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# FORMABILITY ANALYSIS OF PARABOLIC CUPS DRAWN FROM Ni 201 USING SINGLE POINT INCREMENTAL FORMING PROCESS

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## ABSTRACT

Numerical simulation of single point incremental forming process (SPIF) for Ni 201 sheet material was carried out using finite element analysis software and Taguchi experimental techniques. Reduction in thickness during SPIF process of the parabolic cups was estimated. Formability diagrams were drawn based on minor and major strains, and normalized major and minor stresses. The significant process parameters were identified using analysis of variance (ANOVA). Local thing along the walls of the parabolic cups were also estimated. It has been found that the maximum thinning ranges from 58% to 61% in the parabolic cups drawn from Ni201 using single point incremental forming process.

**KEYWORDS**: single point incremental forming process, Ni201, blank thickness, tool radius, step depth, coefficient of friction, parabolic cups, local thinning.

## INTRODUCTION

Single point incremental forming (SPIF) is a new sheet metal forming process wherein local stretching of the sheet is carried out using a point tool. The process is carried out on a computer numerical control (CNC) machine. In a series of research on single point incremental forming process, abundant explorations have been convinced to manufacture variety of shapes such as conical [1-4], pyramidal cups [5-7], elliptical cups [8], parabolic cups [9], hyperbolic cups [10] and hemispherical cups [11]. Feed rate, rotational speed, step depth, tool diameter, lubrication, wall angle and tool path are some of the most important parameters that affect the mechanics of SPIF process [12-13]. The formability in SPIF increases with decreasing tool radius. The numerical results have been validated with the grid-based experimental results for several materials [14-19]. In the case of SPIF the forming limit curve is a quite different from that in conventional forming [20-21]. Ni201 has exceptional corrosion resistant against caustic soda and chlorine gas. It is used for manufacturing of equipment for caustic soda and parts used in automotive, electrical and electronic applications.

The present work was to predict formability of single point incremental deep drawing of parabolic cups using Ni 201 sheet material. The design of experiments was carried out using Taguchi technique. The single point incremental deep drawing was executed using the finite element analysis software code namely ABAQUS.

## MATERIALS AND METHODS

In the present work, Ni 201 was used to make parabolic cups. The chemical composition of Ni201 is given in Table 1. The levels chosen for the controllable process parameters are summarized in Table 2. Each of the process parameters was chosen at three levels. The orthogonal array (OA), L9 was preferred to carry out experimental and finite element analysis (FEA) using ABAQUS software code. The obligation of parameters in the OA matrix is given in Table 3.

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***Table 1. Chemical composition of Ni 201***

| Element | C | Si | Mn | Cu | Fe | S | Ni |
|---|---|---|---|---|---|---|---|
| %wt. | 0.02 | 0.30 | 0.30 | 0.20 | 0.40 | 0.01 | 98.77 |

***Table 2. Control parameters and levels***

| Factor | Symbol | Level–1 | Level–2 | Level–3 |
|---|---|---|---|---|
| Blank thickness, mm | A | 1.0 | 1.2 | 1.5 |
| Step depth, mm | B | 0.50 | 0.75 | 1.00 |
| Tool radius, mm | C | 4.0 | 5.0 | 6.0 |
| Coefficient of friction | D | 0.05 | 0.10 | 0.15 |

***Table 3. Orthogonal array (L9) and control parameters***

| Treat No. | A | B | C | D |
|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 | 2 |
| 3 | 1 | 3 | 3 | 3 |
| 4 | 2 | 1 | 2 | 3 |
| 5 | 2 | 2 | 3 | 1 |
| 6 | 2 | 3 | 1 | 2 |
| 7 | 3 | 1 | 3 | 2 |
| 8 | 3 | 2 | 1 | 3 |
| 9 | 3 | 3 | 2 | 1 |

The rectangular sheet blank was created with desired diameter and thickness using CAD tools [22]. The sheet was meshed with S4R shell elements [23] as shown in figure 1. The cylindrical single point tool was also modeled with appropriate inner and outer radius and corner radius using CAD tools (figure 1). The mechanical interface between the contact surfaces was implicated to be frictional contact and modeled as Coulomb's friction model [1-9]. In the current work, the tool path profile as shown in figure 2 was used to generate parabolic shape. In profile tool path, the tool was moved in one plane till it had reached to its initial point. Thereafter, it was moved vertically downward direction by specified step depth. After reaching to the next plane, the tool was continued its motion in the same direction as that of earlier cycle. This process continued till the complete geometry was formed.

