Multistage cup drawing of AISI 1040 graded medium carbon steel

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In this paper a new modified processing route, as an innovative approach, has been proposed for producing cylindrical cups from thicker circular blanks, like 12 mm thick and 60 mm diameter. Rolled strips of aluminium (Al)-killed AISI 1040 graded medium carbon steel in hardened and tempered condition was used as an alternative high strength material. The processing route mainly consisted of pre-forming of flat blanks to a little draw in shape, followed by multistage deep drawing accompanied with wall ironing held without blank-holders and with inter-stage stress relief annealing. Thus, evolution of different processing effects such as cup dimension and cup quality, wall thickness distribution profiles, drawability and ironability parameters, strain distribution profiles, spring back tendency of cups in terms of residual hoop stress distributions, and microstructures at cup wall zones, were obtained and discussed.

Keywords: Medium carbon steel, Multistage deep drawing with ironing, Thicker blank, Cylindrical cup

In general, low carbon steels are widely used in cup drawing due to their inherent high formability. Low carbon contents make these steels not to receive heat treatments, resulting low intrinsic mechanical properties, limiting their usage and requesting the application of medium and high carbon steels\textsuperscript{1}. Medium carbon steels with carbon content, 0.30\% to 0.60\%, are mostly used in general engineering applications. The heat-treatability makes these steels applicable with moderate strength and toughness. Inherent low formability is the main limitation of these steels. In these steels pearlite lamellar morphology imparts undesirable cold working mechanical properties, whereas globular cementites in ferrite matrix improves cold workability\textsuperscript{2}.

Metallic cups are mostly used in automobile, can making and defence industries. These cups are manufactured by deep drawing method which needs to maximize the mean normal anisotropy ($r_m$) and minimize the planar anisotropy ($\Delta r$) values of the material. Multistage deep drawing technique is applied for forming of long cylindrical cups and the process is found suitable for a sheet metal with low drawing ratio. Sometimes, wall ironing process combining with deep drawing is applied in single or multi steps to produce cups with greater height-to-diameter ratio, reduced uniform wall thickness\textsuperscript{3-6} and also to optimise the process time\textsuperscript{7}. In metal forming, the ironing is not affected by $r_m$-value of the sheet metal, rather reduces earring effect of cups\textsuperscript{2}. Moreover, it reduces residual stresses which are favourably distributed along the cup wall with regard to fatigue and stress corrosion\textsuperscript{8}.

In this study, aluminium-killed AISI 1040 graded medium carbon steel strips were selected for cup drawing experiment. A suitable microstructure was developed in the steel by applying a typical heat treatment, i.e., hardening by water quenching and then followed by prolonged tempering at a higher temperature. Thus, a good strength-ductility-formability combination was obtained for enhancing drawability. Further, unlike conventional sheet metal work, thicker circular blanks (12 mm thick, 60 mm diameter) were used for producing long cylindrical cups by a modified processing route consisted of pre-forming of blanks followed by multistage stage drawing without blank-holders. By using suitable die-punch designs, simultaneous wall ironing process was advantageously accompanied with deep drawing in order to address forming difficulties\textsuperscript{5} associated with medium carbon steels. Thus, stage-wise evolution of different processing effects was determined as main objectives of the work.

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To the best of authors’ knowledge, the study on cup drawing from a thicker blank (12 mm thickness), particularly of medium carbon steel, is less attended. It is therefore tried to create a real time data bank for filling up the knowledge gap.

Experimental Procedure

Material
The chemical composition of the as received vacuum treated Al-killed AISI 1040 graded medium carbon steel is given in Table 1. The basic input material in form of 15% cold reduced 14 mm thick strips of 78 mm wide were used for cup drawing, after subjected to a heat treatment cycle consisted of hardening (heating at 923 K for 4 h - further heating to 1133 K with 1 h soaking - water quenching) followed by a prolonged tempering (heating at 923 K for 36 h, followed by furnace cooling to 472 K and air cooling to the room temperature, 298 K).

Material properties
The specimens represented the steel strips in heat treated condition were characterized for obtaining basic material properties such as microstructure, hardness, tensile, uniaxial formability characteristics, biaxial strechability and formability limit curve (FLC).

