Original Article

Studies on texture and formability of Zircaloy-4 produced by pilgering route


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Abstract

Zircaloy-4 is a widely used material in nuclear industries due to its excellent corrosion resistance at elevated temperatures, low neutron absorption cross section and balanced strength and ductility. In the present study, the formability of Zircaloy-4 sheets produced through pilgering route has been investigated. Nakajima dome tests have been conducted on sheet samples taken along rolling, transverse and diagonal directions with respect to the rolling direction of the sheet to construct the forming limit diagrams (FLDs). The strain signature of deformed samples has also been studied to determine the peak limiting strains. Further, limiting dome height values are calculated and all the results are validated with FE-Simulations. Finally, XRD studies have been performed to understand the relationship between the texture and formability. The FLD and texture studies reveal that the Zircaloy-4 possesses higher drawability in comparison to that of the stretchability. The orientation of the specimen has negligible influence on FLD in tension–tension region and marginal influence in tension–compression region.

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1. Introduction

Zirconium and its alloys are widely used as structural materials in nuclear power plants due to their unique combination of strength and ductility, resistance to high temperature corrosion and low neutron absorption cross section [1–3].
above properties are due to their alloying elements: tin, iron, niobium, nickel, chromium and other elements. The alloys contain zirconium and other alloying elements more than 95% and less than 2% respectively. The development of zirconium alloys was started in 1950s and along with the improvements in properties of the alloys, the names also given like, Zircaloy-1, Zircaloy-2, Zircaloy-3 and Zircaloy-4. The Zircaloy-1 and Zircaloy-3 have become obsolete due to their deleterious effects in corrosion resistance. Hence, Zircaloy-2 and Zircaloy-4 are highly used alloys for the nuclear applications.

In recent time, Zircaloy-4 are extensively used in fuel cladding tubes of pressurized water reactors, spacer grids of light water reactor, and channel box of boiling water reactors (BWR) [4–7]. The materials for these applications are processed through different fabrication routes in order to impart suitable properties of these components as per the service requirement. In the present work, the materials used are for the fuel cladding tubes which are manufactured by pilgering route are studied. In pilgering process, initially a slab of alloy with predrilled hole is used to subject a series of passes thorough pilgering dies. In the process, simultaneously the diameter of the slab decreases and length increases in such a degree that a very thick slab converted into a very thin tube. The process is characterized by Q-factor. The Q-factor is defined as the ratio between a strain resulting from thickness reduction and strain resulting from reduction of diameter. The effect of Q-factor on final product has been found that the increase of Q-factor will increase the durability of final product [3,7]. A systematic pilgering steps were followed to estimate the effect of Q-factor and forming behavior of Zircaloy-2 while quenching [6]. Recently, Vertikaler Massenausfeuchling Ringwalzei (VMR) technology is used to increase the deformation ratio and decreasing in homogeneity of the strain distribution, thereby increasing the productivity by reducing the number of pilgering steps [8]. The in-reactor performance of these components demands stringent quality control, which in turn, demands detailed understanding of microstructure and forming property evaluation for the successful manufacturing process.

Formability is the ability of the material represents the maximum extent to which sheet metal can be deformed until plastic instability occurs in a material. Forming Limit Diagram (FLD) is the one from which the formability of the material can be observed for all strain conditions ranging from tension–tension to tension–compression deformation mode. The concept of FLD was pioneered by Keeler and Backofen [9] based on the observations of Gensamer [10] that local deformations have to be considered instead of global indices. Later, Hecker [11] introduced an organized approach involving the stretching of aluminum killed steel sheets of various widths over a hemispherical punch to obtain different strain paths. Hecker obtained a forming–limit curve lying mostly within the Keeler-Goodwin FLD band. In this regard, FLD of various automotive grade steel, aluminum, nickel, and magnesium alloy sheets had been successfully evaluated in the past, and moreover, these were implemented as a diagnostic tool for failure prediction during stamping [12–15].