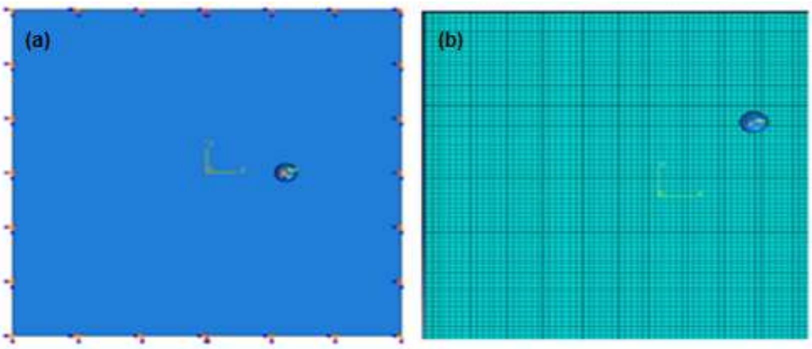


***Figure 1. Modelling (a) and discretization (b) of Ni201 sheet.***

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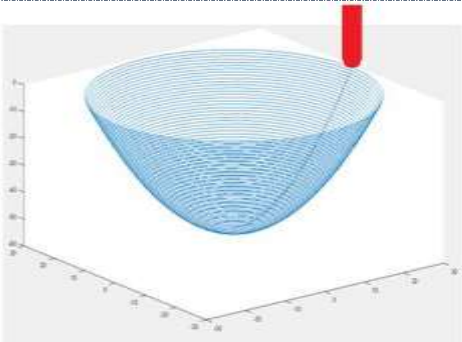

***Figure 2. Tool path profile.***

## RESULTS AND DISCUSSION

The rotating cylindrical tool was assumed to be rigid body. The cylindrical tool was also given three linear motions along z-direction to enable step depth and along x- and y-directions to outline profile of the cup. The sheet was given fixed displacement boundary conditions along its edges. In the present work, the significance of process parameters should have at least 90% of confidence.

### A. Effect of Process Parameters on von Mises Stress

The analysis of variance (ANOVA) of von Mises stress is summarized in Table 4. The Fisher's ratio is 3.46 at 90% of confidence. Due to insignificance of process parameters viz., blank thickness (A), tool radius (C) and Coefficient of friction (D), they were pooled to error. The most significant parameter is step depth (B) which contributes the most toward the variation in the von Mises stress: almost 55.16%.

***Table 4. ANOVA summary of the von Mises stress***

| Source | Sum 1 | Sum 2 | Sum 3 | SS | v | V | F | P |
|---|---|---|---|---|---|---|---|---|
| A | 2122.50 | 2130.00 | 2201.74 | 1275.76 | - | - | - | - |
| B | 2019.94 | 2204.32 | 2229.99 | 8753.12 | 2 | 4376.56 | 4.08 | 55.16 |
| C | 2148.17 | 2104.33 | 2201.74 | 1586.67 | - | - | - | - |
| D | 2148.17 | 2176.08 | 2130.00 | 359.04 | - | - | - | - |
| e-pooled | - | - | - | 6442.93 | 6 | 1073.82 | - | 44.84 |
| T | 8438.79 | 8614.74 | 8763.48 | 11974.59 | 8 | - | - | 100.00 |

**Note:** SS is the sum of square, v is the degrees of freedom, V is the variance, F is the Fisher's ratio, P is the percentage of contribution and T is the sum squares due to total variation.

Figure 3 represents the von Mises stress as a function of step depth. The von Mises stress increases with an increase in the step depth. The increase in the von Mises stress is very small for the change in the step depth from 0.75 mm to 1.0 mm. The von Mises increases with an increase in the equivalent plastic strain up to 0.6, 0.8 and 1.0, respectively, for 1.0 mm, 1.2 mm and 1.5 mm thick sheets as shown in figure 5.

