Materials and Design 51 (2013) 457–465

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Flow behavior modeling of a Ti–6Al–7Nb biomedical alloy during manufacturing at elevated temperatures

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ARTICLE INFO

Article history:
Received 22 January 2013
Accepted 13 April 2013
Available online 25 April 2013

Keywords:
Biomaterials
Titanium alloy
Flow behavior modeling
Mechanical characterization

ABSTRACT

A proper constitutive base model has been developed to predict the high temperature compressive flow behavior of a Ti–6Al–7Nb biomedical alloy in two phase $\alpha + \beta$ region. The isothermal hot compression tests were carried out in the temperature range of 850–1000 °C under the strain rates of 0.0025, 0.025 and 0.25 s^{-1} up to the true strain of 0.65. The constitutive model has been developed through a hyperbolic-sine Arrhenius type equation to relate the flow stress, strain rate and temperature. The influence of strain has been also incorporated by considering the variation of material constants as a function of strain. The proposed constitutive equation has been described in terms of Zener–Hollomon parameter in an exponential type equation, the accuracy of which has been evaluated using standard statistical parameters. The predicted flow stress curves are appropriately found to be in good agreement with the experimental ones.

1. Introduction

The ideal biomaterial for implant applications, especially for joint replacements, is expected to exhibit excellent properties such as no adverse tissue reactions, corrosion resistance in the body fluid medium, high mechanical strength and fatigue resistance, low modulus, low-density, and good wear resistance [1–3]. In this regard, many efforts have been devoted to assess the capability of Ti-base biomaterials specifically steered in the direction of implant applications. Commercially pure (CP) titanium was pointed out to have disadvantages of low strength, difficulty in polishing, and poor wear resistance [4]. In addition, the CP-Ti was realized to be insufficient for high-stress applications; e.g., long spanned fixed prostheses and the frameworks of removable partial dentures [5,6]. Ti–6Al–4V alloy was then tested as a replacement for CP-Ti, because of its higher strength with sufficient corrosion resistance. However, the elemental cytotoxicity of vanadium was still questionable [7]. Subsequently, Ti–6Al–7Nb alloy was developed for orthopedic applications as a wrought biomedical $\alpha + \beta$ titanium alloy. Niobium, added up to 7 wt.%, was found to be sufficient to stabilize the β phase near room temperature similar to vanadium in Ti–6Al–4V alloy. Thanks to the modified chemical composition, this alloy is characterized by a more beneficial set of mechanical properties [8], higher corrosion resistance and bio-tolerance [9] in comparison to the commonly used Ti–6Al–4V alloy. The processing of Ti–6Al–7Nb biomedical alloy often comprises a series of steps each of which possesses some specific microstructural goals. Primary hot working (and recrystallization annealing) to produce a uniformly wrought microstructure is usually conducted in the single-phase beta field, where the morphology of transformed microstructure is a function of cooling rate. Following such beta working/annealing operations, the breakdown of the transformed microstructure is executed at temperatures below the beta transus. This plays a key role in development of the equiaxed alpha microstructure frequently desired for final shaping or services. As a matter of course, the evolution of the related microstructures is very sensitive to the processing parameters such as temperature, strain rate and strain [10,11]. Accordingly, to precisely control the processing route, the profound knowledge of the material flow behavior (i.e. prediction and modeling) is of great importance.

As is well established, there is a nonlinear relationship between the high temperature material flow stress and the related processing variables (strain, strain rate and temperature) which is usually described using constitutive base model in the form of $\sigma = f(\varepsilon, \dot{\varepsilon}, T)$. The constitutive models take a great potential to describe the change in mechanical response under an external loading, and to develop a valid processing map by which is possible to delineate the boundaries between safe and unsafe processing regions. Various analytical, phenomenological, and empirical constitutive models have been established to predict the high temperature behavior of the metallic materials [12–15]. Due to the nonlinear relationship between the flow stress and process variables, it is difficult to establish an advisable empirical relation that alone describes the flow behavior in a wide range of temperatures and strain rates. Analytical models are also based on kinetics and dynamics of dislocations thereby requiring very clear understanding of the deformation mechanisms and are hardly possible to apply in

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http://dx.doi.org/10.1016/j.matdes.2013.04.046

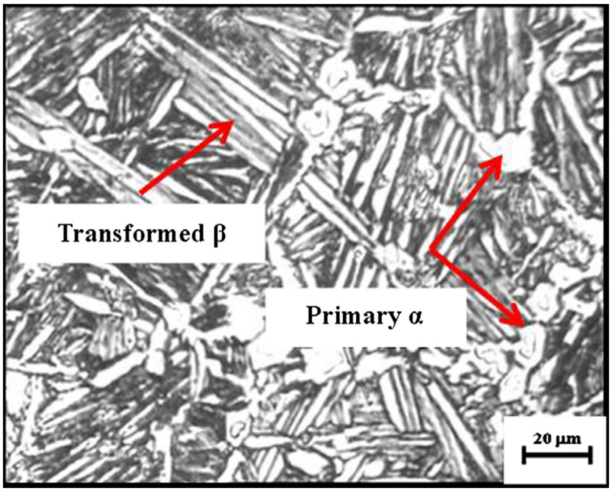

Fig. 1. The initial microstructure of Ti–6Al–7Nb experimental alloy.

