International Journal of Impact Engineering 119 (2018) 1–13

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Multiscale modelling of the response of Ti-6Al-4V sheets under explosive loading

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ARTICLE INFO

Keywords:
Blast load
Numerical simulation
Titanium alloy
Ti-6Al-4V sheets

ABSTRACT

The objectives of the current study are to develop a multiscale numerical modelling method to predict the plastic deformation of Ti-6Al-4V sheets under blast loading, validate the method with experiments and characterise, at room temperature, the impulsive mechanical behaviour of the alloy. The numerical modelling technique relates the microstructure of the alloy with its macroscopic behaviour taking into account anisotropic effects by combining the viscoplastic self-consistent polycrystal model (VPSC7c) with the Cazacu–Barlat orthotropic yield criterion (CPB06) as implemented in the finite element (FE) solver of LS-DYNA. Sheet specimens of two thicknesses are tested using an experimental setup which applies a planar blast load. High speed cameras and the digital image correlation (DIC) technique are used to measure the evolving strains in the specimens. In addition, an analytical model is used to calculate the maximum displacements. The obtained values are compared with the outcome of the tests and FE simulations.

1. Introduction

Ti-6Al-4V has excellent properties: it combines a high strength with a low density and good resistance to corrosion [1]. Currently, it is the most used titanium alloy accounting for more than 50% of all titanium tonnage in the world. It is a two phase $\alpha + \beta$ type of alloy. Its primary phase, denoted as α, has a hexagonal closed packed (hcp) structure [2]. As a result, its flow stress depends on temperature and strain rate as seen in various studies [3–7]. The presence of approximately 4% of β-phase with a body centred cubic (bcc) structure gives the material a good balance between strength and toughness, and a good response to heat treatments. Sheet metal forming is one of the major processes to fabricate titanium alloy components [8]. However, compared to other traditional metallic materials, Ti-6Al-4V components are more difficult to form [9]. They exhibit a high degree of springback, and the lower formability causes the material to crack or tear easily during forming processes at room temperature [8]. In addition, Ti-6Al-4V exhibits a strength asymmetry between tension and compression [7,10].

Considering the above observations on Ti-6Al-4V, modelling the behaviour of such a material is a challenging task. Additionally, the mechanical behaviour of polycrystalline materials, such as Ti-6Al-4V, is dependent on their texture which changes during deformation due to grain reorientations. Several crystal plasticity (CP) models have been proposed to simulate the deformation of polycrystalline materials. One of these models is the viscoplastic self-consistent (VPSC7c) model which has been extensively used to describe the plastic behaviour, the evolution of hardening and texture associated with plastic forming [11–19]. The VPSC7c model uses a self-consistent scheme based on the relationship between the response of individual grains and the response of the polycrystal composed of these grains. As such, it does not only predict the macroscopic mechanical behaviour, but also the evolution of the microstructure, including grain shape and texture, during deformation. Therefore, the VPSC7c model is ideally suited to model metals subjected to complex forming processes. To model real forming process, numerical simulations based on the finite element (FE) method are often used. However, the disadvantage of CP models is that their implementation, as material model, in FE simulations is computationally expensive and requires a comprehensive set of parameters [20–22].

Next to CP models, various phenomenological and physically-based modeling approaches have been developed for metals. The physically based models include the mechanical threshold stress (MTS) model [23] and the Bammann–Chiesa–Johnson model [24]. Both models represent the plastic behaviour over a wide range of

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https://doi.org/10.1016/j.ijimpeng.2018.04.008
Received 5 September 2017; Received in revised form 30 March 2018; Accepted 8 April 2018
Available online 17 April 2018

temperatures and strain rates. However, major disadvantage of both models is that strictly controlled experimental conditions are required in order to define their parameters [25]. Empirical models such as the Johnson–Cook (JC) [26], the Zerilli–Armstrong (ZA) [27] and the Khan–Huang–Liang (KHL) [28,29] flow stress models can also be found in literature. Of these models, the JC model is by far the most broadly used for Ti-6Al-4V as a result of its good combination of accuracy, simplicity and range of applications considering the temperature and strain rate sensitivity [6,30–32]. In order to define some of the parameters for ZA the athermal stress for the material is required, as well as the stress at 0 K [33,34]. The KHL model has been used for a broad range of strain rates starting from 10^{-6} s^{-1} to 3378 s^{-1} [28]. All mentioned hardening models give a straightforward relation between stress and strain in uniaxial, dynamic loading conditions.

For multiaxial loading of hcp metals, yield criteria have been developed which capture both the anisotropy due to texture and the strength differential effect, such as the macroscopic orthotropic yield criterion for hexagonal closed packed metals (CPB06) proposed by Cazacu et al. [21]. Used as flow surface in an associative plasticity framework, the CPB06 model in combination with a hardening law, not only allows to describe the yield locus and how it evolves during deformation, however, it provides a complete constitutive model for hcp metals. CPB06 is implemented in the commercial FE solver LS-DYNA [48]. The identification of the CPB06 parameters, based on experimental results, is presented in [3,7,8,35–39]. Ideally, it is based on an extensive database consisting of tensile and compression tests in various directions and multiaxial tests, for example shear and bulge tests. Setting up this database is not straightforward, in particular, if dynamic loading conditions are considered.