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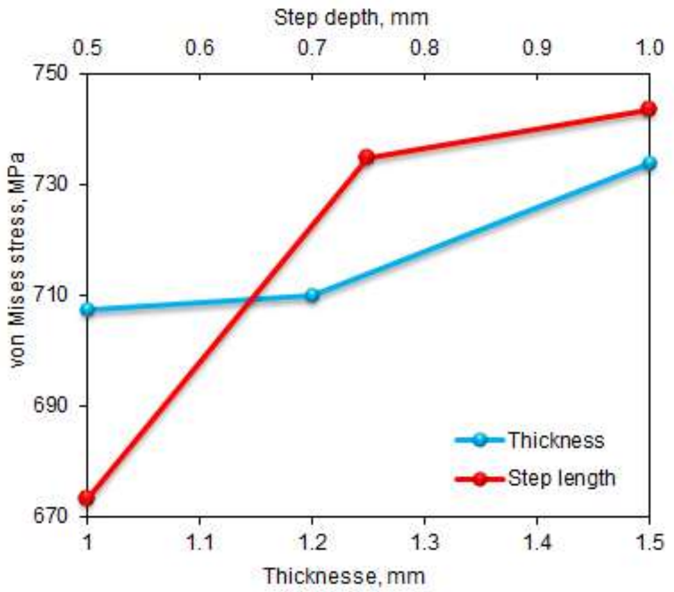


***Figure 4. Effect of sheet thickness and step depth on von Mises stress.***

The equivalent plastic strain reaches its maximum value at half portion (P3) of the cup wall from the flange and it starts decreasing along another half portion (P2) of the cup wall till the bottom of the cup (P1) as shown in figure 6. But, the von Mises stress increases from the flange to the bottom of cup, of course with fluctuation. The von Mises stresses induced in the cups are 685 MPa, 718 MPa, 743 MPa, 645 MPa, 743 MPa, 743 MPa, 731 MPa, 743 MPa, and 743 MPa, respectively for trials 1, 2, 3, 4, 5, 6, 7, 8, and 9 as shown in figure 7. The trials 3, 5, 6, 8 and 9 have nearly the same von Mises stress. The least stress induced is 645 MPa in the trial 4. It is also observed that the maximum stress (red in color) is induced in bottom of the cup. In all the parabolic cups, the von Mises stress is minimum in the flange area. In another study, the thickness strain distribution along the component and the effect of coefficient of friction have been studied [24]. It has been found that a lower friction coefficient results in a better thickness strain distribution along the component.

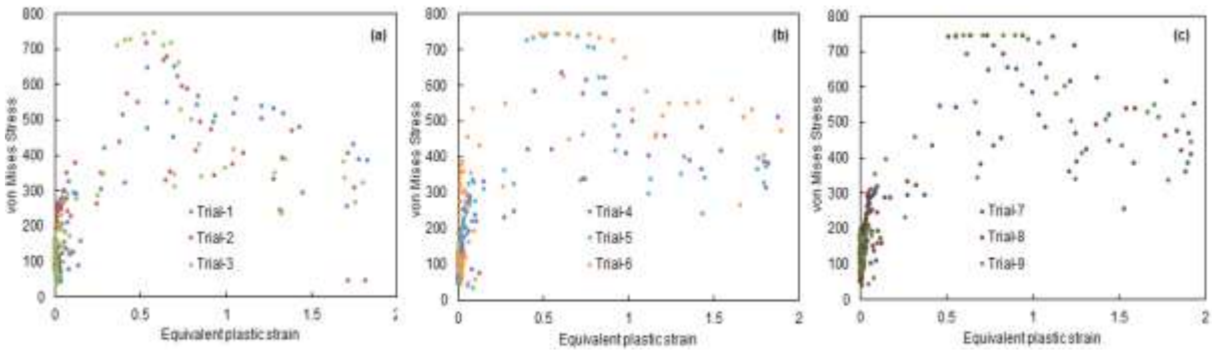


***Figure 5. Effect of equivalent plastic strain on von Mises stress: (a) 1.0 mm, (b) 1.2 mm and (c) 1.5 mm sheet thickness.***

