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Influence of dwell time on fatigue crack propagation in Alloy 718 laser welds

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ABSTRACT

The introduction of welded assemblies in aerospace components aid in weight reduction, but also lead to an increased risk of defects. It is therefore important to analyze the high temperature crack growth resistance of such welds. The results from high temperature cyclic and dwell-fatigue testing of surface flawed Alloy 718 welds are presented here. An increasing temperature and application of a dwell time accelerate the crack growth and increase interaction with secondary phases. During cyclic loading at 550 °C, there is little interaction with the microstructure during transgranular propagation, but the application of dwell times results in a mixture of transgranular propagation and intergranular cracking of boundaries between different dendrites. At 650 °C, mixed intergranular and transgranular mode of crack growth is seen under both cyclic and dwell conditions. However, during dwell-fatigue the interfaces between the secondary arms of the same dendrite are also weakened, leading to an interfacial type of crack growth also in the intergranular parts.

1. Introduction

Due to increasing environmental concerns, the focus on sustainability has been intensified in virtually all fields of engineering. One of the aspect of sustainability in the transportation industry is the reduction of emissions. For the aero engine industry, this translates to either changing to more sustainable fuel options ("green fuels", which are currently under development but not in commercial use), or increasing the engine efficiency. Two common ways of addressing an increased efficiency are through an increase in operating temperature (thereby consuming less fuel for a given distance) and/or a reduction of the engine weight (which reduces the total dead weight of the airplane). Increasing the operating temperature requires new or modified materials that can withstand the higher temperature, whereas weight reduction can be done through optimization of both individual components and engine design. One of the ways to achieve weight reduction on the individual component level is to change the manufacturing process from casting to welded assemblies [1]. This allows the production of smaller and better optimized parts and sub-components made of sheet metal, forgings, and cast materials, which can be joined together by welding.

However, a consequence of this approach is the presence of welds in the load path of the structures. Welds are generally the weaker parts in an assembly, with an inherent risk of manufacturing defects, which raises concerns regarding fatigue life and crack growth behavior in welded structural components. During operation, these components experience variations in thermal and mechanical loads in an oxidizing atmosphere, leading to multiple factors contributing to the crack growth at high temperature, such as fatigue, creep, oxidation, plasticity and combinations of these [2]. Consequently, the use of welded structural components requires materials with both good weldability and high temperature mechanical properties.

One such material is Alloy 718, which has been used in gas turbine components like turbine discs over a long period of time. It is a γ" strengthened alloy which has a maximum operating temperature of 650 °C, and has an excellent combination of high temperature properties and very good weldability due to the sluggish precipitation kinetics of γ" precipitates [3]. However, it has been shown in previous studies that the application of a tensile dwell time during fatigue testing (referred to as dwell-fatigue) in oxidizing environment, representative of more service-like loading conditions, causes a significant increase in crack growth rate compared to pure cyclic fatigue [4–7]. This is a critical issue for the design of safe and reliable aero engine components. Several different mechanisms have been proposed for this increase: dynamic embrittlement (DE) which involves the diffusion of oxygen into grain boundaries resulting in their embrittlement [8]; stress

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assisted grain boundary oxidation (SAGBO) [9] which leads to formation of an oxide ahead of the crack tip and crack propagation occurs through repeated fracture of the brittle oxide; or oxidation of primary Nb grain boundary carbides [10]. Although the relative contributions and synergies between the different mechanisms have not been clarified, recent evidence stemming from high-resolution microscopy and microanalytical investigations of crack tips in specimens from dedicated tests seem to point towards SAGBO as a main factor during high temperature dwell-fatigue of Ni-base superalloys [11,12].

The susceptibility to dwell-fatigue cracking is mainly determined by the microstructure. It has been shown that parameters such as grain size [13,14] and the presence [15] and distribution [16] of delta phase can have drastic effects on crack growth rates. Studies on the effects of batch-to-batch variations have confirmed that even a small change can have a significant effect [17]. However, all available dwell-fatigue crack growth studies have been performed on forged materials (sheets, plates or forgings). No information is presently available on crack propagation in Alloy 718 welds, which present very different microstructures compared to plastically worked materials. This is potentially a critical issue when structural welds are introduced in assemblies.

This work focuses on the fatigue behavior of laser welded Alloy 718 sheets in order to understand the effect of dwell time on the crack growth behavior. Fatigue specimens with an artificially introduced surface defect in the welds were tested at temperatures of 550 °C and 650 °C under cyclic and dwell-fatigue conditions. Results are presented in the form of crack growth data and electron microscopy of crack cross sections, which together are used to understand the dwell-fatigue crack growth in Alloy 718 weld metal.

Additionally, additive manufacturing has garnered attention in the aerospace manufacturing sector due to its versatile design capabilities. We would like to point out that the solidification microstructure generated through many additive manufacturing processes, particularly those with high deposition rates, is similar to those found in welds [18,19]. Thus, the problems experienced in additively manufactured components can be expected to be similar to those of structural welds. The findings in the current study clearly emphasize the need to consider these issues in such parts.

