Crack growth studies in a welded Ni-base superalloy

Anand. H. S. Iyer [1,a] *, Krystyna Stiller[1,b] and Magnus Hörnqvist Colliander [1,c]

[1]Department of Physics, Chalmers University of Technology, SE-41296 Gothenburg, Sweden

[a]harihara@chalmers.se, [b]stiller@chalmers.se, [c]magnus.colliander@chalmers.se,

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Abstract. It is well known that the introduction of sustained tensile loads during high-temperature fatigue (dwell-fatigue) significantly increases the crack propagation rates in many superalloys. One such superalloy is the Ni-Fe based Alloy 718, which is a high-strength corrosion resistant alloy used in gas turbines and jet engines. As the problem is typically more pronounced in fine-grained materials, the main body of existing literature is devoted to the characterization of sheets or forgings of Alloy 718. However, as welded components are being used in increasingly demanding applications, there is a need to understand the behavior. The present study is focused on the interaction of the propagating crack with the complex microstructure in Alloy 718 weld metal during cyclic and dwell-fatigue loading at 550 °C and 650 °C.

Introduction

Understanding the behavior of superalloys at high temperatures in an aggressive environment is critical for the performance of gas turbines and jet engines. During operation, the material experiences thermo-mechanical fatigue where the cycles generally include periods of sustained load. It has been shown in various studies that the introduction of a hold time during fatigue at high temperature, termed *dwell-fatigue*, changes the fracture mode from transgranular to intergranular [1-3]. The change in the mode of crack propagation was accompanied by an increase in the crack growth rate. Sadananda *et al*. [4] and Pfaendtner *et al*. [5], among others, have investigated the influence of environment on the crack growth rate and found that the crack grew at a much higher rate in air, compared to vacuum. This has been referred to in the studies of Woodford, who coined the term Gas Phase Embrittlement (GPE) [6]. Oxygen was identified as the main embrittling element in the case of nickel superalloys [6, 7], but the specific embrittling mechanism has not been decisively determined. The influence of grain size on dwell-fatigue crack growth was studied by Pédron *et al.* [1] on wrought material which showed that coarse grained material performed better than fine grained material. The crack interaction with the secondary phases also plays an important role, where e.g. studies by Viskari *et al*. [8] and Ponnelle *et al.* [9] highlight the role of grain boundary precipitates in fracture resistance. As discussed above, the fatigue cracking in nickel superalloys at high temperature is a result of interplay of different mechanisms. However, most of the studies focus on forged microstructures. There have been no studies of dwell-fatigue in the case of welded nickel superalloys, which has a more complex microstructure. The aim of this work is to study the crack interaction with the microstructure of welds in the case of dwell-fatigue crack growth at high temperature.

Experimental

Material for testing was obtained by laser welding 6.35 mm thick sheets of Alloy 718 together, which were then solution treated and aged according to standard procedures. Specimens for mechanical testing were cut with the weld joint perpendicular to the loading direction (see Fig. 1(a)). The specimens were ground down to 4 mm thickness, ensuring straight and parallel surfaces, and the width in the rectangular gage section was 10 mm. A notch was machined at the center of the weld using Electrical Discharge Machining (EDM) to initiate the crack (see Fig. 1(a)). The testing was conducted in two different steps: fatigue pre-cracking at room temperature to generate a sharp crack with an approximate radius of 2 mm, followed by high temperature testing using either pure fatigue (at 0.5 Hz, R=0) or dwell-fatigue fatigue testing with a 15 min dwell at maximum tensile load (R=0.05). During the tests the crack size was monitored using direct current potential drop (DCPD). However, as can be seen from the fracture surface of a fractured specimen, Fig. 1(b), the crack shape did not generally develop as a semi-circle or semi-ellipse. Therefore, extraction of crack growth rates and stress intensity factors become difficult. Thus, from hereon this paper is focused on the investigations of the crack path and interaction with the microstructure, and not on the crack growth rates. The tests temperatures were 550°C and 650°C, and the tests for microscopy analysis were stopped before complete fracture in order to allow investigations of the cross-section. The specimens were then cut perpendicular to the crack surface and one of the halves was used for metallurgical preparation. Grinding using SiC papers and polishing with diamond suspension was carried out in order to prepare a surface with minimum damage to allow the use of electron channeling contrast imaging (ECCI). Using ECCI allows visualization of orientation differences, secondary phases and plastic strains in the material without further surface modifications.

Results and Discussion

Figure 1(c) shows the microstructure in the weld, which is complex compared to typical forged microstructures. The structure is equiaxed at the center and dendritic towards the sides. During solidification, Laves phases precipitate in the interdendritic regions due to Nb segregation, and then partially transform to δ during subsequent heat treatment (Fig. 1(d) and (e)).

