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Deformation behavior of commercially pure (CP) titanium under equi-biaxial tension

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ABSTRACT

Biaxial tensile tests on commercially pure titanium were carried out using cruciform specimen geometry and the effect of biaxial tensile stress state on the mechanical properties was discussed. An optimum cruciform specimen geometry obtained using a commercial FE code was subjected to equi-biaxial tensile loading and the load-strain response was captured using data acquisition system. In addition, non-contact digital image correlation technique was employed for the measurement of failure strain. It is observed that the ultimate tensile strength approximately doubled and the failure strain decreased in contrast to uniaxial mechanical properties of commercially pure titanium. Increased effective modulus under biaxial condition is justified based on the generalized Hooke's relation. Strong basal and split-basal texture components of as-received sample resulted in biaxial strengthening effect. Significant textural evolution observed upon biaxial deformation can be attributed to constrained deformation under such stress state.

1. Introduction

Titanium and its alloys are extensively used in aerospace industries because of their high strength to weight ratio and excellent corrosion resistant properties [1]. More often, such structural components (pressure vessels and propellant tanks) are designed based on their uniaxial properties, although they experience biaxial loading condition during its service. In addition, metal forming operations such as deep drawing also involves complex biaxial state of stress, and hence finite element (FE) simulations of such operations demand experimental data under biaxial stress state to predict accurate failure strain during forming operations. Hence, biaxial tensile testing of materials seems more appropriate for understanding the material response under such stress state.

Several experimental methods offer the possibilities of testing materials under biaxial loading configuration such as hydraulic bulge test [2,3], Marciniak punch test [4], thin walled tubes subjected to combined axial loading and internal pressure [5], and cruciform (cross-shaped) specimen under biaxial loading [6–8]. However, cruciform technique attracts interest because of its ability to test under in-plane configuration and also offers the possibility for studying elastoplastic deformation behavior under any arbitrary chosen stress ratios [9,10]. Deng et al., [11] proposed cruciform geometry for testing of sheet metals under biaxial tension, however, their geometry was primarily meant for yield loci construction but not designed for probing fracture and failure. In addition, strain experienced by the gage section of the cruciform specimen was too low for characterizing the formability behavior of sheet metals under biaxial stress state [12]. Hence, a cruciform specimen was designed based on the following considerations: (1) homogenous strain distribution in the gage section (2) minimization of shear strain in gage section (3) specimen failure in the biaxially loaded zone and (4) minimization of strain concentration outside the gage section [13,14]. Due to the complicated design of cruciform specimen, load bearing area under biaxial stress state is not properly defined [14] in contrast to uniaxial tensile testing. Each loading arm in cruciform specimen is common to two principal loading directions, hence, by-pass correction factor (BCF) proposed by Welsh et al., [15] is used for the estimation of effective cross-sectional area.

As a direct implication of indirect estimation of load bearing area, the need for the accurate estimation of strain increases [16]. Hence, a non-contact digital image correlation technique (DIC) [17] is essential for strain mapping of the entire gage section. The non-contact method also offers the possibility to capture the entire

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Table 1
Chemical composition of as-received CP titanium (Grade 2).

Element	Nitrogen	Carbon	Hydrogen	Iron	Oxygen	Titanium
wt%	0.03	0.08	0.015	0.30	0.25	Bal.

strain response till failure, since it is difficult to measure strain using foil gages beyond yielding.

Though yielding and deformation behavior of aluminum alloys [18,19] and magnesium [20,21] under biaxial tensile stress are studied extensively, biaxial tensile properties of titanium and titanium alloys are relatively unexplored with very limited literature available. Ishiki et al., [22] reported the work hardening behavior of pure titanium under biaxial tension to a maximum plastic strain of 0.002 using cruciform geometry. In addition, the work hardening behavior of pure titanium was measured using tubular specimens for various linear stress/strain paths, but their study was limited to a maximum plastic strain of 0.085. This is due to detachment of strain gages during testing, hence, biaxial stress-strain curves up to failure were not reported [23].

Here, we report equi-biaxial tensile testing of commercially pure (CP) titanium using an optimized cruciform specimen, primarily designed to facilitate large deformation in the gage section of cruciform specimen. Non-contact strain measurement technique was employed to obtain biaxial stress-strain curves up to failure. Also, the effect of biaxial stress state on mechanical properties of CP titanium such as ductility, strength, effective modulus and strain hardening exponent was discussed in relation to its uniaxial properties. Fractographic features, X-ray diffractograms of deformed samples under uniaxial and biaxial stress state was compared and discussed. Texture evolution upon biaxial deformation of CP titanium was correlated with its mechanical properties and such a study has not been reported earlier to the best of our knowledge.