Microstructure
Figure 1 shows the typical micrograph of the steel that presents spheroidized cementites within ferritic matrix, indicates of good cold workability. The average grain size is determined as ASTM No. 7-8, which is suitable for good surface finish in deep drawing.

Tensile properties
Table 2 summarizes the tensile properties of the steel along 0°, 45°, and 90° to the rolling direction and also their mean values. The mean tensile strength, ~634 MPa, total elongation, ~38 %, and uniform elongation, ~23%, indicates a good combination of strength and ductility.

Formability characteristics
Table 2 also shows values of conventional formability indicators such as strain hardening exponent (n), normal anisotropy (r_n), and planar anisotropy (Δr) values. The high n -value, 0.42, signifies to uniform strain dispersibility and high strechability in deformation process. The r_n -value, 1.1 (>1) and a low Δr -value, 0.18, indicate moderate deep drawability of the steel. Further, Ericshen index, IE-value, 11.95, confirms to a high drawability.

Table 1 — Chemical com position of Al-killed AISI 1040 graded steel (%wt)

<table>
<thead>
<tr>
<th>Elements</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Al</th>
<th>Cu</th>
<th>Sn</th>
<th>As</th>
<th>Sb</th>
<th>Fe</th>
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<tr>
<td>wt%</td>
<td>0.39</td>
<td>0.79</td>
<td>0.34</td>
<td>0.009</td>
<td>0.005</td>
<td>0.12</td>
<td>0.18</td>
<td>0.05</td>
<td>0.08</td>
<td>0.0059</td>
<td>0.0053</td>
<td>0.0018</td>
<td>Bal.</td>
<td></td>
</tr>
</tbody>
</table>

Note: H, O, and N are 1.8, 18.4, and 82.3 ppm, respectively. Bal. = Balance

Table 2 — Mechanical properties of the 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>UEl.32 (%)</th>
<th>TEl. (%)</th>
<th>n  -value</th>
<th>r  -value</th>
<th>IE-value</th>
<th>Hardness (BHN)</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>11.95</td>
<td>202</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>11.95</td>
<td>202</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>11.95</td>
<td>202</td>
</tr>
<tr>
<td>Normal mean</td>
<td>373.44</td>
<td>633.97</td>
<td>58.89</td>
<td>23.18</td>
<td>38.13</td>
<td>0.418</td>
<td>1.1</td>
<td>11.95</td>
<td>202</td>
</tr>
<tr>
<td>(X_m)</td>
<td>≈ 634</td>
<td>≈ 59</td>
<td>≈ 23.2</td>
<td>0.42</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planar mean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.18</td>
</tr>
</tbody>
</table>

Note: X_m = (X_0 + 2X_45 +X_90)/ 4; ΔX = (X_0 - 2X_45 +X_90) / 2; UEl.32, uniform elongation (true) in 32 mm gauge length; r -value measured at 16-17% of UEl.; IE = Ericshen index at 2 mm thick samples.
biaxial strechability, attributed to the high \( n \) value with the increased total elongation value\(^{10,12}\).

Figure 2f represents the true formability limit curve (FLC) of the steel, which were experimentally obtained by Ericshen cup tests equivalent to Nakajima method, conducted on 2 mm thick samples of various widths (Figs 2a-2e), by help of 20 mm diameter ball punch. Thus true FLC\(_0\), 33.451%, is obtained, which is significant.

**Cylindrical cup manufacturing**

A series of cup drawing experiments were conducted by multistage (three stages) deep drawing with simultaneous ironing process on high speed mechanical press machines, without using blank-holder considering relatively thicker blanks\(^{13}\). The sequence of processing steps those were followed in the experimental work such as: blanking of strips to obtain circular flat blanks - facing of blanks at both sides - stress relief annealing, surface treatment and lubrication - stamping of blanks to obtain a performed shape - stress relief annealing, surface treatment and lubrication - first stage of cup drawing - stress relief annealing, surface treatment and lubrication - second stage of cup drawing - stress relief annealing, surface treatment and lubrication - third stage of cup drawing - stress relief annealing.

