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Effects of microtexture and Ti_3Al (α_2) precipitates on stress-corrosion cracking properties of a Ti-8Al-1Mo-1V alloy

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ABSTRACT

Effects of microtexture and Ti_3Al (α_2) precipitates on the Stress-Corrosion Cracking (SCC) properties of Ti-8Al-1Mo-1V (Ti-811) have been investigated using a constant displacement SCC test in 0.1 M aqueous sodium chloride (NaCl) solution. SEM, TEM, and EBSD were employed to characterize microstructure and microtexture. Results reveal that both microtexture and α_2 precipitates increase the SCC susceptibility of Ti-811. The SCC propagation direction aligns with microtextured regions, and most α grains were preferentially orientated for basal <*a*> slip along the SCC crack. SCC susceptibility was eliminated by implementing hot isostatic pressing (HIPping) and post heat-treatment processes through eliminating both crystallographic microtexture and α_2 precipitates. Fractography showed that the formation mechanism of the propagation facets could be attributed to Hydrogen Enhanced Localized Plasticity (HELP).

1. Introduction

For aircraft, extra weight leads to an increase in fuel consumption [1–3], therefore the cost penalty of extra weight is approximately €1000 per kg [4]. Weight reduction can be achieved by using materials having low density and good mechanical properties, such as high elastic modulus (stiffness) and strength [4–7]. Compared to the widely used Ti-6Al-4V (Ti-64) alloy, Ti-8Al-1Mo-1V (Ti-811) is characterized by a lower density and a higher stiffness, but unfortunately it suffers Stress-Corrosion Cracking (SCC) [8–12].

The excellent corrosion resistance of titanium (Ti) alloys in oxidizing environments is due to the native protective passive Ti oxide film. For Ti-811, spontaneous passivation occurs in 3.5% sodium chloride (NaCl) solution [10,13–15]. However, the protective film will be broken if load applied is beyond the yield point of Ti oxide, and corrosive media will then contact with the underlying fresh metal, and initiate SCC [11,16].

In Ti alloys, aluminium (Al) and oxygen (O) additions increase SCC susceptibility and change the slip mode to planar slip [17,18]. This in part is ascribed to the high Al content (>6 wt.%) promoting ordered Ti_3Al (α_2) precipitate formation at appropriate aging temperatures. The α_2 precipitate has an ordered $D0_{19}$ structure, in which Ti and Al atoms occupy specific positions in the Hexagonal Close Packed (HCP) structure [6,8,10,19,20]. In Ti-811, SCC is attributed to localized planar slip due to the presence of ordering in the α phase. An increase in ordering will contribute to an increasingly coarse and planar slip [18]. In a previous study on rolled Ti-811 plate, the threshold stress intensity factor of SCC (K_{Iscc}) was found to decrease, and the SCC crack velocity was found to increase by 4 times in a sample containing α_2 phase compared to one in the precipitate-free condition [17]. It should be noted that the study [17] was conducted on the samples from a rolled sheet, which had a pronounced crystallographic texture.

In addition to ordered precipitates, crystallographic texture has also been found influence SCC susceptibility. The effect of texture on SCC has been widely studied in Ti-811 and Ti-64 alloys, and a correlation between SCC susceptibility and orientation of $(0001)_\alpha$ texture relative to loading axis has been established [8,9,18,21–26]. However, all previous studies of the texture effects have been performed at a macro-scale (macro-texture). On the other hand, microtexture or macro zones, region of grains with a similar crystallographic orientation, have been found to affect the fatigue and dwell fatigue properties of Ti alloys [27–34]. To the best of our knowledge, no investigation has been carried out into the effects of microtexture (or macro zone) on SCC for Ti alloys.

Electron Backscatter Diffraction (EBSD) analysis was employed to characterize microtexture in this work. Hot Isostatic Pressed (HIPped) Ti-811 with a random texture [35–38], was compared with wrought Ti-811 containing an intrinsic microtexture in this

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Table 1
Descriptions of various Ti-811 samples.

Samples ID	Description
Wrought Ti-811	Sample with a C-L orientation in the wrought Ti-811 bar was used for SCC tests. C-L indicates the loading direction-crack opening direction in the Double Cantilever Beam (DCB) specimen (Fig. 1). In the Ti-811 bar, R: radial direction, C: circumferential direction, and L: longitudinal direction. (see Fig. 3e)
Wrought Ti-811 + HT860	Wrought Ti-811 was subjected to a post heat-treatment at 860 °C/30 min + water quench (WQ). DCB samples with the same C-L orientation was used for SCC tests.
HIPped Ti-811	Powder HIPped Ti-811 at 100 MPa, 990 °C for four hours with a ramp rate of 5 °C/min.
HIPped Ti-811 + HT860	HIPped Ti-811 was subjected to a post heat-treatment at 860 °C/30 min + WQ.

Two DCB specimens (Fig. 1) were prepared for SCC tests in all the four conditions as listed in Table 1.

Table 2
Chemical compositions of tested samples.

	Wrought Ti-811 and Wrought Ti-811 + HT860	HIPped Ti-811 and HIPped Ti-811 + HT860
Al (wt.%)	7.94	7.97
Mo (wt.%)	1.04	0.99
V (wt.%)	0.99	0.99
C (ppm)	60	90
O (ppm)	950	760
H (ppm)	34	24
Ti	bal	bal

study. The present research investigated the independent effect of α_2 precipitation and microtexture on the SCC susceptibility of Ti-811 by using appropriate heat-treatments and hot isostatic pressing (HIPping) schemes with the aim of identifying possible means to reduce the SCC susceptibility. A constant displacement SCC test was used to characterize SCC susceptibility. The effects of α_2 precipitates and microtexture on SCC susceptibility were studied by using TEM and EBSD respectively. The mechanism of SCC propagation was investigated by fractography fracture surfaces and metallography of cross section through fracture path using SEM and EBSD.

