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Significance of crystallographic misorientation at phase boundaries for fatigue crack initiation in a duplex stainless steel during high and very high cycle fatigue loading

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ABSTRACT

The current investigations on the austenitic–ferritic duplex stainless steel X2CrNiMoN22-5-3 documents that the misorientation at a phase boundary determines its strength concerning the transition of plastic deformation from the austenite to the ferrite phase. The misorientation can be described by means of the tilt, twist and slip direction angle between two slip planes of neighboring grains. It has been found that plastic deformation can be transferred from an activated slip system in an austenite grain to a slip system in a neighboring ferrite grain with a moderate Schmid factor, even if not-activated slip systems in this ferrite grain have higher Schmid factors. For this, the tilt and twist angle between the activated austenite slip system and the ferrite slip system with the lower Schmid factor have to be smaller as compared to that of the tilt and twist angle between the activated austenite slip system and the ferrite slip system with the higher Schmid factor. The transition is very localized and mostly followed by microcrack initiation. Beside their significance concerning microcrack initiation, phase boundaries also determine significantly the short fatigue crack propagation.

1. Introduction

Austenitic (fcc) ferritic (bcc) duplex stainless steels are used in applications, where high corrosion resistance and reasonable strength are required. Typical examples are off-shore systems for wind energy generation as well as mechanically-loaded components for the chemical and petrochemical industry. Many of these components are subjected to cyclic loadings at stress amplitudes, which are close to the fatigue limit.

The previous assumption that all bcc materials exhibit a fatigue limit, whereas it does not apply to fcc materials, is becoming more and more questionable by the latest results from experiments in the very high cycle fatigue (VHCF) regime. These findings have revealed that bcc materials may fail even beyond two million load cycles, showing a tendency to crack initiation from internal inclusions. This phenomenon is qualitatively described by Sakai [1] and quantitatively by means of the Murakami approach, where the fatigue limit is related to the inclusion size [2]. It is also proved that fcc materials can show a durability limit due to formation [3] or existence [4] of a second phase.

The mechanisms, which stop an initiation of damage in form of local plastic deformation and crack initiation in two-phase materials with different crystal structures, cannot be explained by the fatigue behavior of the single phases only. Moreover, the particular barrier effect of phase boundaries is of importance [4–9]. The mechanism-based description of this effect is the key for the understanding and assessment of the fatigue behavior of two-phase materials in the high and very high cycle fatigue regime.

In the present investigation, the effect of misorientation on the strength of phase boundaries and its significance for crack initiation and short crack propagation at high and very high numbers of load cycles were studied. For this, ultrasonic fatigue testing, high resolution scanning electron microscopy (SEM), electron backscatter diffraction (EBSD) and transmission electron microscopy (TEM) in combination with focused ion beam (FIB) preparation of TEM-lamellae were applied.

2. Experimental

Symmetric push–pull fatigue experiments were carried out by means of ultrasonic fatigue testing at about 20 kHz at room

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temperature in laboratory atmosphere. To reach this high testing frequencies, an axially symmetric hour glass shaped sample is stimulated in the range of its resonant frequency at around 20 kHz by means of an ultrasonic converter, which transfers a sinusoidal electric signal into a sinusoidal mechanical stress wave. This stress wave is magnified in its amplitude by means of a narrowing horn and transferred into the sample. The stress amplitude is maximum at the most narrow cross section of the sample. This is measured by means of strain gages during calibration and kept constant during testing by means of a control system (designed by Boku Vienna).

The investigated duplex stainless steel X2CrNiMoN22-5-3 has a two-phase microstructure consisting of the austenitic γ phase and the ferritic α phase. The chemical composition is given in Table 1 [4,8]. The heat generation of the material during the fatigue tests requires a pulse-pause mode (100 ms/1200 ms) and an air-cooling system to restrict the temperature rise to maximum 5 °C. The effective testing frequency enables the testing up to very high numbers of load cycles in a reasonable testing time (e.g., 10^9 cycles in around 7.5 days).

The fatigue samples were produced from cylindrical bars with a diameter of 25 mm by machining and subsequent grinding and polishing. The polishing was executed mechanically or electrolytically, respectively. The delivered material was hot rolled and solution annealed with a fine, lamellar microstructure and a volume fraction of approximately 50% austenite and 50% ferrite, respectively. This as-received condition was annealed at 1250 °C for 4 h, subsequently cooled down to 1050 °C within 3 h and finally quenched in water. The heat treatment was required in order to simplify the experimental investigations by means of grain coarsening. The mean grain diameters after the annealing procedure were 33 μm for the austenite and 46 μm for the ferrite phase (Fig. 1). The volume fraction of the two phases was maintained at 50% each. By means of a Hall–Petch analysis [10,11], the critical cyclic shear stresses were determined to be 137 MPa for the austenite phase and 198 MPa for the ferrite phase [8]. Further mechanical properties of the heat treated condition (HTC) and the initial condition (IC) are presented in Table 2.

