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Effects of hydrogen on fatigue behavior of near-alpha titanium alloys

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ABSTRACT

The influence of hydrogen content on fatigue response was examined for a near-α titanium alloy, Ti-6Al-2Sn-4Zr-2Mo-0.1Si, in bimodal microstructural condition with ~70 vol% primary α. The hydrogen content was varied in the range 7–127 ppm (by weight). The fracture mechanism at crack-initiation sites changed from ductile tearing with localized plasticity in low (<50 ppm) hydrogen alloys to a more brittle fracture with facets in high (≥100 ppm) hydrogen alloys. The variation in fatigue life (by a factor of ≤1.8) was partially associated with the differences in hydrogen level and partially with the statistical scatter in life.

The life management of fatigue-critical components made from near-α titanium alloys is challenging and an investigation of the variables influencing the fatigue properties of these alloys is crucial. Hydrogen is considered to be one of the important factors affecting the fatigue behavior of these alloys [1]. Hydrogen potentially can affect several important aspects of material behavior (e.g., deformation characteristics [2,3], tendency to form brittle hydrides [2–4], etc.), which in turn can change its propensity for fatigue failures.

Most of the prior studies examining the effects of internal hydrogen on fatigue behavior of near-α titanium alloys have focused on one particular alloy, namely IMI 685 [5–9]. In a more recent study, Gerland, et al. [1] examined the influence of hydrogen on fatigue behavior of another near-α titanium alloy, Ti-6242Si. Table 1 summarizes the results of prior studies on the influence of hydrogen content on fatigue life in near-α titanium alloys.

Most of the prior studies on the influence of internal hydrogen on fatigue behavior reported results for β-heat treated or β-forged near-α titanium alloys with lamellar (i.e., colony or a mixture of colony and basketweave) microstructure, which did not contain any primary α grains. However, one common microstructural condition in which the near-α titanium alloys, such as Ti-6242Si, are used in practice is a *bimodal microstructure* consisting of primary α grains in addition to the $\alpha + \beta$ transformation product. There are limited reports on the correlation between hydrogen content and fatigue behavior of the near-α titanium alloys with bimodal microstructure. In the current study, we have selected Ti-6242Si alloy with a bimodal microstructure to examine the effects of hydrogen content on its fatigue behavior. This study is especially important, as the *environmental* hydrogen embrittlement is reported to be significantly different for the two microstructures (i.e., lamellar and bimodal) in Ti-6Al-4V [10,11].

The Ti-6Al-2Sn-4Zr-2Mo-0.1Si alloy, examined in this study, was thermomechanically processed at ATI Forged Products (formerly Ladish Co., Cudahy, WI) as follows [12,13]: the billet was α/β forged at $T_\beta - 28$ °C to a strain of ~58%, solution heat treated at T_β-56 °C, and then air cooled. This was followed by aging at 593 °C for 8 h and then air cooling to room temperature. The alloy was provided as a pancake-shaped forging (i.e., a round forging with a diameter of 470 mm and thickness of 77 mm) by ATI Forged Products. The examined alloy had a bimodal microstructure (Fig. 1a), consisting of globular primary α grains (~65 to 70 vol%) and lamellar transformed β regions (~30 to 35 vol%). The chemical composition, microtexture, and macrotexture of the as-received alloy are described in earlier reports [12,14]. The specimen blanks (square cross-sections of ~12.7 × 12.7 and ~19.1 × 19.1 mm^2 for tensile and fatigue tests, respectively) were sectioned from the pancake-shaped forging, with waterjet cutting, in an orientation that resulted in the loading axis of the machined specimens to be aligned with the circumferential (tangential) direction of the forging.

The specimen blanks for tensile and fatigue tests were degassed under dynamic vacuum (chamber pressure ~3×10^{-6} torr) at 600 °C for 48 h to reduce the hydrogen content of as-received alloy. The degassed specimen blanks were subsequently aged in air at 600 °C for 8 h and then air cooled to room temperature prior to final machining.

The specimen blanks for tensile and fatigue tests were hydrogen-charged in a Sieverts apparatus [15,16] at a temperature of 550–600 °C to increase the hydrogen content of as-received alloy. After hydrogen charging at 550–600 °C, the specimen blanks were cooled to room temperature inside the Sieverts apparatus at a rate slower than air cooling,

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Table 1
Literature data on fatigue life (N_f) as a function of hydrogen content in near-α titanium alloys.

