

Constitutive modeling and fracture behavior of a biomedical Ti–13Nb–13Zr alloy



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ABSTRACT

The dynamic compression tests were performed at various strain rates (0.01, 1700, 2700 and 3500/s) and temperatures (25, 200, 400 and 600 °C) for a biomedical Ti–13Nb–13Zr alloy. Based on experimental data, constitutive models were established using the Modified Johnson–Cook (J–C) model, Modified Khan–Huang–Liang (KHL) model and Artificial neural network (ANN) model, respectively. The new modified J–C model considers the coupled effects of strain hardening, strain rate hardening and thermal softening. In this work, a radial basis function artificial neural network (RBF–ANN) model was also developed to predict the high strain rate flow curves of Ti–13Nb–13Zr alloy. The results demonstrate that the flow behavior of Ti–13Nb–13Zr alloy is considerably influenced by the strain rate and temperature. The modified KHL model and ANN significantly enhance the predictability. The deformation behavior represented by dynamic recrystallization (DRX) and the instability flow has been discussed with reference to microstructural evolution during high strain rate compression. The validation of the developed constitutive model is embedded in the finite element analysis (FEA) to perform numerical simulations with ABAQUS/Standard to obtain the charpy impact energy.

1. Introduction

Titanium alloys have found extensive uses in defence applications especially in explosive forming or ballistic studies. Under these conditions, components are normally subjected to high strain rates and high stresses [1–5]. In recent times, titanium alloys [6–10] have received emphasis due to its remarkable properties such as low density, biocompatibility, high melting point, good oxidation resistance and high specific strengths etc. Ti–13Nb–13Zr alloy has been developed due to its low density, biocompatibility and attractive specific strength [11,12]. Ti–13Nb–13Zr beta alloy is one such implant material developed in late nineties whose elastic modulus is 79 GPa. Overall, the published literature on the Ti–13Nb–13Zr alloy is limited and very few researchers have made an attempt to investigate its mechanical properties over a wide range of strain rates and temperatures. Understanding of the high strain rate deformation behavior of titanium alloys is extremely essential for the numerical modeling of many manufacturing and other applications. The basic requirement for an efficient modeling of high strain rate deformation behavior is to develop finite element model (FEM). The high strain rate deformation of metals is often a complex process [13–15]. The hardening and softening mechanisms are appreciably governed by different important factors such as, strain rate, strain and temperature [16,17]. Generation of accurate constitutive

model is a crucial step in the numerical simulation process.

In the recent past, to describe the flow behavior, many constitutive models have been developed and these can be mostly classified into three groups [18–20]: Physically based, empirical and artificial neural network (ANN). Physically based models can present more precise representation of material deformation behavior under various temperatures and strain rates. Numerous physically based constitutive models were developed or modified to precisely characterize the flow behavior of materials [21–24]. Empirical models do not require a comprehensive analysis of the physical phenomena involved in the deformation process [25–27]. Among the empirical models, Johnson Cook (J–C) model [28–30] has been effectively integrated with finite element analysis packages to interpret the high strain rate deformation behavior of metals owing to its simplicity. Nevertheless, the original J–C model cannot provide an accurate prediction of high strain rate deformation behavior because it could not consider the coupled effects of strain rates and temperature. ANN demonstrates good capability to predict flow behavior as it does not require mathematical equation [30–35].

From the literature [14–17], it is known that, so far no attempt has been made to establish constitutive models of this titanium alloy. In order to perform reasonably accurate finite element analysis for different conditions of biomedical Ti–13Nb–13Zr alloy and cut down the experiment cost, it is essential to develop high-accuracy constitutive

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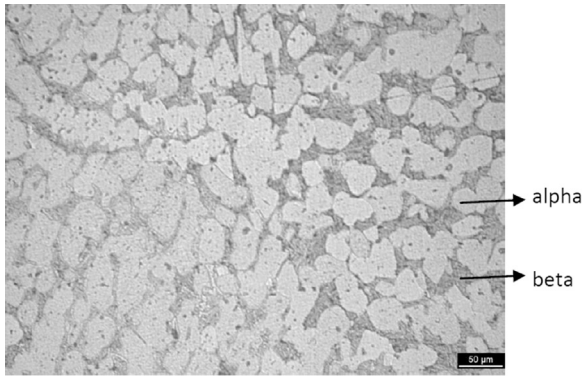


Fig. 1. Optical micrographs of solution treated Ti–13Nb–13Zr alloy.

Table 1
Modified Johnson-Cook Model constants.

A (MPa)	B (MPa)	n	C	m
840	861	0.3	0.015	0.71

models. In the current investigation, the high strain rate deformation behavior of biomedical Ti–13Nb–13Zr alloy was studied by performing compression tests at various strain rates and deformation temperatures. Modified Johnson cook model was established to predict the experimental data. Modified Johnson cook model, Modified KHL model and ANN model were established based on the experimental data obtained by the SHPB tests. In addition, the accuracy of these models was determined by comparing the experimental and predicted flow stresses.