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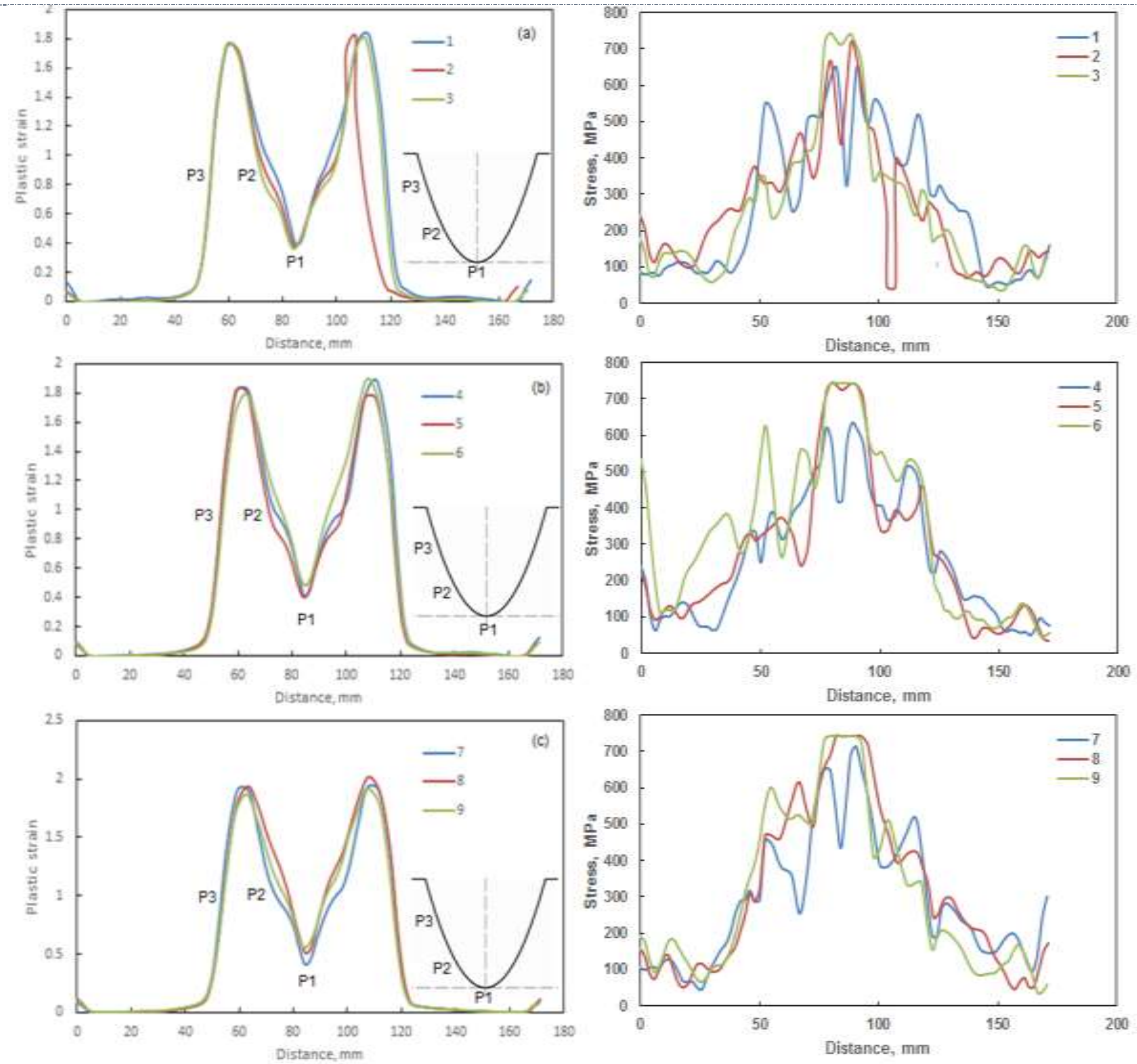


***Figure 6. Variation of equivalent plastic strain and von Mises stress along a path from flange to bottom of cup: (a) 1.0 mm, (b) 1.2 mm and (c) 1.5 mm sheet thickness.***

