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An investigation of micro-mechanisms in hydrogen induced cracking in nickel-based superalloy 718

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ABSTRACT

Hydrogen embrittlement of the nickel-iron based superalloy 718 has been investigated using slow strain rate tests for pre-charged material and also in-situ hydrogen charging during testing. Fractography analyses have been carried using scanning electron microscopy, electron back-scattering diffraction and orientation image microscopy concentrating on the influence of microstructural features and associated micro-mechanisms leading to hydrogen induced cracking and embrittlement. It was observed that hydrogen induced transgranular cracking initiates at micro-voids in the crystal lattice. Similar behaviour has been observed in multi-scale finite element chemo-mechanical numerical simulations. In contrast, hydrogen induced localized slip intergranular cracking was associated with the formation of micro-voids in intergranular regions. The effects of grain boundary and triple junction character on intergranular hydrogen embrittlement were also investigated. It was observed that low end high angle misorientations (LHAM), $15^\circ < \theta \leq 35^\circ$, and critical high angle misorientations (CHAM), $35^\circ < \theta \leq 50^\circ$, are preferential sites for hydrogen induced cracking. In contrast, few or no hydrogen induced cracks were observed at low angle misorientations (LAM), $0^\circ \leq \theta \leq 15^\circ$, high end high angle misorientations (HHAM), $50^\circ < \theta \leq 55^\circ$, or special GB misorientations (SGB), $\theta > 55^\circ$. Finally, the use of grain boundary engineering techniques to increase the resistance of super alloy 718 to hydrogen induced cracking and embrittlement is discussed.

1. Introduction

Superalloys are widely used in a variety of applications including aerospace and land based gas turbine engines, nuclear power plants and chemical plants. This group of materials possess a range of superior properties in elevated temperature applications which are difficult to obtain from other groups of materials [16]. Their main advantage is retention of strength at high temperatures (typically ≥ 500 °C) coupled with adequate ductility. Despite their advantages these alloys are know to be susceptible to degradation caused by the ingress of hydrogen which causes the material to become brittle. The aerospace industry has experienced hydrogen embrittlement problems for many years [21,49,72]. Hydrogen embrittlement is a delayed failure mechanism related to loss of ductility due to the presence of hydrogen in the material. Hydrogen may enter the material during manufacturing processes such as welding or electroplating where this is usually termed 'internal hydrogen embrittlement'. Hydrogen may also enter the material from the surrounding environment during service exposure and this is known as 'environmental hydrogen embrittlement' [3,12,15,51]. Hydrogen is a common fuel in rocket engines and these rocket engines are made of polycrystalline Nickel and Nickel based super alloys 718 especially in combustion chambers. It is well known that hydrogen causes embrittlement in many polycrystalline materials, including high nickel content polycrystalline alloys, and catastrophic failure can occur in hydrogen fuel rocket engine components [25,32–34,65].

Alloy 718 is a multi-component alloy containing several alloying elements and is commonly used in the aerospace industry [5,48,50,58]. In the aerospace sector Alloy 718 is used in large static casings, as well as in rotating disks used in aero engines, Fig. 1. Alloy 718 possesses a complex microstructure which is known to be