In recent past, Roamer et al. [16] followed Hecker’s simplified technique to evaluate FLD on three different grades of Inconel sheet metal at room temperature. The 3 different grades were Inconel 625, 718 and 718SPF. The noteworthy observation of the experiment was that all the Inconel sheets failed without a significant hint of necking, hence FLD was constructed considering the maximum safe strains. A similar approach have been adopted reported for different automotive grade steel sheets [17–19]. A geometrical constraint such as usage of sub-standard punch plays a crucial role in the prediction of forming limits, which was first clearly reported by Ghosh and Hecker [11] and later by Charpentier [20]. Prasad et al. [13] followed Hecker’s simplified technique to evaluate FLD using a hemispherical punch of 50 mm diameter for Inconel-718 sheets. Due to this, bending strains are imposed on the sheet metal, and compensation has to be made to get corrected limiting strains. In the recent past, Yunmi Seo et al. [21] constructed forming limit diagram of Zircaloy-4 and Zirlo sheets for the fabrication of spacer grids of nuclear fuel rod. In their work they have pointed out that the effect of lubrication on specimen. Further, the FLD of Zircaloy-4 was compared with both FLD of Zirlo sheets and analytical FLD constructed from M-K Model. Venkateswarlu et al. [22] studied the effect of microstructure and texture on formability of friction stir processes magnesium alloy. Recently, Karuppasamy et al. [23] constructed the FLD of Zircaloy-4 to find out the effect of surface pit on the sample and its influence on the fuel spacer grid. The pits at the distance of 1/20 of sample length from the center of the sample were more prone to bring high risk of fracture than the pits at other locations of the sample.

The experimental stretching operations involve trial and error methods in optimizing the process parameters. In this regard, finite element method (FEM) plays a pivotal role in the simulation of forming processes to reduce the experimental trials [24–26]. Moreover, to avoid the failure and to obtain a defect-free component, the knowledge about the forming limit of sheet material is the essential aspect in designing the tooling and process sequence [13,24]. Based on the above discussions, it is well understood that there is a little focus on the formability of Zircaloy-4. Hence, in the present work, the formability limits of the Zircaloy-4 at room temperature are analyzed by limiting dome test and these are validated by simulation of the process. In summary, the highlights of the work are:

- Construction of FLDs for Zircaloy-4 produced through pilgering route.
- Studies on strain signature of deformed samples in three different orientations.
- Finite element analysis to material formability.
- Investigate the relationship between the texture and formability.

2. Materials and methods

2.1. Microtexture measurements

The as-received sheet material has 1.34% Sn, 0.2% Fe, 0.1% Cr, 1292 ppm Oxygen and Zr-remaining. The samples of 25 × 15 mm size were cut along RD-TD plane from as-received sheets and mounted using copper conductive powder. Further, the mounted samples were polished mechanically using SiC papers of decreasing granulometry, and diamond paste.
(3 µm) was used prior to colloidal silica (1 µm) polishing [27]. The specimens were then electrochemically etched using 80% Methonal + 20% Perchloric acid with etching parameters of: 21 V, 22 s, 70% flow rate. Further, ultrasonic cleaning using ethanol was finally conducted on the electrochemically etched samples before being placed into the field emission scanning electron microscopy (FESEM).

X-ray diffraction (XRD) studies on the as-received sheets were performed using a inel equinox diffractometer with Cu Kα radiation equipped with position sensitive detector. The HKL system, Nordyls, mounted on a Carl Zeis Dual Beam FEG microscope, Auriga, was used for the EBSD measurements. The microstructure of the Zircaloy-4 material is obtained from Electron Back Scatter Diffraction (EBSD) technique is depicted in Fig. 1. An inel G3000 texture goniometer coupled with curved position sensitive detector was employed for texture measurement based on Schulz reflection technique. Incomplete pole figures (0002), (10T0), (10T1), (10T3), and (10T2) were obtained from 0.5 thickness of ND plane. A fluctuation stage was used with 20.0 mm sample translation to improve measured area. The texture results are presented (in Fig. 2) as {0002} basal pole figures, ODF figures at ϕ2 sections of 0° and 30° with iso-intensity contours defined by ϕ1, ϕ, ϕ2 angles and fiber plot.

