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ORIGINAL RESEARCH

Forming of hemispherical and hemi-ellipsoidal parts of low carbon steel sheet by mandrel free metal spinning process

R. Arunkumar[1] · **G. Chandramohan**[2]

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Abstract

Metal spinning (MS) is an efficient and economical alternative method for low-volume functional sheet metal products. It has higher potential to shape three dimensional parts without employing matching die. The focus in advancement of shape forming shall bring an effective approach to produce defect free shapes and economically viable products. This paper is going to discuss about the modification in the MS process, without using matching dies or mandrel to produce a hemispherical and hemi-ellipsoidal profile product. The forming occurs by the deformation of sheet metal when the roller feed is against the rotating metal blank. Low carbon extra deep drawing Al killed steel sheets of thickness 1.6 mm were exploited as forming material. Further the paper illustrates on thickness variation, hardness, micro-structure, surface roughness and forming limit diagram (FLD) of the various zone of the formed part. It is examined that as the depth varies, the changes in thickness of formed part also varies. Also, the surface roughness was proportionally increased with increasing in percentage of reduction in thickness. In all zone of the formed steel part are in tension- tension strain conditions, there is no tension compression and plane strain condition occurred in the forming process. Due to this reason wrinkles failure is eliminated in die less MS process.

Keywords Die less metal spinning · Hemispherical and hemi-ellipsoidal shapes · Thickness variation · Forming limit diagram of spun parts

Introduction

MS is the oldest method of forming a metal into axisymmetric hollow thin walled shapes using combination of rotational motion of blank and tool forces against metal blank. However in past years, MS lost ground to other metal forming process owing to wrinkling, thinning, profile error of spun parts and necessity of skilled operators for conventional spinning (CS). However due to benefits like inexpensive tooling, lower forming load, improved metallurgy and growth of numerical controlled (NC) and computer numerical controlled (CNC) spinning machines, MS permits manufacturing of complicated and accurate shapes with small-batch production.

Spinning is a process of converting circular flat metal blanks or preformed blank to hollow cross-section geometries through feeding of spinning tools against a metal blank that forces the blank to deform locally to a defined axisymmetric shape with or without using a mandrel [1–4]. Because of the local deformation of the metal blank, the total forming forces need to complete the process are reduced significantly compared to deep drawing or other sheet metal forming processes.

MS process includes three major classifications namely CS, shear spinning (SS) and tube spinning (TS) which are extensively employed in industries. CS or manual spinning is also known as compression forming process where the tool is moved either manually or powered by power source on mandrel to form the component [1]. The CS operation can be performed using single pass or multi pass depending on the complexity of profile. Wall-thickness of blank is constant for full process; hence the final wall-thickness of the spun part is similar to the thickness of blank. Also the diameter of formed part is smaller than the diameter of blank. In SS the radial position of element in the blank, remains similar when performing material deformation. Because, forming method uses higher shear forces. In SS, flat blank or pre formed metal

R. Arunkumar
nkr.arunkumar@gmail.com

[1] Arun Engineering Works, Coimbatore, Tamil Nadu 641 035, India

[2] Department of Mechanical Engineering, PSG Institute of Technology and Applied Research, Coimbatore, Tamil Nadu 641 062, India

sheet is deformed on mandrel with greater speed. Using SS, each ductile metal is shaped. But, SS is exploited with one roller or with two rollers to balance radial forces in mandrel and bearings inside lathe. Huge plastic strains and greater strain rates are produced which generates imperative heat in SS. This heat is dissipated through coolant/lubricant.

TS is a process of producing hollow metal components by flow forming process. In TS, a disc or a tube is mounted on a rotating mandrel and the material flows axially on the rotating mandrel using one or more rollers. It improves the flexibility of incremental forming technology and offers manufacturers with an alternative to conventional forging and deep drawing.

Metal spinning equipment

The general arrangement of MS apparatus resembles the lathe with appropriate modifications. There are three major types of MS apparatus used in industries. They are manual MS lathe, hydraulic powered copying lathe and advanced NC spinning lathe.

The manual MS apparatus comprises of a head stock to hold and rotate, the mandrel or blank holding device. The tail stock is employed to hold the blank to the mandrel by the anti-friction center and follower. The suitable pressure to hold the component during forming is created by the tail stock. The spinning rollers or form blocks are mounted on the front end of the long lever. The lever is rested on pedestal and the pedestal support pin acts as a fulcrum to move and rotate the lever to various positions. MS is accomplished by manually using a friction-type spinning tool on the rotating blank.

In hydraulic powered copying lathe, the copying arrangement is used to trace the template and moves the lever accordingly. This copying arrangement is replaced by servo mechanism in NC spinning lathe. In NC or CNC machine, the rotation of blank and tool movement is controlled by servo mechanism.

Defects in metal spinning process

Wrinkles, cracks, wall thickness variation, thinning and spring-back deformation are the major defects observed in MS processes [1]. Wrinkles defects are common in conventional MS because it is a compression forming process. But these defects are not observed in die less spinning and SS. Bending close to the inner edge of clamping plate and spring back are the other defects. Those are observed in the parts formed by this process. The spring-back defect of formed part in die less spinning is lower, which is easily managed. The spring back occurs due to the generating curves of the formed part which does not coincide with the roller path curves [5].

Advanced spinning process

New spinning processes, such as non-axisymmetrical spinning, non-circular cross-section spinning and tooth-shaped spinning are developed. The recent developments in spinning process are non-circular and non-axisymmetrical tooth-shaped spinning. The incremental stretch expanding is also one type of MS process. CNC forming process termed as incremental stretch expanding was presented by Kitazawa [6]. In this process, the forming tool is a steel rod with smooth hemispherical tip, feeding against the rotating blank to form symmetrical shapes. Kitazawa improved the metal flow phenomena in CNC incremental stretch-expanding by several passes [7], two-path stretch expanding of hemispherical [8], and hemi-ellipsoidal [9] shells.

The spinning of curvilinear surface of revolution like hemispheres, ellipsoids and paraboloid are more complicated than spinning of conical shape. The present MS process is unable to create curvilinear surfaces with enhanced quality. To enhance quality of formed part, modification in MS process is necessary.

This paper is discussed on the process developments and analyses of cold, mandrel-less, inner, axisymmetric spinning process which has a profile with curvilinear surface of revolution.

Experimental setup and procedure

For experiments, cold rolled low carbon steel with 1.6 mm thickness is taken. The following quality characteristics of the particular steel has been evaluated and experimented.

Chemical composition of steel sheet

The chemical compositions by weight percentage of the extra deep drawing Al killed steel sheets were analyzed by an emission spectrometer, and the results are provided in Table 1.

The amount of carbon in the steel was 0.039%, which is the desired value of carbon for good formability. To increase formability of sheet, the amount of carbon in steel sheet is limited to lower than 0.10%. Greater carbon content of steel, improves strength and lessens formability.

Tensile properties and hardness of steel sheets

Table 2 portrays mechanical properties of extra deep drawing (EDD) aluminum-killed steel that is measured with test specimen axis oriented at 0^0, 45^0, and 90^0 to steel sheet rolling direction.

