

Effects of various environments on fatigue crack growth in Laser formed and IM Ti–6Al–4V alloys

E.U. Lee^{a,*}, A.K. Vasudevan^b, K. Sadananda^c

^aNaval Air Warfare Center Aircraft Division, Patuxent River, MD 20670, USA

^bOffice of Naval Research, 800 N. Quincy Street, Arlington, VA 22217, USA

^cNaval Research Laboratory, Washington, DC 20765, USA

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Abstract

The fatigue crack growth behaviors of Laser formed and ingot metallurgy (IM) Ti–6Al–4V alloys were studied in three environments: vacuum, air and 3.5% NaCl solution. Taking the Unified Fatigue Damage Approach, the fatigue crack growth data were analyzed with two intrinsic parameters, stress intensity amplitude ΔK and maximum stress intensity $K_{\max}$, and their limiting values ΔK^* and $K_{\max}^*$. Fatigue crack growth rates da/dN were found increase with stress ratio R , highest in 3.5% NaCl solution, somewhat less in air and lowest in vacuum, and higher in IM alloy than in Laser formed one. In 3.5% NaCl solution, stress corrosion cracking (SCC) was superimposed on fatigue at $R=0.9$ for where $K_{\max} > K_{\text{ISCC}}$, the threshold stress intensity for SCC. This and environment-assisted fatigue crack growth were evidenced by the deviation in fatigue crack growth trajectory (ΔK^* vs. $K_{\max}^*$ curve) from the pure fatigue line where $\Delta K^* = K_{\max}^*$. Furthermore, the fractographic features, identified along the trajectory path, reflected the fatigue crack growth behaviors of both alloys in a given environment. Published by Elsevier Ltd.

Keywords: Fatigue crack growth; Stress ratio; ΔK ; $K_{\max}$; Environmental effect; Stress intensity; Stress corrosion cracking; Laser formed and IM Ti–6Al–4V alloys

1. Introduction

The manufacturing process for many metallic structures includes forging or mechanical working and machining of alloy ingots. To cut down the time-consuming and costly process and fabricate near-net shape structures without wasting materials, Laser forming process has been developed. It consists of Laser heating and depositing pre-alloyed or blended elemental powders directly into a near-net shape structure without any mold or die in an inert environment. Subsequently, the structure is subjected to heat treating and final machining to the net shape. Although the Laser forming process has a merit of cost saving, the integrity and applicability of its product remain to be established. In particular, the fatigue crack growth behavior has not been fully established.

The fatigue crack growth behavior is significantly influenced by the interaction of cyclic loading

and environment. To understand the fatigue mechanisms involved, Vasudevan and Sadananda [1–7] have developed a Unified Fatigue Damage Approach, which considers fatigue as requiring two intrinsic parameters: stress intensity amplitude ΔK and maximum stress intensity $K_{\max}$. In addition, the environmental interaction is a time- and stress-dependent process, and affects the fatigue crack growth through $K_{\max}$ parameter. A plot of their limiting values at each crack growth rate, ΔK^* vs. $K_{\max}^*$, defines a fatigue crack growth trajectory, which provides a comparative measure of fatigue and environmental effect for a given material and loading condition. This trajectory falls on the reference line of $\Delta K^* = K_{\max}^*$ for a purely cyclic stress-controlled fatigue crack growth in an inert environment. Deviation from this line occurs, if the environmental and/or monotonic fracture modes are superimposed on fatigue [6,7]. As contribution from environmental or monotonic modes increases, the fatigue crack growth mechanisms become increasingly $K_{\max}$ -dependent, and the trajectory swings more and more towards the $K_{\max}^*$ -axis.

In this study, taking the Unified Fatigue Damage Approach, the fatigue crack growth behaviors of Laser formed and IM Ti–6Al–4V alloys were analyzed

* Corresponding author.

E-mail address: eun.lee@navy.mil (E.U. Lee).

