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

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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
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.

<table>
<thead>
<tr>
<th>Element</th>
<th>Nitrogen</th>
<th>Carbon</th>
<th>Hydrogen</th>
<th>Iron</th>
<th>Oxygen</th>
<th>Titanium</th>
</tr>
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<tbody>
<tr>
<td>wt%</td>
<td>0.03</td>
<td>0.08</td>
<td>0.015</td>
<td>0.30</td>
<td>0.25</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Table 1

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

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 $2.6 \times 10^{-4} \text{s}^{-1}$) 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 $250 \times 250 \times 8$ 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 ($2448 \times 2048$) corresponding to pixel size of $3.45 \mu m^2$ 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...
reference image (undeformed) under zero load configuration with images of deformed specimen. Subset size and step size used for the analysis was 25 x 25 pixels and 4 pixels respectively. The aforementioned post-processing parameters were chosen based on the generated speckle pattern. The entire gage area was chosen for the correlation analysis to obtain principal strain contour plots as well as strain contours in X and Y directions respectively.

2.5. Characterization of as-received and deformed samples

Standard metallographic polishing techniques were carried out for probing the microstructure of the samples. Prior to microscopic analysis.
analysis, as-polished specimens were etched using Kroll’s reagent (3 ml HF, 6 ml HNO₃ and 91 ml water) for about 15 s. The microstructure of as-received sample with an average grain size of 70 μm is shown in Fig. 3. FEI quanta 200 (USA) scanning electron microscope (SEM) was employed for the fractographic analysis of the tested samples. Fractured region of the sample was cut using a slow speed diamond saw to avoid damage during sectioning.

X-ray diffraction on deformed samples was carried out using D8 Discover Bruker AXES diffractometer using Cu Kα radiation. The step size and scan speed used for the measurement was 0.04 s° and 2 s° step respectively. Each diffractogram was an average of 3 scans and each peak was normalized with respect to its most intense peak.

X-ray texture analysis was carried out on as-received and deformed samples using Schulz back reflection technique in D8 Diffractometer. Voltage and current settings was 40 kV and 40 mA respectively and copper Kα radiation was used for measurements. Six incomplete pole figures were experimentally determined and used for calculation of orientation distribution function (ODF) by ADC method (arbitrarily defined cell) using LaboTex 3.0 software. Subsequently, pole figures were recalculated from the estimated ODF function.

Micro-indentation hardness was evaluated using pyramidal Vickers micro-hardness indenter (model 402 MVD, Wolpert-Wilson Instruments, USA) by applying a load of 300 g for about 10 s. For each sample, 20 indentations were performed and the average value is reported with standard deviations.

3. Results

3.1. Uniaxial stress-strain response

Fig. 4 shows representative uniaxial stress-strain responses of CP titanium till failure along rolling direction (RD), transverse direction (TD) and 45° to the rolling direction (DD), respectively. In addition to Instron in-built displacement sensor reading, a non-contact DIC technique was also employed for measurement of strain beyond plastic instability. For the sake of brevity, for the TD sample alone, strain obtained from both the strain measurement techniques is shown in Fig. 4.

It is evident that strain (averaged over the entire gage section) measured using DIC technique is in good agreement with gage based displacement sensor till the ultimate tensile point. However, beyond that point, strain measured from the complementary techniques differs considerably. Strain history (strain vs. time) obtained from the Instron gage based sensor and the DIC technique, corresponding to TD sample revealed similar phenomenon as shown in the Fig. 5. DIC strain was extracted from the strain contour plots and plotted against strain obtained from the gage based sensor for the TD specimen until failure (Fig. 5). In addition, strain contour plots for the TD sample, taken at discrete steps corresponding to an ultimate tensile point in the stress-strain curve (point a) and various stages in plastic regime beyond the ultimate point (point b and point c) and just prior to failure (point d) are shown in Fig. 6. Intense strain localization in the necked region and strain as high as 1.75 is observed, just prior to failure (Fig. 6). Similarly, DD sample (45° to RD) revealed early onset of plastic instability with intense strain localization, whereas, RD sample displayed higher uniform elongation and higher ultimate tensile strength. Uniaxial mechanical properties at various orientations are summarized in Table 2.