Reference	Material/microstructure	Stress ratio	Applied peak stress	H-Content (ppm, by wt.)	Results relevant for current study
Evans, 1987 [6]	IMI 685/colony		800–850 MPa	<10 50	$N_f^{50ppm\ H} \sim 2 \times N_f^{<10ppm\ H}$
Neal, 1988 [5]	IMI 685/colony	0	700 MPa	<10 50	$N_f^{50ppm\ H} \sim N_f^{<10ppm\ H}$
			750 MPa	<10 50 190	Similar N_f for three hydrogen levels
			800 MPa	<10 50 190	Similar N_f for three hydrogen levels
			850 MPa	<10 50 190	$N_f^{190ppm\ H} \sim 2 \times N_f^{low\ H}$
			900 MPa	<10 50 190	$N_f^{50-190ppm\ H} \sim 2\text{–}3 \times N_f^{<10ppm\ H}$
Evans and Bache, 1994 [7]	IMI 685/colony	0.1	$0.88 \times \sigma_{UTS}$	20 60	Similar N_f for 20 and 60 ppm H materials
Evans and Bache, 1995 [8]	IMI 685/colony	0.1	$0.86 \times \sigma_{UTS}$	20 60	$N_f^{60ppm\ H} \sim N_f^{20ppm\ H}$
			$0.75 \times \sigma_{UTS}$	20 100–275	$N_f^{100-275ppm\ H} \sim 1/4 \times N_f^{20ppm\ H}$
Bache, et al., 1997 [9]	IMI 685/colony	0.1	$0.8 \times \sigma_{UTS}$	60 250	$N_f^{250ppm\ H} \sim 1/4 \times N_f^{60ppm\ H}$
Gerland, et al., 2009 [1]	Ti-6242Si/(Colony + Basketweave)	0	$\sigma_{ys}^{30ppm\ H}$	30–300	$N_f^{300ppm\ H} \sim 3 \times N_f^{30ppm\ H}$

which was the final cooling step after aging of the as-received alloy. To be consistent with the final air cooling step after aging of the as-received alloy, several hydrogen-charged specimen blanks were subsequently aged in air at 600 °C for 8 h and then air cooled to room temperature. The response, including yield strength and fatigue life, of the alloy at a given hydrogen level changed negligibly as a result of the final air cooling step after aging. Therefore, the specimens with and without the final air cooling step from the aging temperature are not differentiated in this article.

The reported values of hydrogen content for each of the specimens are based on inert gas fusion (ASTM E1447) analyses on the material taken from the grip section of broken specimens.

The specimens for tensile tests had a uniform circular cross-section with a gage section diameter of 6.35 mm and a reduced section length of 31.75 mm. The tensile tests were conducted at room temperature in air under displacement control at an actuator speed corresponding to a strain rate of ~ $1 \times 10^{-4}\ s^{-1}$.

The specimens for fatigue tests had a uniform circular cross-section with a gage section diameter of 5.08 mm and a reduced section length of 19.05 mm. The machined specimens were shot peened with shot-type CW14 at an intensity of 005 A and a coverage of 200%.

The fatigue experiments were conducted at room temperature in air under load-control at a load ratio (R) of 0 using a triangular waveform at a frequency of 0.5 Hz. The applied maximum stress (σ_{max}) for fatigue tests was ~$0.95 \times$ (0.2 % offset yield strength (σ_{ys})).

The failed fatigue specimens were cleaned ultrasonically in acetone and then in alcohol. To preserve the pristine fracture surfaces representing the underlying fatigue micromechanisms, no additional preparations (e.g., etching) were carried out. The failure modes of the fractured specimens were examined in a scanning electron microscope (SEM) using a secondary electron detector.

The 0.2 % offset yield strength (σ_{ys}) and the ultimate tensile strength (σ_{UTS}) of as-received (49 ppm hydrogen, by weight) alloy were 950 and 1017 MPa, respectively. The elongation to failure of the as-received alloy was 17.6%. For the alloy with hydrogen in the range 6–173 ppm, σ_{ys} and σ_{UTS} varied in the range 945–986 MPa and 1006–1048 MPa, respectively, and the elongation to failure varied in the range 17.6–21.8%. A slight increase in the σ_{ys} and the σ_{UTS} with hydrogen content was observed, with both σ_{ys} and σ_{UTS} being ~4% higher for the 173 ppm than for the 6 ppm hydrogen material. The elongation to failure did not change systematically with hydrogen content, in the range 6–173 ppm hydrogen.

Evans conducted fatigue tests at the same stresses on IMI 685 with two different hydrogen contents and reported longer lives for the hydrogen content of 50 ppm in comparison with the hydrogen content below 10 ppm, which was opposite to the trend expected from

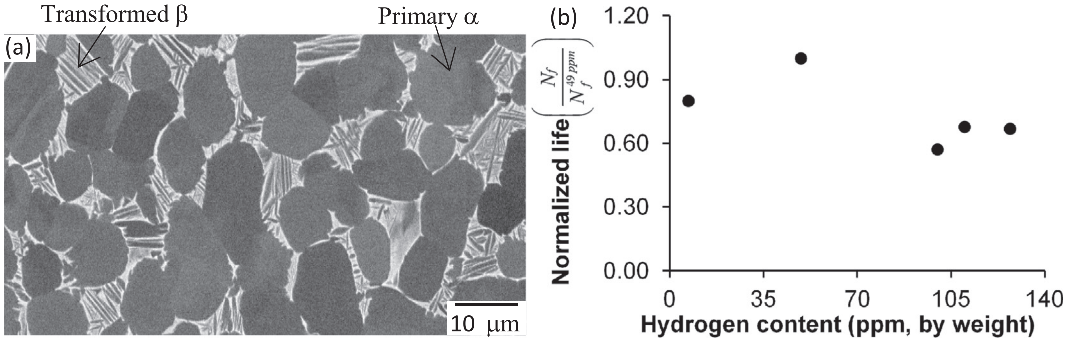

Fig. 1. (a) SEM (backscattered electron) micrograph of the as-received α/β forged Ti-6242Si alloy, and (b) Influence of hydrogen content on normalized fatigue life.