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High temperature deformation processing maps for boron modified Ti–6Al–4V alloys

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ABSTRACT

The alloy, Ti–6Al–4V is an $\alpha+\beta$ Ti alloy that has large prior β grain size ($\sim$2 mm) in the as cast state. Minor addition of B (about 0.1 wt.%) to it refines the grain size significantly as well as produces in-situ TiB needles. The role played by these microstructural modifications on high temperature deformation processing maps of B-modified Ti64 alloys is examined in this paper. Power dissipation efficiency and instability maps have been generated within the temperature range of 750–1000 °C and strain rate range of 10^{-3}–10^{+1} s^{-1}. Various deformation mechanisms, which operate in different temperature–strain rate regimes, were identified with the aid of the maps and complementary microstructural analysis of the deformed specimens. Results indicate four distinct deformation domains within the range of experimental conditions examined, with the combination of 900–1000 °C and 10^{-3}–10^{-2} s^{-1} being the optimum for hot working. In that zone, dynamic globularization of α laths is the principle deformation mechanism. The marked reduction in the prior β grain size, achieved with the addition of B, does not appear to alter this domain markedly. The other domains, with negative values of instability parameter, show undesirable microstructural features such as extensive kinking/bending of α laths and breaking of β laths for Ti64–0.0B as well as generation of voids and cracks in the matrix and TiB needles in the B-modified alloys.

1. Introduction and background

Ti–6Al–4V (also referred as Ti64), an $\alpha+\beta$ titanium alloy is an important engineering alloy that is extensively used particularly in aerospace industry. This is due to its low density combined with high strength and toughness as well as outstanding corrosion resistance. An additional benefit associated with Ti alloys, in general, is that their properties are relatively temperature-insensitive between cryogenic temperature and $\sim$500 °C. In the as-cast state, Ti64 exhibits the classical Widmanstätten microstructure of (hcp) α and (bcc) β phases. However, Ti alloys – and Ti64 is no exception – typically suffer from large prior β grain size, which tends be in the order of a few mm. Therefore it becomes necessary to break this coarse microstructure down, through several thermomechanical steps. Typically, this involves upset forging in the β regime, i.e. above 1000 °C. This not only adds considerably to the cost of the final product, but also brings in additional complexities. For example, the oxide layer that forms on the surface during forging has to be machined out at each step, causing loss of material as well as adding to the manufacturing cost, as it otherwise could get included in the material leading to low fatigue performance. Thus, the necessity to break the coarse as-cast structure makes the finished Ti alloy products considerably expensive vis-à-vis competing alloys.

Recently, it was discovered that the addition of B in minor amounts (within the hypo-eutectic range) to Ti64 reduces the grain size significantly (by an order of magnitude) [1,2]. This circumvents the need for processing steps such as β upset forging and hence makes Ti alloys relatively more affordable. As a result, there has been considerable interest in understanding the mechanical behavior of these alloys. It has been shown that the microstructural refinement leads to anomalous increase in elastic modulus, moderate enhancement in yield and ultimate strengths, and significant benefit in terms of the unnotched fatigue performance of the Ti64 [3–7].

Although the addition of B leads to a markedly reduced grain size, it does not completely eliminate the need for some thermomechanical processing steps subsequent to casting of the alloy. These are necessary for, at least, two reasons. The first is to impart the desired shape to the alloy and the second is to close any as-cast porosity, which is otherwise detrimental to the fatigue performance of the alloy. Therefore, it is essential to determine the hot working conditions, i.e., optimum temperature and strain rate combination, for deformation that will yield required microstructures

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without significant defects in them. The identification of these, through the processing maps approach, is the objective of this work.

Hot working of α/β Ti alloys is a widely studied area with considerable literature available on it. The principle dynamic deformation mechanism that leads to an optimum condition in the working zone of Ti64 alloys with lamellar structures is the spherodization/globularization of α laths [8–10]. Since the addition of B to Ti64 reduces its grain size and also introduces stiff and hard TiB particles into the microstructure, a pertinent question to ask is the following: "Do these microstructural modifications, which are imparted through the addition of B to Ti64, alter the optimum processing conditions?" An additional, and related, question is "what are the differences in micro-mechanisms during high temperature deformation that occur at different temperature–strain rate combinations?" Answers to these questions are sought through processing maps, which are generated based on the results obtained by conducting high temperature compression experiments on a series of Ti64–B alloys with the test temperature and applied strain rate as variables. These are coupled with detailed microstructural studies of the deformed specimens for corroborating the inferred deformation mechanisms operating in various domains. The stress–strain responses and detailed analyses of them are reported in a companion paper [11]. Since this paper's focus is on processing maps, the scientific basis for their construction is described briefly below. Interested reader can find detailed information about them in the reviews by Prasad et al. [12,13] who originally came up with the concept of processing maps.