As compared to another axis orientation, Yield strength and Ultimate tensile strength values are greater at 45^0. The maximum uniform elongation of 31.2% was found in 45^0 inclined

Table 1 The chemical compositions by weight parentage of the extra deep drawing Al killed steel sheets

Element	Carbon C	Silicon Si	Manganese Mn	Phosphorous P	Sulfur S	Chromium Cr	Nickel Ni	Aluminium Al	Iron Fe
Measured value average	0.039	0.010	0.210	0.016	0.010	0.016	0.019	0.0428	Balance

specimens and the maximum total elongation of 46.1% was found in parallel to rolling direction specimen. The hardness of the steel sheet measured by vickers hardness tester was 124.1 HV at 0.1Kgf load.

Micro-structure of EDD steel sheets

Microstructure of steel sheet was observed under optical microscope, the Fig. 1 shows optical micrographs of EDD steel sheet in transverse section. Kumkum Banerjee [10] studied the micro structure of EDD steel sheet. Microstructure portrays equiaxed ferrite grains.

Forming limit diagrams of EDD steel sheet

Sheet metal formability is evaluated as capability of metal to deform into necessitated shape without necking or fracture. The formability of sheet metal in industry is assessed through forming limit curve (FLC) measurement. Keeler [11] and Goodwin [12] presented the concept of FLD. FLD is a useful method for the assessment of formability of sheet metals [13]. FLDs signify a locus of major and minor strains in onset of strain localization and it is generated from spherical-punch test. Through experiment, the FLDs are measured from strain distributions. In FLD, the area above the curve is the failure region and beneath the curve is the safe region. Shape of FLDs based on deformation is imparted.

Figure 2 portrays different specimen sample geometries. Each sample represents one strain path on the FLD. This technique requires use of diverse sample geometries to measure all possible strain paths. The stages followed in the experiment are grid marking on sheet specimens, stretching samples to failure or necking and measurement of strains.

Sheet samples are subjected to dissimilar states of stain, i.e. the tension–tension zone, plane strain and the tension-compression zone with different width of sheet samples. Non-contacting grid of 2.5 mm diameter circles is marked on test specimens by screen printing method. The punch-die assemblies were designed and manufactured as per ISO 12004-2:2008.

FLD of EDD steel sheets of 1.6 mm thickness results are given in Fig. 3. In tension–tension region, sheet possesses a maximum minor strain of 36% and maximum major strain of 63.5%. In plane strain condition, the limiting major strain is about 54%. In tension–compression strain condition, the maximum minor strain offered by steel sheet is 31.3% and the maximum major strain offered by steel sheet is 97.5%.

The limiting strains of the sheet are varied depending on the strain path. It is crucial to discover limiting strains for diverse strain paths. In this analysis, totally ten strain paths are analyzed. Four strain paths in tension–tension region, one strain path in plane strain region which coincides with y-axis and five strain paths in tension compression region have been considered. To produce precise FLC, number of strain paths is enhanced.

Experimental set-up

The aim of the mandrel less MS process is to obtain the hemi-spherical and hemi-ellipsoidal profile of the product by the longitudinal (x axis) and cross wise (y axis) movement of a roller in contact with sheet metal blank, without using mandrel. Spinning process is executed by two axis CNC lathe machine. Servo motors were used to control tool motion numerically in die less MS process. Besides, the desired tool path is directly drawn in CAD/CAM software. To control the tool

Table 2 Tensile properties and hardness of EDD steel sheets

Orientation with respect to rolling direction (in Deg)	Yield strength (in MPa)	Ultimate tensile strength (in MPa)	Uniform Elongation (in %)	Total elongation (in %)	Hardness (in HV 0.1Kgf)
0^0 (parallel to RD)	183.5	291.2	30.5	46.1	124.10
45^0 (inclined to RD)	192.6	308.1	31.2	43.9	
90^0 (Perpendicular to RD)	185.8	290.9	30.4	45.9	
Average	187.3	296.7	30.7	45.3	

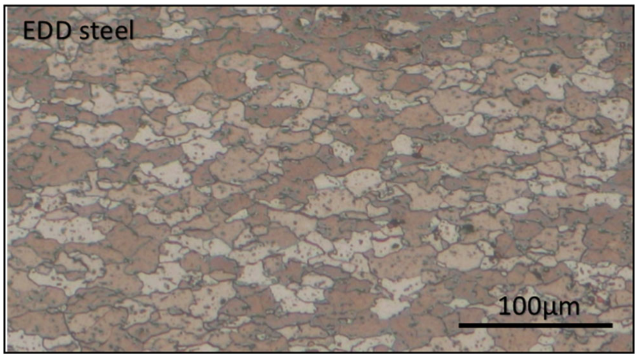


Fig. 1 Optical micrographs of EDD steel sheet in transverse section

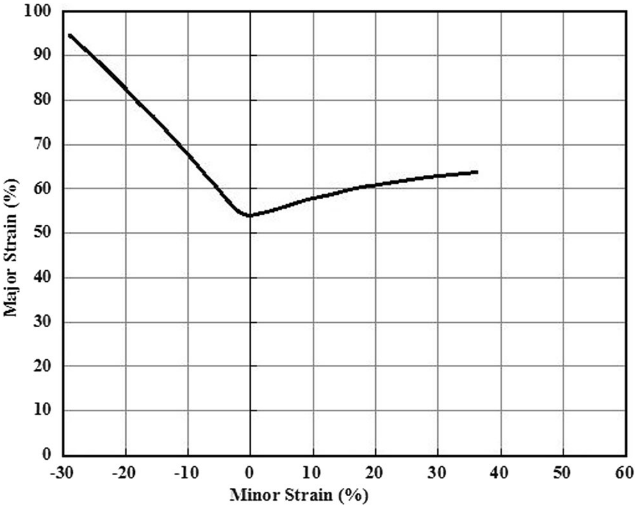


Fig. 3 The forming limit diagrams of extra deep drawing quality steel sheets of 1.6 mm thickness

motion, CNC codes were obtained from the drawn tool path and transmitted to CNC machine as a CNC code.

A flat sheet metal blank of 300 mm diameter is clamped around its circumference by means of bolts on the special blank holding fixture. Figure 4 illustrates the schematic view of the mandrel less MS device. The hemispherical and hemi-ellipsoidal profile with an inner diameter of 270 mm was formed by this process.

The blank holding fixture is clamped to the spindle. A spherical steel roller was mounted on the tool post by means of roller holder and bearings to ensure the free rotation of roller, relatively with blanks. The metal blank is marked with non-contacting grid of 2.5 mm diameter circles through screen printing method, to identify strain distribution on formed parts using FLD.

In this process, a layer of metal blank at constant depth in longitudinal direction is formed by a continuous X and Y movement of the roller and the roller moves in concave path. After completion of each layer, the roller moves with constant increment in X and Y towards the blank, along the axis, to process the subsequent layers till the completion of the process.

The influence of the process parameters was not taken into account, because the experiments were planned in order to develop a new process of forming hollow asymmetrical curve linear surface of revolution through die less MS process.

