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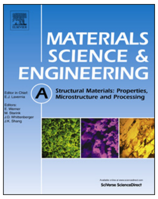

# Effect of microstructure evolution of the lamellar alpha on impact toughness in a two-phase titanium alloy

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ABSTRACT

The effects of the evolution of the lamellar alpha microstructure on the impact toughness of Ti-17 alloy are investigated. For this purpose, the beta-processed material is isothermally forged at 820 °C and subsequently heat treated using the combination of solid solution and aging treatment. Then the impact tests are carried out at room temperature. The corresponding microstructure and fracture surface are examined by scanning electron microscope (SEM). Microstructural observations reveal that globularization behavior is the main feature of microstructure evolution and the globularization fraction increases with the increasing of prestrain. However, globularization behavior has a negative influence on the impact toughness of Ti-17 alloy. In this work, the impact toughness have been obtained in the range of 29–55 J/cm$^2$ via varying globularization fraction of alpha phase. A linear relationship between the impact toughness and globularization fraction can be observed though the quantitative analysis. The linear equation is expressed as $A = -0.3232f + 59.885$. The two major reasons can be used to explain the effect of globularization fraction on the impact property of Ti-17 alloy. One explanation is that the lamellar structure can provide excellent interfacial strengthening effect, which can improve the toughness of material, and makes it not easy to fracture. On the other hand, the fracture surface of specimen with the lamellar structure has larger amplitude of ups and downs. A long crack path length will be generated during fracture process. By contrast, the fracture of specimen with the equiaxed structure presents more flat surface and shorter crack path.

## 1. Introduction

Ti-17 (Ti–5Al–2Sn–2Zr–4Mo–4Cr) is the biphasic alpha/beta titanium alloy, and it is an attractive material for aeronautic industry due to its excellent high-temperature properties as well as a strong resistance to crack propagation and corrosion. It has received the increasing attentions from aviation industry as a candidate of materials to manufacture dual-property blisk [1]. The thermomechanical processing (TMP) of Ti-17 alloy typically includes many hot working and heat treatment steps [2]. The initial TMP is usually carried out in the high-temperature (beta phase field) in order to produce a basketweave-alpha structure. The subsequent hot working and heat treatment steps are conducted below beta transus (the two-phase field). The objective of such operations is to obtain the more homogeneous microstructure morphology [2]. The parameters during deformation and heat treatment have significant impact on the service performances of the alloy. The basketweave microstructure, which is produced in the initial TMP, has moderate strength and fatigue crack growth resistance but low ductility. However, hot working and heat treatment in the two-phase field can change microstructure morphology and further influence the mechanical properties [3,4]. The level of globularization is significantly influenced by deformation degrees during hot working [1,5–11]. Microstructure maintains the lamellar structure for a small strain, whereas enough strain can break down the colony-alpha structure into fine and uniform equiaxed-alpha morphology [1,4]. In contrast to the lamellar structure, a microstructure comprising equiaxed-alpha in transformed beta matrix will process a better balance of ductility and strength [12]. The specific properties are a function of microstructure features. In turn, these features are a function of the parameters during hot working and heat treatment. Thus, it is beneficial to both science and engineering perspective for the quantitative analysis of the relationship between technical parameters and service properties.

The impact toughness is an important indicator to evaluate the damage tolerance of material [13]. With this purpose, a lot of studies about the impact toughness have previously been developed [14–27]. For instance, Tian et al. [14] investigated the relationship between annealing temperature and the notch impact

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toughness of a laser melting deposited titanium alloy Ti–4Al–1.5Mn. They found that the impact toughness of the as-deposited alloy was equivalent to that of wrought counterpart and was largely improved by annealing in the two-phase field. Buirette et al. [15] studied the crack propagation mechanisms during impact toughness tests for both equiaxed and lamellar microstructures of Ti–6Al–4V alloy. The result indicated that the lamellar alpha microstructure presents higher fracture energy than the equiaxed alpha structure. Balasubramanian et al. [18] developed a mathematical model to predict impact toughness of pulsed-current gas tungsten arc-welded Ti–6Al–4V alloy, and impact toughness of the joints could be predict with 99% confidence level. Zhou and Chew [24] evaluated the impact toughness of a gas tungsten arc-welded Ti–6Al–4V alloy butt-joint. Mohandas et al. [27] investigated the effect of electron beam welds on the impact toughness of Ti–6.8Al–3.42Mo–1.9Zr–0.21Si alloy. Although some investigations have been conducted to study the impact toughness of titanium alloy, most studies are related to welding technique. The studies focusing on the relationship between the traditional forging and heat treatment parameters and the impact toughness are limited. Especially for Ti-17 alloy, the investigation of the impact toughness is not discovered.

This paper is aimed at discussing globularization behavior of primary alpha phase during hot working and heat treatment, and then studying the effect of globularization behavior on the impact toughness of Ti-17 alloy. For this purpose, a series of hot working and heat treatment steps in the two-phase field are conducted for Ti-17 alloy with the initial lamellar structure. And then the impact tests are conducted at room temperature. Finally, the experimental data are analyzed to obtain a quantitative relationship between globularization fraction and the impact toughness.

