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Investigations of twin boundary fatigue cracking in nickel and nitrogen-stabilized cold-worked austenitic stainless steels

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ABSTRACT

Implant retrieval studies have indicated that the primary cause of failure in stainless steel devices is fatigue, and time or cycles required for fatigue crack initiation often consumes the majority of implant lifetime. Stainless steels with significant nitrogen additions have shown an improved fatigue response, but have also shown a peculiar preference for fatigue crack initiations at or along annealing twin boundaries in the face-centered cubic (FCC) materials. In a recent comparison study on cold-worked implant grade stainless steels, a number of fatigue crack initiations were found along former annealing twin boundaries on both nitrogen-stabilized austentitic (HNASS) and nickel-stabilized austenitic steels. Further investigations were warranted to determine the crystallographic conditions present around these annealing twin boundary cracks, since not every twin boundary showed crack initiation. The present study examined the crystallographic conditions present around each of the former annealing twin boundary cracks relative to the applied loading direction. It was determined that the former annealing twin boundary cracks showed the complete range of misorientation deviations allowed by the Brandon criterion. The textures of the cracked twin boundaries were found to be random relative to the overall global textures of the materials. Most of the cracked twin planes in the HNASS steel were shown to be high angles, and in many cases were nearly perpendicular to the material surface. The nickel-stabilized steel showed a preference for lower twin plane inclination angles relative to the material surface. High Schmid factors were shown for all grains surrounding the cracked twin boundaries indicating each grain was oriented favorably for slip relative to the applied loading direction. A high Taylor factor mismatch was also shown across most of the cracked twin boundaries in both steels indicating strong difference in expected yield response for each of the grains which suggest localized strain incompatibility was another important factor in twin boundary cracking.

1. Introduction

Implant retrieval studies have indicated that the primary cause of failure in stainless steel devices is fatigue, so the improvements shown in the fatigue response due to nitrogen additions is of particular interest [1,2]. Fatigue crack initiation may take up to 90% of the total cycles to failure of an implant [3,4]. Implant grade "nickel-free" high-nitrogen austenitic stainless steels (HNASS) have been developed recently in response to escalating nickel costs and reports of increasing nickel-based allergic reactions in patient populations [5]. Nitrogen enhancements to steels have been shown to lower the stacking fault energy (SFE) and promote planar slip instead of the wavy slip mechanisms typically exhibited by nickel-stabilized steels such as 316L [6–15].

316L is a nickel-stabilized stainless steel with a long history of implant use. Fatigue studies on annealed 316L steels have shown crack initiation to occur intergranularly at grain or twin boundaries [16–20], or transgranularly at surface intrusions and extrusions associated with persistent slip markings [21–24]. Recently, fatigue studies have been conducted on implant grade 316L in the approximately 30% cold-worked condition as it is commonly ordered for bone fixation device manufacturing [4,25,26]. Fatigue cracks in the cold-worked steel with a 12 μm grain size were shown to preferentially initiate along slip markings, but a high percentage of intergranular cracks were also found under both low and high cycle fatigue (LCF and HCF) conditions. Of the intergranular cracks found, the majority were located along former annealing twin boundaries [26]. The prevalence of intergranular crack initiations was attributed primarily to the degree of cold-working present in the 316L alloy.

Annealed HNASS materials have shown preferential fatigue crack initiation sites at intergranular grain or twin boundaries

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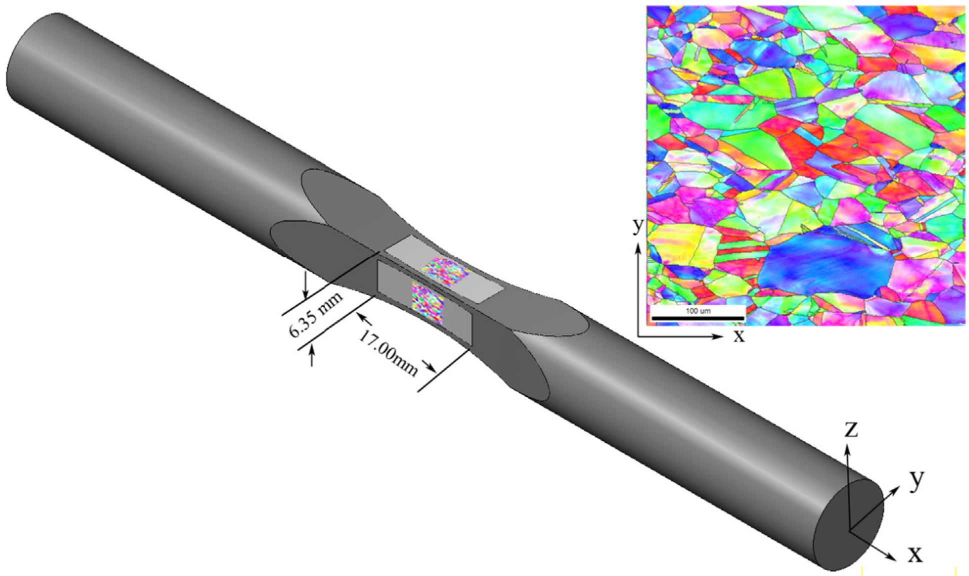

Fig. 1. Specimen design and EBSD scan placements with orientations.