When a material is deformed at a strain rate, $\dot{\varepsilon}$, its instantaneous response in terms of true stress, σ, will follow the power law [13–15]:

$$\sigma = K \cdot \dot{\varepsilon}^m \tag{1}$$

where K is a constant and m is the strain rate sensitivity. The total energy spent on the work piece, given by the product $\sigma . \dot{\varepsilon}$, can be partitioned into that dissipated as heat (G-content) and the one which leads to change in the microstructure (J-co content) as:

$$\sigma \cdot \dot{\varepsilon} = \int_0^{\dot{\varepsilon}} \sigma \, d\dot{\varepsilon} + \int_0^{\sigma} \dot{\varepsilon} \, d\sigma \tag{2}$$

The first integral on the right-hand side of Eq. (2) gives the G-content whereas the second gives the J-co content. Practically, major portion of the energy input to the work piece is dissipated as the rise in temperature i.e. thermal energy which is represented by the G-content. J-co content, which represents the microstructural changes that occur during deformation, is relatively small in comparison to the G-content. The partitioning between the two is decided by m, which is defined as:

$$m = \frac{dJ}{dG} = \frac{\Delta \log \sigma}{\Delta \log \dot{\varepsilon}} \tag{3}$$

The value of m varies between 0 and 1. From Eqs. (1)–(3), we get:

$$J = \frac{m \cdot \sigma \cdot \dot{\varepsilon}}{m+1} \tag{4}$$

When $m = 0$, $J = 0$ whereas $J = G$ for $m = 1$ [13]. For a linear power dissipater, $m = 1$ and $J \sim J_{\max}$ [13]. The efficiency of power dissipation, η, for microstructural changes can be obtained by normalizing J with $J_{\max}$ as:

$$\eta = \frac{J}{J_{\max}} = \frac{2m}{m+1} \tag{5}$$

Thus, the constitutive equation, which captures the intrinsic characteristics of the work piece, will dictate the path it will follow in response to the applied strain. This path is a strong function of $\dot{\varepsilon}$. For example, application of higher $\dot{\varepsilon}$ may lead to internal cracking whereas the same material may undergo dynamic recovery at lower $\dot{\varepsilon}$.

From the true stress, σ– true strain, ε curves generated at various T– $\dot{\varepsilon}$ combinations, m can be calculated by assuming that the work-piece is a non-linear energy dissipater. Consequently, η can be computed for a fixed value of ε by using eqn. (5), which in turn can be utilized to construct iso-efficiency contour maps in the 2-D space of T and $\dot{\varepsilon}$ (η maps). These contour maps are utilized to identify the different deformation mechanisms prevailing over different combinations of T and $\dot{\varepsilon}$. For instance, the dynamic recrystallization (DRX) regime, which is important from the workability point of view, typically exhibits the highest η over a broad range with widely spaced contours indicating small gradation to the efficiency hill. The width of the DRX regime obtained from the processing maps will dictate the limits, in terms of T and $\dot{\varepsilon}$, for the industrial hot working schedule. However, a region with very high η value (>90) in the efficiency maps is also usually associated with void formation at hard particles or can be an indication of superplastic regime as well. The former is also characterized by a rapid rise in η with the decrease in temperature. Therefore, the information from processing maps alone is insufficient. Complementary microstructural characterization thus plays a vital role in understanding of the deformation mechanisms associated with a specific regime.

An instability criterion, which is based on the maximum rate of entropy production, gives the following equation [8,13,16]:

$$\zeta(\dot{\varepsilon}) = \frac{\partial \ln(m/m+1)}{\partial \ln \dot{\varepsilon}} + m < 0 \tag{6}$$

where $\zeta(\dot{\varepsilon})$ is a dimensionless parameter that represents the instability in the system. Similar to η maps, ζ contour maps can also be generated in the T– $\dot{\varepsilon}$ space for a fixed value of ε. The region of instability is indicated by a negative ζ value. Typical signatures of instability are shear band formation, flow localization, formation of cavities, breaking of particles etc. [8–10,13,17–19]. The η and ζ maps together can then be utilised to identify the domains that are suitable for hot working as well as the ones that give rise to undesirable microstructures and hence should be strictly avoided during industrial practice. This approach has been successfully utilized to correctly predict hot working conditions for a variety of metals and alloys including Ti alloys [8,10,13].

2. Experiments

Five as-cast Ti–6Al–4V-xB alloys, where x = 0.0, 0.04, 0.09, 0.30 and 0.55 wt.%, were examined in this study (referred as Ti64–xB in the remainder of the text). Uniaxial compression tests were conducted at temperatures, (T) of 750, 800, 850, 900, 950 and 1000 °C. This range of T has been chosen for the following reason. The reported β transus temperature for commercial grade Ti64 alloy, which contains about 1500–2000 ppm of oxygen, is ~995 °C [19]. The high temperature bcc β phase exhibits large ductility and hence is easy to process. Therefore, the present work is restricted to the two phase $\alpha + \beta$ regime. At each T, constant true strain rates ($\dot{\varepsilon}$) of 10^{-3}, 10^{-2}, 10^{-1}, 10^{0}, 10^{+1} s^{-1} were employed and true strains ε of 0.7 were achieved at each T– $\dot{\varepsilon}$ combination. Further details of the materials, their initial microstructures, stress–strain responses, and details of analyses of the latter can be found in Ref. [11].

3. Results

3.1. Stress–strain curves

All the σ–ε plots show that softening followed by a peak σ are existent at lower $\dot{\varepsilon}$ of testing (Fig. 2a of [11]), whereas at higher $\dot{\varepsilon}$ the flow curves exhibit oscillations (Figs. 2b and c of [11]). The