2. Experimental procedures

2.1. Materials and testing conditions

Welded sheets of Alloy 718 were used for the study conducted. The 7.1 mm thick sheets were joined using laser welding, and subsequently solution treated and aged according to standard procedures (solution treatment at 954 °C followed by two-step ageing at 760 and 649 °C).

The high temperature fatigue testing was conducted on surface flawed specimens with a weld at the center (Fig. 1), machined from the welded sheets. A starter notch of radius 0.55 mm was machined using spark erosion technique at the center of the weld after revealing the weld through etching. The specimens were then pre-cracked at room temperature using a stress ratio $R = 0$ and a frequency $f = 10$ Hz to obtain a semi-circular crack with a radius of 1.75 mm. Pure cyclic fatigue and dwell-fatigue tests were carried out at 550 and 650 °C. Testing details are summarized in Table 1.

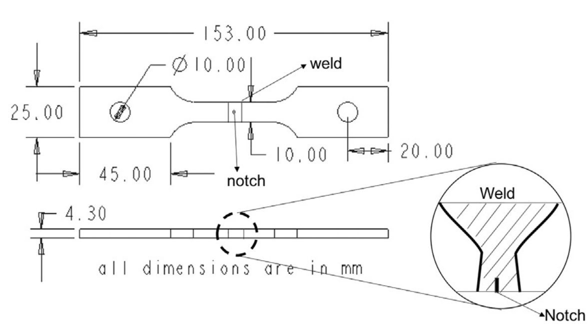

Fig. 1. Geometry of surface flaw type specimen used for fatigue testing.

Table 1
Test details of specimens.

ID	Temperature (°C)	Condition	Stress ratio, R	Frequency, f (Hz)
550c	550	Cyclic fatigue	0	3.3
550d	550	15 min dwell	0.1	0.001
650c	650	Cyclic fatigue	0	3.3
650d	650	15 min dwell	0.1	0.001

For the cyclic specimens, a load controlled cycle with 3.3 Hz frequency and $R = 0$ was used. The specimens were heated using induction coils and the temperature was monitored using a spot-welded thermocouple. For dwell conditions, a dwell time of 15 min was used. The load was then decreased to 10% of the maximum load and reloaded ($R = 0.1$). The unloading and reloading together takes about 100 s. The specimens were heated in a resistance furnace and the axial temperature gradient was maintained within ± 1 °C. All tests were conducted in ambient air. The testing was stopped before rupture in order to enable the examination of crack path using microscopy. The crack growth was measured using a direct current potential drop (DCPD) method according to ASTM E647 [20]. This method uses the change in resistance of the cracked cross section which is converted to crack size. A constant DC current is passed through the specimen and the potential drop across the crack plane is measured by spot welded probes placed on either side of the crack. To remove the influence of current or temperature fluctuations, the measured signal is normalized by a reference signal obtained from probes attached far from the cracked cross-section. The potential drop across the crack increases as the crack propagates because the area of the uncracked ligament reduces. This drop is converted into crack size by performing a calibration. The calibration for DCPD signal vs crack size was performed using ruptured specimens by examination of the crack surface. The stress intensity factor range (ΔK) was calculated according to [21] assuming a semi-circular crack since no information on the crack shape evolution during crack growth was available.

2.2. Microscopy and characterization

The tested specimens were first cut using a Isomet2000 high speed saw in order to separate the crack region from the fatigue specimens. Fracture surfaces of ruptured specimens were examined in the stereo optical mode using a Zeiss steREO Discovery V20. Unruptured specimens were cut along the loading axis using a Isomet low speed saw in order to reveal a crack cross section. The samples were mounted in a conductive resin and prepared in accordance with standard metallographic preparation scheme. The initial steps in the preparation involved grinding using SiC papers up to a grit size of 1200. It was followed by diamond polishing using 3, 1 and 0.25 μm particles for 15–20 min each. The final step involved oxide polishing using colloidal silica. This results in a surface with a superior quality ideal for microscopy and microanalysis. Electron channeling contrast imaging (ECCI) was used to image the cracks in a FEI Quanta 200 FEG-ESEM. The contrast in ECCI is obtained from the orientation difference of different grains with respect to the sample surface. Grains with their planes oriented parallel to the beam channels more electrons than the ones with their planes perpendicular to the beam [22]. This not only allows clear visualization of different grains and phase, thus eliminating the need for chemical etching, but also enables the detection of plasticity around the crack due to higher dislocation density. Electron backscatter diffraction (EBSD) was performed in a LEO Ultra 55 FEG-SEM using a HKL Channel 5 EBSD system with a Nordlys II detector, for obtaining crystallographic information in relation to crack propagation.