3.2. Validity of biaxial tensile tests

In order to verify the validity of the biaxial tests, post-processed strain contour plots were analyzed to reveal any strain concentrations, present due to factors other than mechanical loading. Irrespective of geometry optimization of cruciform specimen using FEM analysis, strain concentration often builds up in the gage section, during biaxial loading due to machining-induced defects (undercuts). Fig. 7 shows the first principal strain–contour plot of gage section of one such cruciform specimen where strain concentrations are observed near the thickness transition zone. This is further supported by the fact that significant reduction in failure load whenever strain concentration regions are observed in the post-processed strain contour plots. Since these defects contributed to failure rather than failure due to biaxial stress state,
This is considered to be non-representative of biaxial failure. Fig. 8 shows the principal strain contour plot of another biaxial test specimen which failed primarily due to biaxial stress state and no strain concentration regions (at least within the elastic regime) are observed. Moreover, it is evident from the contour plot, that the crack propagated along the diagonal of gage section (at 45° to loading directions X and Y respectively) exemplifying equi-biaxial condition.

In addition, it is also observed that the final crack propagation for yet another test specimen deviated slightly from 45° crack propagation to the loading axes. For this scenario, evolution of strain at various load steps is shown in Fig. 9. It is clear from strain evolution map that prior to yield; homogenous strain distribution is seen in the gage section (within the elastic regime) which is always desired. However, beyond yielding, region over which crack initiates solely depends upon the local magnitude of the strain in that region. Hence, this is also considered to be a true biaxial failure, though crack propagation deviated from ideal 45° direction to the loading axes.

3.3. Biaxial stress-strain response

From the strain contour plots, strain along X (RD) and Y (TD) directions, averaged over the entire gage section was extracted and subsequently plotted as shown in Fig. 10. Reduction in biaxial failure strain/ductility with a corresponding increase in ultimate strength is observed in contrast to uniaxial condition (Table 3). The biaxial failure strength is around 581 ± 21 MPa which is approximately equal to twice that of the uniaxial failure strength. While, DIC technique is successful in capturing failure strain and failure location, the elastic portion of the stress-strain curve was not captured faithfully due to very low magnitude of elastic strain. Hence, strain gages were employed for the measurement of elastic strain. It is interesting to mention that slope of the stress-strain curve is also influenced by the stress-state (Fig. 11 and Table 3). The slope of the biaxial stress-strain curve, henceforth, will be referred as effective modulus is higher in contrast to the slope of the uniaxial stress-strain curves. The decrease in strain with a corresponding increase in slope is observed under equi-biaxial stress state.

3.4. Fractography of tested samples

Fractographic analysis of tested samples shows predominantly a dimpled type of fracture irrespective of stress state. It was reported in the literature that size and shape of the dimples would depend upon the stress state [25] and hence fracture surfaces of failed samples under uniaxial and biaxial stress state are compared and contrasted with respect to dimple size and morphology. By and large, fracture surface of biaxially tested sample is relatively smooth with an average dimple size of around 5 μm, whereas uniaxially tested sample displayed rough fracture surface with a dimple size of around 10 μm with voids interspersed within them. In addition, depth of dimples is also reduced under biaxial condition which is evident from Fig. 12.

3.5. X-ray diffraction analysis of deformed samples

X-ray diffractograms (20 scans) of deformed samples under uniaxial and biaxial condition indicates changes in peak intensities of some of the prominent peaks in contrast to as-received sample (Fig. 13). To facilitate easy comparison, intensity ratios of some of the peaks of the deformed samples are compared with that of untested samples (Table 4). For instance, I₀₀₁/I₂₀₀ ratio of both uniaxially and biaxially deformed sample decreased indicating the activity of (0002) basal plane with respect to deformation. In addition, I₁₀₁/I₁₁₀ intensity ratio of biaxially deformed samples also decreased significantly indicating the re-orientation of (1120) plane parallel to the surface.