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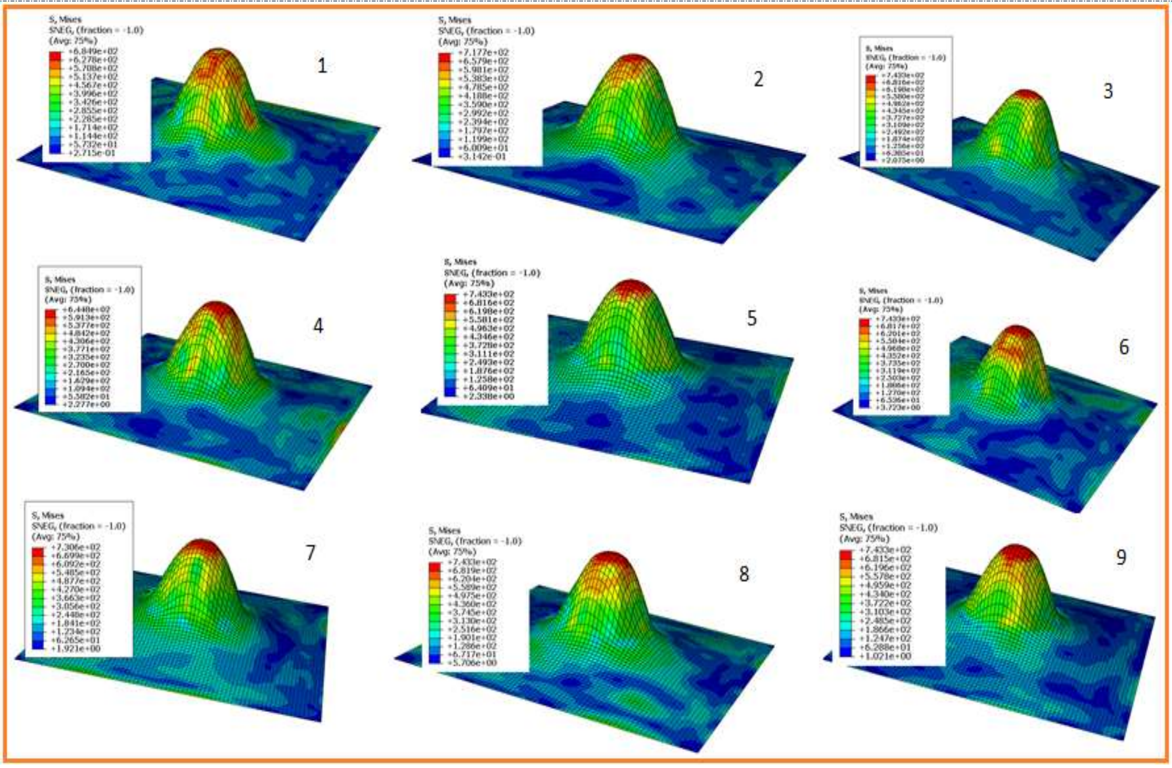


*Figure 7. The von Mises stress induced in the parabolic cups of all trial runs.*

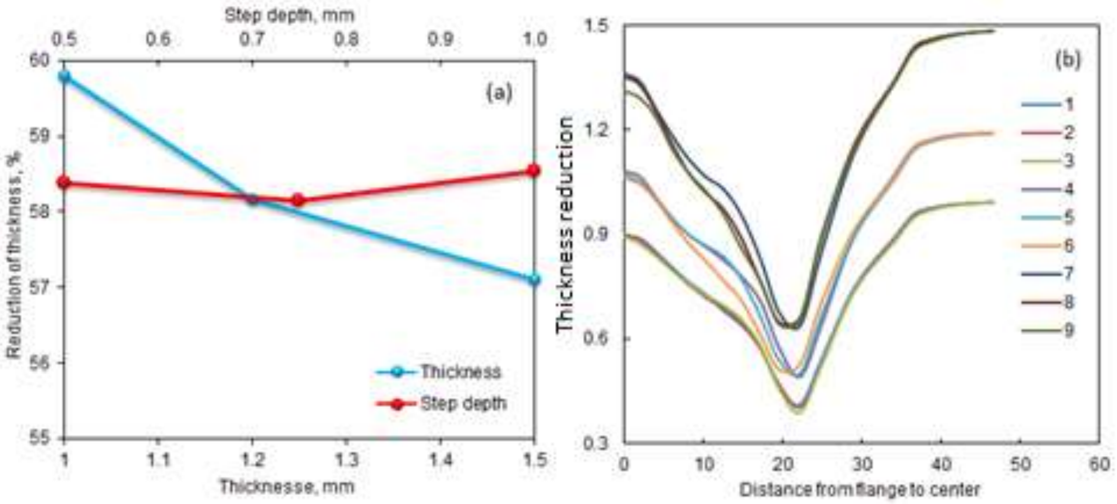


*Figure 8. Effect of sheet thickness and step depth on thickness reduction: (a) ANOVA results and (b) thickness reduction along a path from flange to center of the cup.*