2.2. Uniaxial tensile test

Tensile specimens from Zircaloy-4 sheets of 0.8 mm thickness were fabricated by using wire-cut electrical discharge machining process as per ASTM-E8M standard [28,29]. Specimens were cut along three orientations with respect to the rolling direction (RD) of the sheets viz. parallel (l), diagonal (R) and perpendicular (T) directions. The tensile tests were conducted in a 50 kN universal testing machine at a crosshead speed of 2 mm/min. The tensile response in terms of true stress–true strain was estimated from the engineering stress–strain data obtained from the machine. Also, the different tensile properties such as 0.2% (pct.) yield strength (YS), ultimate tensile strength (UTS), % elongation, strength coefficient (K), strain hardening exponent (n) were evaluated. The n and K values were quantified using Hollomon as per Eq. (1), and the accuracy of the fit was evaluated in term of coefficient of determination (R²)

\[ \dot{\sigma} = K\varepsilon^n \]  \hspace{1cm} (1)

The Lankford anisotropy coefficients (r-values) were evaluated in three directions with respect to RD (viz. r0, r45 and r90). The tensile tests were stopped within the uniform deformation regime consistently at a load of 6.5 kN corresponding to approximately 75 pct. of the ultimate tensile strength of the materials. The r-values were found out after the measurement of width and longitudinal true strains as per Eq. (2), where, \( w_0 \) and \( l_0 \) represent the initial width and gauge length

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Fig. 1 – Microstructure of the Zircaloy-4.

Fig. 2 – Texture of pilgered Zircaloy-4 in terms of (A) ODF (ϕ2 = 0° and 30° sections), (B) (0002) basal pole and (C) [0001][ND] fiber plot.
of the specimen, w and l are the width and gauge length of the specimen after the deformation, respectively. The detailed procedure are mentioned elsewhere [13,30].

$$r = \frac{\ln \frac{w}{w_0}}{\ln \frac{l}{l_0}}$$ (2)

2.3. Limiting dome height test

Forming limit diagram (FLD) is often used as a diagnostic tool for formability prediction in sheet metal forming processes. In the present study, forming limits of Zircaloy-4 alloy sheets were evaluated using a laboratory scale LDH set-up consisting of a 50 mm sub-sized hemispherical punch. The schematic diagram of test set-up is shown in Fig. 3(a). The tools such as lower die, upper die, and punch were mounted in a 100 ton double action hydraulic press. The blanks were placed between the lower and upper die, and the exact centering of the blank was ensured before conducting the forming experiments. In order to restrict the flow of sheet material into the die cavity, the circular groove of lock bead at a diameter of 99 mm was provided in the lower die and the boss of the lock bead at the corresponding location was provided in the upper die. Fig. 3(b) depicts the circular specimen of 150 mm diameter and the Hasek specimens of 25 mm width used to evaluate the forming limits of the material.

Sample 1 represents the 150 mm circular shape blank where sufficient lubrication using polyethylene sheet with hydraulic oil was used on the circular blank to impose deformation close to equi-biaxial strain path, and dry condition (without lubrication) was used to induce near to plane strain path in the material. Hasek specimen of the same length with a narrower width of 25 mm (Sample 3) was used to achieve tension-compression strain path during deformation. The samples were prepared using milling process along three orientation of sheets namely rolling (L), diagonal (R), and transverse (T) directions with respect to the rolling direction of the sheet as shown in Fig. 3(c). Prior to deformation, circular grids of 5 mm diameter were imprinted on the surface of blanks using screen printing technique to evaluate the major and minor strains of the deformed blank. The blank-holding force (BHF) was applied within a range of 6–15 BHF and the punch was moved at a deformation speed of 20 mm/min. The blanks were stretched with the progression of punch movement, and a mirror was placed below the lower die to observe the appearance of necking/failure during the test. The circular grids turned into ellipses after deformation, and both the major and minor diameters were measured using Leica Stereo zoom microscope. The major (ε1) and minor (ε2) engineering strains were evaluated by Eq. (3) and were transformed into corresponding true strains (ε_{1,2m}) as per Eq. (4). The major and minor strain data obtained from the safe and failed regions were plotted in the principal strain loci.

