Cylindrical Cup Manufacturing Using 12 mm Thick Circular Blanks of AISI 1040 Graded Medium Carbon Steel: an Innovative Approach

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In this paper processing effects were studied while 12 mm thick circular blanks of hardened-tempered AISI 1040 graded medium carbon steel, applied in cylindrical cup manufacturing by a new modified processing route as an innovative approach. The processing route mainly consisted of pre-forming of flat blanks to a little draw in shape, followed by multistage drawing without blank-holder. The wall ironing was purposefully accompanied with deep drawing by ensuring suitable die-punch design to reduce wall thickness as well as earing tendency on cup edges. Thus, evolution of cup dimensions and quality, wall thickness distribution profiles, drawability and ironability parameters, punch force history, hardness distribution profiles, strain distribution profiles, spring back tendency by Demeri split ring test, and microstructures of cup wall zones were discussed.

With appropriate heat treatment cycle, the steel showed a good combination of strength-ductility-formability and thus indicated its moderate drawability with high strength applications, i.e. up to ~634 MPa. The multistage cup drawing process feasibility was confirmed by manufacturing of >50 mm long cylindrical cups with uniform wall thickness and without any common forming defect. The microstructure study of cup walls also further substantiated the process feasibility. Moreover, the data pertaining to strain distribution profiles and spring back tendency of cups were shown for the process engineers to optimise the process and draw tool design, as a future scope of work.

KEY WORDS: cylindrical cups; thick circular blanks; medium carbon steel; multistage deep drawing; wall ironing.
phylogeny impart undesirable low formability, which makes the steels to find limited uses in deep drawing practices. It is also known that a microstructure consisting of globular morphology of cementite in ferrite matrix provides some benefits such as high toughness, good cold formability and strength, which can be obtained by proper heat treatment practice.

Numerous studies have been carried out on cup manufacturing process from thin blanks of low carbon steel sheets. There exists a series of attempts to manufacture cups from some high strength steels such as dual phase (DP), TRIP and TWIP grades. The study on medium carbon steel, as an alternative high strength grade, applied for cup drawing is less attended. Further, a literature related to cylindrical cup forming by using thicker blanks made of medium carbon steel, particularly by multistage deep drawing with simultaneous ironing method, is seen almost nonexistent. An attempt has been made, therefore, to manufacture cylindrical cups by using thicker circular blanks (12 mm thick, 60 mm diameter) of Aluminum (Al)-killed AISI 1040 graded medium carbon steel in hardened tempered condition, by a modified processing method, consisted of pre-forming of blanks followed by multistage drawing without blank holders and with inter-stage stress relief annealing. By using suitable die-punch designs, simultaneous wall ironing process was advantageously accompanied with deep drawing to address inherent forming difficulties of the medium carbon steel. Thus, evolution of the various process effects such as cup dimensions and quality; wall thickness distribution profiles; drawability and ironability parameters; punch force history; hardness distribution profiles; strain distribution profiles; spring back tendency of cups; microstructures at cup wall zones were obtained and discussed as main objectives of the present work.

2. Experimental

2.1. Material

The chemical composition of the as received vacuum degassed Al-killed AISI 1040 graded medium carbon steel is reported in Table 1. The steel ingot was forged into 95 mm round corner square (RCS) billets, hot rolled to 78 mm wide × 16.5 mm thick strips with finish roll temperature (FRT) 1223°K and subsequently cold rolled to 14 mm thick in running length. These strips were subjected to a heat treatment cycle consisted of pre-forming of blanks followed by multistage drawing without blank holders and with inter-stage stress relief annealing. By using suitable die-punch designs, simultaneous wall ironing process was advantageously accompanied with deep drawing to address inherent forming difficulties of the medium carbon steel. Thus, evolution of the various process effects such as cup dimensions and quality; wall thickness distribution profiles; drawability and ironability parameters; punch force history; hardness distribution profiles; strain distribution profiles; spring back tendency of cups; microstructures at cup wall zones were obtained and discussed as main objectives of the present work.