Table 1
Chemical composition (wt%)

Element	Laser formed	IM
Al	6.28	6.74
V	4.08	4.20
C	0.02	0.01
Fe	0.17	0.16
O	0.21	0.22
H	39 ppm	59 ppm
Other-Each	<0.05	<0.05
Other-Total	<0.20	<0.20
Ti	Balance	Balance

Table 2
Mechanical properties

Alloy	UTS (MPa)	YS (MPa)	Elong. (%)	Hardness (R_C)
Laser formed (X orientation)*	955.6	861.9	12	35
IM (L orientation)	1031.5	972.2	16	34

and compared in three environments, vacuum, air and 3.5% NaCl solution. In addition, the SCC in the alloys was investigated to define its role in the fatigue crack growth in 3.5% NaCl solution. After the fatigue and SCC tests, the associated fractographic features were examined.

2. Experimental procedures

2.1. Testing materials and specimens

Laser formed and IM Ti–6Al–4V alloy plates, 12.7 mm (0.5 in.) thick, were employed for the tests. The Laser formed one was HIPed at 899 °C (1650 °F) under 103.4 MPa (15 ksi) pressure of argon for 2 h. Both of the plates were subjected to an identical heat treatment in argon

atmosphere: solution treating at 913 °C (1675 °F) for 2 h, cooling, aging at 538 °C (1000 °F) for 4 h, and furnace cooling. Their chemical compositions and mechanical properties are shown in Tables 1 and 2.

The grain diameters were 600 and 15 μm for the Laser formed and IM alloys, respectively, and their optical micrographs are shown in Fig. 1. Interestingly, such a large difference in the grain size between the two processes affected the mechanical properties by about 10%.

The heat treated plates were machined to compact tension specimens, 38 mm (1.5 in.) wide and 4.8 mm (3/16 in.) thick, in X – Z deposit and L – T crack plane orientations for the Laser formed and IM ones, respectively. (* In the Laser formed plate, X indicates the lateral and Z the vertical orientations of deposit.)

2.2. Fatigue tests

For the fatigue tests, two closed-loop servo-hydraulic mechanical test machines were used. One was a 490 KN (110 kip) vertical MTS machine for the fatigue tests in vacuum, air and gas environments. The other was a 45 KN (10 kip) horizontal mechanical test machine for the fatigue test in a liquid medium, circulating between a liquid container and a 3.5 L reservoir by a pump without aerating. Each test machine was suitably interfaced with a computer system for automatic monitoring of fatigue load and crack growth, employing either compliance or DC potential drop technique.

The fatigue tests were conducted under stress control in tension–tension cycling of frequency 10 Hz with a sinusoidal waveform and stress ratios, 0.1 and 0.9, at ambient temperature. The test environments were vacuum of 2×10^{-8} torr, air of relative humidity 50–60% and aqueous 3.5% NaCl solution of pH 7.3. The fatigue crack length was continuously monitored with a computer system, employing compliance technique. The fatigue

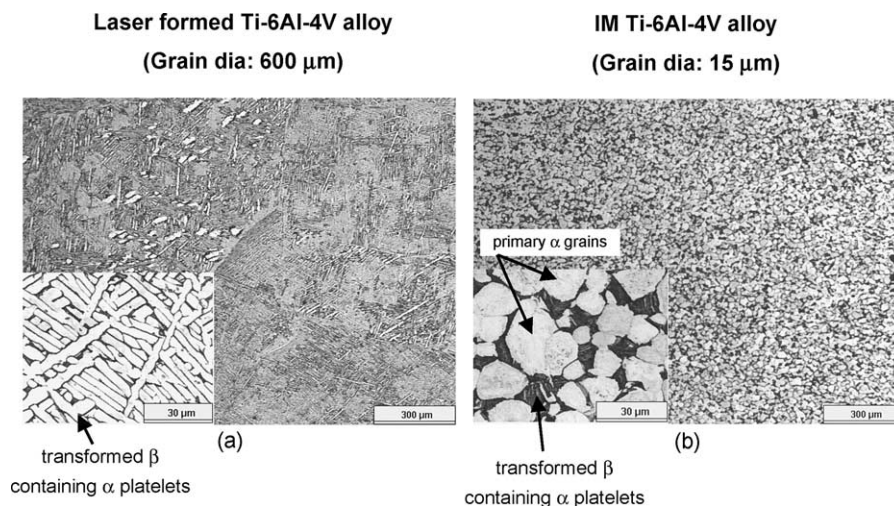


Fig. 1. Optical micrographs of: (a) Laser formed Ti–6Al–4V alloy and (b) IM Ti–6Al–4V alloy.

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