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Anisotropy and tension–compression asymmetry modeling of the room temperature plastic response of Ti–6Al–4V

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The mechanical behavior of the alloy Ti–6Al–4V is characterized using uniaxial tension, uniaxial compression, simple shear and plane strain tests in three orthogonal material directions. The experimental results reveal tension/compression asymmetry, anisotropic yielding and anisotropic strain-hardening. These features are incorporated into an elasto-plastic constitutive law based on the macroscopic orthotropic yield criterion "CPB06" adapted to hexagonal metals. A new identification method for the yield criterion parameters is proposed by inverse modeling of the axial strain field of compression specimens in the three orthogonal directions of the material. The sensitivity of different sets of material parameters to the identification method is also analyzed and the capacity of the model to accurately predict the forces and displacement field is discussed. A validation of the best set of identified CPB06 material parameters is performed by comparing the load–displacement curves in different loading directions for tensile tests on notched round bars with different levels of stress triaxiality and for compression tests on elliptical cross-section specimens, both tests involving multiaxial strain fields and large deformations.

1. Introduction

In engineering applications, titanium (Ti) and its alloys have replaced other metallic materials owing to superior strength to density ratio, giving reliable, economic and more sustainable systems and components. The most commonly used and relatively economical Ti alloy is the Ti–6Al–4V composition, called hereafter TA6V. This two phase $\alpha + \beta$-type alloy is found in many applications principally in the aerospace industry, such as for fasteners, aircraft structural and engine components, because of its high strength over density ratio in the low to moderate range of operating temperatures. Offshore petroleum industry have also taken advantages of using TA6V, for instance in applications as drilling risers owing its high flexibility (low ratio of modulus over strength), excellent corrosion and fatigue resistance (Deyuan et al., 2001; Gurrappa, 2003; Lütjering and Williams, 2007). These high mechanical performances combined with a good biocompatibility motivate extensive use of the TA6V in the medical industry such as orthopedic and dental implants (Elias et al., 2008; Long and Rack, 2006; Rack and Qazi, 2006). The high strength to weight ratio and its good ballistic capability have attracted the interest of the defense industry for its use in armor for military vehicles (Burkins et al., 2000, 2001; Montgomery and Wells, 2001; Sukumar et al., 2013).

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The wide range of applications of the TA6V has set the motivation to develop and enhance the state of modeling of its mechanical behavior involving the plastic response. The primary phase noted α of the alloy TA6V is a hexagonal closed packed (hcp) structure. As for other hcp alloys, the flow stress is strongly dependent on both temperature and strain rate (Khan et al., 2004, 2007; Lee and Lin, 1998; Majorell et al., 2002; Peirs et al., 2010; Tuninetti et al., 2012b; Tuninetti and Habraken, 2014; Porntadawit et al., 2014). In addition, TA6V exhibits a strength asymmetry between tension and compression also called strength differential (SD) effect (Gilles et al., 2011; Hammami et al., 2011; Khan et al., 2012; Odenberger et al., 2012; Tuninetti et al., 2012b). Gilles et al. (2011) and Nixon et al. (2010) explain that this effect is the result of the combination of a sharp initial basal texture and of the polarity of the deformation twinning mechanism, even for monotonic loadings. Because of the twinning and texture evolution, the shape of the yield surface of hcp metals significantly changes with accumulated plastic deformation and, therefore, traditional hardening laws cannot accurately capture these phenomena (Plunkett et al., 2006). Most of the previous studies have focused on capturing these features (SD, anisotropy) and the validation has been essentially based on the assessment of true stress-true strain curve predictions of monotonic tests.

The main objectives of the current study are to characterize, at Room Temperature (RT), the quasi-static mechanical behavior of TA6V alloy for different multi-axial stress states, to develop a methodology to identify the macroscopic orthotropic yield criterion CPB06 developed by Cazacu et al. (2006) and, finally, to verify the capabilities of Finite Element (FE) simulations, based on this constitutive model to predict the evolution of the load and shape changes due to plastic deformation in more complicated specimen geometries such as notched round bars and elliptical cross-sections.