## B. Effect of Process Parameters on Thickness Reduction

The analysis of variance (ANOVA) of thickness reduction of Ni 201 sheet during cup drawing process is summarized in Table 5. The insignificant process parameters are step depth (B), tool radius (C) and Coefficient of friction (D) according to 90% confidence for which Fisher's ratio is 3.46. The noteworthy parameter is sheet thickness of Ni 201 (A) which gives 72.77% of variation in the thickness reduction. It is observed from figure 8(a) that thickness reduction decreases with an increase of sheet thickness. The thickness is gradually decreases up to middle of the cup wall, and again it increases from middle of the cup wall to bottom of the cup as shown in figure 8(b). The necking is formed at the middle of the cup wall. This phenomenon (blue in color) can be seen in the raster images shown in figure 9. In evaluation of local thinning during cup drawing of gas cylinder steel using isotropic criteria [25], it has been observed that the strain is maximum at the thinner sections. The maximum local thinning ranges from 56% to 61% for the parabolic cups drawn using SPIF. The thinning and thickening indicate the flow of metal in the SPIF.

***Table 5. ANOVA summary of the thickness reduction***

| Source | Sum 1 | Sum 2 | Sum 3 | SS | v | V | F | P |
|---|---|---|---|---|---|---|---|---|
| A | 179.39 | 174.48 | 171.31 | 11.06 | 2 | 5.53 | 4.01 | 72.77 |
| B | 175.14 | 174.43 | 175.60 | 0.23 | 0 | - | - | - |
| C | 172.90 | 175.70 | 176.57 | 2.44 | 0 | - | - | - |
| D | 174.10 | 174.30 | 176.76 | 1.46 | 0 | - | - | - |
| e-pooled | - | - | - | 8.28 | 6 | 1.38 | - | 27.23 |
| T | 701.54 | 698.90 | 700.23 | 15.20 | 8 | - | - | 100.00 |