2.2. Mechanical Properties and Formability Parameters Evaluation

Intrinsic mechanical properties of the steel in heat treated condition were determined by tensile test at ambient temperature (298°K) on flat specimens (5 mm thickness, 6.5 mm width and 32 mm gauge length) along 0°, 45°, and 90° to the rolling direction (RD), by using a 20 kN, KIL make (model PC 2000) electronic tensometer, at a strain rate 2.5 × 10⁻⁴ s⁻¹, according to standard IS 1608: 2005. True values of tensile properties, yield strength (YS); tensile strength (UTS); yield ratio (TR); uniform elongation (UEL); total elongation (TEL) were determined from load-extension curves. The strain hardening exponent (n), an indicator of formability, was evaluated by regression method, applying on tensile flow curves. The uniaxial formability parameters such as: normal anisotropy (rn) and planar anisotropy (Δr) values were evaluated by conducting tensile tests up to 16–17% of UEL, and using the following equations as per standard IS 11999: 2007:

\[ r = \frac{\varepsilon_w}{\varepsilon_l} = \frac{\ln(w_0)}{\ln(t_0/t)} \]  

Where, \( r = \frac{\varepsilon_w}{\varepsilon_l} \) is plastic strain ratio of width to thickness in a flat tensile specimen; \( \varepsilon_w = \) true plastic strain along width; \( \varepsilon_l = \) true plastic strain along thickness; \( w_0 \) and \( t_0 \) = original specimen width and thickness respectively; \( w \) and \( t \) = specimen width and thickness respectively obtained after test.

Then \( r_n \) and \( \Delta r \) values were calculated using standard formulae as follows:

\[ r_n = \frac{(r_0 + 2r_{0.5} + r_0)}{4} \]  

\[ \Delta r = \frac{(r_0 + r_{0.5} - 2r_{0.5})}{2} \]

Where, the subscripts, 0, 45° and 90° are orientations to the RD of the steel strips.

The biaxial stretch formability was determined by conducting Erichsen cup test on 2 mm thick, 75 mm square specimens at ambient temperature (298°K), as per Indian standard IS 10175 (Part 1): 1993, by an electro-hydraulic drive Erichsen sheet metal testing machine (Model-140, drawing force 0–30 kN, sheet holding force 0–34 kN), assembled with die-punch arrangements (Fig. 1(a)). After completion of the test, height of the cup (Fig. 1(b)) was measured and expressed as Erichsen Index (IE).

2.3. Microstructure Examination

The specimens were prepared by grinding, polishing and etching with 2% NITAL solution and microstructure was examined by a Scanning Electron Microscope (SEM). The average grain size was determined on ×100 micrographs taken by an Inverted Camera type Optical Microscope (OM), as per IS 4748: 1988 (1989).

2.4. Multistage Cup Drawing

Cup drawing experiments were conducted by multistage (three stages) deep drawing with simultaneous ironing processes on high speed mechanical press machines, without using blank holders, considering relatively thicker blanks. First of all, 60 mm diameter circular blanks were cut from 14 mm thick heat treated steel strips by using blanking

| Table 1. Chemical composition of Al-killed AISI 1040 steel (in %wt.). |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Elements | C | Mn | Si | S | P | Ni | Cr | Mo | Al | Cu | Sn | As | Sb | Fe |
| wt% | 0.39 | 0.79 | 0.34 | 0.009 | 0.005 | 0.12 | 0.18 | 0.10 | 0.05 | 0.08 | 0.0059 | 0.0053 | 0.0018 | Bal. |

Note: H, O and N are 1.8, 18.4 and 82.3 ppm respectively; Bal. = balance quantity.
die-punch arrangements assembled (Fig. 2(a)) on a 500 Ton mechanical press machine. The decarburized layer on surfaces of the blanks was discarded by face turning up to 12 mm thickness. In order to eliminate the strain hardening effect due to blanking operation, the blanks were subjected to a stress relief annealing treatment by heating at 933–983 K for 4 hours, followed by furnace cooling up to 473 K, and then air cooling to room temperature. Then blanks were subjected to surface cleaning, phosphating and lubricating processes, before taking into the next deformation step. The surface cleaning was done by acid pickling bath (HCl: 6–7%, PH: 2–5) which removed oxide layers on the surface. By phosphating, a thick (5–10 μm) porous layer was provided on the component surface, which enhanced carrying ability of lubricant during the deformation process. Next, the component lubrication was done by immersing in soap solution (33% soap flakes) for ≥ 2 hours for a complete diffusion of the solution into pores of the pre-exist phosphate coating layer.