In hcp materials, the type of active operating slip system has a direct correlation with the deformation texture that develops afterwards [26] hence, texture analysis was carried out on as-received and deformed samples. Texture of as-received and deformed samples measured using X-ray diffraction technique are presented in the form of pole figures (0002) and (1120), respectively. As-received CP titanium exhibits split-basal type texture (Fig. 14a) where the basal (0002) pole is tilted away from normal direction (ND) by ± 35° towards TD with a maximum intensity of around 5.4 times that of random. Also, it is evident from (1120) pole figure that (1120) plane preferentially aligned along the rolling direction (RD). As-received texture observed in this case is consistent with rolling texture of CP titanium reported in the literature [27,28].
Uniaxial samples deformed along RD revealed basal pole (0002) intensity maximum at 72° away from the ND but tilted towards TD, whereas, not much difference is observed in the case of {11\overline{2}0} pole figure when compared to as-received texture (Fig. 14b). Uniaxial samples deformed along 45° to rolling direction (DD) shows texture similar to uniaxial RD samples, however, texture components are rotated by 45° since the samples are extracted and tested along 45° to the rolling direction. (Fig. 15a).

Texture of biaxially deformed samples revealed a weakening of basal texture as shown in the Fig. 15b. The split-type basal texture

![Fig. 9. First principal strain contour plots of gage section of cruciform specimen at various load steps (a) 42 kN (b) 62 kN (c) 72 kN (d) 77 kN.](image)

![Fig. 10. Biaxial stress-strain response CP titanium until failure.](image)

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Uniaxial and biaxial mechanical properties of CP titanium.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress state</td>
<td>0.2% yield strength in MPa</td>
</tr>
<tr>
<td>Uniaxial (DD)</td>
<td>181 ± 13</td>
</tr>
<tr>
<td>Biaxial</td>
<td>320 ± 20</td>
</tr>
</tbody>
</table>

Uniaxial samples deformed along RD revealed basal pole (0002) intensity maximum at ±20° away from the ND but tilted towards TD, whereas, not much difference is observed in the case of {11\overline{2}0} pole figure when compared to as-received texture (Fig. 14b). Uniaxial samples deformed along 45° to rolling direction (DD) shows texture similar to uniaxial RD samples, however, texture components are rotated by 45° since the samples are extracted and tested along 45° to the rolling direction. (Fig. 15a).

Texture of biaxially deformed samples revealed a weakening of basal texture as shown in the Fig. 15b. The split-type basal texture...
is lost completely along with development of new texture component \(\{11\overline{2}0\}\) oriented along the ND direction. Texture results are in good agreement with normal X-ray diffractogram of biaxially deformed samples with an increased intensity of \(\{11\overline{2}0\}\) plane as shown in Fig. 13.

4. Discussion

It is clear from Fig. 4 that CP titanium displayed in-plane anisotropic response under uniaxial stress state with variation in mechanical properties along RD, DD and TD, respectively. Such orientation dependent mechanical properties of commercially pure titanium were also reported in the recent literature [29–31]. Since hcp materials such as titanium possess only four independent active slip systems [32], deformation is primarily governed by favorable orientation of the operating slip system with that of stress-axis [33]. Unfavorable orientation with respect to stress axis always results in increased yield strength whereas

<table>
<thead>
<tr>
<th>Intensity ratio</th>
<th>As-received</th>
<th>Uniaxial</th>
<th>Biaxial</th>
</tr>
</thead>
<tbody>
<tr>
<td>(h_{101}/h_{002})</td>
<td>1.3</td>
<td>0.83</td>
<td>0.80</td>
</tr>
<tr>
<td>(h_{101}/h_{112})</td>
<td>12.5</td>
<td>16.6</td>
<td>3.22</td>
</tr>
</tbody>
</table>

Fig. 11. Elastic stress-strain response of CP titanium tested under uniaxial and biaxial condition.

Fig. 12. Fractography of uniaxial and biaxial tested samples.

Fig. 13. X-ray diffractograms of as-received and deformed samples.
favorable orientation leads to increased ductility in that direction. Hence, the observed in-plane anisotropic response can be attributed to influence of loading mode on the operating deformation mechanism [34].