Spin forming occurs by rotational motion of the metal blank, in addition to the sweeping passes of the freely rotating spherical roller. The direction of tool movements and tool-path trajectory will affect strain distributions. The spinning roller forces the blank to deform locally to a defined axisymmetric shape. Because of the local deformation of the metal blank, the total forming forces required to complete the process are very less compared to other sheet metal press forming processes. It enhances possibility of enormous reductions and changes in shape with simple tooling; also it lessens load capacity and cost of tooling and forming machine. To create components with improved mechanical properties and surface finishes, spinning is exploited. Figure 5 shows the view of formed profiles (a) Hemi-ellipsoidal (b) Hemispherical.

Tool path

Three type of roller paths are preferred namely straight line, concave and convex curves. Among these three curves, concave paths are widely used in spin forming process.

The concave paths are further classified as inward and outward profile paths. For example, the elliptical shape can be

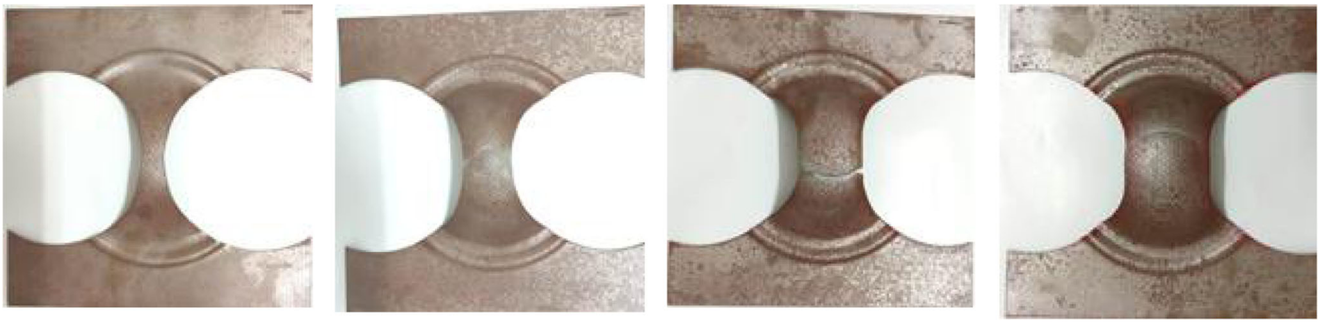


Fig. 2 FLD tested sample geometries

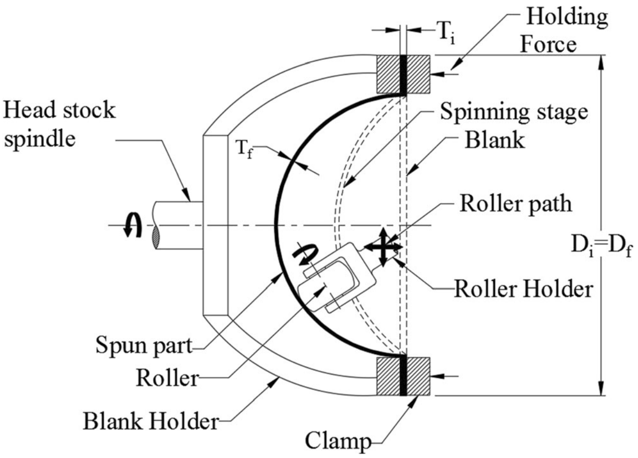


Fig. 4 The schematic view of the mandrel less Metal spinning apparatus

formed by inward or outward elliptical path. The selection of roller path is based on the profile to be formed. To lessen thickness variation and strain distribution of formed parts, the combination of inward and outward elliptical path for hemi-ellipsoidal shape and combination of inward and outward circular path for hemispherical shapes are used. Figure 6 shows the different tool paths of profile forming process (a) Combination of inward and outward circular path (b) Combination of inward and outward elliptical path.

Process parameter

The hemispherical and hemi-ellipsoidal has been produced with the source of available forming machine. The set parameters for the formation of shapes have been carried out with respect to the basic settings to evaluate the quality characteristics of the component. Table 3 lists the parameters of die less MS process.

Sample preparation from formed parts

There is some limitation in determining the thickness, surface roughness, hardness and micro structure of the formed part as a whole; therefore, the formed parts was cut into 20 × 20 mm sized pieces using a wire cut machine. The thickness, surface roughness, hardness and micro structure are determined with diverse points of cut samples. The various zones for hemispherical cut samples are numbered from H1 to H12 and for hemi-ellipsoidal cut samples are numbered from E1 to E10. Figure 7 shows the wire cut pattern of formed parts (a) hemi-ellipsoidal (b) hemispherical. The depth of each zone varies because of the cut samples are maintained with 20 mm length.

Results and discussion of the experimental work

The zone number E1 & H1 of the part was clamped by the blank holding fixture to prevent the deformation of the blank during forming. Due to this reason E1 & H1 are eliminated for analysis.

Wall thickness measurement and thickness distributions

The thickness variation of hemispherical and hemi-ellipsoidal formed part at various zone are shown in Figs. 8 and 9. As the depth varies, the thickness of the part also varies. In each zone, 5 thickness values are taken for analysis. Thickness was measure at different points using a digital plunger dial gauge [14].

The zone number E2 & H2 of the part are near the clamping area of the blank holding plate. The sheet blank bends near the clamped edge and it prevents the deformation near to the clamping zone. Hence, the thickness distribution on the zone number E2 & H2 starts with raw material thickness.

In hemispherical formed part, the maximum thickness variation is 0.260 mm observed in zone H3. In zone H6, H7, H8 and H9, the observed thickness variation is less than 0.1 mm. The thickness variation between 0.1 mm to 0.2 mm was observed in the following zones H2, H4, H5, H10 and H11. Zone H7 has the maximum percentage of reduction in thickness. The Table 4 shows zone wise thickness variation and maximum percentage of reduction in thickness of hemispherical

(a) Hemi-ellipsoidal (b) Hemispherical

Fig. 5 View of formed profiles (**a**) Hemi-ellipsoidal (**b**) Hemispherical

Fig. 6 Different tool paths of profile forming process

(a) Combination of inward and outward circular path (b) Combination of inward and outward elliptical path

formed part. The average percentage of reduction in thickness is 51.88%.

In hemi-ellipsoidal formed part, the maximum thickness variation is 0.250 mm observed in zone E3. In zone E5, E6 and E10, the observed thickness variation is less than 0.1 mm. The thickness variation between 0.1 mm to 0.2 mm was observed in the following zones E2, E4, E7, E8 and E9. Zone E6 has maximum percentage of reduction in thickness. The Table 5 shows zone wise thickness variation and maximum percentage of reduction in thickness of hemi-ellipsoidal formed part. Average percentage of reduction in thickness is 34.30%.

When moving from the entry to the side region of the formed part at various zones, it is observed that as the forming tool deforms, the blank material towards center of the part and the side region of the formed part undergoes stretching, leading to maximum thickness variation. This is due to greater plastic strain. Since the deformation is less at the bottom, the region experiences the least reduction in thickness.

