

12 mm Thick Circular Blanks of Al-killed AISI 1020 Steel -Applied for Cylindrical Cup Manufacturing by Multistage Deep Drawing with Simultaneous Ironing

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In this paper a new modified processing route has been proposed for producing long cylindrical cups from 12 mm thick circular blanks of AISI 1020 steel (Aluminium (Al) -killed). In this route, flat blanks were made to preformed shape by stamping operation, followed by multistage deep drawing processes (without blank-holder and with inter-stage stress relief annealing) to increase cup depth. Wall ironing was also purposefully included in each draw step to reduce wall thickness and earing tendency on cup edges. Thus, evolution of wall thickness distribution, Drawability and Ironability, punch force history, and strain distribution profiles on outer cup surfaces were obtained as the effects of interaction between processes, tools and material. The overall draw stages showed: LDR 2.06; overall draw reduction >50% with a drawing efficiency ~72%; LIR 3.55; overall ironing reduction >70% with an ironing efficiency ~68%, which were achieved in the experimental works.

Keywords: Al-killed AISI1020 steel, formability, cylindrical cup, multistage deep drawing, wall ironing

1. Introduction

Sheet metal forming is one of the most widely used manufacturing processes for the fabrication of a wide range of products in many industries. Deep drawing is one of the extensively used sheet metal forming processes in the industries to have mass production of cup shaped components in a very short time. In deep drawing, a flat blank of sheet metal is shaped by the action of a punch forcing the metal into a die cavity. Products include hundreds of components produced in automobile, aviation, submarine, railway, defence and other manufacturing industries.

In cup drawing, the selection of a blank thickness is carried out based on the size of a cup is to be maintained. In general, 0.4 to 5 mm thick blanks are used in the practice. A cup with higher diameter, thickness and depth requires of a thicker blank is to be drawn. In order to maintain the relative thickness, it needs to cut a blank of larger diameter that associated with processing difficulties like, needs of larger die – punches, increased draw forces demands a greater press stroke, requires more numbers of draw steps to accommodate draw ratio and arousal of various forming defects etc. On contrary, increase in blank thickness raises the level of formability limit diagram (*FLD*)¹⁻³, enhances limit draw ratio (*LDR*) value^{2, 4}, reduces tendency of wrinkling^{2, 5} and earing effects on cups⁶, which can

be advantageously manoeuvred for manufacturing of long cylindrical cups. According to Saleh and Ali⁵ and Suchy⁷, often a cup drawing from thicker blanks with relative thickness (thickness to diameter ratio) more than 2% does not need a blank-holder, as the thickness prevents the blanks from collapsing under the tangential pressure.

Multistage deep drawing technique is applied for sheet metals with low drawing ratio and also for increasing the cup depth. Sometimes wall ironing is purposefully accompanied with deep drawing for achieving cups with greater height-to-diameter ratio, reduced uniform wall thickness⁸⁻¹¹ and optimisation in process time¹². According to Saleh and Ali⁵, drawing with ironing also helps in increasing the *LDR* value. Moreover, the metal forming due to ironing is not affected by normal plastic anisotropy (r_m) value, rather it reduces earing effect¹. Further, the ironing reduces residual stress which is favourably distributed along the cup wall with regard to fatigue and stress corrosion¹³.

In this present study, Aluminum-killed AISI 1020 graded low carbon steel was selected. Unlike conventional sheet metal treatment, i.e. annealing, 15% cold reduced strips were undergone a typical heat treatment cycle, i.e. hardening with water quenching followed by prolonged tempering at a higher temperature (953°K for 30 hours), for developing microstructures to yield a good strength-ductility-formability combination in the steel. Further, unlike conventional sheet metal work,

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a thicker blank, *i.e.* 12 mm thick - 60 mm diameter circular blanks were used for producing long cylindrical cups by a modified processing route consisted with pre-forming of blanks followed by multistage deep drawing without blank-holder. By using suitable die-punch designs, simultaneous wall ironing process was advantageously accompanied with deep drawing in each draw step. Thus, stage wise evolution of wall thickness distribution profiles; drawability and Ironability parameters; punch force history; strain distribution profiles of cups were determined.

To the best of authors' knowledge, the study on cup drawing from a thicker blank (12mm thickness) of low carbon steel, particularly by pre-forming of blanks followed by multistage drawing with simultaneous ironing and without using blank-holders is less attended, rather found almost nonexistent. It is therefore tried to create a real time data bank for filling up the knowledge gap.

2. Material and Methods

2.1. Material

The chemical composition of the as received vacuum treated Al-killed AISI 1020 graded steel is reported in Table 1. The steel was forged to billets 95 mm round corner square - hot rolled to strips of 16.5 mm thickness, 78 mm wide - cold rolled to 14 mm thickness. Then the strips were heat treated by a cycle consisted of hardening (preheating at 923°K for 4 hours - further heating to 1173°K for 1 hour soaking - water quenching to ambient temperature, 298°K) followed by a prolonged tempering at 953°K for 30 hours, then furnace cooling up to 472°K and air cooling to the ambient temperature, 298°K). These heat treated strips are used as input material for manufacturing of cups in different steps which are explained in later stages.

2.2. Material properties characterization

The basic inherent material properties of the steel were characterised by different standard tests on a laboratory scale and thus its microstructure, hardness, tensile properties, formability characteristics, biaxial stretchability in terms of Erichsen index (*IE*) value were determined.

In order to find evolution of microstructures during processing stages like, hot rolling and heat treatment, representative specimens of the steel were prepared by grinding, polishing and 2% nital etching

and then characterized by an Inverted Camera Optical Microscope (OM), Make -Olympus, Model -GX-71. The average grain size of the specimens were also determined from micrographs of x100 magnification, as per Indian standard IS 4748:1993¹⁴.