$$\varepsilon_{1,2} = \frac{(\text{ellipse major/minor axis distance} - \text{grid diameter})}{\text{grid diameter}}$$

$$= \frac{(d_{1,2} - d_0)}{d_0}$$ (3)

$$\varepsilon_{1,2} = \ln(1 + \varepsilon_{1,2})$$ (4)

2.4. Finite element modeling

Numerical simulations of stretch forming process were carried out using a commercially available explicit dynamic solver of LS-DYNA971 software. To reduce the computation time, a quarter symmetric model of tool and blank were modeled as shown in Fig. 4. Further, analytical draw bead was provided on the die, and the BHF was applied in a downward direction to ensure that the motion of blank was restricted, and hence inducing tensile stretching in the blank. All the tools were assigned as rigid bodies whereas blank was considered to be deformable body incorporating anisotropy properties. The blank was modeled using Belytschko-Tsay shell element. In the FE model, the optimum mesh size of 1 mm × 1 mm with 4-level of adaptive meshing scheme was implemented. This
optimum element size was fixed by carrying out the sensitivity analysis. The surface contact provides a way of interaction between slave (tools) and master (blank), and for the present work contact one way surface to surface card was adopted [24]. A constant coefficient of friction between the tool and blank was used, and the values were defined to be in the range of 0.25 [31,32]. Also, the mechanical properties obtained from the uniaxial tests (refer Table 1) such as yield strength, strength coefficient, strain hardening exponent were incorporated into the material model. Hollomon’s strain hardening law with Barlat-89 yield function was chosen as the material model, and this was expressed in terms of plane stress state as shown in Eqs. (5) and (6).

\[ a|k_1 + k_2|^M + b|k_1 - k_2|^M + c|k_2|^M = 2\sigma_e^M \]  

\[ k_1 = \frac{\sigma_x + h\sigma_y}{2}, \quad k_2 = \left[ \left( \frac{\sigma_x - h\sigma_y}{2} \right)^2 + \rho^2\tau_{xy}^2 \right]^{0.5} \]

where \( \sigma_e \) is the effective stress, \( k_1 \) and \( k_2 \) are invariants of the stress tensor while \( M \) is an integer exponent. \( a, c, h \) and \( p \) represent anisotropy coefficients which can be expressed in terms of Lankford anisotropy parameters. In addition to this, the experimentally evaluated FLD was incorporated into the FE codes as fracture criterion. Subsequently, the predicted LDH and strain distribution results were compared with the experimental data.

### 3. Results and discussion

#### 3.1. Microstructure and tensile properties

The presence of texture in the Zircaloy-4 is also observed in the microstructure obtained from EBSD as shown in Fig. 1. It is clear from the figure that the grains are well recrystallized and equi-axed. It is also observed that the most of the grains have their basal normal parallel to the sheet plane normal (the red grains) which indicate the presence of moderate texture in the material. As a results, the tensile properties of the material is different in different directions (Table 1). The detailed analysis of tensile properties for Zircaloy-4 is mentioned elsewhere [33]. The yield strength is increased from pilgered direction (L) to transverse (90° to pilgered direction (T)) whereas the trend is in reverse in the case of the UTS. The percent elongation, strength coefficient (K), and the strain hardening exponent (n) are decreased from L to T. The decreasing trend of the 'n' is in good agreement with the strain limits of in left hand side of the FLD.