Because of these thicker (12 mm thick) circular flat blanks were difficult to draw directly into cup form, an additional stamping step was introduced for alteration of the blanks into a little draw-in shape along one side, called as preformed blanks. This pre-forming operation was done on a 250 Ton mechanical press, assembled with special designed die-punch arrangements (Fig. 2(b)). Thus produced preformed blanks were subjected to stress relief annealing, surface cleaning, phosphating, and lubrication, with a similar manner as illustrated for circular flat blanks.

The preformed blanks were then subjected to multistage cup drawing in three different stages with interstate stress relief annealing, surface cleaning, phosphating and lubricating by soap solution, similar to the earlier stated method. These draw operations were conducted on high speed mechanical press machines of capacities such as 500 Ton, 350 Ton, and 250 Ton in first, second and third draw steps respectively, which were assembled with draw die-punch arrangements, schematically shown in Figs. 3(a)–3(c). As per the draw die-punch geometries, the forming process was governed by deep drawing with simultaneous wall ironing technique in each draw step. In the first draw step, the preformed circular blanks were undergone to a sudden change in shape, i.e. from flat form to shallow cup. Then in the second and the third draw steps, there were reduction in cup diameter as well as wall thickness, which made cup length to increase in each step, attributed to long cylindrical cups.

Table 2 illustrates about process parameters which were used in three draw stages. Figures 2(c) and 2(d) exhibit the photo images of circular flat blank and preformed blank, respectively. Figures 3(d)–3(f) represent the photo images of actual cups drawn in first, second, and third draw step respectively.

The effects of cup drawing processes, such as dimensions as well as quality of cups, wall thickness distribution profiles, drawability and ironability parameters, empirically calculated punch force history, hardness distribution profiles, strain distribution profiles, and evolution of microstructures during such complex deformation processes, were determined and discussed. Also, spring back tendencies along the cup walls were determined by conducting a simple and repeatable Demeri split ring test, as described by Foecke and Herold; Danckert. For this, ring specimens (7 mm

![Fig. 1. (a) Schematic showing of Erichsen cup test arrangements; (b) photo images of Erichsen cup specimens.](image1)

![Fig. 2. Schematically showing of arrangements, (a) blanking, and (c) stamping; Photo images, (b) circular flat blank, and (d) preformed blank.](image2)
wide) cut from the cups at different heights and then were mechanically slitted longitudinally along their radial planes, schematically shown in Fig. 4. Thus, obtained gaps of split-ringed rings were evaluated by measuring differences between ring diameters, i.e. before and after splitting and expressed as the spring back tendency of the drawn cup walls.

3. Results and Discussions

3.1. Microstructure of Heat Treated Strips

Figures 5(a)–5(b) represent typical micrographs of the steel strips in heat treated condition, consist of uniformly distributed spheroidized cementites in a ferritic matrix. The processing conditions (i.e. more than 80% hot roll reduction, ~15% cold reduction, hardening by water quenching, and prolonged high temperature tempering treatments) are principally responsible for breaking of pearlite lamellae, dissolution of cementite lamellae, subsequent spheroidization and coarsening of cementites in the steel. The fully spheroidized (coarser) cementite particles (single arrow mark in Figs. 5(a)–5(b)) are observed with maximum numbers and a size range about 1–1.5 μm. These cementite particles are formed from fragments of the former lamellae located at a prior austenite grain boundary, wherein an accelerated diffusion along the boundary, leads to a faster coarsening of these cementite fragments.20) Few partially spheroidized cementites (double arrow mark in Figs. 5(a)–5(b)) with local lamella divisions, in the vicinity of ferrite sub boundaries are also observed. According to Storojeva

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**Table 2.** Equipments, tools and process parameters used in 3-stage cup drawing operations.