The mechanical properties were examined on samples collected from the steel in heat treated condition. Hardness was measured by using a Brinell hardness tester, as per Indian Standard IS 1500: 2005¹⁵. Tensile properties were determined by conducting uniaxial tensile pulling tests up to fracture on flat specimens (5 mm thickness, 6.5 mm width and 32 mm gauge length) along 0° (longitudinal), 45° (diagonal), and 90° (transverse) to the rolling direction (RD). These tests were carried out at ambient temperature (298°K) on 20kN Tensometer (Make -KIL, Model -PC 2000), at a strain rate, $2.5 \times 10^{-4} \text{ s}^{-1}$, according to Indian Standard IS 1608:2005¹⁶. Thus, true values of tensile properties such as: yield strength (*YS*), tensile strength (*UTS*), 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 true stress-strain flow curves (shown in Figure 1). The plastic strain ratios (*r*), known as conventional formability indicators, were evaluated from tensile tests at an elongation 16-17% of *UEL* and using Eq.1, as per Indian Standard IS 11999:2007¹⁷.

$$r = \epsilon_w / \epsilon_t = \ln(w_0/w) / \ln(t_0/t) \quad (1)$$

$$r_m = (r_0 + 2r_{45} + r_{90}) / 4 \quad (2)$$

$$\Delta r = (r_0 - 2r_{45} + r_{90}) / 2 \quad (3)$$

Where, r_m = normal plastic strain ratio, Δr = planar plastic strain ratio, ϵ_w and ϵ_t = true strain along width and thickness respectively; w_0 and t_0 = specimen width and thickness before test respectively; w and t = specimen width and thickness after test respectively.

The biaxial stretchability of the steel was determined by conducting Erichsen cup test (electro-hydraulic drive Erichsen make sheet metal testing machine, Model -140, drawing force 0-30 kN, sheet holding force 0-34 kN, assembled with tooling arrangements shown in Figure 2a) on 2 mm thick, 75 mm square specimens at ambient temperature, 298°K, according to Indian standard IS 10175(Part 1): 1993¹⁸. These specimens were cut from 14 mm thick strips by using CNC Wire-cut EDM machine followed by grind finish,

Table 1: Chemical composition of the steel (in %wt.).

| Elements | C | Mn | Si | S | P | Ni | Cr | Al | Cu | Sn | As | Sb | Fe |
|----------|------|------|------|-------|-------|------|------|------|------|--------|--------|--------|------|
| wt% | 0.19 | 0.51 | 0.11 | 0.016 | 0.013 | 0.05 | 0.12 | 0.06 | 0.06 | 0.0022 | 0.0034 | 0.0023 | Bal. |

Note: H, O and N are 1.67, 19.4 and 82.35 ppm respectively; Bal. = balance quantity.

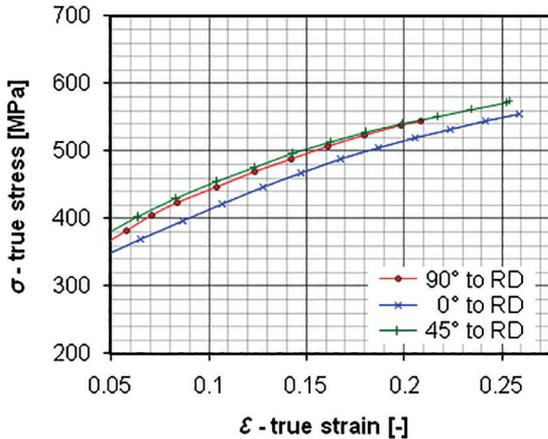


Figure 1: True tensile stress-strain flow curves along 0°, 45°, and 90° to RD.

wherein proper precautions were taken to maintain inherent material properties in an intact condition. After completion of the test, cup height (Figure 2b) was measured and expressed as Erichsen Index (*IE*).

2.3. 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 blanks⁵. 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 preformed 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 tools, schematically shown in Figure 3a. Blanks thus produced (Figure 3c) were undergone surface machining (facing) at both sides up to 12 mm thick, in order to discard the decarburized surface layer generated during the heat treatment. These 12 mm thick, 60 mm diameter circular flat blanks were associated with a low diameter to thickness ratio, resulted to unsuitability for cup drawing directly from them. 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, schematically shown in Figure 3b, and thus flat shape of the circular blank was modified to a little draw-in form (Figure 3b) with concave radius, *R*13, called as preformed blanks (Figure 3d). Then by using these blanks, long cylindrical cups were formed in three draw stages, consisted of deep drawing with simultaneous wall ironing processes. In first draw stage, cups with smaller height were formed on a 500 Ton high speed mechanical press machine, assembled with a suitable die-punch set, shown in Figure 4a. Then in second and third draw stages, cup's height was increased with a simultaneous decrease in its diameter and wall thickness. The second and the third stage cup drawing were performed on high speed mechanical press machines of 350 Ton and 250 Ton capacities respectively with suitable die-punch arrangements, schematically shown in Figures 4b-c, respectively. More importantly, all the process parameters which were followed in cup drawing experiments are illustrated in Table 2.

In order to remove strain hardening effect^{7, 19}, components after each forming step were subjected to a stress relief annealing treatment by heating at 923-933°K for 4 hours 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 explained here, as suggested by BlueScope Technical Bulletin²⁰ and Tschaetsch²¹, 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 μm 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 hours to make sure of a complete diffusion of the solution into pores of the phosphate coat layer.

3. Results and Discussion

3.1. Material properties

Figures 5a-b show the typical micrographs (OM) of as-received hot rolled steel strips, which presented a microstructure, composed of pearlite-ferrite with an average grain size, ASTM No. 5-6. Figures 5c-d present the typical micrographs of the steel after heat treatment, which presented a microstructure composed of uniformly distributed globular cementite in a ferritic matrix. The average grain size was determined as ASTM No. 7-8. In this case, the hardening by water quenching is responsible for refinement of grains to a favourable range³ for good deep drawability,