2. Materials and methods

A wrought Ti-811 bar with a diameter of 80 mm was obtained from Timet UK Limited, and pre-alloyed Ti-811 powders produced by electrode induction melting gas atomization were provided by the Institute of Metal Research, Chinese Academy of Sciences. The pre-alloyed powders had a wide particle size distribution from 5 μm to 832 μm, with 90% having a diameter less than 307 μm. The pre-alloyed powders were encapsulated in mild steel cans and HIPped by an Avure QIH-9 hot isostatic press at 100 MPa and 990 °C for four hours with a ramp rate of 5 °C/min. A post heat-treatment of 30 min at 860 °C followed by water quench (WQ) was designed to supress α_2 phase formation. As the martensitic transformation start temperature and α_2 ordering transformation temperature are approximately 900 °C [9] and 837 °C (based on a calculated phase diagram by PANDAT^{TM} software) respectively, WQ from 860 °C could prevent both the martensitic and α_2 transformation. As martensite microstructure is immune to SCC in Ti-811 [25,39], it is important to avoid martensite transformation.

The description and chemical composition of the four different sample conditions employed in this study are presented in Tables 1 and 2. The wrought Ti-811 bar and powder HIPped Ti-811 have a similar composition in terms of Al, Mo, and V, O and H. As the

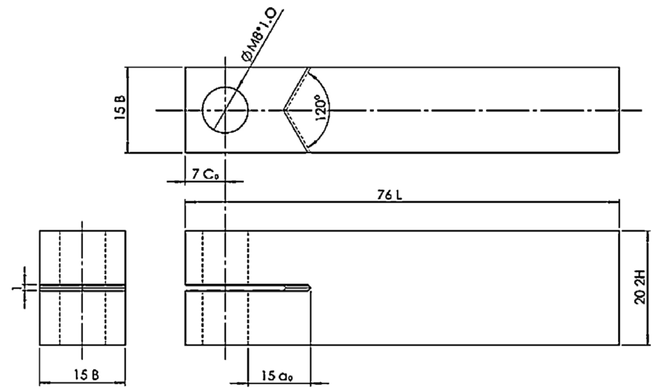

Fig. 1. Schematic diagram of double cantilever beam (DCB) samples with dimensions (mm), a_0–starting crack length, B – width, c_o – distance from sample edge to loading axis, 2H – height, L – length.

post heat-treatment was conducted in vacuum, the chemical composition should have remained the same after the heat-treatment and WQ for samples of wrought Ti-811 + HT860 and HIPped Ti-811 + HT860.

According to the SCC test standard ASTM G168-00 [40], Double Cantilever Beam (DCB) samples were pre-cracked by mechanical overloading in air before immersing them into the test solution. The constant displacement was produced by tightening two stainless steel bolts in the DCB specimen. In order to conduct a study of sample orientations (which is not included in this paper), DCB samples were sectioned from the wrought Ti-811 bar with different orientations. Therefore, sample length (76 mm in Fig. 1) was limited by the wrought Ti-811 bar diameter at 80 mm.

For each condition as shown in Table 1, two tests were carried out. The test solution (pH 5.7) was 0.1 M NaCl, made from distilled water and Analar grade reagent NaCl. The solution volume was 150 ml and open to air at room temperature. A fresh solution was used for each individual test. The specimen potential was allowed to remain at the open circuit potential for the duration of SCC tests. The interim crack length (a_i in Eq. (1)) was measured periodically by marking the crack front on both surfaces of a specimen using a scalpel under an optical microscope. The measurement frequency was higher during the initial stage of a test as the crack propagation rate was high. The stress intensity and crack propagation rate decrease during constant displacement SCC tests with increasing crack length, so the measurement frequency was reduced. The crack propagation velocity was then calculated from the increase in crack length and time interval. The stress intensity factor, K_{Ii}, is a function of a_i, and it was calculated using the following Eq. (1) [40]:

$$K_{Ii} = \frac{[1.732EV_{LL}]}{\left[4H^{0.5}\left(\frac{a_i}{H} + 0.673\right)^2\right]} \quad (1)$$

where a_i is the interim crack length (m), K_{Ii} is the stress intensity factor (MPa $\sqrt{m}$), V_{LL} is the crack opening distance on the loading axis (m), H is the sample half height (m), and E is the Young's Modulus (MPa). As shown in Eq. (1), the stress intensity factor (K_{Ii}) decreases as a function of increasing crack length during crack propagation. After the SCC tests, polynomial curve fittings were applied to the SCC crack velocity and corresponding stress intensity factor based on a previous work [41], and associated confidence bands (95 confidence level) were generated to evaluate the accuracy of curve fitting. The K_{ISCC} is defined as the stress intensity factor when crack velocity is 10^{-10} m/s in this work, and K_{ISCC} is computed based on the curve fitting function.

In order to obtain a value of Young's modulus for use in Eq. (1), tensile tests were conducted for specimens loaded to fracture at a crosshead speed of 1 mm/min at room temperature. M8 round ten-