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A study of intergranular fracture in an aluminium alloy due to hydrogen embrittlement

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ABSTRACT

This work concerns a study of the effects of plasticity on the mechanism of intergranular cracking assisted by hydrogen induced embrittlement in an aluminium alloy. Here, tensile specimens charged with hydrogen were used to investigate quantitatively the effect of plastic deformation on the mechanism of intergranular crack initiation at the scale of the individual grains. An experimental procedure was set up to monitor the evolution of surface strain fields on in situ tested SEM notched specimens using digital image correlation techniques. In addition, measurements of the associated crystal orientation evolution at the micron scale were carried out using electron backscatter diffraction (EBSD). These measurements were then compared with finite element predictions of the local strain fields on the observed regions of the in situ specimen. The numerical predictions were obtained using a dislocation mechanics-based crystal plasticity model to describe the constitutive behaviour of each individual grain. The crystallographic grain orientations of the region of interest were discretised for the finite element analyses from EBSD maps. From this study, it was found that intergranular cracking due to hydrogen embrittlement in the Al alloy is locally triggered by high tensile grain boundary tractions, here estimated to be 170 ± 35 MPa. As importantly, the results also revealed that the conditions needed for grain boundary microcracks to initiate are greatly affected by the deformation of neighbouring grains: i.e. it was established that boundaries between two "hard" grains, inside a neighbourhood of "softer" deformed grains, are the first to fail.

1. Introduction

Aluminium alloys, strengthened by elements in solid solution, can be sensitive to intergranular stress corrosion cracking (ISCC) in some specific microstructural states (Hollinsworth and Hunsicker, 1987). Initially, the mechanism thought to lead to ISCC was understood to be stress assisted localised dissolution (Dix, 1940). It was supported by microstructural observations showing that Mg-rich (Al_3Mg_2 β-phase) precipitates form at grain boundaries during ageing. Here, locally enhanced Mg concentration was thought to create an electrochemical potential inhomogeneity that induced the anodic dissolution of the precipitate and, in so-doing, creating a preferential crack path. This understanding prevailed till the early seventies (Gest and Troiano, 1974) when the crucial role of hydrogen in the fracture process was identified. Then, it was found that when a certain amout of hydrogen is absorbed from the environment into materials such as steels, it can then diffuse along grain boundaries and eventually lead to their embrittlement.

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Initially, the effect of hydrogen contamination in Al alloys was ignored due to the vanishingly small solubility of hydrogen when the metal is in contact with the H_2 gas. Nevertheless, it was shown that a hydrogen flux can develop through Al–Zn–Mg alloys (Gest and Troiano, 1974) even with a free corrosion potential. It was shown unambiguously later on (Gruhl, 1984) that hydrogen can diffuse over depths of some millimeters toward regions of high stress triaxialities (e.g. notch root region), be trapped at grain boundaries and induce intergranular fracture without any contribution of corrosion processes which may be active at the crack tip. The precise nature of "brittle" fracture, i.e. decohesion vs intense localised plasticity, is still debated nowadays. In the specific case of Al–Zn–Mg, TEM studies by Scamans et al. (1976) and Scamans (1978)) show that it is a true intergranular decohesion mechanism (see also Malis and Chaturvedi, 1982). No evidence of grain boundary voids, associated with a ductile-type failure mechanism, has been linked to hydrogen embrittlement in Al alloys.