Micro-structure of steel sheets

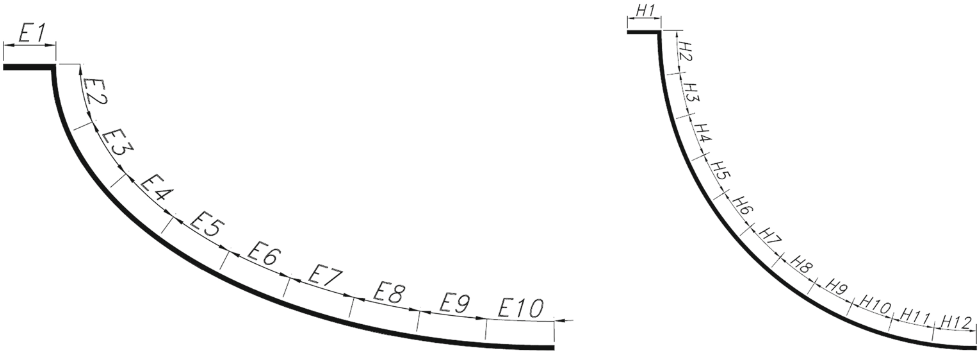
The microstructure of the formed part exhibits elongated grains oriented in forming direction. The morphological change in the matrix with respect to the locations of the profile formed shapes is shown in Figs. 10 and 11. The Fig. 11 shows the optical micrographs of hemi-ellipsoidal formed part at different zone in transverse section. The Fig. 10 shows the optical micrographs of hemi spherical formed part at different zone in transverse section. The micrograph of the formed part is taken at different zone to understand the variations in grain size and grain orientation. The roller feed direction is specified by a line with arrow heads in the micrograph.

Zone H3: Zone H3 illustrates the effect of the second stage in the forming process. Grains in this zone are slightly elongated. 37.5% is the maximum percentage of reduction in thickness of this zone. The minimum thickness within this zone is 1 mm & the maximum thickness within this zone is 1.26 mm.

Table 3 Process parameters for experimental work

Process parameters	Values
1. Blank parameters	
Blank material	EDD steel sheet
Diameter of metal blank	300 mm
Thickness of metal blank	1.6 mm
Clamping width	15 mm
2. Tool (roller) parameters	
width of the roller	65 mm
Spherical Radius of the roller	55 mm
Corner radius of roller	4 mm
Roller material hardness	60Hrc
Roller surface finish	Ra6.3
No.of rollers	1 roller
3. Forming machine parameter	
Rotary speed of the blank	240 rpm
Feed rate of the roller	11 mm per sec
Depth of forming	6 mm
Tool path for Hemi-ellipsoidal	Combination of inward and outward elliptical path
Tool path for Hemispherical	Combination of inward and outward circular path
Lubricant	Synthetic lubricant

Fig. 7 Wire cut pattern of formed pats (**a**) Hemi-ellipsoidal (**b**) Hemispherical



(a) Wire cut pattern of hemi-ellipsoidal formed pats

(b) Wire cut pattern of hemispherical formed pats

Zone H7: This zone illustrates the flow of grains are parallel as no further changes in the grain flow due to the bidirectional pass of the roller. It is a highly strained region. The second stage grains also undergo stretching indicating thin elongated lines. 67.5% is the maximum percentage of reduction in thickness of this zone. The minimum thickness within this zone is 0.52 mm & the maximum thickness within this zone is 0.56 mm.

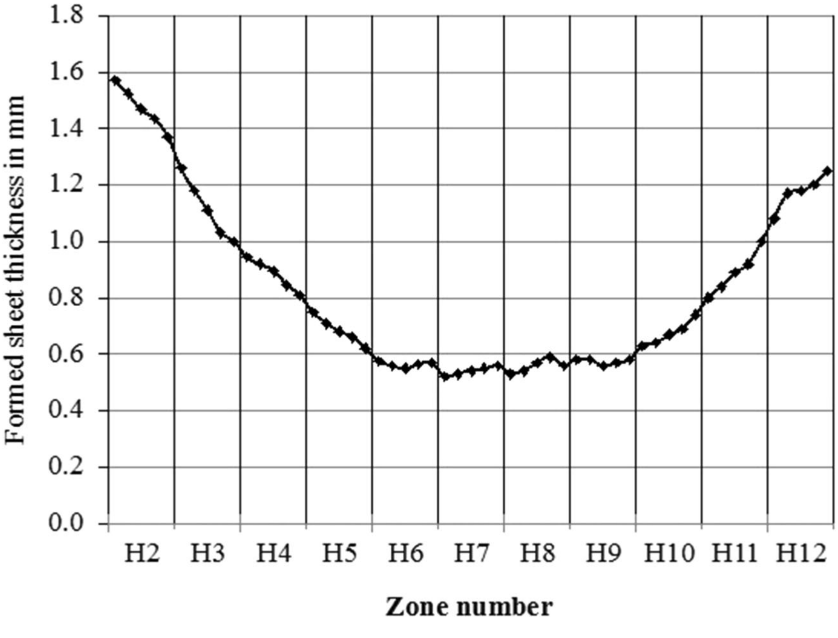
Zone H10: Zone H10 illustrates the effect of middle of the curve of the hemispherical cup. As the process is at the center of the hemispherical cup, the grains of the particles are marginally bigger. 60.6% is the maximum percentage of reduction in thickness of this zone. The minimum thickness within this zone is 0.63 mm & the maximum thickness within this zone is 0.74 mm.

Zone E3: Zone E3 shows the effect of second stage in forming process. Grains in this zone are slightly elongated. 35% is the maximum percentage of reduction in thickness of this zone. The minimum thickness within this zone is 1.04 mm & the maximum thickness within this zone is 1.29 mm.

Zone E5: This zone illustrates the flow of grains are parallel as no further changes in the grain flow due to the bidirectional pass of the roller. It is a highly strained region. The second stage grains also undergo stretching indicating thin elongated lines. 48.1% is the maximum percentage of reduction in thickness of this zone. The minimum thickness within this zone is 0.83 mm & the maximum thickness within this zone is 0.87 mm.

Zone E8: Zone E8 illustrates the effect of middle of the curve of the hemispherical cup. As the process is at the center end of the hemispherical cup, the grains of the particles are marginally bigger.36.9% is the maximum percentage of reduction in thickness of this zone. The minimum thickness within this zone is 1.01 mm & the maximum thickness within this zone is 1.19 mm.

Fig. 8 Thickness variation of hemi spherical formed part at different zone



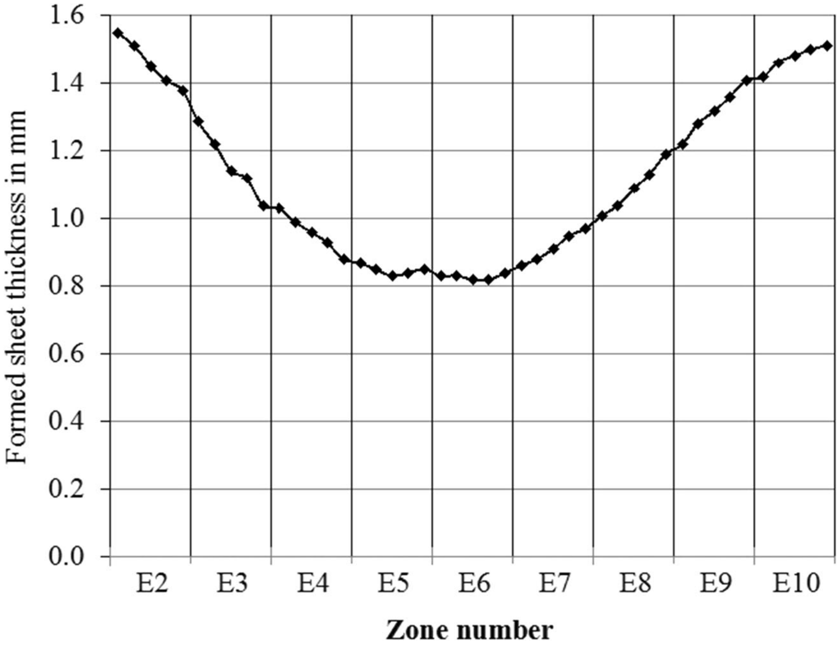


Fig. 9 Thickness variation of hemi-ellipsoidal formed part at different zone

Hardness

The hardness of the raw material and formed part sample was measured using Vickers hardness tester. The hardness values with 0.1Kgf measuring load of EDD steel at various depths in transverse direction are listed in Tables 6 and 7. The maximum hardness is 124.1Hv observed at 0.8 mm depth and surface hardness of 107.5Hv was observed in raw material.

The hardness change in the formed part of various zones is tabulated in Tables 6 and 7. Table 6 tabulates the hardness values of hemi-ellipsoidal formed part at different zone in transverse direction. Similarly, Table 7 tabulates hardness values of hemispherical formed part at different zone in transverse direction. The variations in hardness due to the effect of the die less spinning process are evaluated, by taking the hardness values at various depths from the inner surface (tool contacting surface) of the formed parts at different zones.

In hemi-ellipsoidal formed part, the maximum hardness is 176.1Hv observed in zone E5 at the depth of 0.75 mm from inner surface (tool contacting surface). Owing to the outcome of strain hardening of the formed part, material hardness was enhanced to a higher value. The inner surface of formed parts hardness varies from 127.1Hv to 137.5Hv and outer surface of formed parts varies from 130.9Hv to 136.3Hv.

Zone E3: The location shows the effect of the second stage in the forming process. The maximum value of 146.5Hv measured at 0.8 mm depth. The inner surface hardness 127.1Hv and outer surface hardness 136.3Hv was observed in this zone.

Zone E5: This location is the fourth stage of the formed part. It is a highly strained region with a maximum value of

Table 4 Zone wise thickness variation and maximum percentage of reduction in thickness of hemispherical formed part

Zone number	Minimum thickness within zone	Maximum thickness within zone	Thickness variation within zone	Maximum percentage of reduction in thickness within zone
H2	1.370	1.570	0.200	14.4
H3	1.000	1.260	0.260	37.5
H4	0.810	0.945	0.135	49.4
H5	0.620	0.750	0.130	61.3
H6	0.550	0.575	0.025	65.6
H7	0.520	0.560	0.040	67.5
H8	0.530	0.590	0.060	66.9
H9	0.560	0.580	0.020	65.0
H10	0.630	0.740	0.110	60.6
H11	0.800	1.000	0.200	50.0
H12	1.080	1.250	0.170	32.5

Table 5 Zone wise thickness variation and maximum percentage of reduction in thickness of hemi-ellipsoidal formed part

Zone number	Minimum thickness within zone	Maximum thickness within zone	Thickness variation within zone	Maximum percentage of reduction in thickness within zone
E2	1.380	1.550	0.170	13.8
E3	1.040	1.290	0.250	35.0
E4	0.880	1.030	0.150	45.0
E5	0.830	0.870	0.040	48.1
E6	0.820	0.840	0.020	48.8
E7	0.860	0.970	0.110	46.3
E8	1.010	1.190	0.180	36.9
E9	1.220	1.410	0.190	23.8
E10	1.420	1.510	0.090	11.3

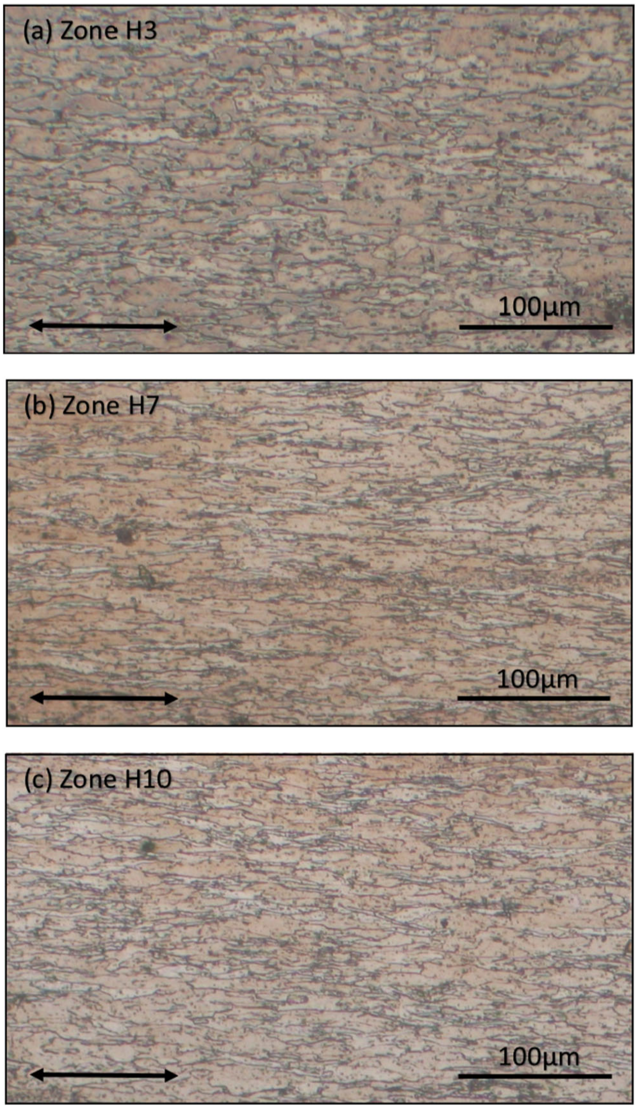


Fig. 10 Optical micrographs of hemispherical formed part at different zone in transverse section (**a**) Zone H3 (**b**) Zone H7 (**c**) Zone H10

