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Experimental and Numerical Studies on Formability of Stainless Steel 304 in Incremental Sheet Metal Forming of Elliptical Cups

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Abstract— New trends in sheet metal forming are emerging rapidly and different processes have been developed and used to accomplish the required goals of flexibility and reduction of cost in production. One of the innovative process in sheet metal forming process is the Incremental sheet forming process(SPIF) for small batch production and rapid prototyping. This is a flexible forming process which eliminates the die, punch and errors due to them. This project discusses about the finite element modelling of single point incremental sheet forming process by considering Elliptical geometry using Stainless Steel 304. ABAQUS 6.14 software code was used for finite element analysis. Experiments were carried on CNC machine and FEA results were validated with experimental results. The major SPIF process variables, which could influence the formability of elliptical cups of 304 stainless steel, were sheet thickness, step depth and tool radius.

Index Terms— AA6082 alloy, incremental forming process, elliptical cups.

1 Introduction

THE new sheet metal forming process known as Single Point Incremental Forming (SPIF) as shown in figure 1 with a high potential economic payoff for rapid prototyping applications suitable for flexible and small quantity production fulfilling this gap in metal forming processes. Relative to other conventional forming processes, SPIF offers low operating costs. It does not require any dedicated dies and it is ideal low production operations.

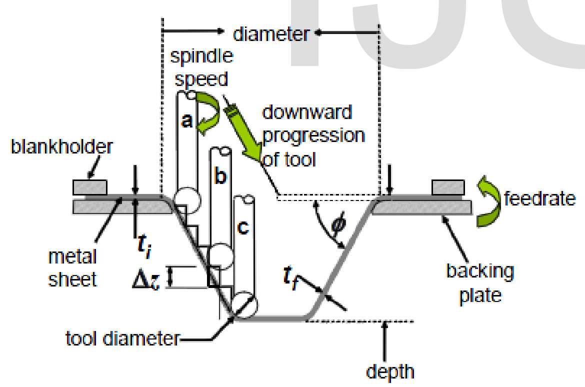

Fig. 1. Single point incremental forming.

The techniques adopted for sheet metal operations in the olden days were pressing, spinning and deep drawing. In a series of research on deep drawing process, a rich investigation have been carried out on warm deep drawing process to improve the super plastic properties of materials such as AA1050 alloy [1], [2], [3], [4], [5,] [6], AA2014 alloy [7], AA2017 alloy [8], AA2024 alloy [9], AA2219 alloy [10], AA2618 alloy [11], AA3003 alloy [12], AA5052 alloy [13], AA5049 alloy [14], AA5052 alloy [15], AA6061 alloy [16], Ti-Al-4V alloy [17], EDD steel [18], gas cylinder steel [19].

Unlike in the conventional sheet forming there are many parameters which affect the process mainly step depth, tool diameter, sheet thickness, friction coefficient, type of lubricant, tool path, increments along X&Y directions, spindle speed, feed rate, wall angle [20], [21].

Kopac et al. [22] given importance to the tool movement along the tool path, i.e tool path from center to the end of the sheet has good effect and also concluded that the optimal inclination of walls on the product are 45°, bigger angles may cause errors, cracks, and product failure.

Malwad et al. [25] described the deformation mechanism by variation of wall angles. Greater formability can be achieved in cups which have wall angle less than 75°. As the wall angle reduces shearing plays an important role in deformation and biaxial starching takes place at the corners so the sheet cracks at corners than sides. The numerical simulations of frustum of cone and pyramid with different slope angles were performed using LS-DYNA and analysed the formability.

Bagade et al. [23] has described the deformation behaviour and microstructure of EDD steels in incremental sheet forming. In which optimum wall angle are 73°, thickness is drastically reduced by 75% of sheet thickness and grain size decreased due to strains developed. Induced biaxial stretching causes failure in sheet.

