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Localized microstructural characterization of a dissimilar metal electron beam weld joint from an aerospace component

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ABSTRACT

Hydrogen induced cold cracking (HICC) and hydrogen embrittlement (HE) are influenced by the microstructural evolution, residual plastic strain (i.e. local misorientation), recrystallization of grains and the resultant grain boundary characteristic distribution (GBCD) brought about by welding processes. HICC and HE are known to cause failures in aerospace components and it is vitally important to quantify the microstructural evolution, degree of residual plastic strain and determine the GBCD across dissimilar weld joints in order to assess the susceptibility of the weld joint to these phenomena. In this investigation a full a microstructural characterization study was carried out at various locations within and around a dissimilar weld joint of pulse-plated nickel (PP-Ni) and Inconel 718 (IN718), taken from an aerospace component. Areas examined included the base metals, weld fusion zone and heat affected zones on both sides of the weld joint, formed via electron beam welding. Scanning electron microscopy (SEM) in combination with electron backscatter diffraction (EBSD) was employed to measure the residual plastic strain, grain structure, grain size distribution, crystal orientation distribution, grain boundary misorientation distribution and GBCD of the dissimilar metal weld joint. Finally a metallurgical examination was carried out using SEM on the IN718 HAZ in order to investigate the secondary phase precipitation arising from the welding process. The results shows large variety of GBCD, crystallographic orientation distribution, local plastic strain distribution and grain size, shape and structure distribution across dissimilar weld joint. And these localized microstructural characterized data sets need to be carefully transferred using data-driven approach in order to develop predictive multiscale material modelling for hydrogen induced cracking and hydrogen embrittlement.

1. Introduction

Hydrogen embrittlement (HE) and hydrogen induced cold cracking (HICC) or cold cracking are costly problems in which structural degradation of the susceptible material can lead to catastrophic failure [1–10,12,17,29,47,48,59,60]. Several catastrophic failures have occurred in metallic material components due to hydrogen embrittlement and one such recent example is a long bolt in the 222-metre Leadenhall "cheese grater building" — the second tallest building in London, further details can be found elsewhere [11]. Another notable example is related to the San Francisco–Oakland bay bridge. In March 2013, the shear key anchor safety rods catastrophically failed due to hydrogen embrittlement during the latter stages of construction. These 5 m long 3-inch diameter threaded safety anchor rods, designed to protect the bridge in the event of seismic activity completely snapped into two parts. [1, 37–38].

HE, HICC and stress corrosion cracking (SCC) in the weld heat affected zone (HAZ), adjacent base metal and HAZ/base metal interfaces can be related to residual stresses present after electroplating and welding processes. Indeed, the presence of residual plastic strain within welded joints has caused concerns within the aerospace industry [12–14]. Hydrogen diffuses towards the tensile residual stress and residual plastic strain and segregates at these regions [12]. The base metal to HAZ interface between nickel and nickel based alloys has a complex microstructure. Grain recrystallization takes place in the HAZ under the thermal effect of the welding process. This can result in residual plastic strains and also changes in the grain structure and GBCD, ultimately leading to altered material properties and resistance to hydrogen embrittlement. A full understanding of these microstructural changes is of great scientific importance in order to determine the susceptibility to hydrogen embrittlement within the HAZ/Base Metal (BM) interface and ultimately the structural integrity of the weldment and component. Scanning Electron Microscopy (SEM)/Electron Back scatter diffraction (EBSD) are an effective tool for measuring the microstructural features

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such as grain size, shape and distribution, crystal orientation, local misorientations (i.e. residual plastic strain) and GBCD [14–18].

The microstructural morphology such as crystal structure, grain size, grain shape, grain boundary characteristic distribution, crystal orientation, grain boundary misorientation, pores, atomic defects, triple junctions affects the bulk diffusion of hydrogen and distribution, segregation of hydrogen in metallic polycrystalline materials. Atomic hydrogen diffusion properties are different in grain interior, grain boundaries, triple junctions [5,6,8,13,24,26–28,30,35,38,68]. And also different in different types of grain boundaries such as low angle grain boundary, high angle grain boundary, random grain boundaries, coincidence site lattice (CSL) and also it various depends on the connectivity of grain boundaries in triple junctions [54,56–58]. The microstructure features and microstructure inhomogeneity are significantly affects the distribution and segregation of atomic hydrogen leads to affects the mechanical properties, strength, ductility and structural integrity of the materials as well as hydrogen induced crack nucleation and crack propagation in the dissimilar weld joints of columnar and polycrystalline metallic materials. So it is important to understand microstructure features and characterize the weld joints microstructure.