The crystallographic orientations and phase distributions were investigated by means of automated electron backscatter diffraction (EBSD). The crystallogrpahic data served as basis for the calculation of Schmid factors, misorientation angles and favorable slip systems. TEM investigations of dislocation arrangements of locally plastically deformed areas and crack initiation sites were executed by means of focused ion beam preparation of TEM lamellae. Moreover, dislocation arrangements in the bulk material of runout samples were investigated by means of electrolytically thinned TEM lamellae.

Ultrasonic fatigue samples with shallow notches were examined during fatigue experiments by means of an optical far field microscope. The damage development concentrates in the shallow notch due to the stress intensification and thus, fatigue crack initiation is more likely in this region of the sample. This enabled the in-situ investigation of fatigue crack initiation and short fatigue crack propagation.

Table 1
Chemical composition of the duplex stainless steel used in this study (wt%) [4,8].

Fe	C	Cr	Ni	Mo	Mn	N	P	S	Si
Bal	0.02	21.9	5.6	3.1	1.8	0.19	0.023	0.002	0.5

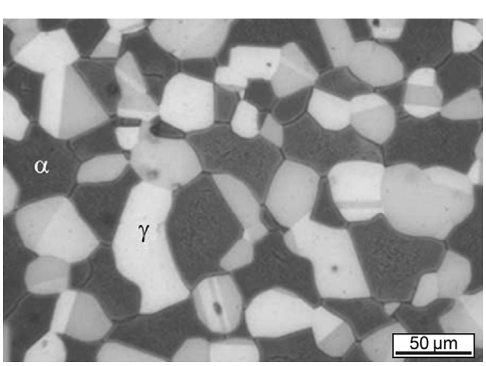

Fig. 1. Microstructure of the investigated duplex stainless steel containing austenite (bright areas) and ferrite (dark areas) after heat treatment [4].

Table 2
Mechanical properties of the heat treated condition (HTC) and the initial condition (IC).

	E [GPa]	$R_{p0.2}$ [MPa]	$R_{p0.01}$ [MPa]	R_m [MPa]
HTC	197	535	380	770
IC	197	720	615	870

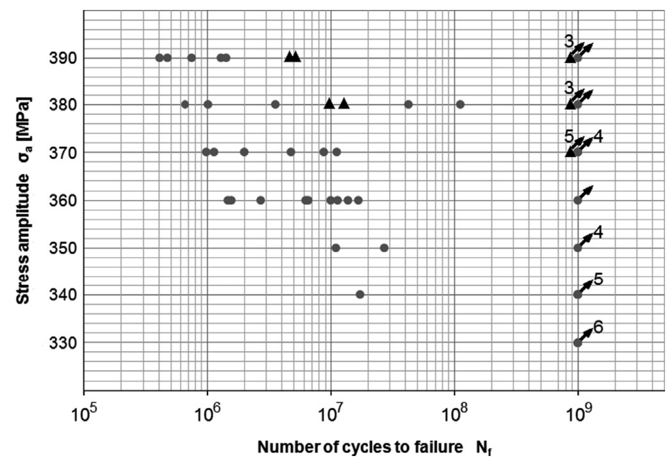

Fig. 2. *S–N* curve of the investigated duplex stainless steel tested at 20 kHz after different sample surface preparations (gray points: electrolytically polished sample surface, black triangles: mechanically polished sample surface, arrows denote runout samples).

3. Results and discussion

3.1. Phenomenological investigations

The results of the fatigue experiments at 20 kHz on electrolytically polished samples showed that fatigue cracks in the investigated duplex stainless steel predominantly initiate at the sample surface. Only when there is an extraordinary big subsurface defect, cracks initiate from the interior of the sample. This was observed solely in the case of two fatigue samples in 130 and 300 Hz experiments [4]. In order to promote internal crack initiation, mechanically polished samples were prepared and fatigued at a testing frequency of 20 kHz (Fig. 2). A delay of surface crack initiation in comparison with electrolytically polished samples was found, probably caused by compressive residual stresses in the surface resulting from the preparation. However, no internal crack initiation was observed. The fatigue experiments on electrolytically polished samples showed that surface cracks with a length of up to 120 μm initiate at the stress amplitude of 330 MPa, which defines the fatigue limit. However, these cracks do not lead to