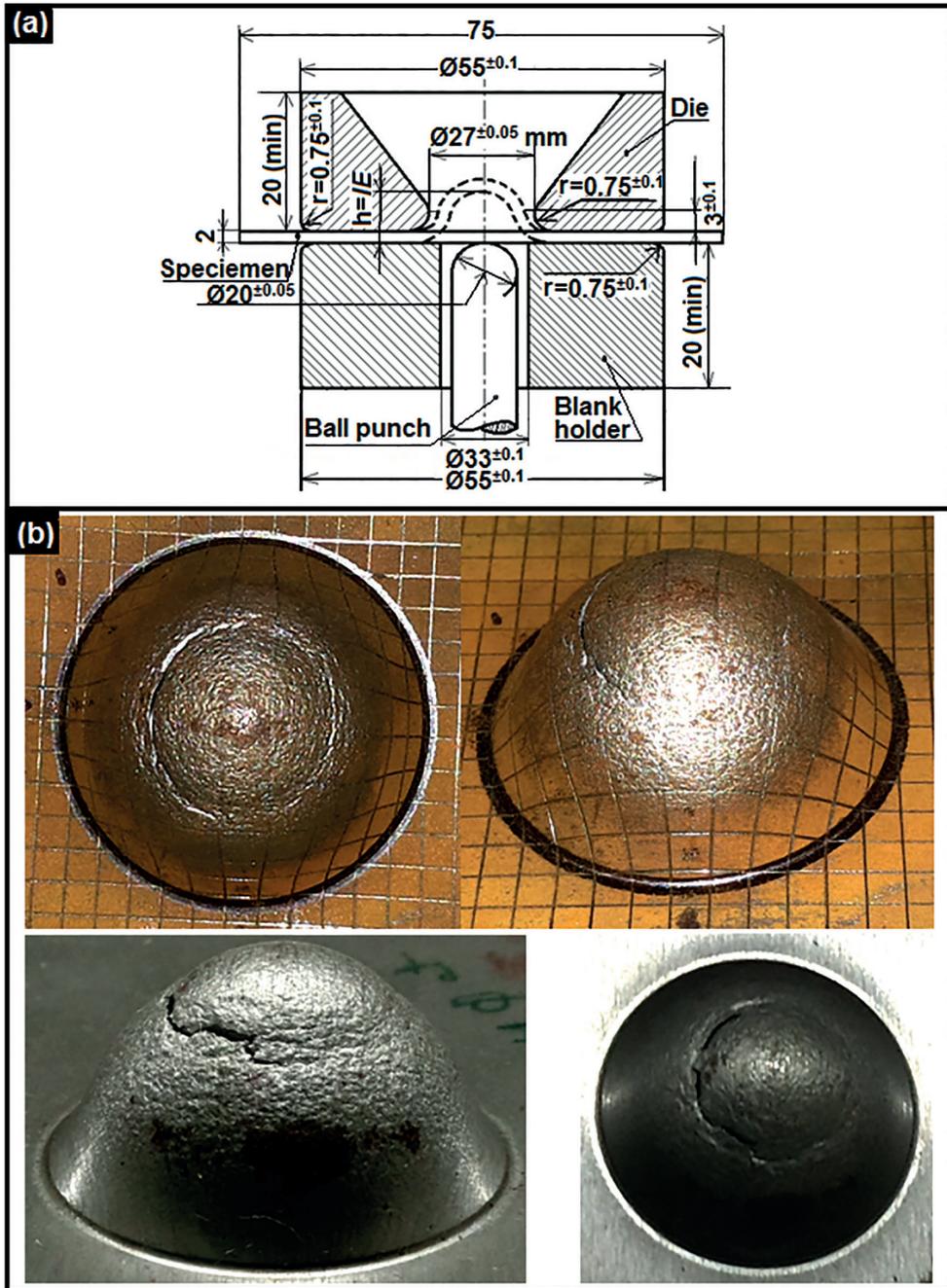


Figure 2: a) Schematic showing of Erichsen cup test arrangements; b) photo images of Erichsen cup specimens.

by maintaining a balance between formability and orange peeling effect in cup drawing process. Also, the prolonged tempering cycle is found to contribute in globulization of cementite, which indicates the enhancement of formability²² by ensuring dislocations to move easily during metal deformation.

Table 3 summarizes the mechanical properties (mean values of anisotropic components) of the heat treated steel as the potential input material for cup manufacturing processes. It shows the surface hardness

as ~ 134 BHN. The tensile strength (*UTS*) ~ 561.4 MPa with yield ratio 57.28% and total elongation (*TEL*) $\sim 40.01\%$ with uniform elongation (*UEI*) $\sim 24.37\%$, altogether indicate a good strength-ductility combination. The high strain hardening exponent (*n*)-value 0.274, signifies its uniform strain dispersibility as well as high stretchability^{1,3,23}. By showing the normal plastic strain ratio (r_m)-value, 1.18 (>1) with a low planar plastic anisotropy (Δr)-value, 0.17, the steel is found moderate in deep drawing²⁴. On a comparison of mechanical

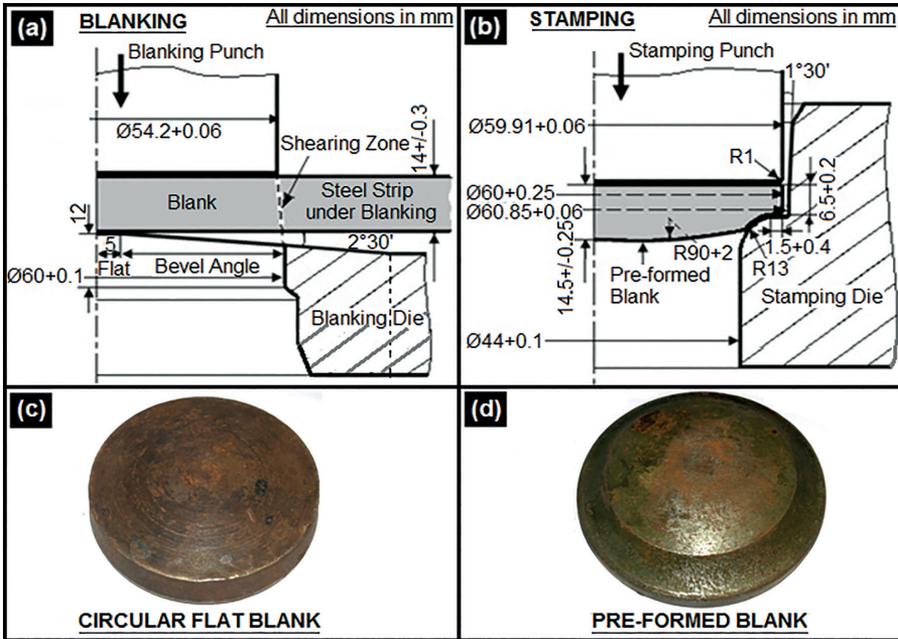


Figure 3: Schematically showing of arrangements, a) blanking operation, and c) stamping operation; Photo images, b) circular flat blank, and d) preformed blank.