Tisza, et al. [24] has stated that due to the special incremental nature of deformation process, significantly higher deformation can be achieved compared to conventional sheet metal forming processes and it also follows from its unique deformation characteristics that materials with lower formability in conventional forming may be manufactured in an economic way.

The objective of the present work was finite element analysis of elliptical cups formed by SPIF and the same was validated experimentally.

2 Materials and Methods

Stainless Steel 304 sheet is used in this study of single point

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incremental sheet forming is used. Stainless Steel contains Iron(Fe) more than 67% and rest varies as given in Table 1. The mechanical properties SS304 are given in Table 2.

TABLE 1
COMPOSITION OF STAINLESS STEEL 304

C	Cr	FE	Mn	Ni	P	S	Si
Max 0.08%	18-20%	67-74%	Max 2%	8-11%	Max 0.045%	Max 0.03%	Max 1%

TABLE 2
MECHANICAL PROPERTIES OF STAINLESS STEEL 304

Density	8 g/cc
Young's modulus	215 MPa
Tensile strength	0.29
Poisson's ratio	200 GPa

Plasticity data is obtained by conducting tensile test of Stainless Steel 304, from which the data obtained is represented as in figure 2. The obtained values were taken as material properties-plasticity for simulation of SPIF process.

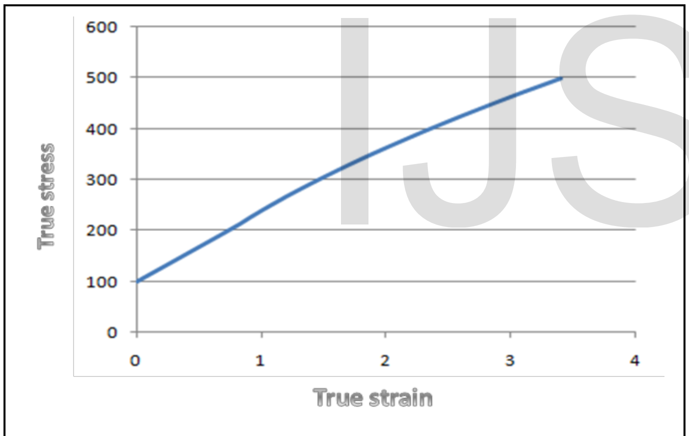


Fig. 2. True stress-strain curve of SS304.

2.1 FEM Pre-processing

The finite element method (FEM) has become an important tool for the numerical solutions of engineering problems. It is the piecewise approximation of object where the object is divided into number of small elements and each element is analysed, the integration of all such small elemental analysis finally give the solutions [26]. The finite element modelling of SPIF process was carried out using ABAQUS (6.14) software to fabricate elliptical cups. In geometric modelling a square sheet of dimensions 150 mm×150 mm and tool of cylindrical rod having hemispherical end 6 mm radius was created. The sheet and tool were modelled as deformable, analytical rigid body respectively and assembled together as shown in figure 3. In order to reduce the complexity of the model the other parts like tool holder, work holder were simulated by boundary conditions, hence this is a simplified model. Tool was given a reference point for governing tool motion. Contact is the interaction between tool and the sheet. Since the sheet undergoes the localised deformation at the contact, modelling of contact should be correct. The contact was modelled as frictional contact. Coefficient of friction was considered at different levels as 0.15.

Meshing is the process of discretizing the component. Here the sheet was meshed as shown in figure 4 with quad dominated S4R shell elements [26]. Element size has impact on computational time and results. Fine mesh gives the good results with greater computational time. Coarse mesh leads to inconsistent results, penetration and convergence problems during simulation process. A fine mesh of 2mm was generated for consistent results. The number elements are 5777 as given in Table 3.