[5,13,15,27] and transgranular slip bands [15]. Recently, ambient temperature fatigue examinations were conducted on 21Cr–23Mn–1N HNASS steel in the 30% cold-worked condition commonly ordered for implant manufacturing [4,25,26]. Former annealing twin boundaries were found to be a strongly preferred location for fatigue crack initiation in the cold-worked HNASS alloy under both LCF and HCF conditions [26]. The preference for twin boundary cracking was attributed to a combination of the probable low stacking fault energy of the HNASS material, the relatively large material grain size (57 μm), and the substantial degree of cold-working prior to fatigue testing.

A number of fatigue studies have modeled the unusual occurrence of annealing twin boundary fatigue crack initiations in FCC alloy systems. The formation of non-coherent boundary steps and evidence of primary or secondary slip markings on grain surfaces near twin boundaries during early fatigue cycling have been shown to be indicative of locally raised stress concentrations caused by additional surface tractions that occur due to slip interactions near twin boundaries [20,28–31]. Surface areas showing early slip accumulation near twin boundaries have been shown to form cracks along boundaries as early as 10% into the fatigue cycling lifetime [20]. Large grains and clusters of smaller grains separated by low-angle grain boundaries (LAGBs) in the microstructure have also been suggested to act as preferential intergranular crack nucleation sites due to substantial amounts of dislocation pile-up accumulating along the outer boundaries during fatigue cycling [32]. Contrasting grain orientations across twin boundaries have been shown to enhance these effects due to inelastic incompatibilities for dislocation movements across the boundaries. Materials with low stacking fault energies (SFE) have been shown to be more prone to fatigue cracking along twin boundaries primarily due to a change in the slip mode from wavy to planar which allows greater amounts of dislocation pile-ups along the boundaries [33–35]. Finally, the unfavorable alignment of twin boundaries within the material texture has been documented to promote twin boundary cracking in some steels and nickel-based materials [16,17,36].

The purpose of the present study is to further investigate the prevalence of fatigue crack initiation along cracked former annealing twin boundaries in datasets previously collected [26] for 316L and HNASS steels in the cold-worked condition as ordered for implant manufacturing. The cracked twin boundary datasets will be compared and contrasted using a series of EBSD based analyses.

2. Materials and experimental methods

2.1. Materials

316L (ASTM F 138 [37]) centerless ground bar produced by Ergste Zapp was provided by Synthes in an approximately 30% cold-worked condition. 21Cr–23Mn–1N (ASTM F 2229 [38]) HNASS bar was produced and provided by the Specialty Alloys division of Carpenter Technology Corporation in condition B (17–23% cold worked).

2.2. Experimental methods

The round-cornered square gage fatigue specimen design for the present study is shown in Fig. 1. The gage section had a 17.0 mm length and a 6.35 mm width. A filet radius of 1.59 mm was used to reduce stress concentrations at the corners of the gage section. The specimen scan orientation directions relative to the EBSD scanning procedure are also provided in Fig. 1. A detailed description of the sample preparation and the electropolishing procedure used within the gage section is provided elsewhere [26].

2.2.1. SEM/EBSD data collection

EBSD scans were performed in approximately the center of the gage section of each electropolished specimen side (Fig. 1) at 250× magnification using a hexagonal grid with a step size resolution of 1 μm. Each EBSD scan covered a surface area of approximately 350 μm^2 and therefore, the combined scanned area of the twenty-four selected regions for each alloy and fatigue cycling condition tested was approximately 3 mm^2.

2.2.2. Fatigue testing

Fatigue testing was conducted in ambient temperature air under stress control using the guidelines of ASTM F 1801[39] at 1 Hz, with the suggested R (Φ_{min}/Φ_{max}) ratio of 0.053 to mimic an average human gait cycle. Both HCF (lifetime > 100,000 cycles) and LCF (lifetime < 100,000 cycles) conditions were evaluated for each alloy system. A more detailed description of the fatigue cycling and EBSD scanning process used in this study is given elsewhere [26]. The LCF and HCF cycling procedure for each alloy