

Plastic deformation of high-purity α -titanium: model development and validation using the Taylor cylinder impact test

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Abstract. Results of an experimental study on the quasi-static and high-rate plastic deformation due to impact of a high-purity, polycrystalline, α -titanium material are presented. To quantify the plastic anisotropy and tension-compression asymmetry of the material, first monotonic uniaxial compression and tension tests were carried out at room temperature under quasi-static conditions. It was found that the material is transversely isotropic and displays strong strength differential effects. To characterize the material's strain rate sensitivity, Split Hopkinson Pressure Bar tests in tension and compression were also conducted. Taylor impact tests were performed for impact velocity of 196 m/s. Plastic deformation extended to 64% of the length of the deformed specimen, with little radial spreading. To model simultaneously the observed anisotropy, strain-rate sensitivity, and tension-compression asymmetry of the material, a three-dimensional constitutive model was developed. Key in the formulation is a macroscopic yield function [1] that incorporates the specificities of the plastic flow, namely the combined effects of anisotropy and tension-compression asymmetry. Comparison between model predictions and data show the capabilities of the model to describe with accuracy the plastic behavior of the α -Ti material for both quasi-static and dynamic loadings, in particular, a very good agreement was obtained between the simulated and experimental post-test Taylor specimen geometries.

1. Introduction

High-strain rates of the order of 10^4 - 10^5 s⁻¹ can be achieved using in a Taylor-impact test, which consists of launching a solid cylindrical specimen at an elevated velocity of the order of 100-300 m.s⁻¹ against a stationary rigid anvil [2]. The data obtained in such impact tests are invaluable both for development and validation of models for description of the plastic deformation in the dynamic regime. Few Taylor impact tests have been reported on titanium (Ti) materials. For example, Holt et al. [3] reported results of reverse ballistic impact tests at 225 and 294 m/s on commercially-pure Ti specimens. Metallographic examination revealed extensive deformation twinning. To account for the increase in hardening induced by twinning an incremental stress term, which depends on grain size and number of twins per grain, has been added. However, yielding was modeled using von Mises yield criterion, thus neglecting both the anisotropy and tension-compression asymmetry induced by deformation twinning. In this paper, we present a new three-dimensional model that was developed in order to model simultaneously the anisotropy, tension-compression asymmetry and strain-rate sensitivity of the



plastic deformation of a high-purity α -Ti material. Furthermore, we report Taylor impact tests conducted on the same material and compare the model predictions with the measurements of the deformation of the impacted specimens. Taylor cylinder impact tests were conducted to investigate the dynamic behavior of the material (strain rates of the order of 10^5s^{-1}) and to validate the proposed model. The test results, namely photographs of post-test specimen profiles and measurements of their deformation are reported.

2. Constitutive modeling of impact behavior of pure Ti

The material used in this work was a high purity (99.999%) Ti that was purchased from Alpha Aesar of Johnson Matthey Electronics, Inc., (Spokane, WA). Optical microscopy showed that the material has equiaxed grains with an average grain size of about $20 \mu\text{m}$. To quantify the plastic anisotropy and the tension-compression symmetry of the material, monotonic uniaxial compression and tension tests were carried out at room temperature under quasi-static conditions. The test results indicated that the material is quasi-isotropic in the plane of the plate, while there is a marked difference between the yield stress in the through-thickness plate direction and the average in-plane yield stress. Irrespective of orientation, the material displays strength-differential effects (stronger in compression than in tension). The Split Hopkinson Pressure Bar (SHPB) tests in tension and compression that were performed indicate that although there is an increase in flow stress with increased strain rate, the strain hardening rate or slope of the stress-strain curve exhibits little dependence on strain rate (see fig.1). This indicate that the relative activity of the plastic deformation mechanisms that are operational is very little affected by the change in strain rate.