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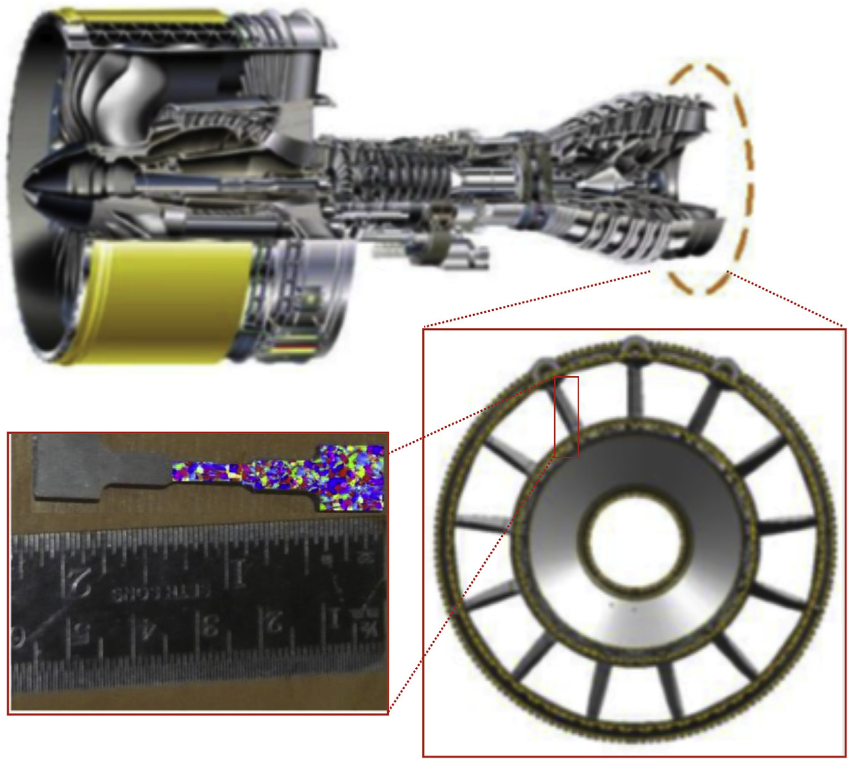

Fig. 1. An example of a commercial aero engine with load carrying alloy 718 structures in the rear part of the GP7000 engine and the sample specimen used for this investigation.

susceptible to hydrogen embrittlement which can lead to delayed failure.

In terms of microstructure it is known that grain boundaries play a pivotal role in hydrogen induced cracking and embrittlement in polycrystalline metallic materials, including superalloy Alloy718, [10,23,24,27,31,46,59,60,63,67]. Also, intergranular regions represent preferential sites for crack nucleation and propagation in intergranular hydrogen induced cracking and intergranular hydrogen embrittlement [4,26–30,35,51]. Triple junctions may also play a significant role in the intergranular hydrogen induced cracking in polycrystalline materials. Compatibility stresses at triple junctions may act as preferential sites for cavitation leading to crack nucleation and propagation [28,29].

Researchers have investigated the metallurgical nature of grain boundaries and intergranular regions in an attempt to correlate microstructural features with an alloy's susceptibility to hydrogen embrittlement and cracking. It has been reported previously that the grain boundary character distribution (GBCD) based on coincidence site lattice (CSL) shows that high angle grain boundaries (HAGBs) act as preferential sites for crack nucleation in polycrystalline materials [36,63]. Other general reported observations [2,9,43,62,67,68];

(i) Cracks never nucleate at low angle grain boundary (LAGBs).
(ii) Coherent ($\Sigma3$) twin boundaries act as potential sites for crack nucleation.
(iii) Twin boundaries provide improved resistance to intergranular cracking in FCC and BCC polycrystalline materials.

The importance of grain boundaries has led to grain boundary engineering methodologies being applied to nickel based super alloys to enhance resistance to fracture [7,37,40,47,54,56]. However, there is still work to be done to fully investigate the connection between intergranular hydrogen induced crack nucleation/propagation and grain boundary and triple junction character. It is also important to investigate the interaction of hydrogen with slip systems in intergranular regions. Despite many studies on hydrogen embrittlement in superalloy Alloy718, very little information is reported on the relationships between the following:

- Micro-mechanisms of hydrogen induced slip localization, intergranular micro-void formation and intergranular hydrogen cracking/embrittlement.
- Micro-mechanisms of micro-void formation in the crystal lattice and hydrogen induced transgranular cracking.
- Grain boundary misorientations, triple junction character and hydrogen induced intergranular cracking phenomena.

In the present study, the main aim is to investigate the points above using slow strain rate tests on hydrogen charged Alloy 718 material coupled to scanning electron microscopy (SEM), electron back-scattering diffraction (EBSD) and orientation image microscopy (OIM) observations of failed material in order to explore ways of increasing resistivity to hydrogen induced cracking/embrittlement.

Ultimately an improved understanding and quantification of these phenomena should give rise to improved computational predictive tools for manufacturing industry, and this is the spirit in which the current work is presented. As will be shown below different types of grain boundaries and combinations of grain boundaries behave quite differently during the ingress and accumulation of hydrogen. Such behaviour needs to be captured correctly both to improve models and also to be able to devise practical methodologies to reduce hydrogen induced failure.