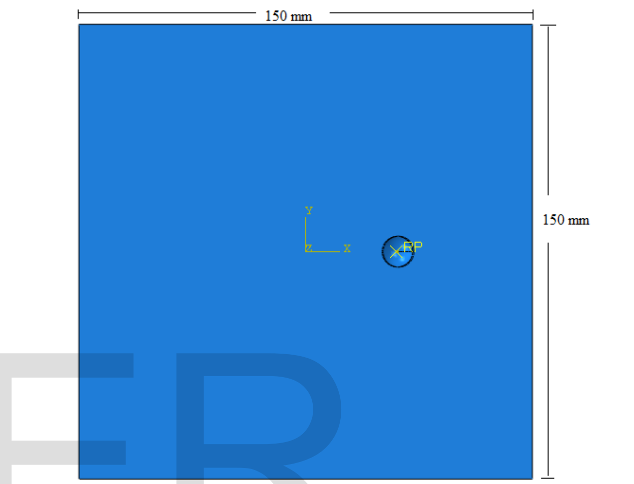


Fig. 3. Modeled sheet and Tool.

TABLE 3
NODES AND ELEMENTS

Element size	2mm
No. of Elements	5777
No. of Nodes	5626

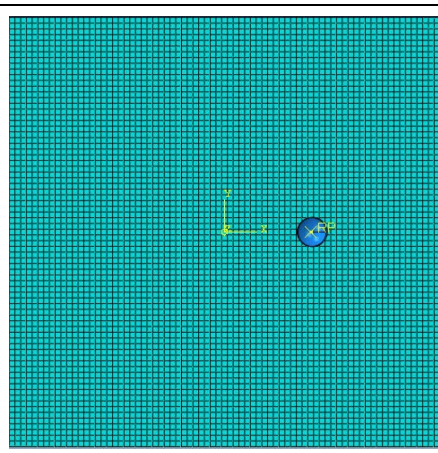


Fig. 4. Meshed sheet.

A simplified model was created by eliminating tool holder and work holder, but they are simulated by the boundary conditions. Edges of the sheet are fixed and tool was given four degrees of freedom, three translatory along x, y, z directions and one rotational around tool axis as shown in figure 5. The motion of the tool was controlled by amplitude data in smooth step form.

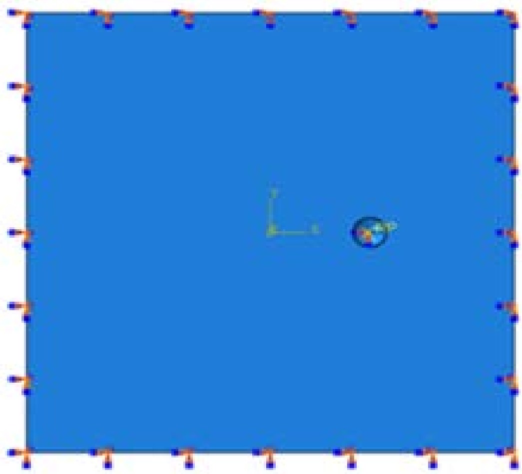


Fig. 5. Boundary conditions.

2.2 Experimental Validation

Initially tool was placed at centre of the square sheet and made it as zero position. Tool was moved in a specified contour till it completed the specified path then tool takes a specific depth in downward direction and moves to a new point. The tool path generated by the CAM package [27] for elliptical cup is as shown in the figure 6.

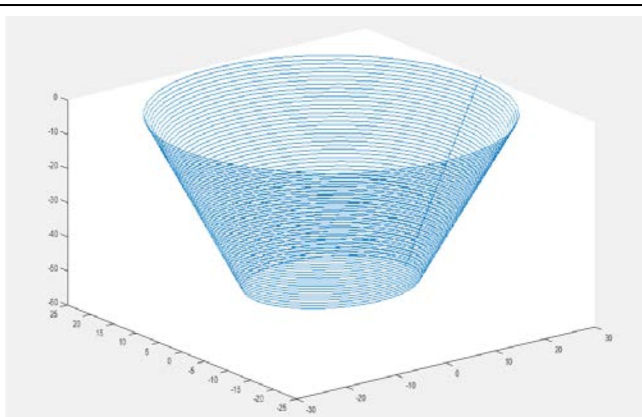


Fig. 6. Tool path generation.