A constitutive model was developed. Key in the formulation is the use of an yield function proposed by Cazacu et al. [1] that accounts for both anisotropy and tension/compression asymmetry. The effective stress associated with the yield criterion is:

$$\bar{\sigma} = B \left[(|\tilde{\sigma}_1| - k\tilde{\sigma}_1)^2 + (|\tilde{\sigma}_2| - k\tilde{\sigma}_2)^2 + (|\tilde{\sigma}_3| - k\tilde{\sigma}_3)^2 \right]^{\frac{1}{2}} \quad (1)$$

where k is an internal variable, its range of variation being $(-1, 1)$, while $\tilde{\sigma}_1$, $\tilde{\sigma}_2$ and $\tilde{\sigma}_3$ are the principal values of the transformed stress tensor $\tilde{\sigma} = [\mathbf{L}] : \mathbf{S}$ with \mathbf{S} the Cauchy stress deviator applied to the material. In Eq.(2), \mathbf{L} is a fourth-order orthotropic and symmetric tensor. In the coordinate system associated with the material symmetry axes (RD, TD and TT, respectively) and in Voigt notations, this tensor is represented by a 6×6 matrix given by

$$[\mathbf{L}] = \begin{bmatrix} L_{11} & L_{12} & L_{13} & 0 & 0 & 0 \\ L_{12} & L_{22} & L_{23} & 0 & 0 & 0 \\ L_{13} & L_{23} & L_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & L_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & L_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & L_{66} \end{bmatrix} \quad (2)$$

In Eq.(1), B is a constant defined such that the equivalent stress $\bar{\sigma}$ reduces to the tensile stress along RD. In the plastic deformation regime, the high purity Ti material investigated is transversely isotropic, the plane of isotropy being the plane of the plate (x, y) while the through-thickness plate direction (TT or z) is an axis of rotational symmetry. Therefore, $L_{11} = L_{22}$; $L_{13} = L_{23}$; $L_{55} = L_{66}$. To model the difference in hardening between tension and compression with accumulated plastic strain, all the parameters involved in the yield function were considered to evolve with the equivalent plastic strain. The model predicts that for this Ti material, at initial yielding and under 10% strain, the yield surfaces have an elliptical shape, the tension-compression asymmetry is small while above 10% strain the yield surfaces have a triangular

shape, the difference in response between tension and compression being pronounced (see fig.2). The observed strain-rate sensitivity was modeled with a Johnson-Cook [4] law that was identified based on the SHPB data in tension. A user material subroutine (UMAT) was developed for the constitutive model described and implemented in the commercial implicit FE solver ABAQUS Standard.

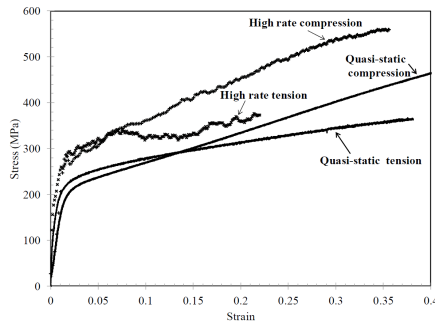


Figure 1. Experimental stress-strain response in uniaxial tension and compression along the in-plane of Ti plate for quasi-static and high-rate loadings.

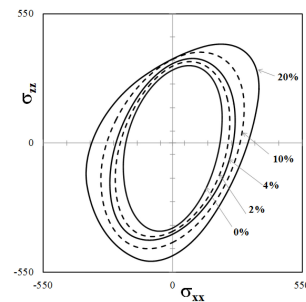


Figure 2. Projection in the $(\sigma_{xx}, \sigma_{zz})$ plane of the theoretical yield loci [1] for the Ti plate, corresponding to individual levels of equivalent plastic strain.

3. Assessment of the predictive capabilities for cold forming

High-rate impact tests (Taylor impact tests) were conducted to examine the material response at strain rates higher than those achieved using a conventional SHPB system. The Taylor impact test consists of launching a cylindrical specimen at an elevated velocity against a stationary target [2]. Similar to a uniaxial compression experiment, a Taylor impact specimen deforms plastically by contracting axially and expanding radially. However, unlike in a quasi-static compression experiment, the state of stress and level of plastic deformation within the Taylor specimen are not uniform. The highest level of deformation is observed at the impacted surface, and the least deformation is observed at the rear surface. Data concerning geometrical shape changes of the post-test specimen and measurements of the actual deformation (lateral spreading; strain profiles i.e. measurements of the deformation at different locations along the length of the specimen) are essential for the validation of the capability of structural-level models to predict dynamic behavior. Fig. 3 presents photographs of the undeformed specimen and the post-impact shape of a typical α -Ti specimen, respectively. The initial through-thickness directions is indicated by an arrow. For more details about the simulation of Taylor impact of Ti, see [5].

