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Crack propagation of Ti alloy via adiabatic shear bands

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ABSTRACT

This study was focused on the characterization of the origin and mechanism of crack propagation as a result of hot induction bending of Ti alloy. Plates of Ti–6Al–4V alloy with 12.5 mm of thickness were submitted to hot induction bending below the beta transus temperature. Optical and scanning electron microscopy analysis showed crack formation in the tensile zone. Microstructural evidence showed that cracks propagate through the adiabatic shear bands by Dimple-Void mechanism. However, voids formation before shear banding also occurred. In both mechanisms adiabatic shear bands are formed via dynamic recrystallization where the alpha–beta interphase works as stress concentrator promoting the formation of dimples and voids.

1. Introduction

Titanium alloys for aeronautical and military applications require to be manufactured. However, it is not easy to deform without damage the microstructure hence mechanical properties. Therefore, understanding the mechanisms of deformation and cracking is vital to determine its performance and effectiveness.

Several studies have pointed the adiabatic shear band (ASB) as one of the principal damage mechanism during manufacturing, which leads to premature failures [1]. The ASB's are formed during high rate deformation or severe plastic deformation, when high percentage of the plastic work is converted into heat, promoting the competition between plastic hardening and strain softening [2]. Therefore, ASB's are more frequently formed in alloys with low density and poor thermal conductivity such as Titanium alloys [3,4]. Subsequent studies on Titanium alloys have determined that failures occur along the ASB's by the growth and arrays of dimples and voids [4–9]. Voids are considered to form during the development of *Transformed* ASB by thermal softening and local melting, whereas dimples are formed in *Deformed* ASB's as a result of intense shear deformation [10,11].

Both ASB's and voids tend to form in interphases or grain boundaries, which create an instability point where the stress is concentrated during the deformation process [10,12,13]. Therefore, the possibility that dimples and voids can be formed before the adiabatic shear bands must be considered. The aim of this project is to characterize the origin and mechanism of crack propagation as a result of hot induction bending.

2. Experimental procedure

The titanium alloy used in this study was Ti–6Al–4V plate with dimensions $254 \times 152.4 \times 12.5$ mm from which the chemical composition is shown in Table 1. The solidus and beta transus temperature were determined through a series of tests with the Single Sensor Differential Thermal Analysis (SSDTA) for which experimental small-scale “buttons” were produced by the button arc melting process under argon atmosphere. These buttons were then partially melted by a stationary GTA spot weld where a type-C thermocouple was plunged into the molten pool just before arc extinction.

The hot induction bending process consisted of deforming the plate on a V block by a mandrel with diameter of 12.5 mm at a speed of 10 mm/s. Before the test, the plate was heated to 538 °C. The microstructural characterization was performed on the cross section of the bent sample, using silicon carbide paper for grinding followed by attack polishing using a mixture of 10 mL hydrogen peroxide and 50 mL colloidal silica (0.05 μm). Final step consisted on a brief vibratory polishing with 0.03 μm colloidal silica. The microstructure was revealed using Weck's reagent and analyzed by optical and scanning electron microscopy. In addition a Vickers hardness mapping was performed on the as-received material and the cross section of the bent sample using 1.96 N (200 gf) load and 300 μm spacing. The yield and ultimate strength values were determined by standard tensile test in the as-received condition.

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Table 1
Chemical composition (wt%) of the as-received alloy.

Material	N	C	H	Fe	O	Al	V	Ti
Ti–6Al–4V	0.0053	0.017	0.0045	0.18	0.176	6.28	4.06	Bal.

3. Results and discussion

3.1. As-received material

The Ti–6Al–4V alloy in the as-received condition consists of equiaxed α and transformed β grains showing some elongated α grains and evidence of banding (Fig. 1A). The α grains present different sizes (ASTM 6 and 8), phenomenon that may be attributed to the rolling process and the HCP lattice of α phase. HCP grains that do not have the same crystallographic orientation regarding the rolling direction, are fragmented due to the anisotropy resulting in smaller grains as shown in Fig. 1B.

Grain size variation definitely influences the hardness distribution in the as-received Ti–6Al–4V alloy as shown in Fig. 2, where values around 310 HV are related to coarse grain size whereas values of 400 HV, to fine grain size. The yield and ultimate strength values were determined at 1069 MPa and 1339 MPa respectively.

Depending on the alloy composition, the beta-transus temperature can range from 700 °C to 1050 °C for conventional α/β alloys. The in-situ measurement of the solidification process and SSDTA software (Fig. 3) determined the beta-transus temperature ($\alpha+\beta \rightarrow \beta$) around 832 °C, whereas solidus temperature around 1590 °C.

3.2. Strain distribution and microstructural observation in bent sample

During the hot induction bending process the stress is distributed across the thickness of the plate. Ideally, the elastic limit is exceeded in order to reach a permanent deformation with no crack formation. However, the bent sample showed the presence of cracks on the outer surface as indicated in Fig. 4A. On the other hand, the hardness map in Fig. 4B represents the strain distribution of the bent cross section, determining the displacement of the neutral axis closer to the inside surface. The area below the neutral axis is under compression (contracted) whereas; the area above the neutral axis is submitted to tension (strained) and comprises a larger area.

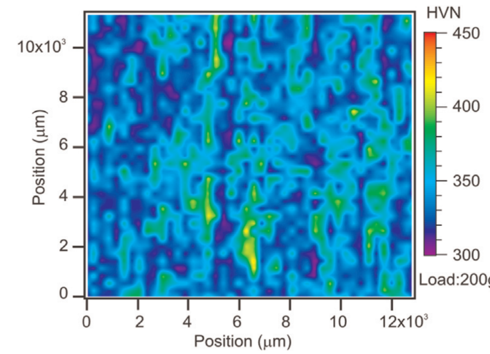

Fig. 2. Hardness mapping of Ti–6Al–4V in the as-received condition.

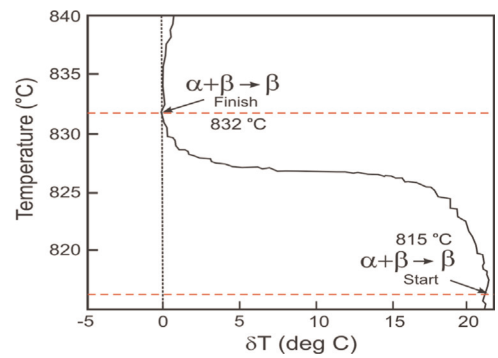

Fig. 3. Determination of beta-transus temperature in Ti–6Al–4V by SSDTA software.

The microstructure of the cross section is distorted, showing the deformation in function of the stress direction that was submitted to. Fig. 5 depicts the microstructure at the mid-thickness making evident an unstable deformation as a response of the material to the stress–strain state. This is related to the lack of stress flow during deformation due to low thermal conductivity of Ti alloys and the high strain rate being experienced, giving rise to flow localization bands, the initial stage of ASB formation [14].

Since the outer surface of the material was stretched more than in the mid-thickness surface, the microstructure is highly

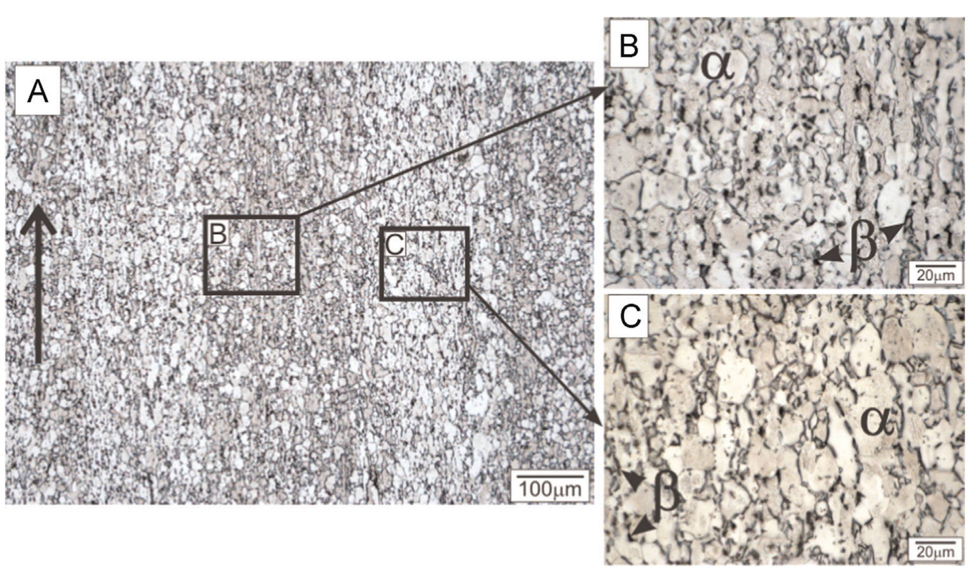

Fig. 1. Microstructure of Ti–6Al–4V as received condition (a) Rolling direction, 20 × ; (b) Fine grain zone ASTM 6, 100 × ; (c) Coarse grain zone ASTM 8, 100 × .