<table>
<thead>
<tr>
<th>(a) Equipments/tools</th>
<th>(b) Technical details/process parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Press machine</td>
<td>First draw: Capacity- 500 Tons, crank type mechanical press of single action, stroke length- 200 mm, and ram speed- 83 mm.s⁻¹. Second draw: Capacity- 350 Tons, crank type mechanical press of single action, stroke length- 610 mm, and ram speed- 183 mm.s⁻¹. Third draw: Capacity- 250 Tons, crank type mechanical press of single action, stroke length- 640 mm, and ram speed- 192 mm.s⁻¹.</td>
</tr>
<tr>
<td>B Draw die</td>
<td>Die Profile: schematically shown in Figs. 3(a), 3(b) and 3(c) for first, second and third draw stages respectively. Surface finish: grind finish with polished surface at the effective working zones. Die material: IS: T108/JIS: SK 3, 4 steel. Die hardness: 578–652 BHN on hardened and tempered condition.</td>
</tr>
<tr>
<td>C Cupping punch</td>
<td>Punch profile: schematically shown in Figs. 3(a), 3(b) and 3(c) for first, second and third draw stages respectively. Surface finish: grind finish with polished surface at the effective working zones. Punch material: IS: T108/JIS: SK 3, 4 steel. Punch hardness: 578–652 BHN on hardened and tempered condition.</td>
</tr>
<tr>
<td>D Stripper</td>
<td>First draw: 31.8 + 0.06 mm (min.) diameter. Second draw: 31.2 + 0.06 mm (min.) diameter. Third draw: 30.5 + 0.06 mm (min.) diameter. (Stripers are fitted at the exit end of draw dies, with peripheral spring tension for extraction of the drawn cups after each stage of drawing).</td>
</tr>
<tr>
<td>E Die-punch clearance</td>
<td>First draw: 6.00 + 0.10 mm. Second draw: 4.20 + 0.10 mm. Third draw: 3.80 + 0.10 mm.</td>
</tr>
<tr>
<td>F Lubricant</td>
<td>Water diluted soap flakes [33% Sodium oleostearate, technical (soap noodles) as per IS 10513-1983, Table 1, clauses 4.4, 8.1 and 8.3, type-1 and 67% H₂O].</td>
</tr>
</tbody>
</table>

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Fig. 3. Three stage cup drawing, (a–c) schematically showing of arrangements; (d–f) photo images of drawn cups.

Fig. 4. Schematically showing of split ring test schedule.
the interface adjacent to the sub boundary in the cementite lamella with a large local curvature and the surrounding ferrite provokes a quick carbon dissolution that leads to a local lamella division. Further, very few numbers of undesirable fine spheroidized cementite particles (about 0.1–0.2 μm) (circle mark in Figs. 5(a)–5(b)) are located at the areas of former pearlite colonies. Also, along the former pearlite lamellae, the ferrite boundaries with the cementite chains (square mark in Figs. 5(a)–5(b)) are seen. The average grain size is obtained as ASTM No. 7–8. Considering the microstructures and grain size, the steel is found favourable for good deep drawability with surface finish.

3.2. Mechanical Properties and Formability Characteristics

Table 3 describes mechanical properties and formability characteristics of Al-killed AISI 1040 steel strips in heat treated condition.

<table>
<thead>
<tr>
<th>Orientation w.r.t. RD (°)</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>YR (%)</th>
<th>UEI. 32 (%)</th>
<th>TEl. (%)</th>
<th>n-value</th>
<th>r-value</th>
<th>Hardness (VH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>390.14</td>
<td>651.84</td>
<td>59.85</td>
<td>22.2</td>
<td>40.97</td>
<td>0.437</td>
<td>1.11</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>374.4</td>
<td>629.8</td>
<td>59.45</td>
<td>23.98</td>
<td>38.9</td>
<td>0.418</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>354.83</td>
<td>624.44</td>
<td>56.82</td>
<td>22.57</td>
<td>33.77</td>
<td>0.399</td>
<td>1.27</td>
<td></td>
</tr>
<tr>
<td>Normal mean (Xₐ)</td>
<td>373.44</td>
<td>633.97 ≈ 634</td>
<td>58.89 ≈ 59 23.18 ≈ 23.2</td>
<td>38.13</td>
<td>0.418 ≈ 0.42</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planar mean (ΔX)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Xₐ = (X₀ + 2X₄⁵ + X₉₀)/4; ΔX = (X₀ − 2X₄⁵ + X₉₀)/2; UEI32, Uniform elongation in 32 mm; r-value measured at 16–17% of UEI.