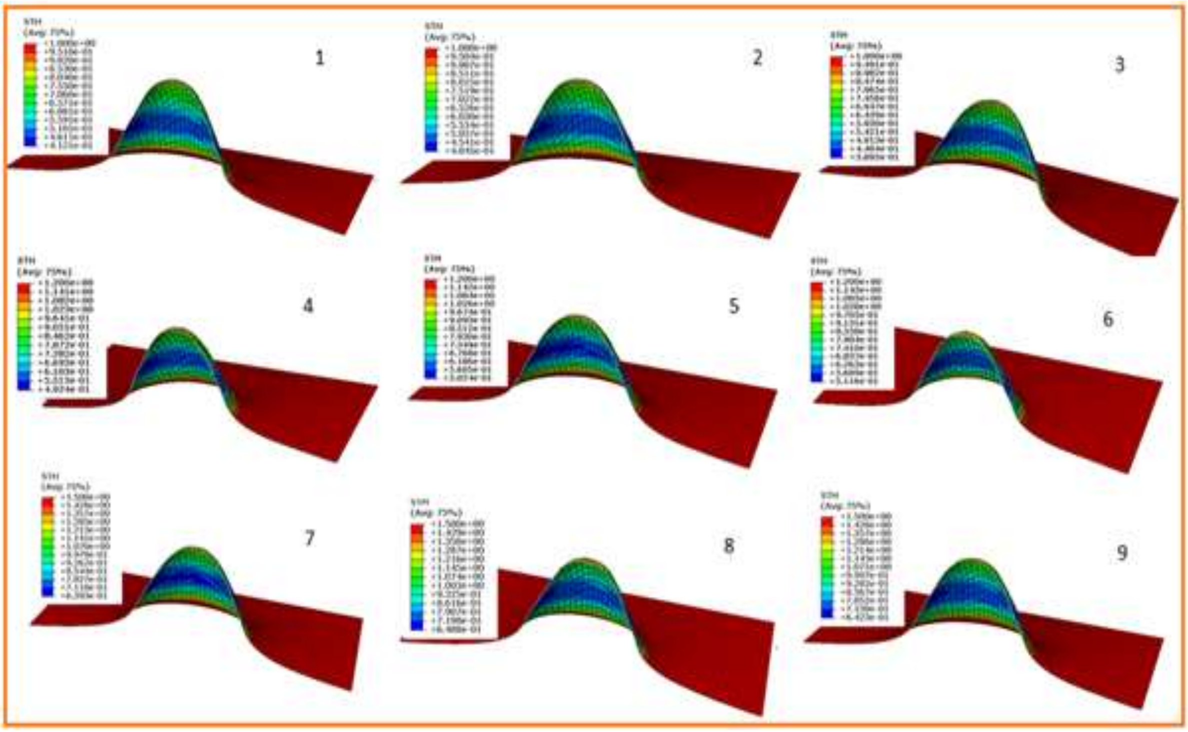


***Figure 9. The reduction in thickness of the parabolic cups for all trial runs.***

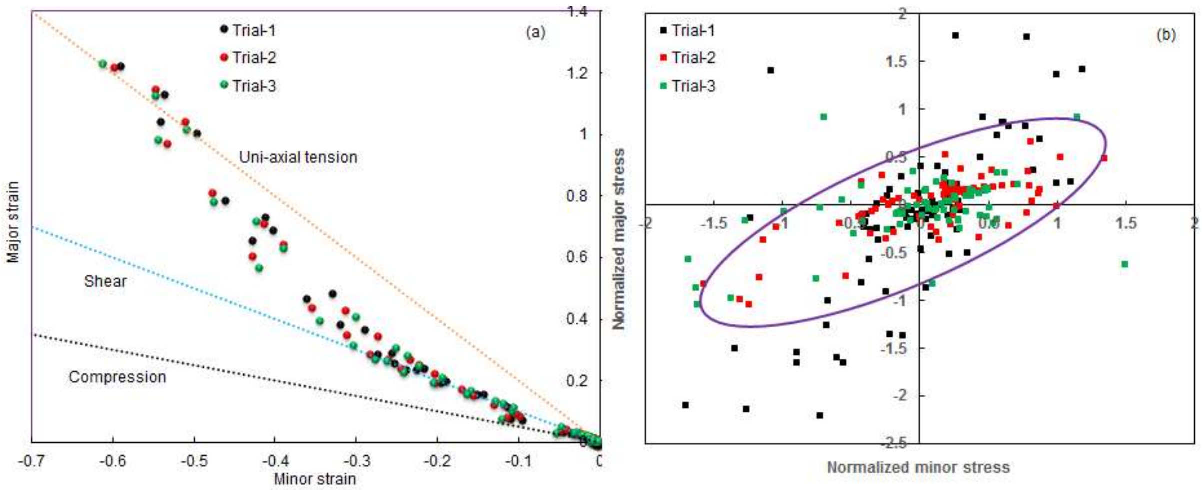


***Figure 10. Formability diagrams of the parabolic cup for all trial runs 1, 2 and 3: (a) strain based and (b) stress based.***

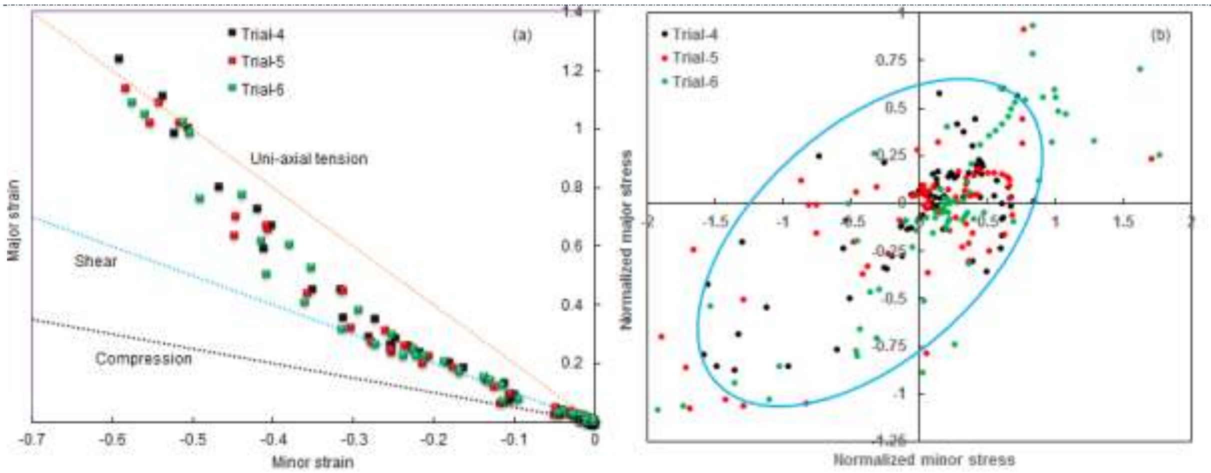


*Figure 11. Formability diagrams of the parabolic cup for all trial runs 4, 5 and 6: (a) strain based and (b) stress based.*