Numerous models have been applied to simulate the quasi-static behavior of TA6V. Several studies rely on the Johnson–Cook or Norton-Hoff models to take into account the strain rate sensitivity of TA6V alloy even when the strain rate range is well below the dynamic regime (Kotkunde et al., 2014; Vanderhasten et al., 2008). These models neglect the strength differential effect and the plastic anisotropy. Other studies were focused on damage prediction, but assuming an isotropic behavior. For instance Peirs (2012), investigated the fracture behavior of the TA6V using either a Johnson–Cook damage initiation criterion combined with a progressive isotropic damage law or the Gurson model. In this study, the true fracture strain was around 40%. Damage in TA6V is known to proceed by the nucleation, growth and coalescence of small internal voids like in most other industrial metallic alloys, e.g. (Peirs, 2012; Lecarme, 2013). Now, a key result recently obtained using 3D in-situ tomography (Lecarme, 2013) is that the porosity in TA6V remains quite small almost until fracture (e.g., it is equal to 0.57% at true axial strain equal to $\sim$0.7) and that it nucleates late in the deformation process (at a true axial strain equal to $\sim$0.4 under uniaxial tension). In other words, the softening induced by damage is very small up to relatively large strain. The focus of the present paper is to check the ability of a phenomenological macroscopic anisotropic elasto-plastic law to predict TA6V plastic flow until equivalent strain typically lower than 0.3–0.6 for damage induced softening can be neglected.

Various constitutive laws have been developed such as the Khan–Huang–Liang (KHL) model (Khan and Liang, 1999) and its extensions (Khan and Yu, 2012; Khan et al., 2012), the asymmetric yield function with dependence on the stress invariants proposed by Yoon et al. (2014), the asymmetric yield function based on Hill 1948 (Verma et al., 2011) and the CPB06 yield criterion developed by Cazacu et al. (2006) which capture both the anisotropy due to texture evolution and the Strength Differential effect (SD). Other models for hcp metals include Cazacu and Barlat (2004) and Lou et al. (2013). The model by Cazacu and Barlat (2004) is simple as the principal stresses are not needed which simplifies the implementation on a FE code. The advantage of the model by Lou et al. (2013) lies in that both the anisotropy in yield stresses and *R*-values are considered under associated flow rule. The CPB06 criterion was selected in this work for its flexibility. A similar criterion was successfully employed by Plunkett et al. (2006, 2008), Cazacu et al. (2010), Nixon et al. (2010), Gilles et al. (2011), Ghaffari Tari et al. (2014) and Yoon et al. (2013).

The CPB06 phenomenological yield function described in Section 4 will be identified at RT and at a strain rate equal to $10^{-3}\ s^{-1}$ from a set of monotonic tests described in Section 2 involving uniaxial tensile, uniaxial compression, simple shear and plane strain tensile states. The "one step" identification method proposed earlier by Gilles et al. (2011) is replaced here by a more accurate 'two steps' method integrating inverse FE modeling described in Section 4.2. The anisotropic hardening behavior is described by linear interpolation of continuous CPB06 yield surfaces identified at several plastic work levels, which makes it possible the description of different hardening rates in tension, compression and shear. Inverse modeling including uniaxial stress–strain responses in tension, plane strain, shear as well as FE analyses of compression tests are used to adjust the material parameters. This identification method is first validated in Section 4.2 by predicting the experimental axial strain distribution measured by 3D digital image correlation (DIC) in the median cross-section of compression specimens with initially elliptic cross-section for three orthogonal material directions. A second validation is also presented in Section 5 by predicting the load evolution and shape of tensile notched round bars and of compression specimens.

Finally, the sensitivity of the different sets of identified material parameters to the identification method as well as the capacity of the model to accurately predict forces and displacement fields are discussed.

This research focuses not only on capturing the SD and anisotropy of TA6V alloy observed in monotonic stress–strain curves, but also on verifying that FE simulations can accurately reproduce the load and shape changes of full scale specimens subjected to multiaxial loading and large plastic strains.

2. Material and experimental procedures

Compression, tension, shear and plane strain specimens are machined from an initial TA6V alloy ingot with the dimensions shown in Fig. 1. Both tensile and compression tests are performed in the three orthogonal directions of the material: