Full field measurements and identification in Solid Mechanics

Compression test for metal characterization using digital image correlation and inverse modeling

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Abstract

In the case of sheet metal characterization, compression tests at normal direction of the sheet can be done by means of the layer compression test. Circular cylinder specimens are commonly used for compression test but the complicated layer alignment is time consuming and may induce a wrong anisotropy characterization. This final goal explains the interest of working on elliptic shape. In this article, an elliptical cylinder specimen is proposed and tested for bulk Titanium alloy. Full-field optical technique (3D Digital Image Correlation) is used for displacement measurements by means of three camera systems (Limess), which allows out-of-plane displacement/strain fields on around 300° of the specimen. The use of this technique easily provides accurate barreling profile used to compute Coulomb friction coefficient by using inverse method. In addition, stress-strain curves computations are more accurate than conventional method, and plastic anisotropy characterization can be obtained by using the measured shape evolution of the specimen and local strain distribution.

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1. Introduction

The accuracy of numerical simulations of forming process highly depends on the quality of the material data provided. This material data can be obtained by performing a set of mechanical tests, as tensile, shear, plane strain and compression tests at several directions. For sheet metal characterization, the compression test at normal direction of the sheet can be done by means of the layer compression test. One of the advantages of this test is that the equi-biaxial stress point for accurate yield locus definition can be computed, assuming that the hydrostatic stress has no effect on the plastic deformation [1]. For this test, circular cylindrical cross-section specimens are widely used but for sheet case, the complicated layer alignment is time consuming and may induce a wrong anisotropy characterization.

In order to compute true stress, evolution of the actual loaded surface must be computed or measured. Merklein and Kuppert 2009 [2] propose 2 methods for circular cross-section specimen and plastic anisotropic materials. They use two 3D-DIC systems placed perpendicularly and one of them is aligned with the rolling direction. Very small local area information is measured at the horizontal middle plane of the specimen. The first method uses the displacement in radial direction for the minor and major axis of the deformed elliptic shape and the actual area is computed by the simple formula \( A = \pi (r_0 + \Delta r_{\text{system}1}) (r_0 + \Delta r_{\text{system}2}) \), where \( r_0 \) is the initial circular radius of the specimen. However, the author could not guarantee that the specimen stays in the center of the testing area. Therefore the accuracy of the method was poor. The second method, proposes an actual area formula \( (A = 0.0625\pi (r_0 (exp(\varepsilon_1) + exp(\varepsilon_2))))^2 \) as a function of the measured tangential strains by the optical system 1 and 2, respectively \((\varepsilon_1, \varepsilon_2)\) in minor and major axis location. These tangential strain values are proportional to the change in diameter of the original geometry.

The current work is the first step towards the design of a layer compression test. A bulk material is investigated as it allowed neglecting the material discontinuity along the axial direction. Compression tests are performed on elliptical cross-section specimens for bulk titanium alloy Ti-6Al-4V called hereafter TA6V. The specimen geometry proposed will be very useful for the alignment of layers in case of sheet stack compression test. The proposed method here for actualized area computation is based on fitting ellipses to the 300° of the measured cross-section data obtained from 3D-DIC at each stage. The algorithm used for the ellipse fitting is proposed by Halir and Flusser 1998 [3]. This accurate method for area computation with appropriate calibration parameters and test conditions assures a maximum relative error of 0.3% on the computed area. Compared to the method described above it presents advantage on accuracy, because it uses no formulas depending on local values of tangential strains, but direct measurements of the cross-section of the tested specimen.

2. Experimental setup and procedure

The tests are performed on elliptical cross-section samples on Titanium alloy TA6V in the Laboratory of Materials and Structures Mechanics in ArGENCo department at the University of Liège. The specimens were cut by using Electric Discharge Machining with the following dimensions: 9.7 mm length for the initial minor axis, 19.42 mm length for the major axis and 14 mm height. The sample is compressed by a SCHENCK Hydropuls 400 kN press and full-field optical technique (3D Digital Image Correlation) is used for displacement measurements by means of three camera systems (Limess). The speckle pattern is applied on the surface of the specimen by using a mat paint in order to avoid reflection (Fig. 1). Fixed focus lens of 50mm and extension tubes were used in order to obtain the highest experimental resolution. A subset size of 15x15 pixels was selected for speckles size of 5 pixels with around 60% optimal speckle coverage [4]. The experimental resolution of the acquired images is 34 pixels per millimeter. The position of the cameras and the specimen in a common plane, and specimen targeted surface between each
adjacent system are essential features for the 3D displacement field reconstruction. Cables must be fixed in order to avoid the relative movement (vibration) between 2 cameras, because the accuracy of 3D field reconstruction could be influenced. One channel of analog loading data is acquired and synchronized with the images. The relative position among the 3 camera systems and the specimen is shown in Fig. 2. This configuration allows an out-of-plane displacement/strain fields on around 300° of the specimen.

Fig. 1. Speckle pattern.