The main objective of current study is to develop a modeling strategy which combines the strengths of a CP model with the merits of a macroscopic plasticity model. In the method, the parameters of a macroscopic plasticity model are identified based on virtual experiments performed with a CP model. The methodology is illustrated using VPSC7c and CPB06 combined with Voce hardening law. Main advantage of the approach is that the cumbersome implementation of the VPSC7c model in a FE program is not required and no excessive processing power is needed. An important second objective is to evaluate the possibility to substitute experimental data with VPSC7c model data in order to identify the parameters of the CPB06 material model for impulsive loading. Indeed, since VPSC7c is implicitly strain rate dependent, the use of VPSC7c in the method opens the possibility to use only quasi-static test results for the estimation of stresses at higher strain rates, thus, avoiding to have to perform an extensive series of dynamic or impulsive experiments on the examined material. The use of VPSC7c then offers the possibility to create an efficient FE model, as well as to replace the experimental campaign required for material identification at high strain rates.

The approach is illustrated and validated by explosive forming experiments on two types of Ti-6Al-4V sheets using a purpose-developed test setup. In the explosive forming setup a planar blast load, generated by the detonation of an explosive charge, deforms the sheet specimen creating a circular dome. The consistency of the explosion tests is evaluated by an analytical model proposed by N. Jones [40]. A FE model of the explosive loading test setup is solved in LS-DYNA, using CPB06 and Voce for the Ti-6Al-4V sheets. The CPB06 and Voce model parameters are calculated using the simulated annealing (SA) optimisation algorithm starting from virtual, dynamic tensile tests in various directions calculated by VPSC7c. The VPSC7c parameters are determined based on electron back-scatter diffraction (EBSD) texture measurements and static tensile tests in different directions on one of the Ti-6Al-4V sheets. The various material models and the entire modeling approach are validated in every step with experiments.

Table 1
Chemical composition (in weight percent) of Ti-6Al-4V products reported by the supplier.

	Fe	*V*	*Al*	*C*	*O*	*N*
0.6 mm	0.16	3.98	6.27	0.009	0.19	0.009
1 mm	0.15	3.96	6.24	0.007	0.17	0.002

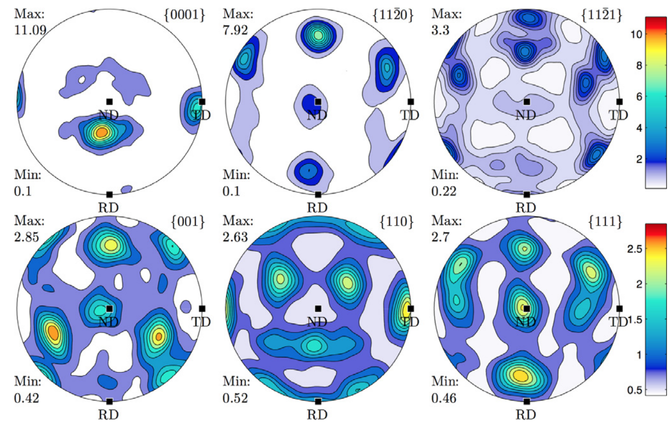

Fig. 1. Crystallographic texture of the 0.6 mm rolled sheet form: the top pole figures represent the α-phase and the bottom ones the β-phase.

2. Experimental methods

Two sheets of Ti-6Al-4V are used with thicknesses of 0.6 mm and 1 mm manufactured by TIMET USA. Their chemical compositions, as reported by the supplier, are presented in Table 1. Scanning electron microscopy (SEM), and in particular the EBSD technique, is used in the present work to measure the crystallographic texture of the 0.6 mm sheet. The pole graphs are presented in Fig. 1. The volume fraction of the α-phase is 95.8%, of the β-phase 4.2%. Tensile tests are conducted at a strain rate of 0.00066/s at 0°, 15°, 30°, 45°, 60°, 75° and 90° and a tensile test at a strain rate of 1007/s at 0°. The results are presented later on in Section 3.

An experimental setup is designed in order to investigate the response of Ti-6Al-4V alloy sheets under explosive loading. A clamping system is created to hold the circular sheet specimen. The specimen has a diameter of 370 mm and after it is clamped, using 10 bolts, its remaining free surface has a diameter of 150 mm as shown in Fig. 2. A torque of 20 Nm is applied to all the bolts (12 mm diameter) that hold the specimen. The clamping system is placed in front of a shock tube through which a planar blast wave impacts the exposed surface of the specimen. The blast load is generated by the detonation of a spherical charge of 15 g of C4 placed at the beginning of the shock tube with a diameter of 150 mm. The blast wave is channelled through the tube and it ends at the other side where the clamping system with the Ti-6Al-4V sheet is located. The generated blast wave has been measured by performing experiments on a rigid wall with sensors and it is based on the calculations conducted by Ousji et al. [41]. At the other end of the sheet high speed cameras are used to capture the deformation process using the digital image correlation (DIC) technique. A speckle pattern is applied on all the specimens: initially, applying white paint and then the black pattern is printed on a decal paper and afterwards transferred on the white painted surface. For the DIC processing the subset size is 25 pixels, the step size 7 pixels, the size of each pixel 0.4 mm and the strain filter size 15. A schematic representation of the setup configuration is shown in Fig. 3. In total 6 tests are conducted: 3 specimens of 1 mm and 3 specimens of 0.6 mm are tested.