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Effect of cryogenic and aging treatments on low-energy impact behaviour of Ti−6Al−4V alloy

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Abstract: The objective of this study is to examine the effects of cryogenic and aging treatments on the impact strength and mechanical properties of Ti−6Al−4V alloy. To accomplish that objective, cryogenic treatment (CT), aging treatment (AT) and cryogenic treatment followed by aging treatment (CAT) were conducted on Ti−6Al−4V alloy. Impact tests were performed on heat-treated and untreated samples using different impactor nose geometries (hemispherical, 60° and 90° conical) to determine the effect of impactor nose geometry on the damage characteristic. The findings showed that energy absorption increased and areas of damage decreased as a result of heat treatment in all treated samples. The highest energy absorption was observed in the CAT samples, due to the increase in energy absorption, the smallest damaged area occurred in the CAT sample, and the largest deformation was seen in the untreated samples. Additionally, it was seen that the damaged area and deflection were strongly dependent on impactor nose geometry. The maximum deflection and narrowest deformation area were seen with 60° conical nose geometry. The deformation area increased with increasing impactor nose angle.

Key words: Ti−6Al−4V alloy; cryogenic treatment; aging treatment; low-energy impact test; impact damage; impactor nose geometry

1 Introduction

Ti−6Al−4V is a titanium alloy that is widely used in the biomedical, aerospace, automotive, space, and other major industries due to its low density, high strength and excellent corrosion resistance specifications. The development of mechanical properties and determination of the deformation behaviour of Ti−6Al−4V alloy under various loads are of importance when the specific applications of the alloy are considered. Due to the sensitivity of the heat treatment of Ti−6Al−4V alloy, it was determined that its mechanical properties could be developed [1−4]. The effects of changes in the microstructure of Ti−6Al−4V alloy on its mechanical properties as a result of different heat treatment procedures have been investigated by many authors in the literature. In particular, β phase transforms, α and β phase morphology, α plate thickness, and the spacing between the plates are the most studied topics [5−7].

One of these treatments is cryogenic treatment, which is frequently implemented to develop the mechanical properties of the alloy. Cryogenic treatment is a low-cost treatment applied once with homogeneous effects on materials that are widely used in the aerospace and automotive industries to increase wear resistance and ensure dimensional stability [8]. In previous studies, it was observed that the tensile and yield strengths of the material decreased slightly, but elongation and reduction of the area and hardness increased by 10.5%, 13.5%, and 2.5%, respectively. Cryogenic treatment tends to change the phase, which prevents the movement of dislocations and therefore decreases plastic deformation [1,2]. Another study about the effect of cryogenic treatment on the wear resistance of Ti−6Al−4V alloy showed that the hardness and wear resistance of the alloy increased due to the reduction of β phase [9]. Although the effects of cryogenic treatment on the mechanical properties are known, its effects on impact resistance and damage behaviour have not been completely explained. This study scrutinized the effects of cryogenic treatment on the impact resistance, deformation behaviour, and mechanical properties of the alloy. Along with the cryogenic treatment, the second heat treatment frequently applied to the alloy is aging treatment. VENKATESH et al [3] applied aging treatment to Ti−6Al−4V alloy

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using different cooling procedures. It was observed that a hard layer was formed on the material as a result of the heat treatments with the aging treatment and this layer affected the mechanical properties of the material. SINGH et al [4] solution-treated the alloy under and over the β transition temperature and then applied aging treatment. Aging-treated samples were ballistic tested with a 7.62 mm-calibre bullet. The ballistic test results showed that the energy absorption of the samples increased, while the amount of back plate deflection and crack formations decreased.

During the impact and ballistic tests, it was observed that the impact nose geometry and impact energy level were the most significant factors affecting the impact resistance of the material [10−14]. Impactor nose geometries were evaluated in three main groups in the literature based on the deformation characteristics that they caused in the material. These are hemispherical, blunt, and changing nose-angle conical geometries [11−16]. Each geometry has different impact characteristics and causes failure of the material. Blunt impactor nose geometries cause failure modes by plugging. Hemispherical and conical geometries penetrate the samples by increasing the compressive stress due to the nose angle and pushing the material from the top face to the back face [10,11]. Blunt impactor nose geometry causes a wider deformation area compared with the hemispherical and conical geometries [8]. However, as the impact energy increases, the blunt impactor geometry causes a smaller deformation area compared with the hemispherical and conical impactor geometries [15,16]. Thus, as the energy levels increase, the deformation characteristics differ as well [16]. Therefore, it would be beneficial to scrutinizing the impactor geometry and impact energy levels together when researching the impact characteristics. In the present work, the effects of the energy level and impactor nose geometries on the impact behaviour of Ti−6Al−4V alloy were examined together.

In the light of those studies, it could be stated that cryogenic and aging treatments increased the mechanical properties of the Ti−6Al−4V alloy. Therefore, it would be correct to assume that these heat treatments could increase the impact resistance of the alloy. Thus, cryogenic treatment, aging treatment, and cryogenic treatment followed by aging treatment were applied to the alloy in this work. Following the heat treatment, in order to investigate extensively the low-energy impact behaviour of the Ti−6Al−4V alloy, low energy impact tests were conducted on samples.

2 Experimental

The experimental works were completed in four steps: 1) heat treatment procedures of Ti−6Al−4V alloy; 2) mechanical testing; 3) low energy impact tests; and 4) investigation of damaged zone and observation of damage modes. The chemical composition of Ti−6Al−4V alloy is shown in Table 1.

Table 1 Chemical composition of Ti−6Al−4V alloy (mass fraction)

Al	V	C	Fe	O	Ti
6.75	3.55	0.08	0.03	0.2	Bal.

2.1 Heat treatment procedures

In this work, cryogenic treatment, aging treatment, and cryogenic treatment followed by aging treatment were conducted on annealed Ti−6Al−4V alloy containing a lamellar α-phase with larger β-grains. Ti−6Al−4V alloy is a two-phase titanium alloy, with aluminium as α stabilizer and vanadium as β stabilizer. In order to investigate the low-energy impact behaviour of Ti−6Al−4V alloy, four different sample groups were tested; the details of the sample groups and codes are shown in Table 2.

Table 2 Details of codes of heat-treated samples

Sample	Before treatment	Cryogenic treatment	After cryogenic treatment
UT (As-received)	Annealed	–	–
AT (Aging treatment)		–	550 °C (3 h)
CT (Cryogenic treatment)		−140 °C (6 h)	–
CAT (Cryogenic+ aging treatment)		140 °C (6 h)	550 °C (3 h

Ti−6Al−4V alloy plates were cut to dimensions of 100 mm × 100 mm × 2 mm according to the dimensions of the pneumatic clamping device of the low-energy impact test machine. After the plates were cut, cryogenic treatment was applied to the samples at −140 °C for 6 h under a protective nitrogen atmosphere using a vacuum oven. The cryogenic treatment temperature and soaking time were determined according to the results of studies performed previously in Refs. [1,2,9]. The cryogenic treatment tank is shown in Fig. 1(a) and illustrated schematically in Fig. 1(b).

The cryogenic treatment system consists of a cryogenic treating tank, nitrogen tank, liquid nitrogen inlet system, fan, control panel, and an outer cladding structure providing insulation. Liquid nitrogen is pumped into the cryogenic tank, where evaporated nitrogen is spread uniformly within the entire tank with the help of the fans. The atmosphere is time and temperature controlled in the system: the sample is cooled to