Blank of 150mm × 150mm was cut from large sheet material using bench shear machine. Holes are made in the corners of the sheet using a drilling machine. Square patterns were drawn with 5 mm distance between them on back side of blank as shown in figure 6 for the purpose of extracting results from finished part. Blank (figure 7) is clamped to the blank holder and tool of 6mm diameter if fixed in tool holder. Tool was placed at one corner of sheet for elliptical cup. This was made zero position using inch mode in CNC machine. The part program was loaded and checked to eliminate errors. Program was run to start the machine. The formation of elliptical is shown in figure 8.

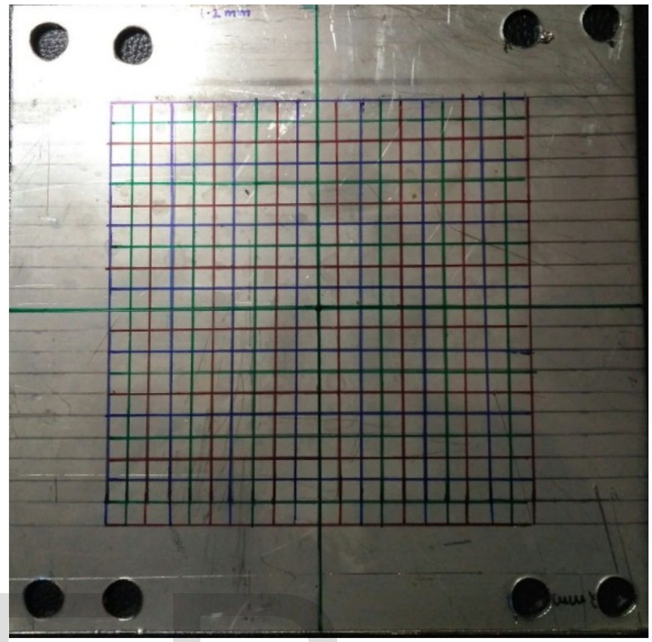


Fig. 7. Prepared sheet.

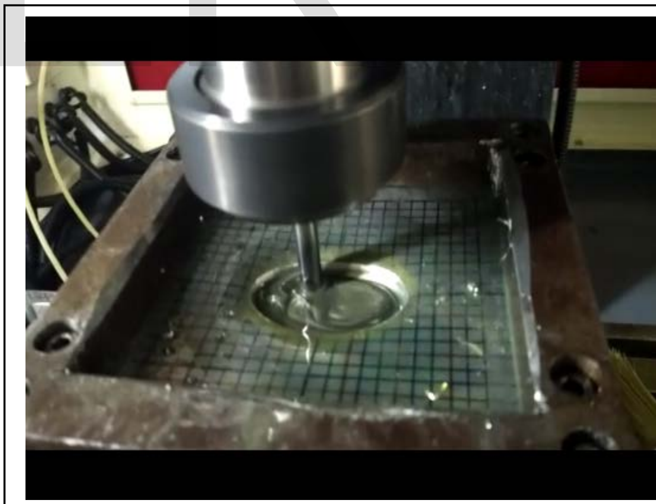
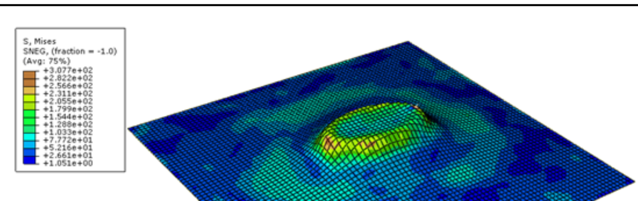


Fig. 8. Forming of elliptical cup on CNC machine.

3 Results and Discussion

For the elliptical cup, the maximum equivalent stress induced is 307.7 MPa (figure 9). The thickness of sheet was 1mm. For the cup the maximum equivalent stress was found in the minor axis side of cups. Maximum equivalent plastic strain obtained is 1.65, it is observed in the minor axis side of wall of the last step of simulation as shown in figure 10.