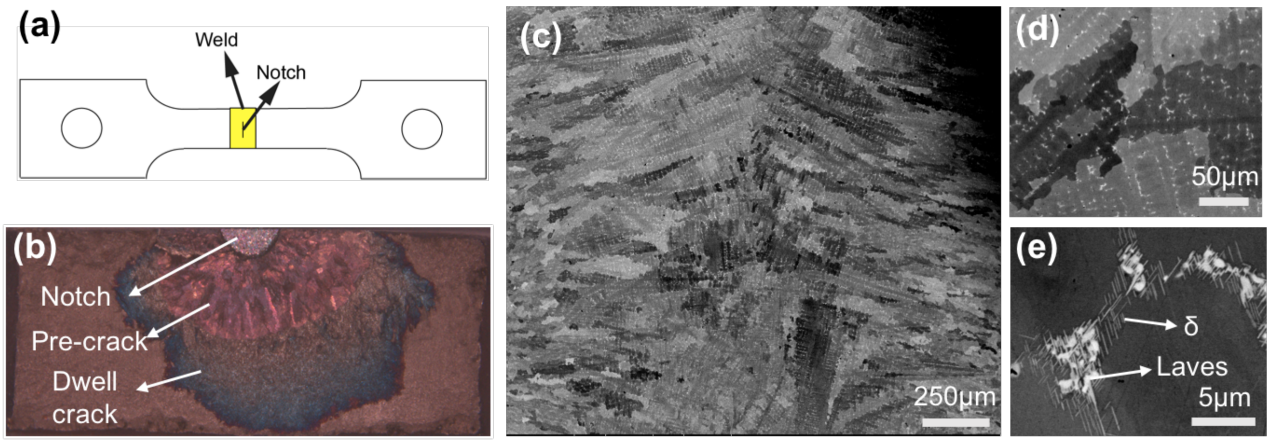

Figure 1: (a) Tensile specimen with weld and EDM notch indicated; (b) Fracture surface; (c) Overview of the weld microstructure; (d) Precipitation of secondary phases between dendrite arms; (d) Close-up of secondary phases (δ and Laves).

There is a strong temperature dependence of the crack interaction with the microstructure. During pure fatigue testing at 550 °C the crack was transgranular, and propagated perpendicular to the loading direction (Fig. 2(a)). Increasing the temperature to 650 °C resulted in mixed transgranular and apparently intergranular propagation (the term "apparently intergranular" will be explained later), with increasing tortuosity of the crack path and increased formation of secondary cracks (Fig. 2(b)). The introduction of a 15 min tensile dwell further increased the proportion of apparent intergranular cracking and the amount of secondary cracks (Fig. 2(c)).

As the crack growth mechanism changes, there is an increased interaction with the interdendtritic secondary phases. During intergranular propagation the crack encounters groups of Laves and δ phases, which cause the front to deflect (Fig. 3(a)). The fact that the particles are grouped leads to bifurcation and crack branching, which is not observed during transgranular propagation. The resulting complex three-dimensional crack geometry leads to the formation of un-cracked ligaments, which have been circumvented by the advancing crack front (Fig. 3(b)). This is consistent with the development of a damaged zone as proposed by Gustafsson et al. [10] in order to explain and model the dwell-fatigue crack propagation in forged Alloy 718.

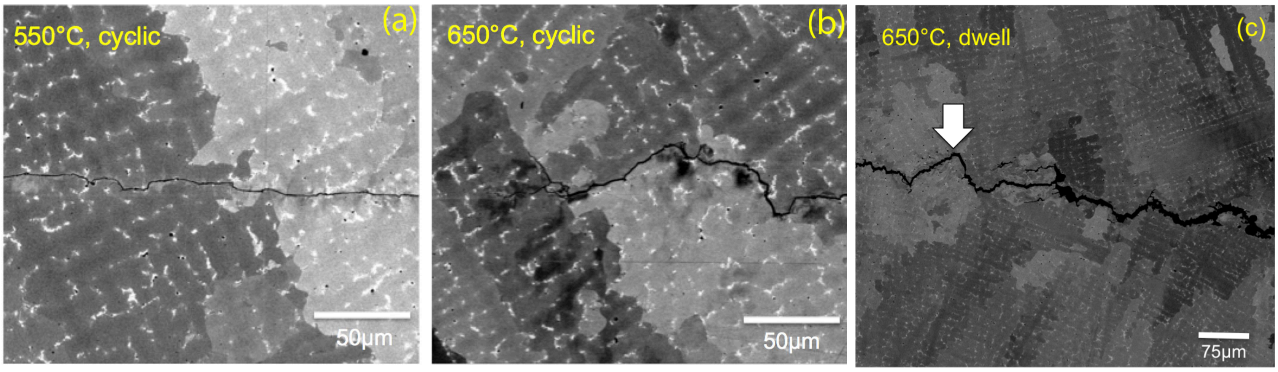

Figure 2: Interaction of crack with microstructure at different conditions. (a) Transgranular growth during fatigue loading at 550 °C; (b) Mixed transgranular and apparently intergranular growth, increasing tortuosity and secondary cracking during fatigue loading at 650 °C; (c) Apparently intergranular growth and extensive secondary cracking during dwell-fatigue at 650 °C.