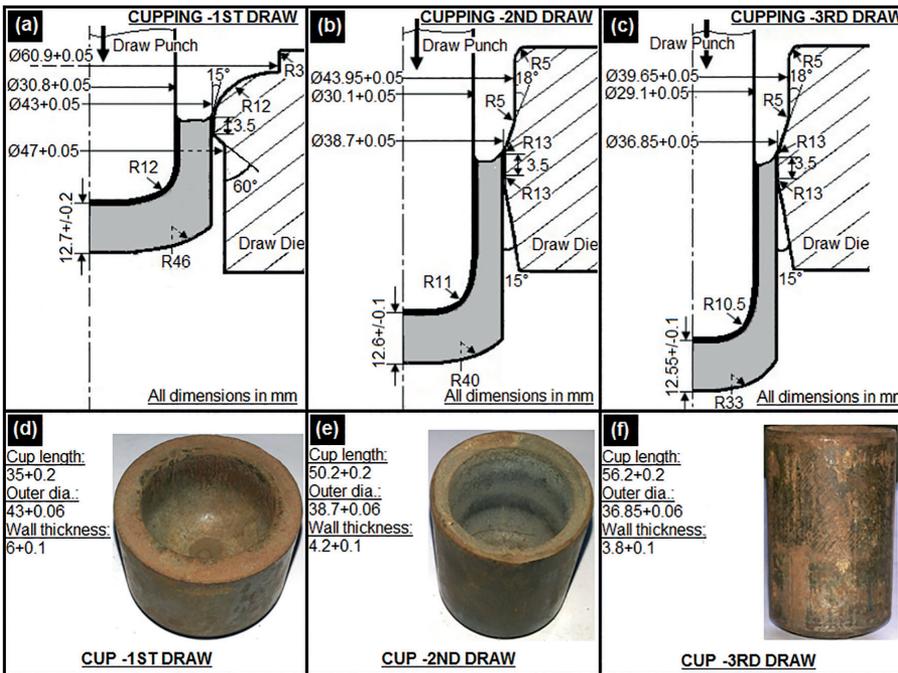


Figure 4: 3-stage cup drawing process, a-c) schematically showing of arrangements; d-f) photo images of drawn cups.

properties as well as formability parameters of the steel with that of conventional low carbon steels and AHSS (Advance High Strength Steels) obtained from various literatures, as shown in Figures 6a-c, the steel stands taller by strength than that of low carbon steels and also is found competitive than few AHSS, which are significant.

Ericksen cup test shows the Ericksen Index (IE) -value, 12.71 (Table 3), which indicates a high biaxial stretchability of the steel attributed to high n -value and elongation^{23, 25}. Moreover, the crack is observed as radially spread over the cup (Figure 2b) which signifies its ductility in biaxial state of deformation.

Table 2: Equipments, tools and process parameters of multistage drawing

| (a) Equipments/ tools | (b) Technical details/ process parameters |
|-----------------------------------|---|
| A Press machine | <i>First draw stage:</i> Capacity- 350 Tons, crank type mechanical press of single action, stroke length – 610 mm ram speed - 183 mm. s ⁻¹ <i>Second draw and Third draw stages:</i> Capacity- 250 Tons, crank type mechanical press of single action, stroke length - 640 mm, ram speed - 192 mm. s ⁻¹ . <i>Die Profile (first - second - third draw stages):</i> Schematically shown in Figures 4(a), (b) and (c) respectively. |
| B Draw die | Surface finish- grind finished with polished surface at effective working zones. Die material- IS: T108/ JIS: SK 3, 4 steel Die hardness- 578-652 BHN on hardened and tempered condition. <i>Punch profile(first - second - third draw stages):</i> Schematically shown Figures 4(a), (b) and (c) respectively. |
| C Cupping punch | Surface finish- grind finished with polished surface at effective working zones. Punch material- IS: T108/ JIS: SK 3, 4 steel. Punch hardness- 578-652 BHN on hardened and tempered condition. |
| D Stripper (three segmented type) | <i>First draw stage-</i> 31.8+0.06mm diameter (minimum). <i>Second draw stage-</i> 31.2+0.06mm diameter (minimum). <i>Third draw stage-</i> 30.5+0.06mm diameter (minimum). (Strippers are fitted at the exit end of draw dies, with peripheral spring tension for extraction of drawn cups after each stage of drawing). |
| E Die-punch clearance | <i>First draw stage -</i> 6.00+0.10mm. <i>Second draw stage -</i> 4.20+0.10mm. <i>Third draw stage -</i> 3.80+0.10 mm. |
| F Lubricant used | Water diluted soap flakes [33% Sodium oleostearate, technical (soap noodles) as per IS 10513-1983, Table 1, clauses 4.4, 8.1 & 8.3, type-I and 67% H ₂ O]. |

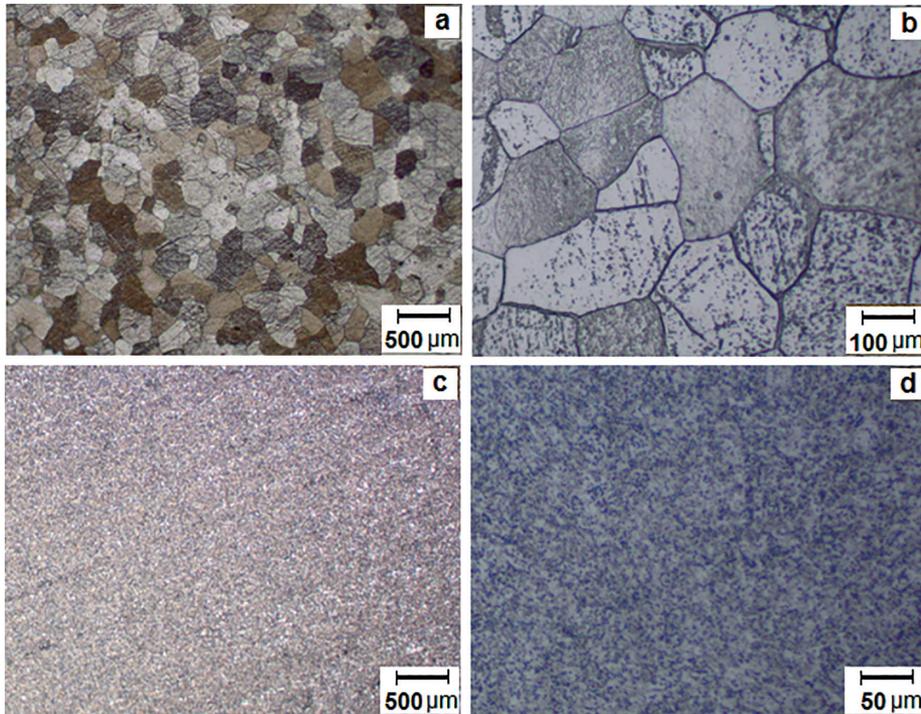


Figure 5: Typical micrographs (OM) of Al-killed AISI 1020 steel strips after, a-b) hot rolling, and c-d) heat treatment.