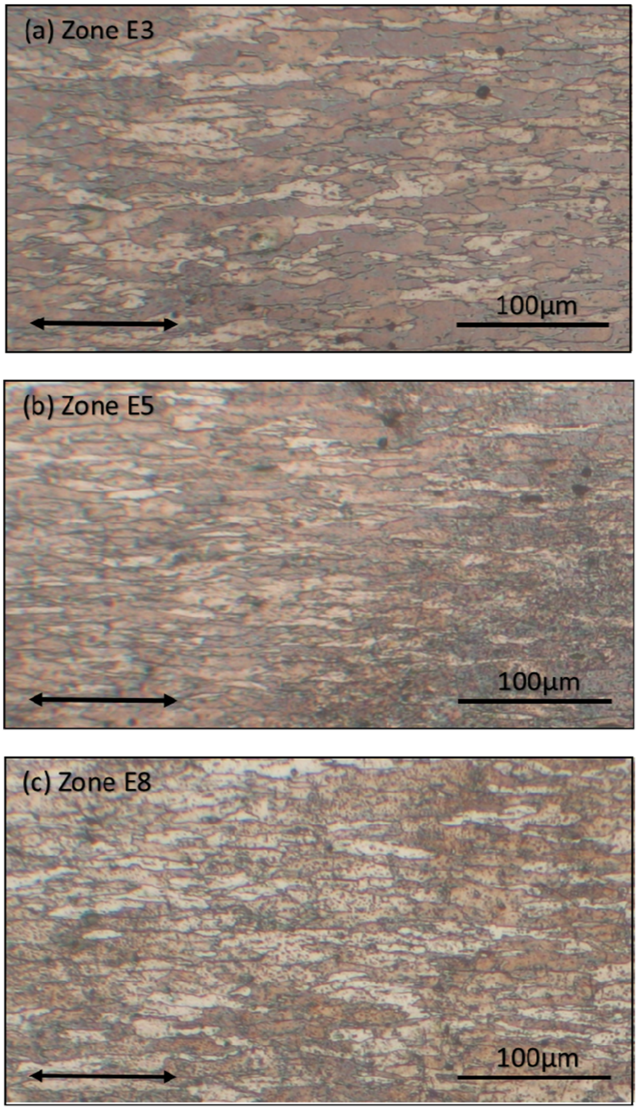


Fig. 11 Optical micrographs of hemi-ellipsoidal formed part at different zone in transverse section (**a**) Zone E3 (**b**) Zone E5 (**c**) Zone E8

176.1Hv measured at 0.75 mm depth. The inner surface hardness 136.8Hv and outer surface hardness 130.9Hv was observed in this zone.

Zone E8: This location is the seventh stage of the formed part. The maximum value of 150.3Hv measured at 0.9 mm depth. The inner surface hardness 137.5Hv and outer surface hardness 132.2Hv was observed in this zone.

In hemispherical formed part, the maximum hardness is 193Hv observed in zone H7 at the depth of 0.25 mm from inner surface (tool contacting surface). Owing to effect of strain hardening, the formed part material hardness was increased. The inner surface of formed parts hardness varies from 129.4Hv to 154.7Hv and outer surface of formed parts varies from 144.4Hv to 171.6Hv.

Zone H3: The location shows the effect of the second stage in the forming process. The maximum value of 153.9Hv measured at 0.6 mm depth. The inner surface hardness 129.4Hv and outer surface hardness 144.4Hv was observed in this zone.

Zone H7: This location is the middle stage of the formed part. It is a highly strained region maximum value of 193Hv measured at 0.25 mm depth from inner surface. The inner surface hardness 154.7Hv and outer surface hardness 171.6Hv was observed in this zone.

Zone H10: This location is the ninth stage of the formed part. The maximum value of 175.1Hv measured at 0.2 mm depth from inner surface. The inner surface hardness 153.3Hv and outer surface hardness 168.4Hv was observed in this zone.

Surface roughness

The Surface roughness variation of hemispherical and hemi-ellipsoidal formed part at various zone, shown in Figs. 12 and

Table 6 Hardness values of hemi-ellipsoidal formed part at different zone in transverse direction

Raw material		Zone no: E3		Zone no: E5		Zone no: E8	
Depth in mm	Hardness in HV@0.1Kgf	Depth in mm	Hardness in HV@0.1Kgf	Depth in mm	Hardness in HV@0.1Kgf	Depth in mm	Hardness in HV@0.1Kgf
0.05	107.50	0.05	127.10	0.05	136.80	0.05	137.50
0.10	111.60	0.10	136.80	0.10	148.40	0.10	138.90
0.20	119.20	0.20	140.50	0.20	156.40	0.20	144.50
0.80	124.10	0.60	142.90	0.60	173.00	0.50	129.90
1.30	116.30	0.80	146.50	0.75	176.10	0.90	150.30
1.50	118.50	1.00	142.50	0.80	130.90	1.00	142.10
1.55	109.80	1.10	136.30	–	–	1.10	132.20

13 are measured by contact type perthometer. As the depth varies, the surface roughness of the part also varies.

The arithmetic average surface roughness of the formed parts is plotted as a graph. In each zone, the inner surface (tool contact surface) and outer surface (tool non-contact surface) roughness values are taken in parallel to the rolling direction of the material for analysis.

In hemispherical formed part, the maximum surface roughness is Ra1.08 in inner surface and Ra1.92 in outer surface was observed in zone H7. In zone H2, H3, H4, H11, and H12 inner surface roughness values are observed lesser than blank roughness, measured as Ra0.63. In all zones, roughness observed between Ra0.5 to Ra1.1 in inner surface and Ra1.22 to Ra1.95 in outer surface. From above outcome, it illustrates that surface roughness was enhanced with enhancing in percentage of reduction in thickness. More than 50% of reduction in thickness results, higher than blank roughness in inner surface of the formed part. In all zones, outer surface roughness of the formed part is above the blank roughness.

In hemi-ellipsoidal formed part, the maximum surface roughness is Ra1.23 in inner surface and Ra1.45 in outer surface was observed in zone E5. In zone E2, E9 and E10 inner surface roughness values are observed lesser than blank roughness, measured as Ra0.63. In all zones, roughness observed between Ra0.53 to Ra1.23 in inner surface and Ra0.81 to Ra1.45 in outer surface. From above outcome, it illustrates that surface roughness was enhanced with enhancing in percentage of reduction in thickness. More than 35% of reduction in thickness results higher than blank roughness in inner surface of the formed part. In all zones, outer surface roughness of the formed part is above the blank roughness.

Chen et al. [15] analyzes causes of parameters involved for surface roughness of the formed parts. They concluded that a lesser roller feed, higher roller nose radius, Low viscosity lubricant, optimum mandrel speed and optimized tool path results in a lower surface roughness for the formed part.

Forming limit diagram or surface strain measurement

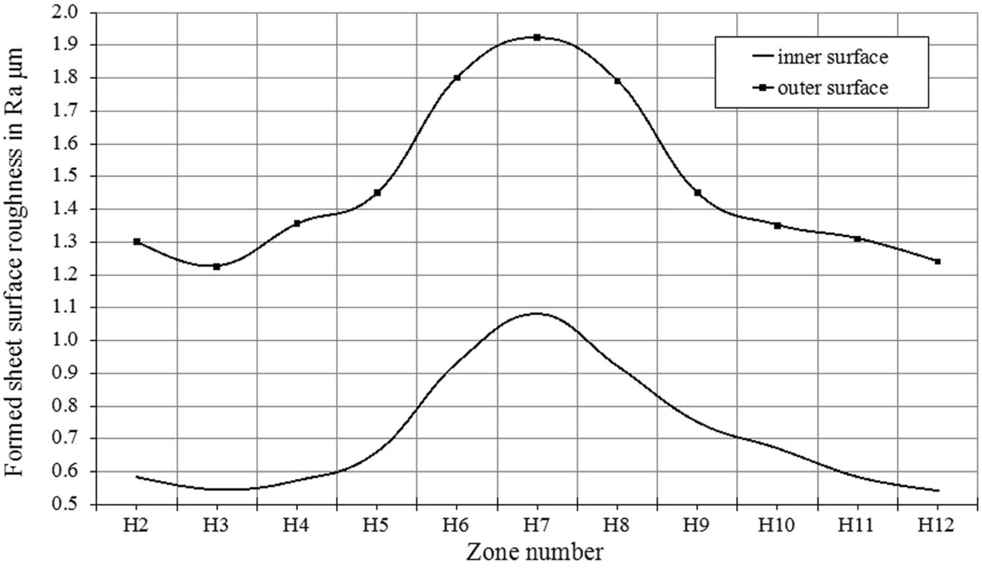
The FLD of hemispherical and hemi-ellipsoidal formed part at various zone are shown in Figs. 14 and 15. The various major and minor strain of the formed part zones are plotted as a FLD. In each zone around 10 grids are taken for the analysis. Using vision measuring instrument (Rapid I), the major and minor diameters of ellipses are determined and drawn on FLD as a graph.