The β intergranular precipitates play multiple roles in the stress corrosion cracking (SCC) of Al–Mg alloys. It was shown (Jones et al., 2001, 2004) that they dissolve actively during SCC and that enough hydrogen must have been produced to embrittle the grain boundary in between successive β particles (Jones and Danielson, 2003). Furthermore, pitting tests (Tanguy et al., 2002) followed by a tensile deformation in air showed that the anodic dissolution of β particles at triple junctions released enough hydrogen to embrittle precipitate-free grain boundary facets. Moreover, the observation of hydrogen bubbles in Al–8%Mg (Ben Ali et al., 2011) suggests that β-precipitates must indeed be preferential sites for hydrogen trapping. Such understanding and the results of the numerical simulation of the intergranular fracture process (Malis and Chaturvedi, 1982) revealed that intergranular fracture is mostly dominated by the damage of the inter-precipitate regions. The role of plasticity in ISCC is known to be important even though it has only been studied macroscopicaly. For instance, Tanguy et al. (2002) showed that pre-straining of an Al–5%Mg alloy increases its sensitivity to ISCC under both tensile and fatigue loading conditions.

Hydrogen induced embrittlement (HIE) processes can be studied experimentally using local strain measurements (Sachtleber et al., 2002). However, even though as more accurate local measurement techniques become available, it still remains difficult to measure intragranular strains in fine grained materials. For such cases, large focal lenses and microdiffraction tomography (Ludwig et al., 2009) techniques are not suitable. Fortunately, plastic strain fields can nowadays be more easily measured at the micrometrer scale thanks to techniques which rely on fine grids or speckles spaced out at distances considerably smaller than the grain size. Examples are those based on local pitting corrosion, photolithography (Schroeter and McDowell, 2003; Liu and Fischer, 1997), micro-lithography (Allais et al., 1994; Biery et al., 2001), and digital image correlation techniques (DIC) (Allais et al., 1994; Tatschl and Kolednik, 2003; Hild et al., 2002; Sachtleber et al., 2002).

Even when the measurement of local strains is possible in small grained materials, numerical techniques are needed to identify the local stress fields. Intergranular stresses are known to play a significant role in intergranular fracture and result from complex phenomena (e.g. strain incompatibilities between adjacent grains) in a variety of materials such as Zn (Parisot et al., 2000), TiAl (Simkin et al., 1999) and duplex stainless steels (Marrow, 1996). The mechanical response of a polycrystalline aggregate can in principle be predicted by using either mean-field homogenisation or finite element (FE) techniques. However, when the spatial local distributions of strain and stress heterogeneities at the level of each individual grain are needed, then full-field computations are required. The finite element method has been used to model the intragranular response of polycrystalline materials under various macroscopic loading conditions, such as homogeneous (Becker and Panchanadeeswaran, 1995) and fretting (Goh et al., 2006) loading, and to study crack initiation and growth using methods such as those based on cohesive zone models (e.g. Clayton and McDowell, 2004). Crystal plasticity constitutive formulations have been based on semi-phenomenological (Asaro, 1983; Barbe et al., 2001a), and dislocations mechanics based local (Busso and McClintock, 1996; Harder, 1999) and non-local (Busso et al., 2000; Cheong et al., 2004) approaches. They are also able to account in some cases for, e.g., statistical effects of grain boundaries and lattice misorientations on local stress and lattice energy density distributions (Bieler et al., 2009; Clayton and McDowell, 2003), and twinning as a deformation mechanism (Staroselsky and Anand, 1998).

The main objective of this work is to understand the effect of local grain plasticity on the mechanism of intergranular crack initiation due to hydrogen induced embrittlement in an Al–5Mg alloy. To that purpose, notched specimens were locally charged with hydrogen and then tested under tension in situ within a scanning electron microscope. A combination of in situ 2D strain field and EBSD measurements, and finite element simulations of the observed specimen regions using a dislocation mechanics-based crystal plasticity model was relied upon to understand the local conditions responsible for intergranular crack initiation.

2. Experimental investigations

2.1. Material

The Al–Mg alloy studied, known as AA 5083, was thermomechanically treated to obtain equiaxed grains. Its chemical composition is given in Table 1. Charging Al alloys with hydrogen is problematic because of the barrier effect of the oxide

Table 1
Chemical composition of the AA 5083 alloy.

Element	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Al
wt.%	0.40	0.40	0.10	0.70	4.50	0.25	0.15	0.25	Balance