3.3. Effects of Multistage Cup Drawing Process

3.3.1. Evolution of Cup Dimensions, Quality, and Wall Thickness Distribution Profiles

Table 4 summarizes the average dimensions of cups drawn in first; second; third draw stages respectively. It is found that cylindrical cups of size, ~56 mm length, ~36.85 mm diameter and ~3.8 mm wall thickness, could be drawn, which is significant. In Figs. 3(d)–3(f), photo images of cups, it is distinguished that the cups have been manufactured with free from common forming defects, like: wrinkling, earring, edge tearing, localized thinning and preferential thickening etc. Moreover, good surfaces finish is being witnessed on cup walls.

The stage wise wall thickness distribution profiles of cups are graphically represented in Figs. 6(a)–6(c), showing thickness variation in term of a divergence of ironing midpoint from the respective geometrical mean of measured dimensions. Thus degrees of deviations are observed as 0.04103 mm (+), 0.02577 mm (+) and 0.00632 mm (−) for the first, the second and the third draw stages respectively. This reducing trend of the divergences confirms to an increasing dimensional control on advancement of the draw steps, manifested by increasing predominance of wall ironing in the forming processes, agreed by Choi and Kim; Barros et al.; Aleksandrovic et al.; Moshksar and Kalvarzi. More importantly, the initial blank thickness under the region of flat bottom face of the draw punch remains almost unchanged throughout drawing stages, ana-
Table 4. Drawability and Ironability obtained in 3-stage cup drawing processes.

<table>
<thead>
<tr>
<th>Draw Stages</th>
<th>Punch Dia. (D₀)</th>
<th>Initial Dia. (D₀)</th>
<th>Finish Dia. (D)</th>
<th>Initial Thick. (t₀)</th>
<th>Finish Thick. (t)</th>
<th>Draw Ratio (β)</th>
<th>Drawing Reduction (D_red) %</th>
<th>Ironing Ratio (IR)</th>
<th>Ironing Reduction (I_red) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st draw</td>
<td>30.8 ±0.05</td>
<td>60.0 ±0.25</td>
<td>43.8 ±0.06</td>
<td>13.5 ±0.5</td>
<td>6.0 ±1</td>
<td>1.95</td>
<td>48.67</td>
<td>2.25</td>
<td>55.55</td>
</tr>
<tr>
<td>2nd draw</td>
<td>30.1 ±0.03</td>
<td>43.8 ±0.06</td>
<td>38.7 ±0.06</td>
<td>6.0 ±1</td>
<td>4.2 ±0.1</td>
<td>1.28</td>
<td>22.22</td>
<td>1.43</td>
<td>30.00</td>
</tr>
<tr>
<td>3rd draw</td>
<td>29.1 ±0.03</td>
<td>38.7 ±0.06</td>
<td>36.85 ±0.06</td>
<td>4.2 ±0.1</td>
<td>3.8 ±0.1</td>
<td>1.26</td>
<td>21.03</td>
<td>1.10</td>
<td>99.52</td>
</tr>
<tr>
<td>Overall Stages</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.06</td>
<td>51.50</td>
<td>3.55</td>
<td>71.85</td>
</tr>
</tbody>
</table>

Overall draw reduction (D_red) % = \(\frac{(D₀ - D_{red})}{D₀}\) × 100

Ironing ratio (IR) = \(\frac{T_{f1}}{T_i}\)

Ironing ratio (I_red) % = \(\frac{(T_{f1} - T_i)}{T_{f1}}\) × 100

3.3.2. Evolution of Drawability and Ironability Parameters

3.3.3. Punch Force History
\[ \kappa_{\text{cm}} = \frac{\kappa_{i0} + \kappa_{i1}}{2} \] .......................... (13)

Where, \( \kappa_{i0} \) = flow stress before forming (for \( \varphi = 0 \)) i.e. yield stress of the material, \( \kappa_{i1} \) = flow stress at the end of forming (for \( \varphi = \varphi_{\text{max}} \)) and its value was evaluated by using the equation of flow stress curve, i.e. \( \kappa_i = C \varphi^{n} \)\(^n\) where, \( \varphi = \) principal strain, \( C = \) strain hardening coefficient and \( n = \) strain hardening exponent.

The bend force, \( B \), was calculated by using the Eq. (14):

\[ B = [\kappa_{i,m} L t^2 / 2 (R_0 + 0.5 t)] \times \tan(\gamma / 2) \] .......................... (14)

Where, \( L \) = total length to bend i.e. perimeter (\( \pi D_0 \)) of the preformed blank = 189.12 mm, \( t \) = thickness of the preformed blank (13 mm, the average measured thickness at the zone under bending action), \( R_0 = \) bend radius i.e. die radius (R12), \( \gamma = \) bend angle i.e. 90° in the present investigation.