FLD of hemi spherical formed part at various zone are shown in Fig. 14. Zone number E2 and H2 of the part is near to inner edge of blank holding plate. This zone prevents deformation near to the clamping area. Due to this reason, the

Table 7 Hardness values of hemispherical formed part at different zone in transverse direction

Raw material		Zone no: H3		Zone no: H7		Zone no: H10	
Depth in mm	Hardness in HV@0.1Kgf	Depth in mm	Hardness in HV@0.1Kgf	Depth in mm	Hardness in HV@0.1Kgf	Depth in mm	Hardness in HV@0.1Kgf
0.05	107.50	0.05	129.40	0.05	154.70	0.05	153.30
0.10	111.60	0.10	143.60	0.10	163.00	0.10	167.00
0.20	119.20	0.20	142.80	0.20	174.90	0.20	175.10
0.80	116.30	0.60	153.90	0.25	193.00	0.30	174.00
1.30	124.10	0.80	146.60	0.30	182.70	0.40	170.50
1.50	118.5	1.00	143.50	0.40	160.80	0.50	164.90
1.55	109.80	1.10	144.40	0.45	171.60	0.60	168.40

Fig. 12 Surface roughness of hemispherical formed part at different zone



major and minor strain distribution in the zone number E2 and H2 starts with value less than one.

In hemispherical formed part, the maximum major strain is 97.36% observed in zone H6. In zone H2, H3, H4, H11 and H12, the observed major Strain is less than 50%. Maximum major Strain value between 50 to 80% is observed in zones H9 and H10. Maximum major Strain value between 80 to 90% is observed in zones H8 and H5. Maximum minor strain is 69.6% is observed in zone H8. In all zones except H6 and H8, minor Strain values are less than 50%. Maximum minor strain value between 50 to 70% is observed in zones H6 and H8.

The FLD of hemispherical formed part shows that the zone number H2, H3, H4, H10, H11 and H12 are in safe

Fig. 13 Surface Roughness of hemi-ellipsoidal formed part at different zone

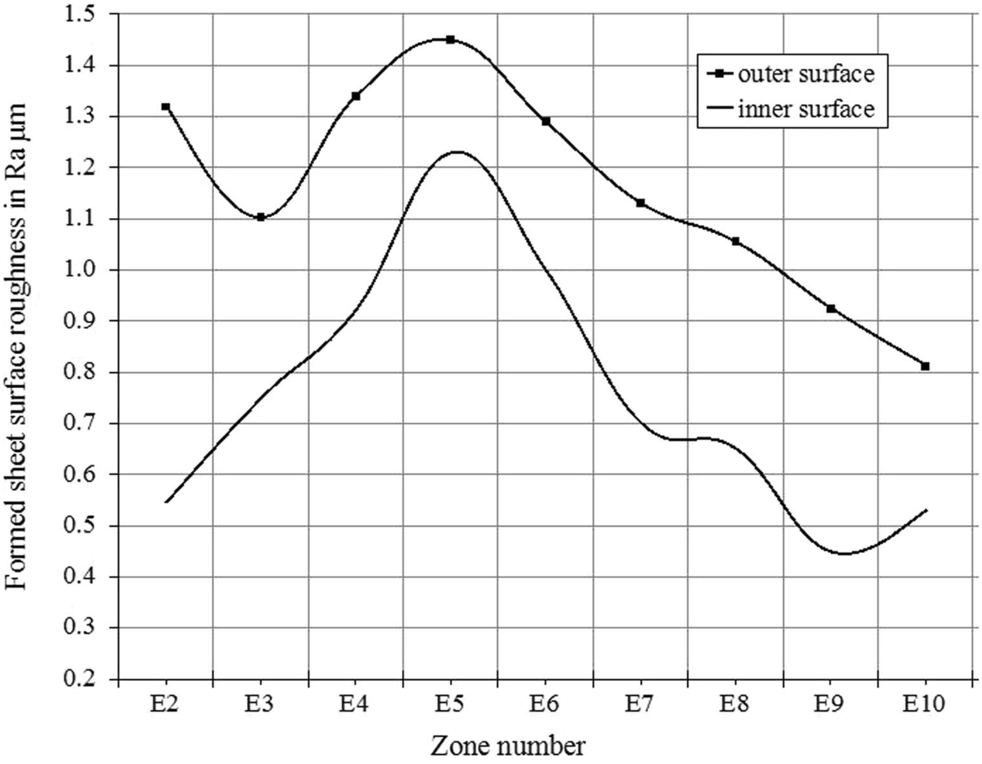
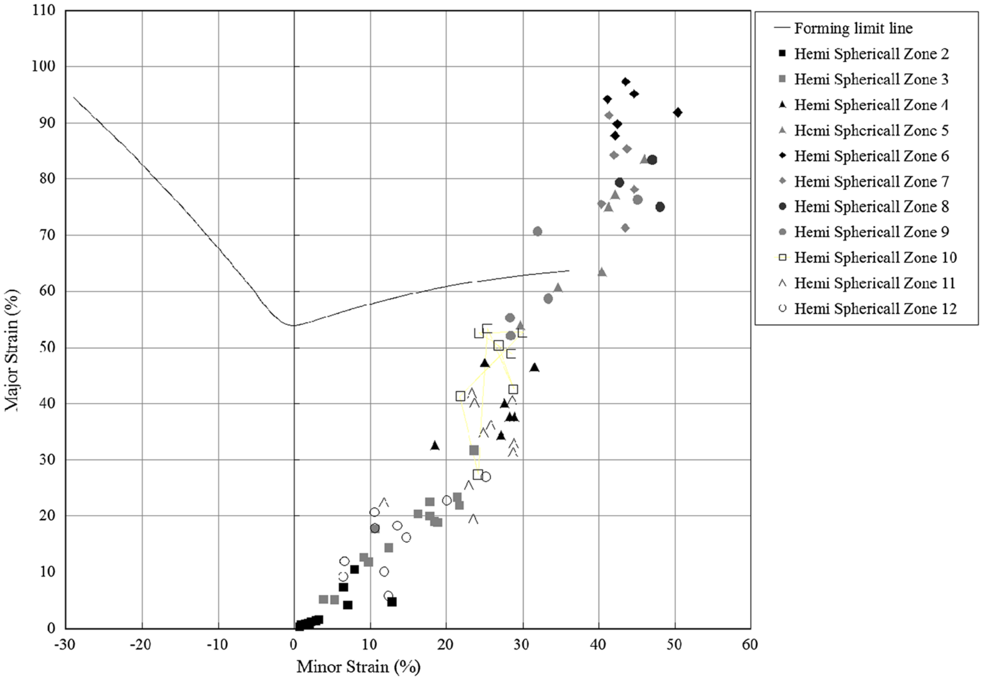


Fig. 14 Forming limit diagram of hemi spherical formed sheet at different zone



deformation region. Zone number H5 and H9 are in intermediate deformation region. Zone number H6, H7 and H8 are in fail deformation region.