#### 3.2. Forming limits

The samples along different orientations with respect to rolling direction of the sheet were stretch-formed to evaluate the forming limits. Fig. 5 shows the deformed samples along different strain path for rolling direction of the sheet. The strains were measured along maximum safe and fractured regions of all the deformed specimens and were plotted in the true principal strain locus as shown in Fig. 6. It is important to note that the strains which are plotted in Fig. 6 are after deducting the bending strains from the total strains. It was observed that the plotted strains were scattered along whole domain, and hence, different colors were assigned to distinguish the safe strains from the fractured strains. It is noteworthy that the while performing stretch forming experiments the materials fractured catastrophically without any hint of necking. It was evident from the figure that there were no necked ellipses in the cluster of fractured grids, and it was due to the failure of sheet metals without the onset of necking during the LDH tests. Hence, as the demarcation of limiting strains to plot the forming limit curve (FLD) was done by drawing a curve separating the maximum safe ellipses from failed ellipses.

Fig. 6(a) shows the measured strain in the principal strain space for the specimens deformed in the rolling direction. The line ‘OA’ denotes the strain ratio \( \mu = \varepsilon_2/\varepsilon_1 = 0.76 \) close to equi-biaxial tension \( \mu = 1 \) mode obtained by deforming sample 1. Deformation path of sample 2 was represented by ‘OB’ which induced the strain path \( \mu = 0.18 \) closer to plane

### Table 1 – Mechanical properties of pilgered route Zircaloy-4 sheet.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>( \sigma_{YS} ) (MPa)</th>
<th>( \sigma_{UTS} ) (MPa)</th>
<th>% Elongation</th>
<th>K</th>
<th>n</th>
<th>( R^2 )</th>
<th>r-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>318.66 ± 0.07</td>
<td>455.62 ± 0.01</td>
<td>27.94 ± 0.02</td>
<td>722.70</td>
<td>0.145</td>
<td>0.99</td>
<td>4.61</td>
</tr>
<tr>
<td>R</td>
<td>358.49 ± 0.01</td>
<td>443.53 ± 0.02</td>
<td>30.22 ± 0.08</td>
<td>746.15</td>
<td>0.139</td>
<td>0.99</td>
<td>3.68</td>
</tr>
<tr>
<td>T</td>
<td>379.17 ± 0.02</td>
<td>438.65 ± 0.01</td>
<td>27.16 ± 0.07</td>
<td>631.36</td>
<td>0.098</td>
<td>0.99</td>
<td>7.35</td>
</tr>
</tbody>
</table>
strain condition whereas the deformation of sample 3 produced tension–compression deformation mode denoted by path ‘OC’. While conducting experiments, it was observed that all the specimens failed without any hint of localized necking. Thus, as a demarcation of forming limits, a line was drawn separating safe and failure strains to obtain the FLD. It is noteworthy to understand that the slope of the line on the left-hand side FLD was approximate −1.1 whereas on the right-hand side the value was −0.6. This negative trend of the slopes indicated the formability of the material decreased drastically from tension–compression region to equi-biaxial tension region. Moreover, the decreasing trend in the formability is in agreement with catastrophic decrease in the LDH value. It is noteworthy that the LDH of sample 3 was around 25.5 mm, and the LDH value decreased by approximately 20% and 33% for sample 2 and sample 1 as compared to sample 3 respectively. This also signifies that material possesses higher drawability in comparison to that of the stretchability. Similar trend in the FLDs were observed for both diagonal and transverse direction specimens as shown in Fig. 6(b) and (c) respectively.

Fig. 7 represents the comparative FLD along three directions of the sheet. It was observed that on the right hand side of FLD, there exists a very negligible difference in the forming limits among all the three direction, whereas marginal difference was observed along tension–compression region as depicted by the enlarged view in the figure. The true major strain for rolling direction specimen was recorded to be around 0.51 while for the diagonal and transverse direction the values were around 0.49 and 0.45 respectively. This variation in the true major strain values ensured different drawability of the material with respect to the orientation of the sheet.