Draw punch forces in second and third draw stages were evaluated by Eq. (15), described by Boljanovic.\(^{26}\)

\[ P_i = \pi D_i t_i \times [1.1/[(\mu_\pi 2\alpha / 180)] \times (1.21 / 1.44) \times \kappa_{i,m}] \times \{1 + (\tan 2\alpha / \mu) \times [1 - (D_{i,m} / D_{i,(i-1)})^{2(\tan 2\alpha)}]\} \] .......................... (15)

Where, \( i \) = draw stage no., \( P_i \) = punch force in i-stage, \( D_{i,k} = \) punch diameter in i-stage, \( t_i = \) cup wall thickness in i-stage after drawing, \( D_{i,m} = \) mean dia. of cup after drawing in i-stage, \( D_{i,(i-1)} = \) mean dia. of cup after drawing in (i-1)-stage, \( \alpha = \) semi die angle in degree, \( \kappa_{i,m} = \) average flow stress of the material because of stress relieving treatment after drawing, \( \mu = \) interfacial friction coefficient, assumed as -0.16.\(^{26}\)

The ironing punch force in each draw step was evaluated by Eq. (16), described by Folle et al.\(^{28}\)

\[ F = \kappa_{i,m} A_{\phi} \varphi [1 + \mu / \alpha + 2\alpha / 3\varphi] \] .......................... (16)

Where, \( \kappa_{i,m} = \) mean flow stress in MPa (Eq. (13)), \( A_{\phi} = \) cross-sectional area of the cup after ironing in i-stage, \( \varphi_\phi = \) principal strain, \( \alpha = \) semi die angle in degree, \( \mu = \) interfacial friction coefficient, assumed as -0.16.\(^{26}\)

**Figure 7** depicts the punch forces, such as draw force and ironing force, with respect to draw stages. From the figure, both types of punch forces are seen decreasing on advance of draw steps. Also, the ironing force is found higher than that of the draw punch force in all draw stages, which indicates significance of the wall ironing in the forming processes.

3.3.4. Evolution of Hardness Distribution Profiles

The hardness of cups formed in first, second, and third draw stages were measured by a Vickers hardness tester at different points on cup surfaces. Thus, hardness distribution profile was plotted for each draw step with respect to the distance from the cup centre, shown in **Fig. 8**. In the figure, a sudden rise of the hardness is seen while it moves from the base to the cup wall (in all the draw stages), because of deformation took place at the wall zones only. The base portion of cups in every draw stage shows hardness that obtained in the inter-state stress relief annealing treatment, because the zone is subjected to nil deformation. The first stage cup shows higher hardness values than that of other two stages, because of the stage is associated with a sudden change in shape, i.e. from the circular blank to the cup form, causes for the severe metal deformation. Moreover, all three draw stages have exhibited uniformity in hardness distribution along the cup wall zones, which indirectly indicates the uniform metal deformation along the wall zones.

3.3.5. Evolution of Strain Distribution Profiles

The major (hoop), minor (radial), thickness, and effective strains on outer surface of the cup in each draw step were evaluated by following standard equations. The major (\( \varepsilon_{\text{maj}} \)) and thickness (\( \varepsilon_{\text{thk}} \)) strains were estimated by Eqs. (17) and (18) respectively,\(^{23}\) considering changes in dimensions before and after drawing of cups. The minor strain (\( \varepsilon_{\text{min}} \)) and the effective strain (\( \varepsilon_{\text{eff}} \)) were calculated by using volume constancy formula, Eq. (19), and slab method, Eq. (20), respectively.

\[ \varepsilon_{\text{maj}} = \ln (L / L_0) \] .......................... (17)

\[ \varepsilon_{\text{thk}} = \ln (t / t_0) \] .......................... (18)

\[ \varepsilon_{\text{min}} = -(\varepsilon_{\text{maj}} + \varepsilon_{\text{thk}}) \] .......................... (19)

\[ \varepsilon_{\text{eff}} = [2 / \sqrt{3 (\varepsilon_{\text{maj}}^2 + \varepsilon_{\text{min}}^2 + \varepsilon_{\text{thk}}^2)}]^{1/2} \] .......................... (20)

Where, \( L_0 = \) height of a point considered for the measurement, on component before drawing, \( L = \) height of the point on component after drawing, \( t_0 = \) thickness of a point con-
sidered for the measurement, on component before drawing, and \( t = \) thickness of the point on component after drawing.