## C. Formability of Parabolic Cups

The strain-based formability diagrams of the cups are shown in figures. 10(a), 11(a) and 12(a). Uni-axial tension is highly dominated during the formation of parabolic cups. The stress-based formability diagrams of the cups are shown in figures. 10(b), 11(b) and 12(b). The major and minor stresses were normalized using the ultimate tensile strength (760 MPa) of Ni 201. For the trial 2 (figure 10(b)), trial 4 (figure 11(b)), and trial 7 (figure 12(b)), the normalized stresses are less than absolute unity. The von Mises stresses induced in the trials 2, 4 and 7 are, respectively, 718 MPa, 645 MPa, 731 MPa and 743 MPa. The lowest stress is 645 MPa for the trail 4. The conditions for the trial 4 given Table 6 are considered as the optimum process parameters for the parabolic cups to be drawn using SPIF.

*Table 6. Optimum process parameters for parabolic cups*

| Trial No. | Sheet thickness (A), mm | Step depth (B), mm | Tool radius (c), mm | Coefficient of friction (D) |
|---|---|---|---|---|
| 4 | 1.2 (level 2) | 0.5 (level 1) | 5.0 (level 2) | 0.15 (level 3) |

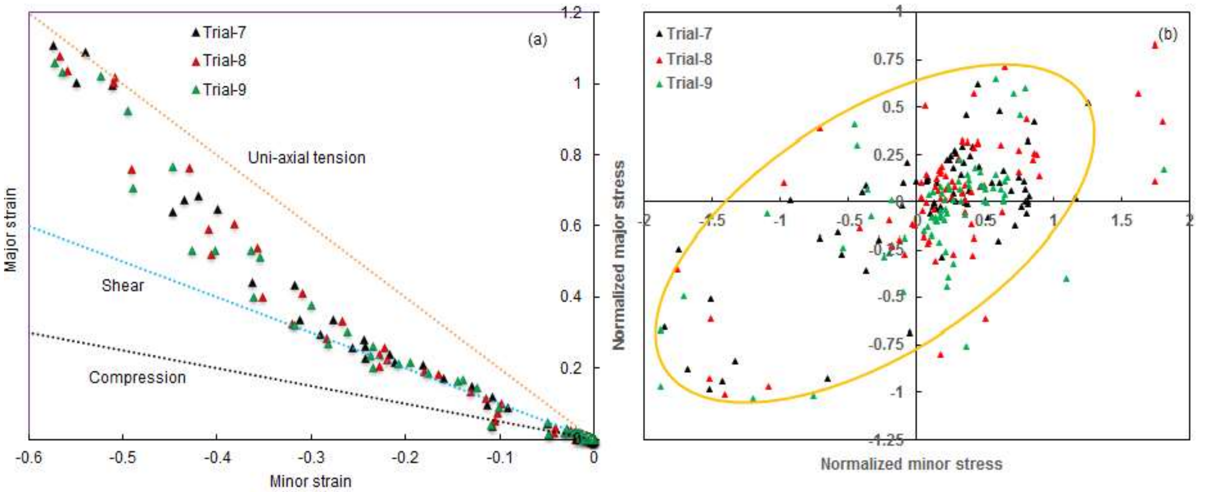


*Figure 12. Formability diagrams of the parabolic cup for all trial runs 7, 8 and 9: (a) strain based and (b) stress based.*

## CONCLUSION

The formability of drawing parabolic cups from Ni 201 using single point incremental forming process has been established. The single point incremental forming process was executed using finite element analysis software code namely ABAQUS. The local thinning is the foremost conclusion of the present project work. The local thinning, which is an indication of metal flow during single point incremental forming process of Ni201, varies from 56 to 61% along the walls of parabolic cups.

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