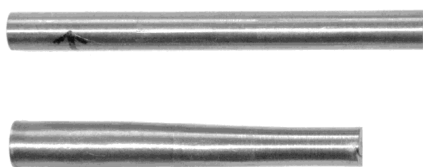


Figure 3. Photographs of a typical Ti Taylor specimen with the long-axis along IP: (a) undeformed specimen; (b) specimen after impact at velocity of 196 m/s.

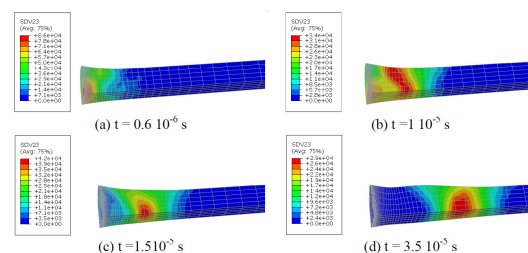


Figure 4. Isocontours of the equivalent plastic strain-rate.

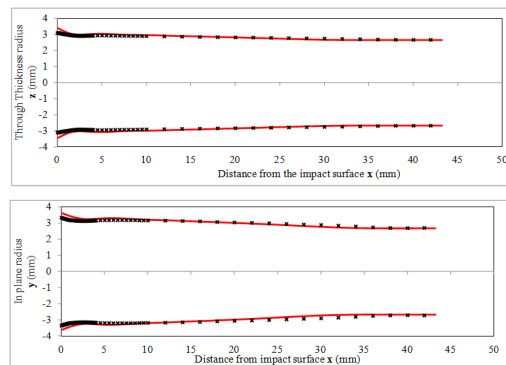


Figure 5. Comparison of the simulated and measured (symbols) minor and major outline of the specimen vs. the distance x from the impacted end.

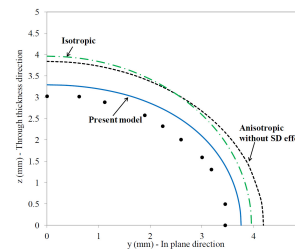


Figure 6. Comparison between the FE simulated deformation of the footprint according to the present model, von Mises yield criterion, and the anisotropic criterion without strength differential effects and the measured cross-section (symbols) after impact at 196 m/s.

Fig.4 shows the isocontours of the equivalent plastic strain rate at different times after the impact between the specimen and the anvil. First, let us note that very high plastic strain rates of the order of 10^4 s^{-1} are predicted, with the largest strain rates, of the order of $8.6 \cdot 10^4 \text{ s}^{-1}$, being near to the impact surface. Furthermore, the largest strain rates were experienced by the material during the initial, transient phase of the deformation when non-zero plastic strain rates occur only in the vicinity of the impacted surface. After about 10^{-5} s , the zone of plastic deformation moves away from the impacted end and the region in the neighborhood of the impacted surface is not subjected to plastic strain rates anymore. Fig.5 show the strain profiles along the major (y or in-plane direction) and minor (z or through-thickness) axes of the impacted specimen, respectively. In these figures are compared the predicted (solid line) major and minor specimen profiles (solid line) with the experimental measurements (symbols) taken at several distances from the impacted end (impacted end corresponds to $x = 0$). Note the very good agreement between the numerical predictions and the experimental data. Furthermore, the model predicts very well the experimentally observed key features of the plastic deformation of the Ti. Indeed, according to the model plastic deformation extended over approximately 64% of the deformed specimen length, with little lateral spreading. Furthermore, the plastic deformation for $0 < x < 3.5 \text{ mm}$ is due only to the impact while at distances $x > 3.5 \text{ mm}$, the observed post-test plastic deformation is due to the plastic wave that has traveled along the length of the specimen. In Fig.6 is shown a comparison between the deformed impacted cross-section and FE simulations using von Mises yield criterion and the anisotropic yield criterion of Eq. (1) without consideration of tension-compression asymmetry, respectively. If the tension-compression asymmetry of the material is neglected, the lateral spreading of the specimen is largely overpredicted and the small ellipticity of the deformed cross-section is not captured. In contrast, the simulated cross-section according to the present model is in good agreement with the data, thus demonstrating the importance of incorporating in the constitutive description the combined influence of anisotropy and tension-compression asymmetry.

References

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