In the present study, SEM and EBSD are utilised to investigate the microstructural evolution within dissimilar weld joints, the degree of residual plastic strain and Grain Boundary Character distribution (GBCD) across a weld joint, the heat affected zone and the base metals (BM) in this joint. A metallurgical examination was carried out in order to understand the secondary phase precipitations within the HAZ in IN718 side using SEM. The specimen examined was taken from an actual aerospace component and is made of pulse-plated nickel (PP-Ni) and Inconel 718. The results are used to access the susceptibility of the part to hydrogen embrittlement.

2. Experimental methods

2.1. Materials and characterization procedure

A dissimilar metal joint, manufactured via electron beam (EB) welding and comprising PP-Ni and Inconel 718 was sectioned from an aerospace component and used for the material characterization within this study. The chemical composition of alloy 718 in weight percentage (wt.%) is shown in the Table 1. The PP-Ni was manufactured using electroplating process were metal ions in the solution are moved to coat an electrode by an applied electric field under galvanostatic conditions. The normalized current density applied for pulse platting process to synthesis nickel as structural material was 150 and detail explanation about the manufacturing of PP-Ni can be found elsewhere [12,47]. The average concentration of impurity content in manufactured structural PP-Ni in parts per million (PPM) is shown in Table 2 and hot gas extraction method was used to measure the average concentration of impurity content and its detail information can be found elsewhere [12,47].

Fig. 1(a) shows a schematic diagram of the materials (PP-Ni/IN718) within the joint, (b) illustrates the position of the rolling direction (RD), transverse direction (TD), and normal direction (ND) of the specimen within the EBSD system and (c) is a macro-image of the dissimilar metal weld joint. EBSD micrographs were taken from the RD-TD plane so that the RD is vertical and the ND is horizontal. The section was prepared by mechanical grinding using P280 SiC grid paper for 3 min and mechanical polishing with 9 μm and 3 μm diamond suspensions for 5 min and 10 min respectively. Final polishing utilised 0.02 μm colloidal silica for 30 min to ensure a good surface finish. Electron backscatter diffraction analysis of the specimen was carried out using an Oxford Instruments channel 5 HKL system interfaced to a SEM. Analyses were performed at an accelerating voltage of 20 kV with a probe diameter (or) beam spot size of 7 nm. Several EBSD runs were carried out at various locations within the joint, namely, along the dissimilar weld joint root, above the weld root, within the In718 HAZ and base metal and within the PP-Ni HAZ and base metal. A step size of 0.2 μm and 4 μm was used in the EBSD analyses and more detailed information about post processing of the EBSD results and applying these data in multiscale modelling can be found elsewhere [19,20].

Table 2
Shows the average concentration of impurity content in PP-Ni in PPM.

Hydrogen	oxygen	sulphur	carbon	Nitrogen
5	25	50	42	2

In order to minimise the chance of any mis-indexing errors, nine Kikuchi bands were used for indexing. HKL-Tango software was used for post processing of the EBSD measured data in order to gather microstructural information such as grain boundary types, grain structure, grain size and crystallographic orientation distributions. In order to eliminate orientation noise, a 2° misorientation angle was used as a cut-off point. Misorientation angles of 15° or less were used to define low angle grain boundaries (LAB). All the EBSD and SEM micrographs were taken in the RD-TD plane.

3. Results and discussion

The experimental results are divided into five sections as follows.

- In the first section, the grain structure and sizes of the dissimilar base metals and the microstructural evolution within the dissimilar weld joint have been studied.
- In the second section, the crystallographic misorientation distributions are mapped for the regions within and around the weld joint.
- The third section focusses on mapping the grain boundary characteristic distribution (GBCD) from the base metals and the highly deformed weld fusion zone (FZ), coarse grained heat affected zone (CGHAZ) and the less deformed fine grained hat affected zone (FGHAZ).
- In the fourth section, metallurgical examination has been carried out on the HAZ in In718.
- Finally, the local residual plastic strain concentration (i.e. local misorientation distribution) as the function of distance from the weld was measured.

3.1. Microstructure of the dissimilar base metals and microstructural evolution within dissimilar weld joints

It has been reported by Oudriss and co-authors that change in the microstructural grain size affects the hydrogen permeation flux which is associated with the diffusion of hydrogen [5]. And the decreases in equiaxed polygonal structured grain size in pure nickel, increases the diffusivity of hydrogen at 300 K. Jothi and co-authors reported that steady state hydrogen flux is smaller in larger grains which lead to decrease in the diffusivity of hydrogen when grain size increases. And increase in the volume fraction of grain boundaries and triple junction also increases the effective diffusion of hydrogen in the bulk

Table 1
Shows the chemical composition of alloy718 in weight percentage (wt.%).

Al	B	C	Nb	Co	Cr	Cu	Fe	Mo	Ni	P	S	Si	Ti	Ta
0.58	0.004	0.067	4.93	0.55	18.1	0.07	18.5	3.06	53.1	<0.005	<0.002	0.06	1.03	<0.05