It is noteworthy to mention that deviation observed between two complementary strain measurement techniques (Fig. 5) is attributed to intense strain localization in the necked volume under uniaxial stress state. This is because, DIC technique (subset-based iterative algorithm) captures strain localization more precisely at every discrete point in the necked region of the gage section, whereas the displacement sensor measures the global displacement between the two cross-heads and it is less sensitive to localized deformation (Fig. 6).

Increased slope and decreased strain under biaxial stress state (Fig. 11) within the elastic limit can be attributed to the influence of Poisson’s ratio as per the below-mentioned relation, which is derived from the generalized stress-strain relation. A similar trend is observed even in the case of isotropic mild steel.

\[ E' = \frac{E}{(1-\nu)} \]

where \( E' \) is the effective modulus (slope of stress-strain curve under biaxial condition).

Significant improvement in yield strength and ultimate tensile strength under biaxial tension (Table 3 and Fig. 11) can be explained on the basis of initial texture. Since biaxial testing involves loading in two orthogonal directions, parallel to the plane of the sheet, deformation in through thickness direction is limited due to the absence of c-direction deformation in close-packed hcp structure. This is because of strong basal and split-basal texture of the as-received material (i.e.) basal plane lying parallel to the plane of the sheet and biaxial loading is also parallel to the basal plane. Hence, significant improvement in yield strength (i.e.) 1.75 times greater than that of uniaxial yield strength is observed (Table 3). Ishiki et al., [22] also reported significant improvement in yield strength of pure titanium under biaxial conditions which is around 1.5 times. Hence, conventional yield criteria’s such as Hill anisotropic criteria cannot be used successfully to predict/model the material behavior under biaxial tension stress state. This corroborates the importance of biaxial tensile testing in understanding the deformation behavior of anisotropic materials under such a stress state.

Strain hardening exponent (n) is calculated as per the ASTM standard E646-07 and the strain range is chosen in such a way that, it lies between the yield point and the ultimate point in the stress- strain curves (5–10% strain). Though strain hardening exponent under biaxial stress state is reported lower when compared to uniaxial tension [35], accuracy of n value strongly depends upon chosen strain range and its agreement with the Hollomon power law relation. In the current investigation, it is
observed that biaxial strain hardening exponent is higher than uniaxial strain hardening exponent, which is contradictory to previous literature [35] (Table 5). Considering the fact that higher strain hardening exponent is beneficial for formability, better stretchability and formability can be achieved under biaxial tension. However, fracture intervenes much earlier due to loss of post-uniform elongation/ductility in contrast to uniaxial counterpart.

In addition, higher strain hardening exponent also means that material strain hardens to a greater extent before fracture. To corroborate this, Vickers indentation was performed near the fracture surface of uniaxial and biaxial tested samples. It is observed that the hardness of biaxially deformed samples is higher than uniaxially deformed samples (Table 5), which is concomitant to higher strain hardening exponent observed under biaxial condition. Also, intense strain localization is observed in the case of uniaxial samples (Fig. 6) but not in biaxially deformed samples (i.e.) absence of localized deformation (Figs. 8 and 9).

SEM images of neck profiles (Fig. 16) of uniaxial tested samples at various orientations revealed sharp localized necking (large reduction in area) in the case of TD samples, whereas less pronounced necking is observed in RD and DD samples, respectively. Observed differences in necking profile are in good agreement with calculated strain hardening exponents and indentation hardness taken close to the fracture surface (Table 5).

Decreased dimple size under biaxial condition (Fig. 12) can be explained on the basis of void nucleation and link up prior to fracture. It was reported by Kestner and Koss [36] that void nucleation, growth and void linking would depend upon stress state and strain path history. Similarly, stress-based fracture criterion by A.K. Ghosh [37] also postulated accelerated shear linking of voids under the presence of high tri-axial stresses. Since higher tri-axiality is normally encountered under biaxial condition, void-link up is enhanced more in contrast to uniaxial stress state which led to smaller dimples.