## 2. Material and experimental procedures

### 2.1. Material

The program material used in this work is the biphasic titanium alloy Ti-17, and it is provided in the form of bar of 75 mm in diameter. The beta transus temperature, which is determined by metallographic observations, is 895 °C. Its measured composition is listed in Table 1. Microstructure of the as-received material is a typical beta-processed material, as shown in Fig. 1. It consists of the fully lamellar alpha structure in the transformed beta matrix. The average thickness of alpha lamellae is approximately 0.35 μm with a random orientation.

### 2.2. Experimental procedures

To investigate the effect of globularization behavior of alpha phase on the impact behavior, some forging and heat treatment steps are conducted in the two-phase field. Firstly, the beta-processed bars are isothermally forged to the height reductions of 20%, 40% and 60% on 2000T hydropress at 820 °C. Air cooling is carried out after deformation. Then, the workblank samples (12 × 12 × 55 mm) are prepared at 1/2 radius of the bars. The local strains at sampling point are determined to be 0.25, 0.52 and 1.03 for 20%, 40% and 60% reductions by finite element analysis (FEA) [28]. The samples are heat treated using the combination of solid solution and aging treatment (820 °C/4 h/WQ+630 °C/8 h/AC). After heat treatment, the U-notch standard impact test sample is machined, as shown in Fig. 2. The impact toughness is evaluated at room temperature, and three samples are tested for each condition to ensure accuracy of this test. Finally, microstructure and fracture surfaces of the impact samples after the test are characterized by a scanning electron microscope (JSM-6390). Micrographs are quantitatively examined by a metallographic image analysis system (Image-pro plus 5.0).

**Table 1**
The chemical composition of Ti–5Al–2Sn–2Zr–4Mo–4Cr alloy (wt%).

| Al | Cr | Mo | Sn | Zr | Fe | C | N | H | O | Ti |
|---|---|---|---|---|---|---|---|---|---|---|
| 5.02 | 3.93 | 3.88 | 2.37 | 1.95 | 0.05 | 0.01 | 0.01 | 0.003 | 0.12 | Bal |

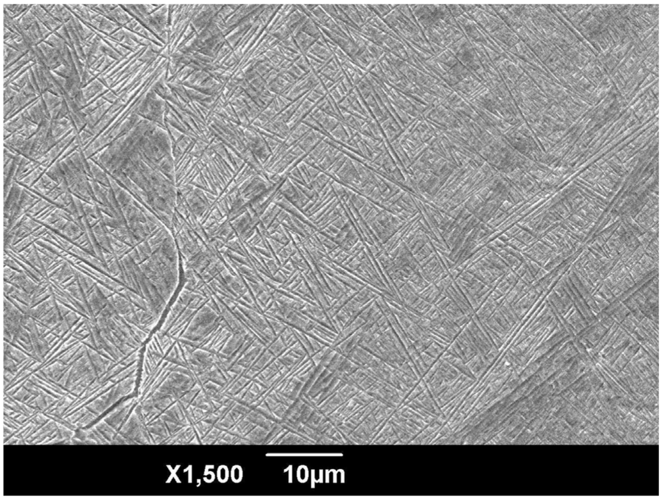

**Fig. 1.** Microstructure of beta-processed Ti–5Al–2Sn–2Zr–4Mo–4Cr alloy.

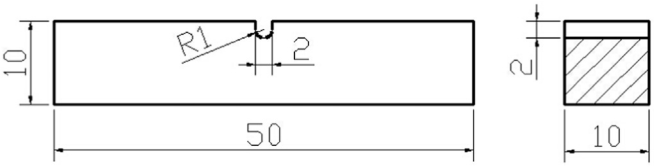

**Fig. 2.** The U-notch impact test sample.

## 3. Results and discussion

### 3.1. Microstructure evolution

It is well known that microstructure evolution is significantly influenced by hot working and heat treatment parameters. Fig. 3 shows microstructure evolution for material deformed to different strains and followed by solution and aging treatment. Microstructure morphology after deformation and heat treatment takes place the obvious changes in contrast to the original microstructure. The main features of microstructure evolution during deformation and heat treatment comprises the coarsening and globularization of alpha phase. The definition of globularization should be firstly given. An alpha plate or particle is considered to be a globular structure if it possesses an aspect ratio of 2.5 or less [28]. Microstructural observations indicate that the coarsening behavior of alpha phase is evident by comparing Figs. 1 and 3. The coarsening behavior is mainly controlled by solute diffusion. As a thermally activated process, temperature is a major factor to determine the diffusivity of solute. Hence, the coarsening behavior of alpha phase is observed after high temperature deformation and heat treatment. Essentially, the coarsening behavior reduces effectively the aspect ratio of alpha phase, and it can be considered as one of the steps of globularization process. During prolonged heat treatment, globularization process of alpha phase is completed via the diffusion-controlled coarsening behavior [30]. Thus,