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Multiaxial and non-proportional loading responses, anisotropy and modeling of Ti–6Al–4V titanium alloy over wide ranges of strain rates and temperatures

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Abstract

Results from a series of multiaxial loading experiments on the Ti–6Al–4V titanium alloy are presented. Different loading conditions are applied in order to get the comprehensive response of the alloy. The strain rates are varied from the quasi-static to dynamic regimes and the corresponding material responses are obtained. The specimen is deformed to large strains in order to study the material behavior under finite deformation at various strain rates. Torsional Kolsky bar is used to achieve shear strain rates up to $1000\,s^{-1}$. Experiments are performed under non-proportional loading conditions as well as dynamic torsion followed by dynamic compression at various temperatures. The non-proportional loading experiments comprise of an initial uniaxial loading to a certain level of strain followed by biaxial loading, using a channel-type die at various rates of loadings. All the non-proportional experiments are carried out at room temperature. Experiments are also performed to investigate the anisotropic behavior of the alloy. An orthotropic yield criterion [proposed by Cazacu, O., Plunkett, B., Barlat, F., 2005. Orthotropic yield criterion for hexagonal closed packed metals. International Journal of Plasticity 22, 1171–1194.] for anisotropic hexagonal closed packed materials with strength differential is used to generate the yield surface. Based on the definition of the effective stress of this yield criterion, the observed material response for the different loading conditions under large deformation is modeled using the Khan–Huang–Liang (KHL) equation assuming isotropic hardening. The model constants used in the present study, were pre-determined from the extensive uniaxial experiments presented in the earlier paper [Khan, A.S., Suh, Y.S., Kazmi R.,

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2004. Quasi-static and dynamic loading responses and constitutive modeling of titanium alloys. International Journal of Plasticity 20, 2233–2248]. The model predictions are found to be extremely close to the observed material response.

Keywords: Kolsky bar; Multiaxial experiments; Titanium alloys; Constitutive behavior; High strain rate; Non-proportional loadings; Anisotropy

1. Introduction

Titanium alloys have found a wide variety of usage in the aerospace industry because of their high strength to weight ratio. Medical industry has uses for titanium in surgical equipment and implants because of its biocompatibility. Petrochemical industry has also found immense usage for this alloy because of its high corrosion resistance. The defense industry is interested in advancing the application of these alloys to armor systems. This is because of the high strength to weight ratio and the corrosion resistance of these alloys encourage their use in armor tanks and also for storing fuel and ammunitions. These alloys come in different grades depending on the impurity contents.

A large number of studies have been carried out in understanding and modeling the response of these titanium alloys (Follansbee and Gray, 1989; Lesuer, 2000; Nemat-Nasser et al., 2001; Picu and Majorell, 2002; Lee and Lin, 1997; Khan et al., 2004). These studies were focused mainly on the uniaxial response of the alloys at different strain rates and temperatures. However, it is well known that the stress states in these alloys, while in use, are definitely more complex and multiaxial in nature. Hence it becomes extremely important to understand the material behavior during these loading conditions. The uniaxial material responses and modeling act only as the first step towards understanding the actual more complex conditions that exist and how they affect the corresponding responses.

There have been a few studies understanding the torsional behavior of the Ti–6Al–4V titanium alloys which are available in the literature. Liao and Duffy (1998), performed a series of high strain rate ($\dot{\gamma} \sim 10^3/s$) torsion experiments to study the process of initiation and formation of adiabatic shear bands in conventional Ti–6Al–4V titanium alloy. The temperature rise in the alloys during deformation was also measured. Macdougall and Harding (1999) have also performed a series of torsion experiments on thin tubular Ti–6Al–4V specimens to achieve the response of these alloys under shear loading. They also measured the temperature rise in the specimens. Constitutive modeling was performed using Zerilli–Armstrong (ZA) model; high strain rate torsional response of the alloys and the material constants were incorporated into the ABAQUS/*explicit* FE code to predict the tensile response of the alloys. They concluded that the ZA model was unable to model the markedly reduced work hardening behavior at high strain rate under torsional deformation. They also suggested that strain rate and temperature dependence of work hardening, required a modification in the model. Chichili et al. (2004) have studied the torsional high strain rate response of α-titanium. They performed high loading rate experiments using the compression–torsion Kolsky bar apparatus. The specimens used in their study were of two different kinds. First one was the conventional thin tubular specimen (Marchand and Duffy, 1988) and the other specimen was solid and had a circumferential notch in the test section to study shear localization.