The circular steel blanks, 60 mm diameter, were cut from 14 mm thick heat treated strips by blanking operation on a 500 Ton high speed mechanical press assembled with blanking die-punch, as schematically shown in Fig. 3a. Blanks thus produced (Fig. 3b) were...
undergone surface machining (facing) at both sides up to 12 mm thick, in order to discard decarburized surface layer that generated during heat treatment of the strips. These 12 mm thick, 60 mm diameter circular flat blanks couldn’t be taken directly into cup drawing operation, because of associated with a low diameter to thickness ratio. Hence by introducing an additional forming step, i.e., stamping operation, which was held on a 250 Ton mechanical press assembled with suitable die-punch arrangements, as schematically shown in Fig. 3c, and thus flat shape of the circular blank was modified to a little draw-in form with concave radius, \( R_{13} \) (Fig. 3c), called as preformed blanks (Fig. 3d). From these preformed blanks, long cylindrical cups were produced in three draw stages, consisted of deep drawing with simultaneous wall ironing processes in each step. In first draw stage, cups with smaller height were formed on a 500 Ton high speed mechanical press assembled with a suitable die-punch set, as shown in Fig. 4a. Then in second and third draw stages, cup’s height was increased with simultaneous reduction in its diameter and wall thickness. The second and the third draw stages were performed on high speed mechanical press machines of 350 Ton and 250 Ton capacities respectively with suitable die-punch arrangements, as schematically shown in Figs. 4b and 4c. Figures 4d-4f show photo images of cups had drawn in first second and third draw stages respectively. More importantly, all the process parameters which were followed in cup drawing experiments are given in Table 3.

In order to remove strain hardening effect\(^{14}\), components after each forming step were subjected to a stress relief annealing treatment by heating at 933-983 K for 4 h followed by furnace cooling up to 473 K and then air cooling to room temperature, 298 K. For achieving an effective lubrication during high speed cold forming processes, as suggested by Tschaetsch\(^{15}\), prior to each forming step (after stress relief annealing cycle) components were undergone to a typical surface treatment consisted of acid pickling (HCl: 6-7%, PH: 2-5) to clean oxide coating; applying phosphate coating with 5-10 \( \mu \)m thick porous layer to ensure a good lubricant carrying ability during deformation processes; lubricating by immersing in soap solution (33% soap flakes) for approximately 2 h to make sure of a complete diffusion of the solution into pores of the phosphate coat layer.

The evolution of various processing effects of the multistage cup drawing steps was determined to represent the actual press formability of the steel. Cup dimensions were measured by digital micrometers after sectioning them at middle. By a visual observation, the drawn cup quality was judged in each draw stage. The drawability and ironability parameters such as drawing and ironing ratios; drawing and ironing reduction values; drawing and ironing efficiencies were

![Fig. 4 — (a-c) schematic arrangements of three stage cup drawing operations, and (d-f) photo images of drawn cups](image-url)
evaluated by using standard formulae obtained from literature\textsuperscript{15-17}. The wall thickness profile in each draw stage was drawn by measuring critical wall thickness of cups at different points with respect to the respective cup height. The strain distribution profile along outer cup wall was determined by evaluating major ($\varepsilon_{mj}$), minor ($\varepsilon_{mn}$), thickness ($\varepsilon_{thk}$) and effective strains ($\varepsilon_{eff}$) of cup walls with respect to the earlier stage dimensions of cups and using Eqs (1)-(4)$^{16}$.

\[
\varepsilon_{mj} = \ln(L/L_0) \quad \cdots (1)
\]
\[
\varepsilon_{thk} = \ln(t/t_0) \quad \cdots (2)
\]

Then by using volume constancy principle:
\[
\varepsilon_{mn} = -\left(\varepsilon_{mj} + \varepsilon_{thk}\right) \quad \cdots (3)
\]

Using slab method:
\[
\varepsilon_{eff} = \left\{\frac{2}{3} \left(\varepsilon_{mj}^2 + \varepsilon_{mn}^2 + \varepsilon_{thk}^2\right)\right\}^{0.5} \quad \cdots (4)
\]

where, $L_0$ is height of a point considered for the measurement, on component before drawing, $L$ is height of the point on component, after drawing, $t_0$ is thickness of a point considered for the measurement, on component before drawing and $t$ is thickness of the point on component, after drawing.