Friction is reduced between samples and the press compression plates by using grease lubricant at each end of the specimen. Let us note that according to the final goal of the measurement: yield locus biaxial
point or general shape of the yield locus defining the anisotropy features, it is not straightforward that friction should always be eliminated. In the current case, low barreling is observed during the test due to low friction and it could be measured with the 3D DIC system. Coulomb’s friction coefficient could be computed by inverse method by fitting the barreling from experimental and numerical results.

3. Results and discussions

Geometry evolution and axial logarithmic strain field were measured with the 3D optical measurement system and VIC3D 2007 software. Fig. 3 shows the measured geometry and strain field evolution of the specimen at 4 stages. Stage 1 corresponds to the unloaded specimen, stages 50 and 100 correspond to the specimen at 0.007 and 0.03 average axial strain, respectively, and the stage 149 at the end of the test at unloaded condition.

Fig. 3. Evolution of the axial strain field on the specimen’s free surface (Cauchy or Henky strain).
The area computed by fitting ellipses to the measured cross-section for the first stage is shown in Fig. 4(a-b). Minor major axis ratio at the middle cross-section of the sample was evaluated in order to determine quantitatively the anisotropy (Fig. 4(c)). A very low plastic anisotropy material behavior is detected for this bulk Titanium alloy Ti-6Al-4V, where the minor axis increases at a negligible higher rate than the major axis during compression.

Barreling as a function of the angle appears due to friction between specimen and press compression plates (Fig. 5). From 0° (major axis, z axis in Fig. 4(a)) to 90° (minor axis, x axis in Fig. 4(a)) the barreling effect increases, which influences the homogeneity on the axial strain distribution. Pronounced barreling induces a lower axial strain as observed at the minor axis position (90°) in Fig. 6a.

![Diagram](image-url)
In order to obtain stress-strain curves, strain ($\varepsilon_{yy}$) is computed by averaging the axial strain at the surface in the middle cross-section of the specimen (Fig. 6a). Cauchy stress $\sigma_{yy}$ is computed by using the force obtained from the load cell and the area computed by fitting ellipses at the middle cross-section of the specimen (Fig. 6b). This Cauchy stress is compared with the stress computed by the load and the actualized area obtained from volume conservation and neglecting barreling ($A_c = A_0 \times \exp(-\varepsilon_{yy})$), where $A_0$ is the initial cross-section area.

Barreling information, computed stress-strain curve, and the fact that anisotropy is negligible (Fig. 4(c)), allow the use of von Mises criterion for numerical simulations of this current Titanium Alloy Ti-6Al-4V. By using inverse modeling, comparing predicted and measured barreling, Coulomb’s friction coefficient is identified (Fig. 5(b)).

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**Fig. 5.** (a) Experimental barreling at various angles (0°, 17.5° and 90°) of the specimen in its last stage (7.5% axial logarithmic strain). (b) Zoomed information of graph and numerical barreling ($\phi=0.08$).

**Fig. 6.** (a) Axial strain distribution along the horizontal center line of the specimen (dashed line in fig. 3). (b) Stress strain curves for compression test controlled by position and at constant average strain rate of 0.00023 s⁻¹.
4. Conclusions

In this work, an elliptic shape for bulk compression tests was used, with the main objective to apply it later on stack of sheets. The main advantage will be the simple way of alignment of the anisotropic directions of the sheet. Furthermore, a reliable methodology was presented in order to determine accurately the evolution of the cross-section of an elliptic cylinder specimen in compression test, by using a 3D Digital image correlation system. This methodology, will lead to a more accurate stress computation and therefore more accurate stress strain curves.

Low plastic anisotropy of a TA6V was found (Fig.4(c)), and von Misses isotropic yield criterion could accurately predict the shape evolution of the sample Fig.5(b). However, experimental results demonstrated that no-negligible inhomogeneous strain field appears on the surface of the specimen (Fig.6). This effect could be explained by the existence of variation on the measured barreling of the specimen.

In order to identify the origin of this variation of the barreling (inhomogeneous strain), numerical simulations of compression test on elliptical cross-section specimens were performed for 2 test conditions: with and without friction tests and 2 materials: isotropic and anisotropic. The isotropic case was simulated by using von Misses and characterized from current compression test data (Fig. 6(b)). The anisotropic material was simulated by using CPB06 yield criterion proposed by Cazacu et al. 2006 [5] and the set of material parameters was characterized by Gilles et al. 2011 [6]. The axial strain distribution along the horizontal center line of the specimen is shown in Fig. 7.

Fig. 7. Evaluation of inhomogeneities on the axial strain at the middle cross-section of the specimen.
Results show that when friction is not considered, homogeneous strain field is obtained for both, isotropic and anisotropic materials. Besides, when comparing axial strain distribution obtained from simulated tests of isotropic and anisotropic material including friction, on can verify that lower inhomogeneous strain is presented for the isotropic material comparing to the anisotropic one. Therefore, on can claim that friction amplifies the visualization of the anisotropic behavior in a compression test of an elliptic cylinder (Fig.7). It is expected that this observation will be very useful for further work in order to characterize the sheet metal anisotropy for layer compression tests on elliptical cross-section specimens.

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