Table 3. Mechanical properties of the steel after heat treatment.

| YS (MPa) | UTS (MPa) | UEI32 (%) | TEL (%) | <i>n</i> | <i>C</i> (MPa) | <i>r_m</i> (17%) | Δr (17%) | <i>IE</i> (mm) | Hardness (BHN) |
|----------|-----------|-----------|---------|----------|----------------|----------------------------|------------------|----------------|----------------|
| 321.56 | 561.4 | 24.37 | 40.01 | 0.274 | 827.52 | 1.18 | 0.17 | 12.71 | 134 |

*Note: All the tensile properties are being expressed as the mean of values along 0°, 45°, and 90° to the rolling direction of the steel strip. UEI32, Uniform Elongation (True) in 32 mm.

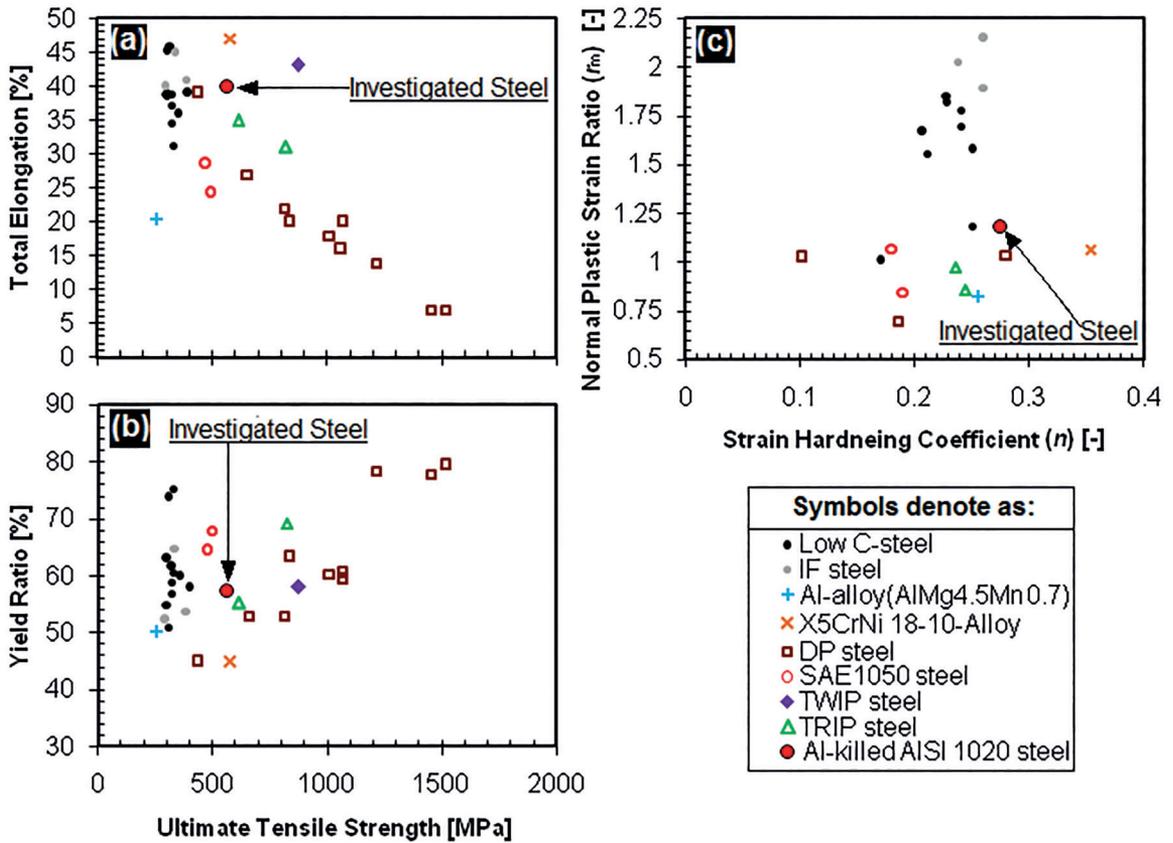


Figure 6: Comparisons of Al-killed AISI 1020 steel with conventional sheet metals (obtained from literatures) with respect to, (a) TEL vs. UTS ; (b) YR vs. UTS ; (c) r_m vs. n -value.

3.2. Effects of multistage cup drawing

Figures 4d-f show the photo images cups drawn in first, second and third draw stages respectively, wherein it is distinguished that cup length increases on the advancement of draw steps. These figures also portray the average dimensions of cups drawn in the respective step, wherein the final draw stage has shown a cup size, ~56mm length, ~36.85 mm diameter and ~3.8 mm wall thickness, which are significant. It is also seen that 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, *i.e.* free from galling, welding, scratch marks, score marks and orange peeling effects, is being witnessed on the cup walls.

Also, few other important effects of cup drawing processes, such as: wall thickness distribution profiles, Drawability and Ironability parameters, punch force history, and strain distribution profiles are evaluated for each draw step and are discussed in the following sub sections.

3.2.1. Wall thickness distribution profiles

The dimensions of drawn cups were measured (shown in Figures 4d-f) by digital micrometers after sectioning the cups at middle by a diamond saw. Thus, cup wall thickness of each draw stage was obtained at different zones, *i.e.* from base to top mouth edge and then the thickness distributions were graphically plotted with respect to the cup height, as shown in Figures 7a-c. These figures indicate thickness variation in term of a divergence of ironing mid-point from the respective geometrical mean of measured dimensions. Thus, degrees of deviation are observed as 0.0728 mm (+), 0.03585 mm (+) and 0.00692 mm (+) in first – second - third draw steps respectively. These trends confirm to the increasing dimensional control on advancement of the draw steps, manifested by increasing predominance of wall ironing in the forming processes, agreed by⁸⁻¹¹. At the same time, it is also observed that the initial blank thickness remains almost unchanged under a region of flat bottom face of the draw punch in all the stages, agreed by Jawad²⁶.