Figures 9(a)–9(c) demonstrate strain distribution profiles on outer surfaces of cups in first, second, and third draw stage respectively. The distribution of inner surface strains, which have almost a same shape and magnitude as of the outer one, is not shown here for the simplicity of data presentation. The figures are self explanatory, showing trends and natures (tensile or compressive) of strains (\( \varepsilon_{\text{maj.}}, \varepsilon_{\text{thk.}}, \varepsilon_{\text{min.}}, \) and \( \varepsilon_{\text{eff.}} \)). Herein, strain curves suggest that the weaker zone of a cup (in a particular stage) exists at its shoulder portion, which is indicated by peaks of the minor and the thickness strains at this zone.

### 3.3.6. Evolution of Microstructures at Cup Walls

The specimens representing to cup walls (top edges, highly deformed zones) in all three draw stages, were cut and prepared by grinding, polishing, etching by 2\% NITAL and then characterized for microstructures by SEM.

Figures 10(a)–10(b); 10(c)–10(d); 10(e)–10(f) represent the micrographs of the cups in first, second and third draw respectively. In the cup drawing process, the frequent metal reduction/deformation, associated with high dislocation density, and also the repeated inter-stage stress relief annealing treatments, which have influenced the cup microstructures. In the micrographs, spheroidized cementite in ferrite matrix are observed, which are similar to the micrographs (Figs. 5(a)–5(b)) of the steel in heat treated condition, although size and distribution patterns of the micro constituents have altered with proceeding of draw steps ahead. In first and second draw steps, the cementite particles are observed with size about 1–1.25 \( \mu m \) and 0.75–1.25 \( \mu m \) respectively, and ferrite zones are seen deformed during the processes consisted with high compressive and tensile stresses. Even, few prolonged cementite particles (single arrow mark in Figs. 10(a)–10(b)) are yielded in particularly in first draw step, may be due to a larger metal reduction is involved in the step. In the micrograph (Figs. 10(e)–10(f)) of third/final draw step, refinement of the cementite particles are found increased by decreasing their size about 0.5–1 \( \mu m \). More importantly, the undesirable fine cementite particles (about 0.1–0.2 \( \mu m \), as discussed in Section 3.1, have been seen almost disappeared in the final draw step. Perhaps, the repeated deformation and stress reliving may have made these fine cementites to dissolve and some carbon atoms may have diffused from the areas of the former pearlite colonies to the cementite free areas of the ferrites followed by a subsequent reprecipitation and coarsening.\(^{20} \) As a result, these undesirable cementites are distributed rather homogeneously in the ferritic matrix (double arrow mark in Figs. 10(e)–10(f)), which is clearly distinguished in Figs. 10(e)–10(f). The grain refinement effect in the final draw component is also witnessed by obtaining an average grain size, ASTM No. 9–10. Moreover, the uniform distribution of spheroidal cementites in the matrix and also the refinement of grains, both are believed to enhance mechanical properties of the final parts.\(^{18} \) Further, non arousal of micro defects like, micro voids, fissures and cracks in the microstructures, confirm to a success of the experimental processes and also validate the reduction ratio (in each draw step) held within its safe limit.\(^{28} \)