The residual hoop stress profiles along outer cup walls were also estimated by conducting a Demeri split ring test, according to Danckert$^8$. In this test, ring specimens (7 mm wide) were cut from drawn cups at various heights and then were splitted longitudinally along radial planes by a mechanical method. By measuring diameters of rings before and after splitting and using Eq. (5)$^8$, the residual hoop stress for each ring specimen was evaluated and then graphically represented.

\[
\sigma_{Hoop-max.} = \left[\frac{E}{s} \cdot (\rho R_c - \rho R_o)\right]/2 \quad \cdots (5)
\]

where, $\sigma_{Hoop-max.}$ is change of maximum residual hoop stress (compressive) on outside of the ring (MPa), $E$ is Young’s modulus, i.e., 200000 MPa, assumed for the present steel, $\rho R_c$ is curvature of the ring before slitting; $\rho R_o$ is curvature of the ring after slitting; and $s$ is thickness (mm) of the ring.

The evolution of microstructures at drawn cup wall zone (top edges as of highly deformed zones) in each
draw stage were characterised for specimens, i.e., cut and prepared by grinding, polishing, etching by 2% NITAL.

Results and Discussion

Evolution of cup dimensions and quality

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 4d-4f, 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 surface finish is being witnessed on cup walls.

Evolution of drawability and ironability

Table 4 presents the stage-wise variation of draw ratio ($\beta$) and ironing ratio ($IR$), showing their maximum values in the first draw stage and a decreasing trend in subsequent stages. It also shows the stage-wise draw reduction ($r_d$) and ironing reduction ($r_i$) values, demonstrating a similar trend that was obtained for ratios. For the overall draw steps, overall draw ratio ($\beta_O$), overall draw reduction ($r_{d-O}$), overall ironing ratio ($IR_O$) and overall ironing reduction ($r_{i-O}$), were evaluated as 2.06, 51.5%, 3.55 and 71.85% respectively. A comparison with literatures shows that both $\beta_O$ and $r_{d-O}$ are lower than the overall draw ratio value, 2.2, reported by Tajally et al.\textsuperscript{18} and overall draw reduction value 70.7%, revealed by Jawad\textsuperscript{16}. But at the same time, $IR_O$ and $r_{i-O}$ are found higher than that of values 2.5-3.3 and 60-70% respectively, shown by Shi and Gerdeen\textsuperscript{17}. Thus it implies that the steel can successfully be drawn with moderate drawability under high ironability conditions.

Evolution of wall thickness distribution

The stage-wise wall thickness distribution profiles of cups are graphically represented in Fig. 5, showing thickness variation in term of a divergence of ironing mid-point 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\textsuperscript{3}; Barros \textit{et al.}\textsuperscript{4}; Aleksandrovic \textit{et al.}\textsuperscript{5}; Moshksar and Kalvarzi\textsuperscript{6}. More importantly, the initial blank thickness under the region of flat bottom face of the draw punch remains almost unchanged throughout drawing stages, analogous to the finding of Jawad\textsuperscript{16}.

Evolution of strain distribution profiles

Figure 6 demonstrates the strain distribution profiles of cups on outer surfaced in three draw stages. The distribution of inner surface strains, which has almost the same shape and magnitude as the outer one, is not shown here for the simplicity of data presentation. The figure is self explanatory, showing trend and nature (tensile or compressive) of different

<table>
<thead>
<tr>
<th>Draw stage</th>
<th>Punch and cup size (mm)</th>
<th>Deep drawability</th>
<th>Ironability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Punch dia. ($D_P$)</td>
<td>Initial dia. ($D_0$)</td>
<td>Finish dia. ($D$)</td>
</tr>
<tr>
<td>1st draw</td>
<td>30.8 $^{+0.05}$</td>
<td>60 $^{+0.25}$</td>
<td>43 $^{+0.06}$</td>
</tr>
<tr>
<td>2nd draw</td>
<td>30.1 $^{+0.05}$</td>
<td>43 $^{+0.06}$</td>
<td>38.7 $^{+0.06}$</td>
</tr>
<tr>
<td>3rd draw</td>
<td>29.1 $^{+0.05}$</td>
<td>38.7 $^{+0.06}$</td>
<td>36.85 $^{+0.06}$</td>
</tr>
<tr>
<td>Overall stages</td>
<td>51.50</td>
<td>51.50</td>
<td>3.55</td>
</tr>
</tbody>
</table>