2. Material and methods

2.1. Material

Commercially pure (CP) titanium Grade 2 (annealed) was chosen for this study with the following chemical composition as per the supplier is shown in Table 1. The thickness of the as-received plate is around 12 mm.

2.2. Uniaxial tensile testing

Uniaxial tensile specimens along the rolling direction (RD), transverse direction (TD) and 45° degree to the rolling direction (DD) were fabricated using wire-cut electrical discharge machining (EDM) as per ASTM E8M standard (sub-sized coupons). The thickness of each specimen is around 2.5 mm and key dimensions of the specimen are shown in the Fig. 1. Quasi-static uniaxial testing was carried out at room temperature until failure, at a cross-head speed of 0.5 mm/min (nominal strain rate of $2.6 \times 10^{-4}\ s^{-1}$) using Instron 25 kN test frame. Non-contact DIC technique was employed to measure strain in addition to in-built displacement sensor readings. Also, strain gages were pasted along the loading direction for the accurate measurement of elastic strain.

2.3. Biaxial tensile testing

An in-plane biaxial test rig of 250 kN capacity was custom designed in-house to carry out equi-biaxial tensile testing of metallic specimens till failure. The test rig consists of hydraulic power pack, loading frames, specimen holding fixtures and four double-acting hydraulic actuators for applying any desired tensile force along each direction. Load cells of 220 kN capacity (HBM-RTN) were used to measure the applied load along each direction. All the load cells were calibrated against the standard load cell prior to its installation into the test machine. Cruciform specimens of optimized geometry (Fig. 2) obtained with the help of FEM analysis [24] were machined using Computer Numeric Controlled (CNC) machine.

The overall dimension of the sample is 250 × 250 × 8 mm with two step thickness transition from a gripping area thickness of 8 mm to gage area thickness of 1 mm with 3 mm intermediate thickness. These dimensional modifications were carried out to ensure homogenous strain distribution in the gage section and also to facilitate failure in the gage section. All machined samples were dimensionally inspected using Coordinate Measuring Machine (CMM) before being subjected to testing. Foil type strain gages were pasted over the mid-portion of cruciform specimen gage section, both in X and Y directions (each loading direction) to capture strain response. The strain gage readings, as well as load cell readings, were recorded at a scan rate of 5 data points per second using strain-smart system 5000 Data Acquisition System (DAQ). Four cruciform specimens were tested till failure and representative strain contour plots and stress-strain relations are reported.

2.4. Non-contact strain measurement technique

Prior to testing, uniaxial and biaxial test specimens were sprayed using white and black acrylic aerosol paints to create random, isotropic speckle pattern on the surface for the non-contact strain measurements. Specimen surface with speckle pattern was captured using a CCD camera under zero load configuration (reference image). Subsequently, images of deformed specimen were captured continuously till the specimen fails. CCD camera (2/3″ Sony ICX625 sensor, PGR solutions) with 5-megapixel resolution (2448 × 2048) corresponding to pixel size of 3.45 μm^2 and 15 frames per second (fps) capability along with high-resolution mega-pixel lens (Edmund Optics) was employed to capture images at every 100 ms interval until failure.

VIC-2D correlation software (Correlated Solutions, Inc., USA) was used to obtain displacement as well as strain contour by correlating

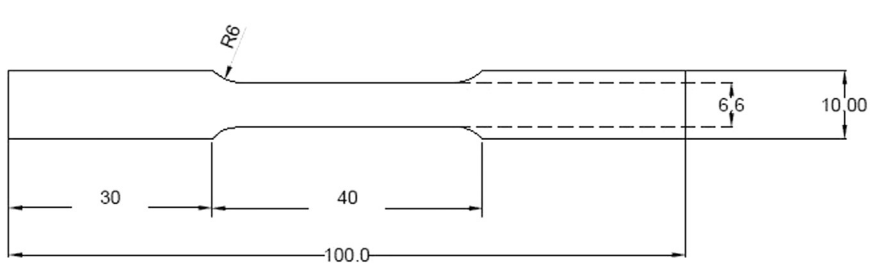

Fig. 1. Uniaxial specimen as per ASTM E8M standard (all dimensions are in mm).