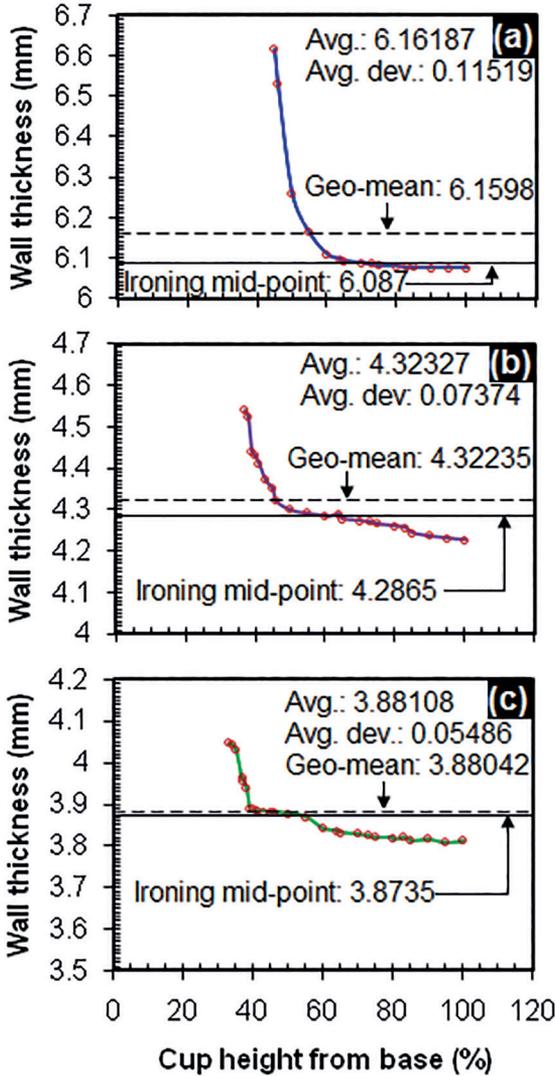


Figure 7: Graphical showing of cup wall thickness distribution, (a) 1st draw, (b) 2nd draw and (c) 3rd draw.

3.2.2. Drawability and ironability parameters

The drawability and the Ironability parameters of draw stages were evaluated by using following standard formulae, obtained from different literatures^{21, 26, 27}.

Draw ratio

$$(\beta) = D_i/D_{p-i} \quad (4)$$

Overall or maximum draw ratio (β_0), i.e. limiting draw ratio

$$(LDR) = D_0/D_{p-f} \quad (5)$$

Draw reduction

$$(r_d)\% = [(D_{i-1} - D_{p-i})/D_{i-1}] \times 100 \quad (6)$$

Overall or maximum draw reduction

$$(r_{d-0})\% = [(D_0 - D_{p-i})/D_0] \times 100 \quad (7)$$

Ironing ratio

$$(IR) = T_{i-1}/T_i \quad (8)$$

Overall or maximum ironing ratio (IRO), i.e. limit ironing ratio

$$(LIR) = T_0/T_f \quad (9)$$

Ironing reduction

$$(r_i)\% = [(T_{i-1} - T_i)/T_{i-1}] \times 100 \quad (10)$$

Overall or maximum ironing reduction

$$(r_{i-0})\% = [(T_0 - T_f)/T_0] \times 100 \quad (11)$$

Principal strain

$$(\varphi_p)\% = \ln[(D_{i-1}^2 - d_{i-1}^2)/(D_i^2 - d_i^2)] \times 100 \quad (12)$$

Reduction of area

$$(r_a)\% = [(A_{i-1} - A_i)/A_{i-1}] \times 100 \quad (13)$$

Overall reduction of area

$$(r_{a-0})\% = [(A_0 - A_f)/A_0] \times 100 \quad (14)$$

Drawing efficiency

$$(\eta_d)\% = \ln(\beta) \times 100 \quad (15)$$

Overall drawing efficiency

$$(\eta_{d-0})\% = \ln(LDR) \times 100 \quad (16)$$

Ironing efficiency in each step

$$(\eta_i)\% = \sqrt{[0.703125 \times (r_{a \text{ in}}\%) / 100]} \quad (17)$$

Overall ironing efficiency

$$(\eta_{i-0}) = \sqrt{[0.703125 \times (r_{a-0} \text{ in}\%) / 100]} \quad (18)$$

Where, D_0 = diameter of the blank (before cupping); D_i, D_{i-1} = outer diameter of the cup after and before the stage-(i) respectively; D_{p-i}, D_{p-f} = diameter of punch in the stage-(i) and the final stage respectively; T_0 = thickness of the blank (before cupping); T_i, T_{i-1} and T_f = thickness of cup wall in the stage-(i), (i-1), and the final stage respectively; d_i, d_{i-1} = inner diameter of cup after and before the stage-(i) respectively; and A_0, A_i, A_{i-1}, A_f = cross section area of cup before the first draw stage, after the stage-(i), after the stage-(i-1) and after the final stage respectively.

Figure 8a graphically presents the stage wise variation of cup drawing ratios, i.e. ' β ' and ' IR ', with showing their maximum values in first draw stage and then decrease in subsequent steps gradually. Figure 8b shows the reduction parameters, i.e. ' r_d ' and ' r_i ', demonstrate a similar trend as of ratios. The reduction in draw reduction % is attributed by increased draw strains, associated with advancement of draw steps, an expected phenomenon explained by Suchy⁷. Also according to him, there is a gradual fall in ironing reduction % observed in the experiment, because of proportionality relation with the corresponding ironing ratio value, which is premeditatedly lowered in advancing the draw steps for an accommodation of forming strains by the material.