In hemi-ellipsoidal formed part maximum major strain is 56.8% observed in zone E6. In zone E2, E3, E8, E9 and E10, the observed major strain value is less than 40%. Maximum major strain value between 30 to 50% is observed in zones E4, E5 and E7. Maximum major strain value above 50%is observed in zoneE6. Maximum minor strain value 31.8% is observed in zone E6. Maximum minor strain value below 20%is observed in zones E2, E3, E7, E8, E9 and E10. Maximum minor strain value between 20 to 30% is observed in zonesE4 and E5.

The FLD of hemi-ellipsoidal formed part shows that all the zones except E6 are in safe deformation region. Zone number E6 is in intermediate deformation region.

Fig. 15 Forming limit diagram of hemi-ellipsoidal formed sheet at different zone

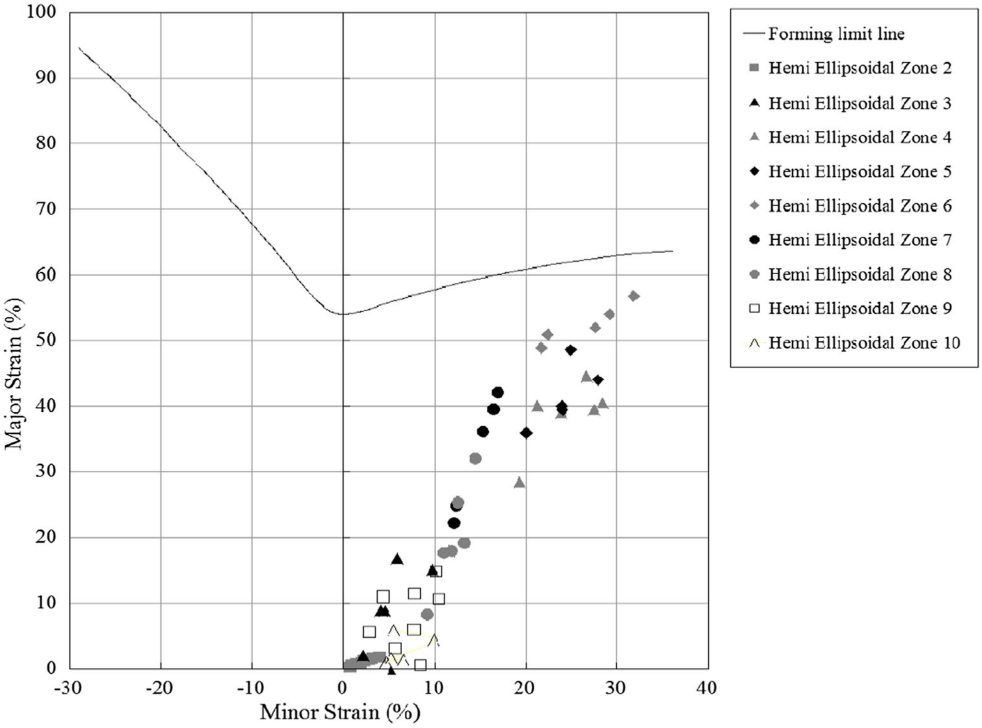


Table 8 Minimum and maximum of major and minor strains percentage in zone wise of hemispherical formed part

Zone number	Minimum major Strain within zone	Maximum major Strain within zone	Minimum minor Strain within zone	Maximum minor Strain within zone	Maximum % of reduction in thickness within zone
H2	0.227	10.400	0.760	12.840	14.4
H3	5.080	31.680	3.880	23.640	37.5
H4	32.640	47.280	18.440	31.520	49.4
H5	53.920	83.600	29.640	45.960	61.3
H6	87.720	97.360	41.120	50.360	65.6
H7	71.320	91.360	40.320	44.640	67.5
H8	70.520	83.440	42.720	69.600	66.9
H9	52.120	76.320	28.320	45.040	65.0
H10	27.440	53.360	21.760	30.000	60.6
H11	19.560	41.960	11.760	28.800	50
H12	5.800	27.000	6.400	25.120	32.5

Tables 8 and 9 shows minimum and maximum value of major and minor strains of hemispherical and hemi-ellipsoidal formed part. Also, the maximum percentage of reduction in thickness within the zone is included in the table to understand the deformation pattern.

In hemispherical and hemi-ellipsoidal formed part, the strain paths are in tension-tension stress condition and there is no tension compression and plane strain condition occurred in the forming process. Due to this reason, wrinkles failure is eliminated in die less MS process.

During the forming process the tool pushes the material, the side regions of the material undergoes stretching which gives maximum strain and less deformation near the center. The center and outer zones experience the least strain values.

Table 9 Minimum and maximum of major and minor strains percentage in zone wise of hemi-ellipsoidal formed part

Zone number	Minimum major Strain within zone	Maximum major Strain within zone	Minimum minor Strain within zone	Maximum minor Strain within zone	Maximum % of reduction in thickness within zone
E2	0.227	1.776	0.760	4.000	13.8
E3	2.040	17.960	2.160	11.560	35.0
E4	28.480	44.560	19.320	28.400	45.0
E5	35.920	48.600	20.040	27.880	48.1
E6	48.880	56.800	21.680	31.800	48.8
E7	22.200	42.080	12.120	16.920	46.3
E8	8.240	32.040	9.200	14.480	36.9
E9	0.640	14.880	2.880	10.480	23.8
E10	1.000	5.800	4.680	9.880	11.3

Conclusion

- The average percentage of reduction in thickness for the hemispherical and hemi-ellipsoidal formed part was 51.88 and 34.30%.
- The micro structure of the formed part exhibits fine-grained micro structure with elongated grains and oriented towards the forming direction.
- In hemispherical formed part, the maximum hardness in transverse direction is 193Hv was observed. The inner surface of formed parts hardness varies from 129.4Hv to 154.7Hv and outer surface of formed parts varies from 144.4Hv to 171.6Hv. In hemi-ellipsoidal formed part, the maximum hardness is 176.1Hv was observed. The inner surface of formed parts hardness varies from 127.1Hv to 137.5Hv and outer surface of formed parts varies from 130.9Hv to 136.3Hv.
- The minimum surface roughness of Ra 0.5 and Ra1.22 has been seen in the inner and outer part of the hemispherical formed part. Similarly, Ra 0.53 and Ra0.81 is observed for the hemi-ellipsoidal formed part.
- A maximum of 97.36 and 56.8% of major strain was noted in hemispherical and hemi-ellipsoidal formed part. Also, maximum minor strain of hemispherical and hemi-ellipsoidal was 69.6 and 31.8% were obtained.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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