2. Experimental procedures

The biomedical Ti–13Nb–13Zr alloy used for the present study is prepared using non-consumable vacuum arc melting process with composition of Nb 13.7, Zr 13.8, Fe 0.05, O 0.01, C 0.04, N 0.02 and a balance of Ti (in wt%). Prior to receipt, the material was solution treated then water quenched (WQ), aged at 760 °C for 1 h, and finally cooled in air. Fig. 1 presents a optical micrograph of the as-received alloy. The microstructure consists of equiaxed alpha primary and transformed beta phases. Cylindrical specimens of 10 mm in diameter and 5 mm in thickness were according to ASTM: E209 standard. The experiments were carried out at 25 °C, 200 °C, 400 °C and 600 °C and strain rates of 0.01/s, 1700/s, 2700/s and 3500/s, respectively. The experiments were performed using Gleeble machine and Split-Hopkinson Pressure Bar (SHPB) device. SHPB consists of striker bar, incident bar, reflected bar and transmitted bar. The Charpy impact test was carried out in a Zwick–Roell make test set-up. The experimental set-up consists of the anvils where the standard (ASTM designation, E23 [39]) notched specimen is freely supported and a pendulum with a mass, 30 kg attached to a rotating arm pinned at the machine body. The specimen length, height and thickness were 55 mm, 10 mm and 10 mm respectively. The depth of the notch was 2 mm. The span length between the anvils was kept 40 mm. The released pendulum follows a circular trajectory and hits the test specimen at the middle span transferring kinetic energy to it.

3. Results and discussion

3.1. Modified J-C model

According to the original form of J-C model [28,29], it is obvious that the influence of strain, strain rate and temperature on the high strain rate deformation behavior is assumed to be independent, while

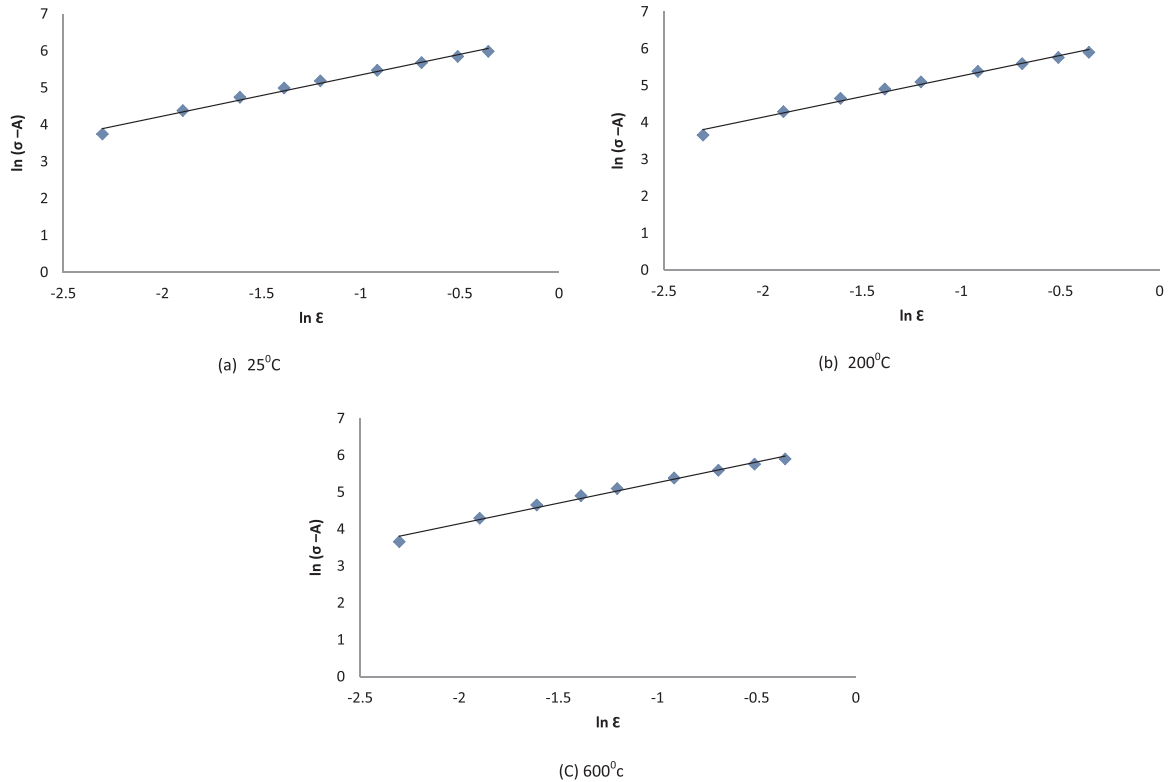


Fig. 2. Relationship between $\ln(\sigma-A)$ and $\ln \epsilon$ under strain rate of 0.01/s at various temperatures.

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