Fig. 5 — Wall thickness distribution profiles of cups in 1\textsuperscript{st} draw, 2\textsuperscript{nd} draw, and 3\textsuperscript{rd} draw stages
strains ($\varepsilon_{mj}$, $\varepsilon_{thk}$, $\varepsilon_{mn}$, and $\varepsilon_{eff}$) evolved during deformation in three draw stages. 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.

Evolution of residual hoop stress distribution along cup walls

Figure 7 displays the stage-wise trends and degrees of residual hoop stresses on cup walls, representing their spring back intensity. Herein, linear regression lines indicate to an increasing propensity of stresses in each draw stage. From the figure, a decreasing trend of these stresses is also observed on advancement of draw steps. The reduction of stresses in the second and the final draw stages may be due to predominance of wall ironing in these steps. These data have significance in improvement in die-punch design for a low deviation in cup dimensions.

Evolution of microstructures along cup wall zones

Figures 8a-8c show the typical micrographs (SEM) on cup walls after undergoing deformation in the first, the second and the final draw stages respectively, wherein no appreciable microstructural alteration was observed. The analysis also substantiates to nonexistence of any micro defect aroused by cup drawing, which confirms the success of deformation processes. Further by contrasting with the microstructure of the steel after heat treatment (Fig. 1), the grain refining effect is observed due to cupping processes, which is agreed by Suresh et al., who has found an similar effect in single-point incremental forming process applied for extra deep drawing steel. The grain size of cup after final draw is determined as ASTM No.9-10, indicating an enhancement of mechanical properties.

Comparison between modified and conventional cup drawing methods

In comparison to the conventional methods, three modified processes have been proposed in the present work. The steel was subjected to hardening and prolonged tempering instead of the conventional approach of annealing treatment. This modified approach has yielded a good combination of strength-ductility-formability properties with average grain size.
size ASTM No. 7-8, suitable for good surface finish in deep drawing. The second modification, i.e., by introducing pre-forming operation, the long cylindrical cups could be drawn from thicker blanks, which were associated with a low diameter to thickness ratio. Further, by incorporating wall ironing process accompanied with deep drawing, AISI 1040 graded medium carbon steel (with inherent low formability) could be drawn into cup form to a considerable length.

Conclusions

In this paper, cylindrical cup manufacturing process feasibility was studied for 12 mm thick, 60 mm diameter circular blank of Al-killed AISI 1040 graded medium carbon steel was studied and thus evolution of various processing effects were discussed. The conclusions of the study may be summarized as follows:

(i) Water quenched and tempered (at 923 K for 36 h) Al-killed AISI 1040 steel strips had yielded uniformly distributed spheroidized cementite within an equiaxed ferrite matrix with an average grain size ASTM No. 7-8. This as a whole entailed a good combination of strength-ductility-formability, which indicated that the steel could find cup drawing applications with moderate drawability and a maximum strength up to ~634 MPa.

(ii) Pre-forming of blanks followed by multistage deep drawing accompanied with wall ironing processes were found as feasible solutions for manufacturing cylindrical cups (~50 mm long) from thicker blanks (~12 mm thickness) and also to address the forming difficulties associated with AISI 1040 graded medium carbon steel, which could be advantageously used in high strength applications in automobile, defence, and other deep drawing industries.

(iii) The success of interaction between the material, processes and tools, was evidenced by, showing good surface finish on cup walls; revealing no micro defect; and manifesting grain refinement as an additional advantage.

(iv) The cup wall thickness distribution profiles, strain and residual stress distribution profiles were also obtained as potential real time data bank, which could be used for further improvement in the process and tools.

Acknowledgements

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