<table>
<thead>
<tr>
<th>Stress state</th>
<th>Strain hardening exponent (strain range – 5 to 10%)</th>
<th>Vicker’s indentation hardness HV0.3</th>
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<tbody>
<tr>
<td>As-received</td>
<td>–</td>
<td>158 ± 5</td>
</tr>
<tr>
<td>Uniaxial (TD)</td>
<td>0.12</td>
<td>158 ± 6</td>
</tr>
<tr>
<td>Uniaxial (DD)</td>
<td>0.14</td>
<td>169 ± 5</td>
</tr>
<tr>
<td>Uniaxial (RD)</td>
<td>0.18</td>
<td>170 ± 7</td>
</tr>
<tr>
<td>Biaxial</td>
<td>0.21</td>
<td>212 ± 7</td>
</tr>
</tbody>
</table>

Table 5
Strain hardening exponent and Vickers indentation hardness of as-received and deformed samples.

![Fig. 15. Pole figures of (a) uniaxial 45° to RD sample (b) biaxially deformed sample (PI max – pole intensity maximum).](image-url)
Texture evolution upon biaxial deformation revealed dramatic changes in contrast to uniaxially deformed samples (Fig. 15b). Though the observed biaxial strengthening effect can be attributed to split-basal texture, significant textural changes and loss in ductility under biaxial tension needs further explanation. It is reported that for basal textured material under uniaxial stress state, straining in thickness direction is largely avoided but not under biaxial condition due to nature of loading [20].

Due to this additional constraint during biaxial loading as well as absence of c-axis deformation (thickness direction) resulted in...
reduced ductility with significant improvement in tensile strength of about 76%. Furthermore, loss of split-basal texture is manifested itself in the form of orientation rotation of (0002) basal pole towards TD, thereby resulting in development of new texture component [1120] pole oriented parallel to TD direction. Transformation from strong basal type to [1120] type observed upon biaxial deformation could be due to operation of specific type of twinning system during loading. Important texture components of as-received, uniaxial and biaxially deformed samples are outlined in ODF $\Phi_1$ sections (Fig. 17). As-received samples revealed the presence of strong basal texture components ($\Phi_1=0\(^\circ\), $\Phi_2=5\(^\circ\)$, $\Phi_2=60\(^\circ\)$), whereas, upon deformation, basal components are progressively weakened. In addition, biaxially deformed samples revealed distinct texture components developed at the expense of basal component (Table 6). Such a texture transition could be due to imposed mode of deformation and absence of c-axis deformation of basal textured material during biaxial loading.

5. Conclusions

Cruciform specimens were machined based on optimized geometry obtained using FEM simulation and biaxial testing was carried out to understand the influence of stress state on the mechanical properties of CP titanium. The decrease in ductility with an increase in strength is observed under biaxial conditions. Increased slope under biaxial stress state is explained based on the generalized Hooke’s relation. The increased indentation hardening of biaxially tested sample in contrast to uniaxially tested sample is attributed to differences in strain hardening behavior. Albeit similarities in fracture mode, decreased dimple size and depth in biaxially tested samples is evidenced through fractographic studies. Strengthening effect under biaxial tension is attributed to split-basal texture of as-received samples and texture analysis of biaxial deformed samples indicated alignment of [1120] pole with the normal direction.

Acknowledgments

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<table>
<thead>
<tr>
<th>Sample</th>
<th>Texture component</th>
<th>$\phi_1 (^\circ)$</th>
<th>$\phi_2 (^\circ)$</th>
<th>$\phi_2 (^\circ)$</th>
<th>ODF value (Max)</th>
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<td>As-received</td>
<td>(01215) [TTT41] (0001) [1100]</td>
<td>50</td>
<td>4</td>
<td>30</td>
<td>7</td>
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<tr>
<td>Uniaxial RD</td>
<td>(0001) [1100] (11172)</td>
<td>350</td>
<td>29</td>
<td>10</td>
<td>10</td>
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<tr>
<td>Uniaxial DD</td>
<td>(0001) [1100] (0113) [T2211]</td>
<td>349</td>
<td>30</td>
<td>10</td>
<td>13</td>
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<tr>
<td>Biaxial</td>
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<td>94</td>
<td>30</td>
<td>50</td>
<td>6</td>
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<tr>
<td></td>
<td>(0115) [2T00]</td>
<td>350</td>
<td>15</td>
<td>45</td>
<td>4</td>
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</tbody>
</table>

References