### 3.3.7. Evolution of Spring Back Tendency along Cup Walls

Figure 11 shows the trends and degrees of spring back tendencies of cup walls (in first, second and third draw stages) with respect to cup heights. Herein, lines connected to data points indicate to an increasing propensity in spring back behaviours (split ring gaps) of cups in every draw stage, agreed by Foecke and Herold.\(^{19} \) Moreover, it is also observed that the degree of spring back tendencies reduces on advancement of draw steps, which perhaps due to decrease in residual hoop stresses on cup walls, caused by increasing predominance of wall ironing\(^{12} \) in second and third draw steps. Further, the trends of split ring gaps of cup walls (Fig. 11) are correlated with the strain distribution patterns (Fig. 9) and thickness distribution profiles (Fig. 6) of the corresponding draw stages, and thus found the following observations.
In Fig. 9, the peaks of the thickness strains are observed near base/bottom portion of the cups in three draw stages, which implies deformations farther beyond the yield stress, thus reducing the hoop stress, and also the magnitude of the through-thickness strain in-homogeneities (difference in plastic strain from one location to another) decreases, which, in turn, decreases the split ring gaps (Fig. 11). Again, the considerable vertical increase of the ring opening gaps of cups in three draw steps, are attributed to the corresponding gradual decrease of the thickness strains (Fig. 9) heading towards the open ends/mouth zones of the cups. Further, a close observation of the strain distribution profiles signifies the higher level of thickness/plastic strain, concentrated along the cup wall of the second draw than that of the third draw step, which entails comparatively lower split ring gaps in the stage. Besides that a higher ironing reduction, 30% (Table 4), might have reduced the residual hoop stresses in the cup of 2nd draw stage.

Considering the wall thickness distribution profiles of cups, Foecke and Herold have stated that a higher standard deviation of wall thickness along vertical position indicates an increased circumferential material flow and higher strain.
levels attribute to reducing spring-back as more material is deformed beyond the yield stress. In the present investigation, estimation shows the standard deviations of the cup wall thicknesses, such as 0.150821, 0.091756 and 0.079243 respectively for cups of first, second, and third draw stages. According to this, a good correlation is observed for the cups of second and third draw stages, wherein, the lower ring gaps are measured in the second draw stage than that of the third draw stage, attributed to the higher standard deviation in the stage. But this relation doesn’t stand true for the cup of first draw, which has shown the highest standard deviation of wall thickness distribution profile. On contrary, it displays the highest level of split ring gap at each location (Fig. 11), which is attributed to the application of severe bending and unbending to the blanks for a sudden shape change from flat to cup form. Also, an effect of preferred orientation\textsuperscript{19)} due to the higher draw reduction, 48.67% change from flat to cup form. Also, an effect of preferred orientation\textsuperscript{19)} due to the higher draw reduction, 48.67% change from flat to cup form.

Moreover, these spring back data of the cups have significance, particularly in improvement in die-punch design for maintaining cup dimensions in close tolerances.

4. Conclusions

In this work, cylindrical cup manufacturing feasibility was experimentally examined on 12 mm thick, 60 mm diameter circular blanks of heat treated Al-killed AISI 1 040 graded medium carbon steel rolled strips, by using a modified processing route consisted of pre-forming of blanks followed by three-stage deep drawing accompanied with wall ironing process. Thus, evolution of various processing effects were studied and discussed. The conclusions of the work may be summarized as follows:

\begin{itemize}
  \item By application of a typical heat treatment cycle, \textit{i.e.} hardening by water quenching followed by prolonged high temperature tempering, the steel showed a microstructure consisting of uniformly distributed spheroidized cementites in ferrite matrix with an average grain size ASTM No. 7–8. This structure entailed to the steel of a good combination of strength-ductility-formability, which indicated its moderate drawability with high strength applications up to \textasciitilde634 MPa.
  \item An alternative method, \textit{i.e.} pre-forming of blanks followed by multistage deep drawing accompanied with wall ironing, was experimentally confirmed as a feasible processing route for manufacturing of cylindrical cups (\textasciitilde50 mm long) from thicker blanks (\textasciitilde12 mm thickness). Also, the multistage deep drawing with simultaneous ironing process was proved as successfully addressed the forming difficulties associated with the investigated medium carbon steel.
  \item The success of the cup manufacturing process with respect to the steel and the blank thickness, was evidenced by, \textit{i)} showing good surface finish on cup walls; \textit{ii)} revealing no micro defects; \textit{iii)} manifesting grain refinement in the forming processes as an additional beneficial condition for the final components.
  \item The evolution of different processing effects such as cup wall thickness distribution profiles; drawability and ironability parameters; punch force history; cup hardness distribution profiles; strain distribution profiles; microstructures of cup wall zones; and also spring back tendency of cups were shown as potential real time data bank, which could serve the process engineers for further improvement of the process and tools.
\end{itemize}

- The overall experimental results recommend that with a proper selection of heat treatment cycle and processing method, AISI 1 040 graded medium carbon steel can be used as an alternative high strength grade in cylindrical cup manufacturing, even from a thick circular blank.

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