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On the mechanism of dynamic embrittlement and its effect on fatigue crack propagation in IN718 at 650°C

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Abstract

IN718 is a commonly used nickel-base alloy for high temperature applications, e.g., in gas and steam turbines. At elevated temperatures, this and other superalloys are prone to the failure mechanism "dynamic embrittlement". Dynamic embrittlement can be considered as a kind of stress corrosion cracking, driven by tensile-stress-controlled oxygen grain boundary diffusion. Oxygen embrittles the grain boundaries by weakening the grain boundary cohesion resulting in fast and brittle intercrystalline crack propagation. In order to reveal the mechanism of dynamic embrittlement, high-temperature fatigue crack propagation tests were carried out at 650°C applying various dwell times and testing frequencies. Most of the tests were performed in laboratory air, but some experiments were run in vacuum as well, in order to eliminate environmental effects and, hence, to define the reference fatigue crack propagation behaviour. The observations show that at low stress intensity factor ranges ΔK_I, continuous crack growth occurs. At intermediate values of ΔK_I, no crack propagation takes place during the dwell part of the cycle. Rather, the crack extends during unloading and reloading between subsequent hold times. The time necessary to grow the crack under sustained load during the dwell time was found to decrease with increasing stress intensity factor. Therefore, at high values of ΔK_I, there is a contribution of the crack propagation at constant stress, since the incubation time is shorter than the dwell time. A mechanism-based model was developed for the range of test parameters, where intergranular and transgranular areas exist side by side in the fracture surface. The total crack growth per cycle is calculated by a linear combination of the intergranular and the transgranular contribution using the corresponding area fractions as weighting factors. It is shown that simulation calculations based on this model approach correspond very reasonably to the experimental observations. Hence, the model provides a quantitative mechanismen-related description of the effect of dynamic embrittlement on fatigue crack propagation rate.

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Keywords: IN718; Dynamic embrittlement; Intergranular fatigue crack propagation; Oxygen diffusion; Damage zone formation; Fatigue lifetime

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1. Introduction

Dynamic embrittlement of Ni-based alloys can take place at temperatures above 500°C. Different mechanisms were proposed in the literature, in order to explain the premature intergranular failure. Pfaendter and McMahon (2001) developed a well-accepted model that comprises of three steps. In the first step oxygen diffuses along grain boundaries in front of the crack tip. The diffusion is activated by high temperatures and promoted by tensile stresses. The oxygen embrittles in the second step the grain boundary leading to grain boundary decohesion. Finally, in the third step the external stress breaks the grain boundary open. A comprehensive consideration of this and corresponding theories on dynamic embrittlement with special emphasis on the alloy IN718 can be found in Krupp (2005) and Krupp (2007).

A slightly different model was introduced by Kang et al. (1995) and is commonly termed SAGBO (Stess Assisted Grain Boundary Oxidation). Here, the diffusing oxygen reacts with an alloying element, such as Niobium in IN718, at grain boundaries ahead of the crack tip forming an oxide. This oxide is considered to be responsible for the embrittling effect and the fast intercrystalline crack propagation. Ma and Chang (2003) have taken this idea up and tried to measure the SAGBO-induced damage zone by determining the zone of accelerated room temperature fatigue crack propagation after a prior hold time at 650°C. However, in a reply to a comment on this study (Ma et al. (2006)) they stated that the damage in front of the crack tip may not be caused by the reaction of grain boundary oxygen to an oxide.

The concept of an oxygen-induced damaged zone was also pursued in recent investigations and particular in studies performed in Sweden (Viskari et al. (2011), Hörnquist et al. (2010), and Gustafsson et al. (2011)). The results obtained convincingly show that a damage zone forms in front of a fatigue crack manifesting itself by a transient crack propagation behaviour after a change from a dwell time cycle to a fatigue cycle of high frequency. The crack grows fast through the damage zone and establishes its normal propagation rate after having reached the end of the damaged area. The transient region increases with increasing temperature and dwell time. According to Gustaffson et al. (2011) a parabolic time dependence, which is typical of diffusion-controlled mechanisms, holds true.

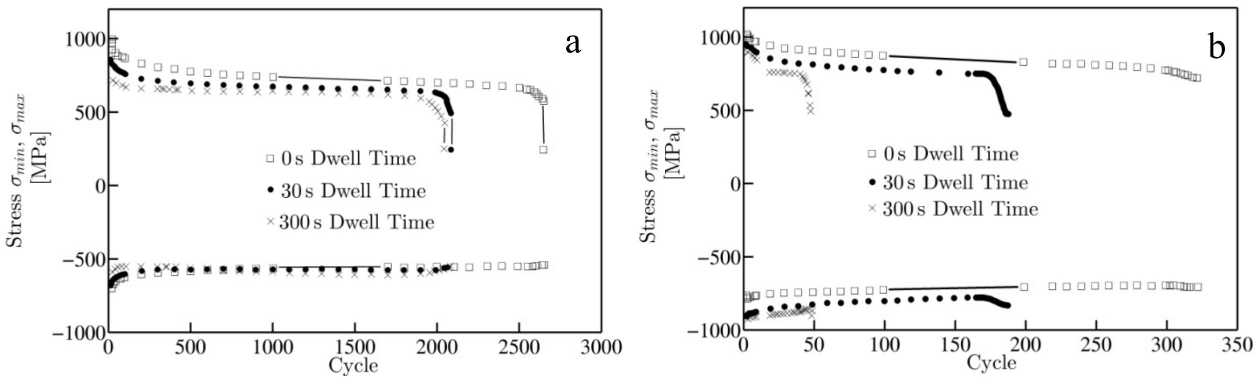

Fig. 1. Cyclic deformation curves of dwell time tests in (a) vacuum and (b) air on IN718 under strain control at a strain amplitude of 0.7% and 650°C applying dwell times of 0s, 30s, and 300s (from Wagenhuber et al. (2005))

Besides the dwell time, the oxygen from the environment (mostly air) plays an important role in the process of dynamic embrittlement, since oxygen is considered to diffuse from the crack tip into the material along grain boundaries. Hence, the extent of fatigue lifetime reduction must be strongly connected to the oxygen (partial) pressure of the ambient atmosphere. In Fig. 1 cyclic deformation curves of strain-controlled dwell time tests at 650°C are depicted, which have been carried out in vacuum (Fig. 1a) and in laboratory air (Fig. 1b) on IN718 (Wagenhuber et al. (2005)). It is evident from the results that the number of cycles until failure is even for the tests without dwell time almost one order of magnitude higher in vacuum as compared to air environment. The effect of dwell time is negligible in vacuum (Fig. 1a), since time-dependent effects such as environmental attack and creep