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Role of processing parameters in the development of tri-modal microstructure during isothermal local loading forming of TA15 titanium alloy

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ABSTRACT

It is critical to precisely control the tri-modal microstructure during the isothermal local loading forming of titanium alloy to obtain high-performance components. To this end, the effect of local loading processing parameters on the development of tri-modal microstructure were experimentally investigated. The key influence factors and laws are revealed as follows. In the first loading step, the deformation temperature plays a decisive role in the volume fraction of equiaxed α, which decreases with the increase of temperature. While, the deformation amount and cooling mode present little effects on the microstructure evolution. In the second loading step, the deformation temperature and amount mainly influence the volume fraction, spatial orientation distribution and globularization of lamellar α. The volume fraction of lamellar α increases with the temperature decreasing. The spatial orientation distribution of lamellar α gradually changes from homogeneous distribution to concentrated distribution with the increase of deformation amount. Besides, the dynamic globularization fraction of lamellar α producing in the second loading step increases with the deformation amount, and their relationship can be well fitted by Avrami type equation. Moreover, higher temperature in the second loading step is beneficial to decrease the critical strain for the initiation of dynamic globularization and promote the kinetic rate of dynamic globularization. On the other hand, the deformation amount of the second loading step has after-effects on the static globularization of lamellar α in the annealing treatment. If the deformation amount exceeded the critical strain for the initiation of dynamic globularization, the static globularization of lamellar α would produce in the annealing, and the static globularization fraction increases with the deformation amount of the second loading step.

1. Introduction

Titanium alloy large-scale complex components with features of high performance and light weight (such as bulkhead) are much-needed structural parts for the advanced equipment in aviation and aerospace fields. However, the high deformation resistance of material, complex shape and large projection area of the structure make it very difficult to form such components. To overcome this problem, Yang et al. (2011) proposed the isothermal local loading forming technology that integrates the advantages of isothermal forming and local loading forming. This forming technology was named as ILLF by Zhou et al. (2011). During local loading forming, the load is applied to part of the billet and the component is formed by changing loading region, as shown in Fig. 1. This forming technology can enhance the plasticity of material, control the flow of material, reduce the forming load and enlarge the size of component to be formed, providing a feasible way to manufacture this kind of components.

The large-scale complex components of titanium alloy often serve as key load bearing structures in severe conditions. Thus, not only the high quality of macroscopical forming but also the fine microstructure and mechanical properties are required in the forming process. Zhou et al. (2005) pointed out that the tri-modal microstructure, consisted of equiaxed α, lamellar α and β transformed matrix, exhibits a good combination of strength, ductility, fracture toughness and fatigue life. The balanced mechanical properties make it a preferable microstructure morphology in the hot working of titanium alloy. However, besides the microstructure morphology, the microstructure parameters (such as the content, scale and distribution of each constituent phase) also play

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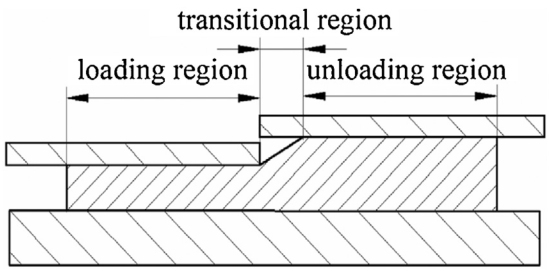

Fig. 1. Illustration of local loading forming (Sun and Yang, 2009).

important roles in the final mechanical properties, as demonstrated by Lütjerin (1998). On the other hand, the isothermal local loading forming is a complicated multi-step hot working process with coupling effects of severe uneven deformation and complex temperature routes. The complex thermomechanical processing history may greatly influence the development of tri-modal microstructure as well as its microstructure parameters and mechanical properties. Consequently, in order to realize the precise control of tri-modal microstructure and properties, it is urgent to study the development mechanisms and rules of tri-modal microstructure in the isothermal local loading forming of titanium alloy.