3.3. Strain distribution

It is vital to have the knowledge of strain induced over the final component. Generally, the strain distribution is plotted along the longitudinal direction of maximum deformed ellipse, and is often referred as the ‘strain signature’. Fig. 8 shows the strain distribution profile of sample 3 along rolling, diagonal, and transverse direction. The true strains are plotted as a function of highest position (pole) on the stretch formed cup. It was observed that the true major strain showed positive values across the profile whereas negative (compressive) minor strain was observed due to lateral drawing in the specimen. All the three directions of sample 3 exhibited similar trend in true major and minor strain profile. However, the peak strain level changed with respect to the orientation of the specimens. It was observed that the peak major strain for rolling direction specimen was around 0.55, and the value was found to be decrease for diagonal and transverse direction specimens with an approximate value of 0.51 and 0.48 respectively. The highest peak strain along rolling direction is in agreement with the higher strain hardening exponent value of 0.1121 as compared
Fig. 7 – Forming limits comparison along rolling, diagonal, and transverse directions of the sheet.

Fig. 8 – Strain distribution profile of sample 3 along (a) rolling, (b) diagonal, and (c) transverse orientation with respect to rolling direction of sheet.

to that of the 0.0978 and 0.0807 for diagonal and transverse direction specimens respectively. The peak major strain was observed at an approximate distance of 5 mm from the pole which coincides with the failure location for all the samples.

As discrepancy in the FLD toward the right-hand was very negligible, the strain distribution of sample 2 and sample 3 along the rolling direction was considered. Fig. 9(a) shows positive major and minor strain profile of sample 2 indicating that the specimen had induced biaxial tensile straining. However, comparatively lower magnitude of minor strain profile signified that the deformation was closer to plane strain mode. It was also observed that the peak major strain was at 20 mm from the pole, and the value decreased drastically by approximately 52% as compared to that of the tension–compression condition. Fig. 9(b) represents the strain distribution of sample 3 where both major and minor strains profile displayed the well-developed positive strains representing biaxial tensile deformation mode. As the minor strain profile was closer to the major strain profile, the deformation mode was near to the equi-biaxial tension mode. However, the development of the major strain was lower compared to that of samples 1 and 2 which is in agreement with the lower limit in the FLD as
3.4. Finite element validation

In order to validate the experimental FLD, it was implemented in the FE model to predict failure. The fracture occurred when the deformation path intersected the incorporated FLD and corresponding FE predicted cups for all the three cases are shown in Fig. 10. It can be observed that the predicted strain paths were close to the experimental strain ratios viz. near to equi-biaxial tension, near to plane strain and tension-compression region. Further, the formability parameters in terms of LDH and strain distribution of predicted results were compared with the experimental data as elaborately discussed in following sections.

The limiting dome height (LDH) of experimentally obtained and predicted results for all three deformation paths were consolidated and compared in Table 2. It was evident from the table that the LDH value obtained experimentally showed a decreasing trend from tension-compression (25.45 mm) to equi-biaxial tension (17.17 mm) region showing an agreement with the lower formability on the right-hand side of FLD in comparison to that of the left side. A similar trend was also observed for the predicted LDH. However, the model slightly under-predicts the dome height from the experimental values. The higher deviation in LDH prediction was observed for sample 3 with the approximate percentage error of 11.4%. Whereas the deviation was found to decrease significantly by 9.6% and 3.8% for sample 2 and sample 3 respectively.

Further, the load–displacement curves obtained during the LDH tests for different samples are shown in Fig. 11. From the curves, it was observed that the load-bearing capacity of the material is generally highest for samples tested in biaxial tension (sample 1) followed by samples tested in plane strain and tension-compression modes due to decrease in deforming area with the decrease in blank width. Also, it can be observed the FE predict the same trend as that of the experimental data. The maximum error in peak load was found to be around 6.9% for sample 3 whereas the sample 1 and sample 2 showed the error of 4.9% and 4.2% respectively. Thus, it can be concluded that the FE model could able to predict the deformation behavior fairly well in accordance with experimental results.