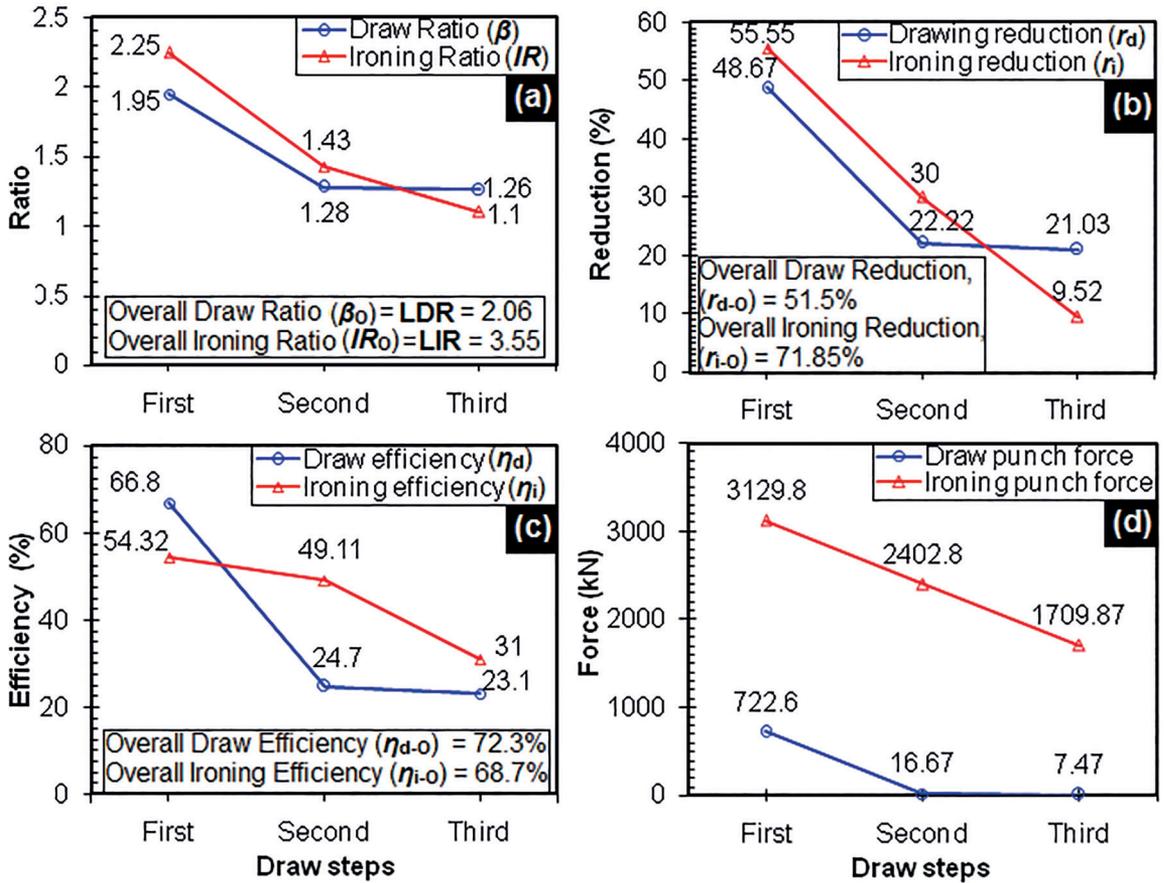


Figure 8: Stage wise graphical showing, a) Draw and Ironing Ratios, b) Draw and Ironing reductions, c) forming efficiencies, and d) punch forces.

The values of critical parameters such as: *LDR*, overall draw reduction (r_{d-o}), *LIR* and overall ironing reduction (r_{i-o}) were evaluated for the overall draw steps, as: 2.06, 51.5%, 3.55 and 71.85% respectively. A comparison with literatures shows that both *LDR* and r_{d-o} are lower than *LDR* value 2.2, reported by Tajally et al.²⁸ and r_{d-o} value 70.7%, revealed by Jawad²⁶. But at the same time, *LIR* and r_{i-o} are found higher than that of values 2.5-3.3 and 60-70%, shown by Shi and Gerdeen²⁷ respectively. These values imply that the steel can successfully be drawn with moderate drawability under high ironability conditions.

Figure 8c represents a stage wise variation of forming efficiencies, persuaded by deep drawing and ironing processes. Herein also, the forming efficiencies exhibit a decreasing trend, which might be due to increasing strain factor as well as of increasing strained % of cup height occurred in subsequent steps⁷. The figure also indicates a predominance of draw deformation in first step and then of wall ironing in further two steps. More significantly, the overall draw and ironing efficiencies were estimated as 72.3% and 68.7% respectively.

3.2.3. Punch force history

The punch forces such as: forces caused by drawing and ironing actions of punches in three draw steps were determined by following equations obtained from various literatures. In these equations a plain strain condition was assumed, because of circumference of the cup wall was constrained by the rigid punch from shrinkage and thus it yielded a negligible (≈ 0) circumferential strain.

Considering a non steady state of plastic deformation in the first draw stage, the draw punch force was calculated by Eq.19, described by Boljanovic²⁹.

$$P_{D-1} = [\{\pi D_p t (1.1k_{f-m}) \cdot \ln(D_0/D_p)\} \cdot \exp(\mu \cdot \pi/2)] + [\{\mu(2H(D_p/D_0))\} \cdot \exp(\mu \cdot \pi/2)] + [B] \quad (19)$$

Where, D_p = Punch diameter, D_0 = Blank diameter, t = wall thickness, k_{f-m} = Average flow stress (MPa) μ = Coefficient of friction at die radius and was assumed a value, ~ 0.16 ²⁹, H = Blank hold down force, B = Force to bend and re-straighten the blank in cup forming.

Since in the present investigation, no blank-holder was used, the Eq.19 was modified to Eq.20 by excluding the blank hold down force (H):

$$P_{D-1} = \left[\left\{ \frac{\pi D_p t (1 \cdot 1 k_{f-m})}{\ln(D_0/D_f)} \right\} \cdot \exp \cdot (\mu \cdot \pi / 2) \right] + [B] \quad (20)$$

The average flow stress was calculated by using the Eq.2²¹:

$$k_{f-m} = (k_{f-0} + k_{f-1}) / 2 \quad (21)$$

Where, k_{f-0} = flow stress before forming (for $\varphi_p = 0$) i.e. yield stress of the material, k_{f-1} = flow stress at the end of forming (for $\varphi_p = \varphi_{max}$) and value of this stress was evaluated by using the equation of flow stress curve, $k_f = C\varphi^n$ ²¹.

The bend force was calculated by using the Eq. 22³⁰:

$$B = [(k_{f-m} \cdot L \cdot t^2) / 2(R_d + 0.5t)] \cdot \tan(\gamma/2) \quad (22)$$

Where, L = total length to bend i.e. the perimeter (πD_0) of the preformed blank (189.12 mm), t = thickness of the preformed blank (13 mm), R_d = bend radius i.e. die radius ($R12$), γ = bend angle i.e. 90° in the present investigation.