practical use [16,17]. Phenomenological models, however, less strictly relate to the physical theories and have been extensively employed in flow behavior modeling of the metallic materials [18–22]. Several modifications have been suggested to date in order to improve the predictability of the aforementioned models. Most of the involved researches have considered the effect of strain, which possesses a critical effect on the accurate prediction of the related flow behavior. Accordingly, Lin et al. [23] and Mandal et al. [24] have revised the strain-dependent hyperbolic sine constitutive model by compensation of the strain rate in Zener–Hollomon parameter (Z). Evidently, all of these modified constitutive models notably improve the agreement of the predicted flow stress with experimental results than unmodified ones. Such phenomenological models have been developed for different magnesium alloys (AZ41 [25], AZ81 [26], AZ31 [27]), aluminum alloys (A356 [28], 2124[21], 7050 [18] and 6061 [29]), steels (42CrMo steel [20], TWIP [30] and TRIP [31]), and also Ti-base alloys (Ti–6Al–4V [32], Ti60 [33], Ti17 [34], and IMI834 [35]). In line to these attempts, the present work deals with predicting the high temperature compressive flow behavior of Ti–6Al–7Nb biomedical alloy in two-phase ($\alpha + \beta$) region over a wide range of strain rates and temperatures. The necessity is overemphasized considering the fact that the deformation-processing window for this biomedical alloy (as a representative $\alpha + \beta$ titanium alloy) is quite narrow compared to the other ferrous and non-ferrous alloys. Essentially, this effort is geared towards defining a proper relationship, which describes the instantaneous material behavior in response to the strain hardening and dynamic softening mechanisms.

2. Materials and methods

The experimental material used in this study was received as rods in mill-annealed condition with 10 mm in diameter. The experimental alloy composes of (wt.%) 5.9Al, 6.75Nb, 0.03Fe, 0.16O, 0.002N, 0.02C, 0.002H, with the balance being titanium. As is depicted in Fig. 1, the microstructure of the as-received bar was bimodal, i.e., the equiaxed alpha in a matrix of transformed beta. The related beta-transus temperature is about 1020 °C [36]. The cylindrical compression specimens were machined directly from the as-received bar with the dimension of Ø10×H15. The hot compression tests were conducted in the temperature range of 850–1000 °C under the strain rates of 0.0025, 0.025 and 0.25 s^{-1} in accordance with ASTM: E209 standard using a Gotech AI-7000 universal testing machine coupled with a programmable resistance furnace. Prior to any hot compression test, the specimens were soaked at the deformation temperature for 7 min to equilibrate the temperature throughout the specimens. The specimens were then hot compressed up to a true strain of 0.65 followed by immediate quenching in water to preserve the deformed microstructures. The true stress values were recorded using a high accuracy load cell (Model: SSM-DJM-20kN) with the capability of measuring the load forces down to 0.1 kg. A thin layer of mica was placed between the face of the specimen and the anvils in order to maintain the uniform deformation and avoid sticking problems during quenching. The deformed specimens were sectioned parallel to the compression axis and prepared for metallography examinations using standard procedures.

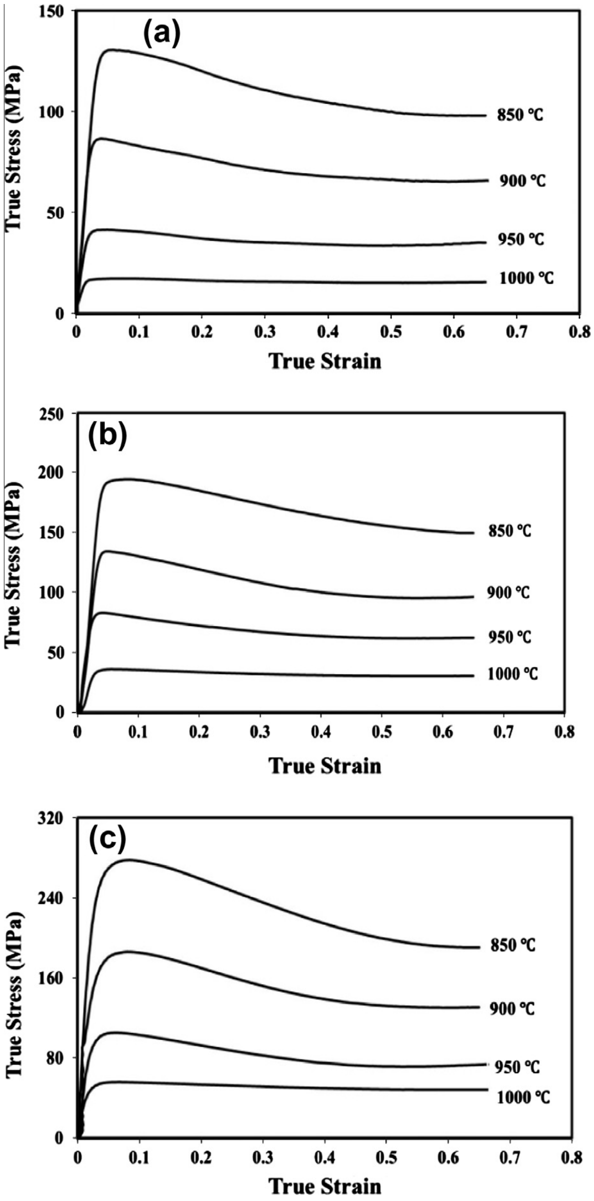

Fig. 2. The true stress–strain curves under strain rate of: (a) 0.0025 s^{-1}, (b) 0.025 s^{-1}, and (c) 0.25 s^{-1} obtained by the isothermal compression test.

3. Results and discussion

3.1. Flow stress characteristics

The experimental true stress–true strain curves resulted from the hot compression tests in two phase [$\alpha + \beta$] region are presented