3.5. Relationship of formability with texture and microstructure

The basal [0002] pole figure of the present alloy exhibits the presence of moderate intensity texture (i.e. 6.1× random) (Fig. 2). This in turn has an important bearing on mechanical properties in particular yield strength and elongation (Table 1). As a result, the n values of the alloy are maximum and minimum along longitudinal (L) and transverse (T) directions, respectively. In addition, the yield strength values are also maximum and minimum along L and T directions, respectively. This clearly supports the nature of formability limit diagram in tension–compression region wherein the formability of the material along L direction is maximum. This region is primarily important for deep drawing applications. Interestingly, tension–tension region of formability diagram of present study does not show any appreciable change which can be attributed to uni-axial tensile tests employed. The orientation dependent formability in tension–tension region can probably be obtained using bi-axial tension tests.

![Fig. 9 – Strain distribution profile along rolling direction for (a) sample 2 and (b) sample 1.](image)

![Fig. 10 – FE predicted cups of (a) sample 1, (b) sample 2, and (c) sample 3 at time step when the deformation path intersects the experimental FLD.](image)
Table 2 – Comparison of experimental and predicted LDH for different strain path.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Experimental LDH (mm)</th>
<th>Simulated LDH (mm)</th>
<th>Error percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>17.17</td>
<td>16.51</td>
<td>3.8</td>
</tr>
<tr>
<td>Sample 2</td>
<td>20.35</td>
<td>18.39</td>
<td>9.6</td>
</tr>
<tr>
<td>Sample 3</td>
<td>25.45</td>
<td>22.53</td>
<td>11.4</td>
</tr>
</tbody>
</table>

Fig. 11 – Comparison of experimental and FE predicted load–displacement curve for all the deformed cases.

The texture of the material is also analyzed in terms of fibers (Fig. 2(A) and (B)). The two sections of the ODF ($\varphi_2 = 0^\circ$ and $30^\circ$ sections) reflect a fiber called [0001][ND]. The [0001][ND] intensity along $\varphi_1$ direction from $0^\circ$ to $360^\circ$ is nearly homogeneous with a little fluctuation between $f(g) = 3.8$ to $f(g) = 5$. The major texture component in ODF is $\varphi_1 = 155.4^\circ$, $\Phi = 10.6^\circ$, $\varphi_2 = 15.0^\circ$ [$f(g) = 6.5$]. The presence of moderate texture is in good agreement with the moderate values of yield strength dependent in plane anisotropy ($A_{\text{HP}}$) and percent elongation dependent anisotropy index ($i$) values. The texture-resulted anisotropy of the mechanical properties is observed and presented in Table 1. In one hand the effect of texture on the left hand side of the FLD is very clear. On the other hand, the effect is not reflected in right hand side of the FLD. However, the texture effect on the FLD is limited level due to the construction of the FLD depends more on the conditions of the fracture of the material rather than that of deformation [17]. This may also be one of the reason to not observing the variation of the FLD in right hand side by the influence of the texture.

4. Conclusions

The formability of Zircaloy-4 sheets produced through pilgering route has been analyzed using FLD, strain signature and texture. The results of the study can be summarized as follows:

1. The limiting dome height close to equi-biaxial tension ($\nu = 0.76$), close to plane strain ($\nu = 0.18$) condition and in tension–compression deformation mode ($\nu = -0.42$) was found to be 17.2 mm, 20.4 mm and 25.5 mm respectively.
2. The slope of the FLC on the left-hand side was approximately $−1.1$ whereas on the right-hand side the value was $−0.6$. This negative trend of the slopes indicate that the formability of the material decrease drastically from tension–compression region to equi-biaxial tension region.
3. The orientation of the specimen has negligible influence on FLD in tension–tension region and marginal influence in tension–compression region.
4. The trend of strain distribution was similar in all three directions. However, peak strain value was changed with respect to sample orientation. The peak major strain was observed in rolling direction.
5. The basal (0002) pole figure of Zircaloy-4 exhibits the presence of moderate intensity texture. This has significant influence on mechanical properties such as yield strength, elongation and strain hardening exponent which in turn influence the formability. The influence of texture was clearly observed in the FLD on tension–compression region.

Conflicts of interest

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The authors declare no conflicts of interest.

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