In second and third draw steps plastic deformation was considered as of steady state process, wherein deformation zone did not change (only diameter changed). The draw punch forces in these steps were evaluated by Eq.23²⁹.

$$P_i = [\pi D_{P-i}] \times \left\{ 1.1 \{1 + (\mu \pi 2\alpha / 180)\} \times \{ (1.21 / 1.44) k_{f-m} \} \times \left\{ 1 + (\tan 2\alpha / \mu) \right\} \times \left\{ 1 - (D_{m-i} / D_{m(i-1)})^{\mu / \tan 2\alpha} \right\} \right\} \quad (23)$$

Where, i = draw stage no., P_i = punch force in i -stage, D_{P-i} = Punch diameter in i -stage, t_i = cup wall thickness in i -stage after drawing, D_{m-i} = mean dia. of cup after drawing in i -stage, $D_{m(i-1)}$ = mean dia. of cup after drawing in $(i-1)$ -stage, α = semi die angle in degree, k_{f-m} = average flow stress in MPa (calculated by Eq.19, assuming k_{f-0} = yield stress of the material because of stress relieving treatment after drawing), μ = interface friction coefficient and was assumed to be ~ 0.16 ²⁹.

The ironing punch force in each draw step was evaluated by using Eq.24, stated by Folle et al.³¹.

$$F = k_{f-m} A_i \varphi_p [1 + \mu / \alpha + 2\alpha / 3\varphi_p] \quad (24)$$

Where, k_{f-m} = mean flow stress in MPa (Eq.19), A_i = cross-sectional area of the cup after ironing in i -stage, φ_p = principal strain, α = semi die angle in degree, μ = interface friction coefficient and was assumed to be ~ 0.16 ²⁹.

Figure 8d depicts the punch forces (both draw and ironing forces) with their stage wise variations. It shows downward trends, which has been obtained

for both types of forces while moving from one draw step to another. Further, it is distinguished that the ironing force is found to be quite higher than that of the corresponding draw force in each draw stage, which confirms a significance of the ironing in deformation processes.

3.2.4. 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 and results were plotted to a graph with respect to the cup height, known as strain distribution profile. The major (\mathcal{E}_{mj}) and the thickness (\mathcal{E}_{thk}) strains were estimated by Eqs.25 and 26 respectively²⁶, considering changes in dimensions before and after drawing of cups. The minor strain (\mathcal{E}_{mn}) and the effective strain (\mathcal{E}_{eff}) were calculated by using volume constancy formula, Eq.27, and slab method, Eq.28, respectively²⁶.

$$\mathcal{E}_{mj} = \ln(L/L_0) \quad (25)$$

$$\mathcal{E}_{thk} = \ln(t/t_0) \quad (26)$$

$$\mathcal{E}_{mn} = -(\mathcal{E}_{mj} + \mathcal{E}_{thk}) \quad (27)$$

$$\mathcal{E}_{eff} = \{2/3(\mathcal{E}_{mj}^2 + \mathcal{E}_{mn}^2 + \mathcal{E}_{thk}^2)\}^{0.5} \quad (28)$$

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 considered for the measurement, on component before drawing and t = thickness of the point on component, after drawing.

Figures 9a-c demonstrates strain distribution profiles of outer surfaces of cups in first, second, and third draw stages 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 (\mathcal{E}_{mj} , \mathcal{E}_{thk} , \mathcal{E}_{mn} , and \mathcal{E}_{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.

4. Conclusions

The conclusions of this paper can be summarized as follows:

- Water quenched and tempered (953°K for 30 hours) Al-killed AISI 1020 steel developed uniformly distributed globular cementite in a

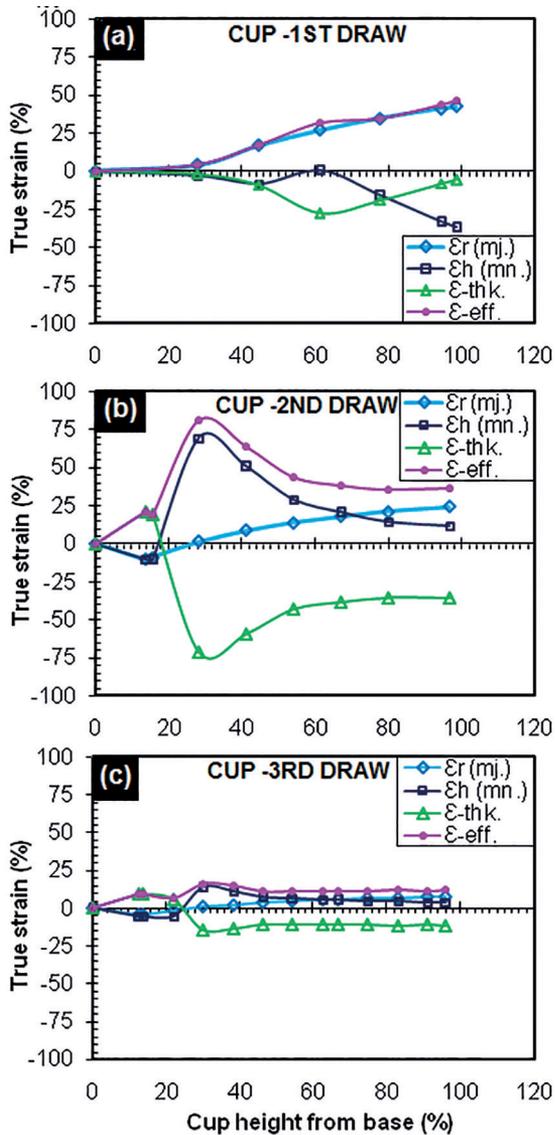


Figure 9: Stage wise graphical showing of strain distribution profiles of cups, a) 1st draw, b) 2nd draw, and b) 3rd draw.

ferritic matrix and having 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 maximum strength up to ~561 MPa.

- Unlike conventional sheet metal works, thicker blanks (12 mm thick, 60 mm diameter circular blanks) were drawn into cylindrical cups of length ~56 mm, diameter ~36.85 mm and wall thickness ~3.8 mm, by using a modified processing route consisted of pre-forming of blanks and three stage deep drawing with simultaneous ironing without using blank-holders.

- The drawability and ironability parameters of overall draw stages were evaluated as: overall draw reduction 51.5 %, *LDR* 2.06, overall ironing reduction 71.85%, and *LIR* 3.86, which indicated the actual press formability of the steel.
- The wall thickness distribution, punch force history, and strain distribution profiles of cups, were also obtained and shown for further improvement of the process and the tools used in.

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