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The effect of the embrittlement on the fatigue limit and crack propagation in a duplex stainless steel during high cycle fatigue

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ABSTRACT

In order to evaluate the effects that the "475° embrittlement" produces on the fatigue life during high-cycle fatigue, stress-controlled cyclic loading tests were conducted on a standard duplex stainless steel in two different heat treatment conditions (homogenized and embrittled). Transmission (TEM) and scanning electron microscopy (SEM) in combination with automated electron back-scattered diffraction (EBSD) techniques were carried out to analyze the surface damage as well as the initiation and propagation of fatigue cracks. These studies have revealed that the fatigue limit of the embrittled samples is substantially larger than that of the conventional samples at 10^7 cycles in the homogenized condition. Finally, an existing numerical short-crack propagation model was adapted using the stereological values obtained by EBSD to reproduce the propagation of microstructural fatigue cracks in the homogenized and embrittled conditions.

1. Introduction

Duplex stainless steels (DSS) are commercially attractive because of the excellent combination of mechanical properties and corrosion resistance obtained from a balanced amount of ferrite and austenite in the microstructure. However, this grade of steel embrittles when exposed in the temperature range of 280–500 °C limiting its application to temperatures below 280 °C. This phenomenon is called "475 °C embrittlement" since the rate of embrittlement is the highest at 475 °C. The main drawback of this embrittlement is that it modifies the tensile and fracture behavior of this steel. Many applications imply cyclic loading and thus the prediction of the fatigue life as well as the knowledge of fatigue limit is essential. Fatigue limit is based on the assumption that below a certain stress value no cycle-dependent damage occurs. Krupp et al. [1] have found that a standard DSS exhibits a technical fatigue limit up to $N = 10^8$ cycles since phase boundaries were identified as effective barriers against slip transfer. In the embrittled material, the information about cyclic behavior is very scarce. Recently, it was reported that fatigue life of a standard DSS at lower strain amplitudes is longer in the aged condition as compared to the non-aged condition. It becomes similar at intermediate strain amplitudes and it is shorter at higher strain amplitudes [2]. Crack initiation and growth in individual grains in DSS depend on the orientation, inherent strength and toughness properties of neighboring grains and it is very important to know and understand how these factors determine fatigue damage evolution. The aim of this work is to evaluate the effect that the "475° embrittlement" could produce on the fatigue life during HCF. Damage evolution and crack propagation studies were carried out combining scanning electron microscopy observations (SEM) with electron backscattered diffraction (EBSD) measurements. Moreover, the dislocation structure was analyzed and correlated with the formation and propagation of microcracks.

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Nomenclature

DSS	Duplex Stainless Steel
HV	Vickers Hardness
HCF	High-Cycle Fatigue
α phase	ferrite phase
γ phase	austenite phase
$\Delta\sigma/2$	stress amplitude
R	stress ratio, $R=\sigma_{\min}/\sigma_{\max}$
f	frequency
EBSD	Electron Back-Scattered Diffraction
SEM	Scanning Electron Microscope
TEM	Transmission Electron Microscope
SF	Schmid Factor
σ_{nn}^{i}	stress normal to slip band (element i)
τ_{tn}^{i}	shear stress parallel to slip band (element i)
b_n	normal displacement
G_{ij}	influence function
$\sigma_{nn}^{i\infty}$	external normal stress
$\tau_{tn}^{i\infty}$	external shear stress
τ_b	resistance to dislocation motion
τ_{crit}	critical shear stress
k_c	cyclic Hall–Petch constant
r	distance between the center of the sensor element and the boundary
ΔCTSD	Crack Tip Slide Displacement
ΔCTOD	Crack Tip Opening Displacement
da/dN	crack propagation rate
α	twist angle of the crack-plane deflection at a grain boundary
β	tilt angle of the crack-plane deflection at a grain boundary
LEFM	Linear Elastic Fracture Mechanics

Finally, a numerical short-crack model, which takes into account the real two-phase microstructure and its elastic/plastic anisotropy, was adapted to the embrittled condition. This model, validated by experimental data, permits to describe quantitatively the propagation behavior of microstructurally short fatigue cracks.

2. Experimental procedure

The present study was carried out on the DSS of German standard 1.4462 with chemical composition: C: 0.02; Cr: 21.9; Ni: 5.6; Mo: 3.1; Mn: 1.8; N: 0.19; P: 0.023; S: 0.002; Fe balance. The effect of the embrittlement on the damage evolution, initiation and propagation of microcracks was evaluated during HCF under stress-controlled cyclic tests in this steel in two different heat treatment conditions, homogenized and 475 °C-embrittled. In order to increase the grain size, the as-received steels was homogenized 4 h at 1250 °C followed by slow-cooling to 1050 °C and water-quenched. The resulting microstructure consists of approximately 50% austenite with a mean grain size of 30 μm embedded in 50% ferrite with a mean grain size of 27 μm, Fig. 1. Finally, the material was aged at 475 °C for 100 h, resulting in an increase of Vickers hardness values in the ferrite from 259 HV in the annealed DSS to 465 HV in the embrittled DSS.

Cylindrical specimens were manufactured for push–pull and rotating bending fatigue tests. The evolution of the fatigue damage was studied on a shallow notch by direct observation in real time using a long-distance QUESTAR optical microscope coupled to a digital camera.

Push–pull fatigue tests were carried out at room temperature in a servo-hydraulic testing system under stress control, $\Delta\sigma/2$ = 350 MPa, stress ratio $R = -1$ and frequency f = 5 Hz. The specimens were analyzed by means of analytical SEM (Zeiss Auriga) in combination with automated EBSD and transmission electron microscopy (Philips EM 300, 100 kV).

3. Experimental results and modeling

Rotating bending fatigue tests were carried out to study the effect of the embrittling heat treatment on the fatigue limit of 1.4462 DSS. The results, as shown in Fig. 2, have revealed that the embrittled condition increases the fatigue life compared with the homogenized condition during HCF.