Since the tri-modal microstructure of titanium alloy was first proposed by Zhou et al. (1996), some investigations have been conducted on its development during the integral forging and subsequent heat treatments. Lütjerin (1998) obtained a so called bi-lamellar microstructure of Ti-6Al-4V alloy, in which the single phase β lamellae are hardened by fine α plates. This bi-lamellar microstructure is similar to the tri-modal microstructure. Zhou et al. (2005) reported the new near-β forging process to produce tri-modal microstructure for titanium alloys, i.e. near-β forging followed by rapid water-cooling, then high temperature toughening and low temperature strengthening heat treatments. The new near-β forging process have been successfully applied to manufacture the TC11 alloy compressor disk with tri-modal microstructure. Sun et al. (2014) quantitatively studied the evolution of volume fraction, average grain size and aspect ratio of equiaxed α in the tri-modal microstructure during the near-β forging process of TA15 alloy. Recently, Sun et al. (2016) put forward a new method to obtain the tri-modal microstructure in the hot working of TA15 alloy, i.e., the conventional forging combined with subsequent near-β and two-phase field heat treatment. And, they investigated the effect of conventional forging conditions on the parameters of equiaxed and lamellar α phases. As for the development of tri-modal microstructure during the isothermal local loading forming of titanium alloy, Gao et al. (2012) proposed that the tri-modal microstructure can be achieved through near-β forging in the first loading step combined with conventional forging in the second loading step. Fan et al. (2012a) further found that the volume fraction and morphology of each constituent phase in the final tri-modal microstructure change with the deformation temperature and degrees in the above forming process. However, there is still a lack of quantitative analysis on the effect of local loading processing parameters on the development of tri-modal microstructure, which is necessary to achieve the precise control of tri-modal microstructure and mechanical properties.

In this paper, the effects of processing parameters on the development of tri-modal microstructure during isothermal local loading of titanium alloy were quantitatively studied by staged experiment. It will provide a technological basis for the precise control of tri-modal microstructure in the isothermal local loading forming of titanium alloy large-scale complex components.

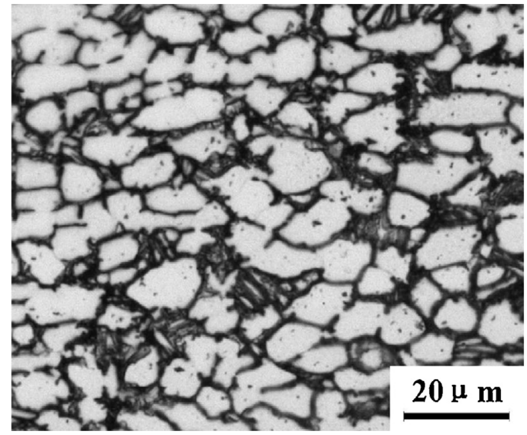

Fig. 2. Original microstructure of the billet.

Table 1
Local loading processing parameters.

Deformation temperature (°C)	910–980
Holding time (min)	15, 60
Reduction rate (%)	30, 50, 70
Nominal strain rate (s^{-1})	0.01
Cooling mode	Air cooling (AC)Water quenching (WQ)

2. Experimental procedures

The material used in this investigation is TA15 titanium alloy. Its chemical compositions are as follows (wt%), Al: 6.06; Mo: 2.08; V: 1.32; Zr: 1.86; Fe: 0.3 and Ti balance. Its β-transus temperature is 990 °C. The microstructure of the as-received material is equiaxed microstructure consisted of about 60% primary α phase and β transformed matrix, as given in Fig. 2.

The physical analogue experiment of isothermal local loading (Fig. 3) designed in the authors' previous study (Fan et al., 2011) was conducted in this study. It can reflect the deformation characteristics of local loading forming. The local loading experiment is accomplished in one loading pass, which consists of two loading steps. In each loading step, the specimen was heated to the deformation temperature, deformed isothermally and then cooled down. Fig. 4 shows the change of specimen shape during experiment. After local loading, the specimens were annealed in the route of 810 °C/1 h/AC. The local loading processing parameters in this work are given in Table 1.

In this experiment, the effects of processing parameters on the development of tri-modal microstructure were studied in stages. At any stage, the specimen was quartered along the two symmetric planes and prepared for metallographic observation using standard technique. The detailed processing parameters and metallographic observation locations in each stage would be demonstrated in Section 3. The microstructure parameters under different conditions are quantitatively measured by Image-Pro Plus software as follows. The area fraction of each phase is measured as its volume fraction. The size of equiaxed α is measured by the average length of diameters measured at 2° intervals and passing through the grain's centroid, called as mean diameter (d_{mean}). The aspect ratio of each phase is represented by the ratio between major axis and minor axis of ellipse equivalent to object. And the spatial orientation of lamellar α is evaluated by the angle between the major axis of object and the vertical, i.e. the compression direction. For each microstructure parameter, the average value of large numbers of objects is adopted as the final result. According to the basic stereological procedure, i.e., the area fraction (A_A) and volume fraction (V_V) are equivalent, it is reasonable to represent the volume frac-