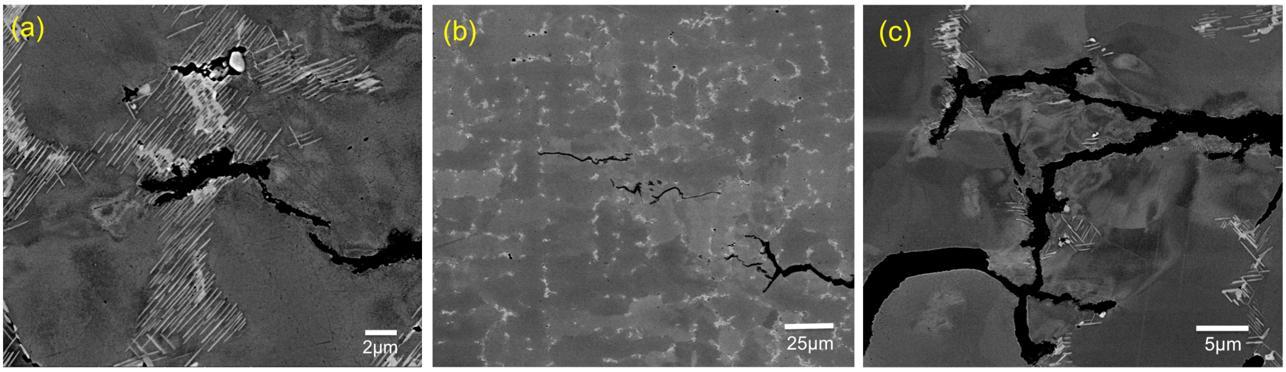

Figure 3: (a) Interaction of crack with second phase particles; (b) Complex crack tip geometry with un-cracked ligaments; (c) Plasticity around the crack.

A prominent feature seen during dwell-fatigue crack growth is the presence of extensive plastic deformation around the crack (Fig. 3(c)). The cause of the increased plasticity compared to pure cyclic loading is not clear at present. One possible explanation is that the linking of crack branches occurs by fracture of the unbroken ligaments, which suffer local plastic deformation before delayed failure [11]. Other potential explanations include contributions from creep deformation or shearing due to increased tortuosity.

The occurrence of mixed transgranular and intergranular crack growth is more clearly seen in the EBSD map in Fig. 4. In fact, the crack has mainly grown in a transgranular manner, even when the propagation direction deviates from the plane perpendicular to the applied load (e.g. at the arrow in Fig. 4). However, in such cases the crack growth direction is parallel to the direction of the dendrite arms, leading to the appearance of intergranular fracture. Thus, in dendritic microstructures both grain boundaries and interdendritic regions can act as preferential paths for dwell-fatigue crack propagation. Interestingly, the strong interaction with secondary phases during propagation of the crack could potentially offer the possibility to tailor the microstructure for increase dwell-fatigue resistance.

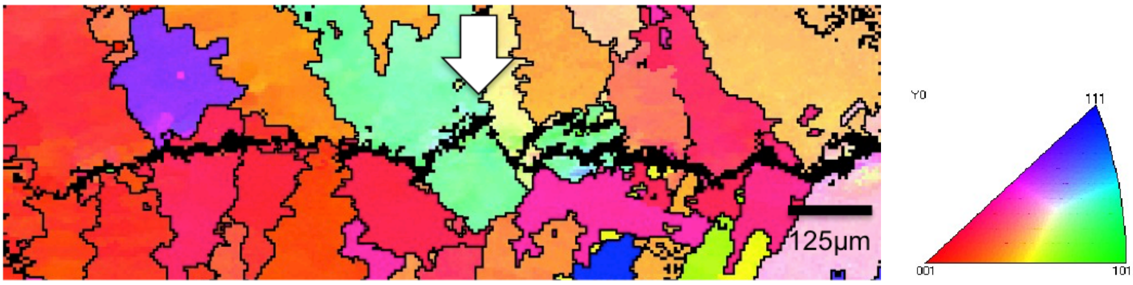

Figure 4: EBSD map with IPF colouring (indicating the vertial loading direction) shows both transgranular and intergranular crack growth. The white arrow shows the same feature as in Fig. 2(c).

Conclusions

The present work is focused on the effect of temperature and dwell times on the propagation of cracks, and their interaction with the complex microstructure, in the weld metal of Ni-Fe-base superalloy Alloy 718. The following conclusions can be draw from the studies conducted:

- The combination of temperature and load cycle plays a pivotal role in interaction between the crack and microstructure during fatigue.
- Introduction of a dwell time increases the tendency for apparent intergranular crack growth, secondary cracking and branching due to interaction with secondary phases.
- Dwell-fatigue crack growth in weld microstructure is not strictly intergranular (as in the case of forged microstructures), but rather the crack propagates in grain boundaries and along interdendritic regions.

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