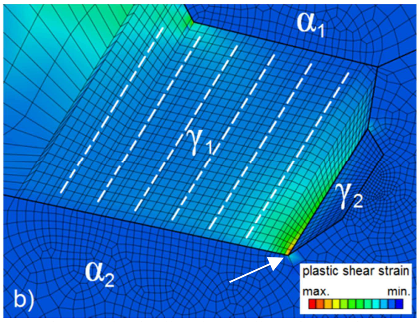


Fig. 4. Elastically/plastically anisotropic FE calculation to predict strain concentration/crack initiation sites (see arrow).

As subject of ongoing work, equ. 1 is being used as a damage criterion to predict crack propagation within individual grains. According to the calculated plastic strain, a starter crack is initiated resulting in a partial loose of stiffness within individually meshed slip bands. Hence, for the following calculation step, the stress acting on the adjacent grain and/or phase boundaries is changed. Once a critical stress is exceeded, the crack can overcome the boundary. As also found experimentally, such a situation would rule out infinite life.

4. Conclusions

Up to 10^9 cycles, austenitic ferritic duplex stainless steel exhibits a fatigue limit of $\sigma_{FL}\approx 330$MPa. However, fatigue damage was observed in any case, manifesting itself by the formation of slip bands along slip systems exhibiting the highest resolved shear strain. Strain hardening leads to activation of parallel and non-parallel slip bands. The stress concentration due to dislocation pile ups at the austenite ferrite phase boundaries cause plastification of the neighboring ferrite grains and, eventually, crack initiation. Wether these cracks lead or lead not to final fracture depends on the barrier efficiency of the following grain or phase boundary.

Acknowledgements

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