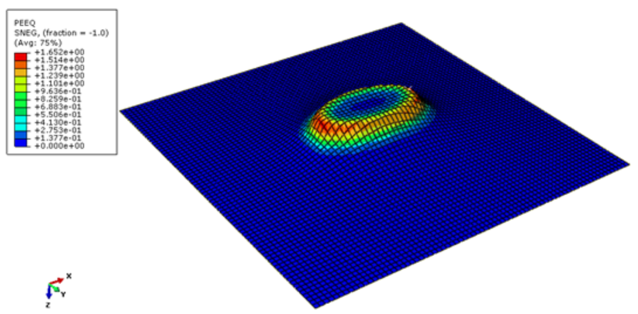


Fig. 10. Equivalent strain induced in (a) 1mm sheet and (b) 1.2mm sheet.

To validate the simulation results, the finite element grid of 5mm size was created on the backside of the cup material. The size of element was 2mm in case of simulation results. The stress and strain obtained by the finite element method coincides with the pattern on the cups.

From the experiments conducted on CNC machine to draw elliptical cup as shown in figure 11, the maximum strain was found to be 1.7. Strains obtained from FEA represent the maximum values of rupture. The experimental strains obtained were larger than that of FEA this is because fracture in the cup. This further indicates experimental strain is not within the allowable limits to form the cup (figure 12).

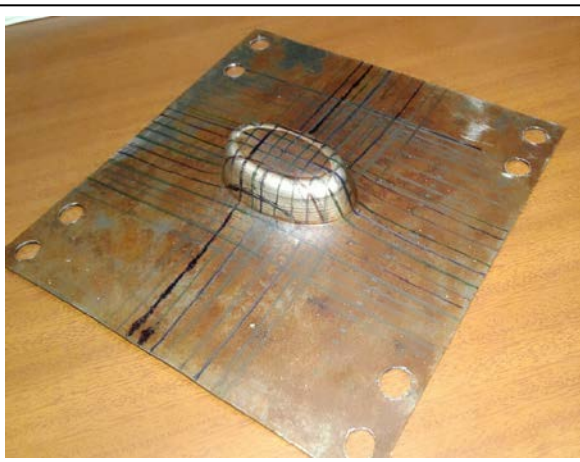


Fig. 11. Grid based deformation on elliptical cup.

The thickness variations along the wall for 1 mm and 1.5 mm cup are shown in figure 13. The thickness variation along the walls followed the same trend as predicted by the simulation. It is the side walls of the cups which experienced the maximum reduction in thickness. This is due to the reason that; the side wall is the most strained part in the formed component as shown in figure 10. So, the elements in this part of the cup are more stretched when compare to other elements. The thickness reduction in the flange and the bottom of the cup was negligible. It was observed that the strain paths are linear in the first stage and highly non-linear in the subsequent stages. The strain variations along the major and minor wall of elliptical cup is shown in figure 12. The thickness variation along the walls of elliptical cup is shown in figure 13. The thickness reduction was found to be maximum in the minor axis side of the cup.

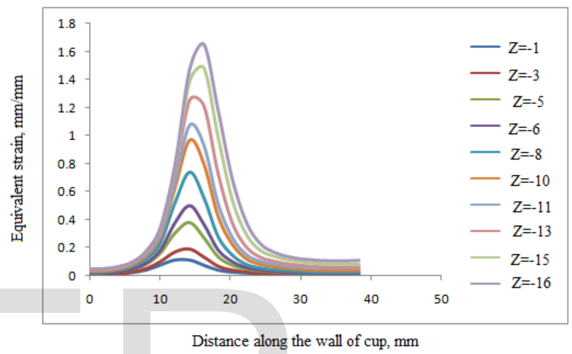


Fig. 12. Strain variation in the wall of the cup on 1mm thick sheet.

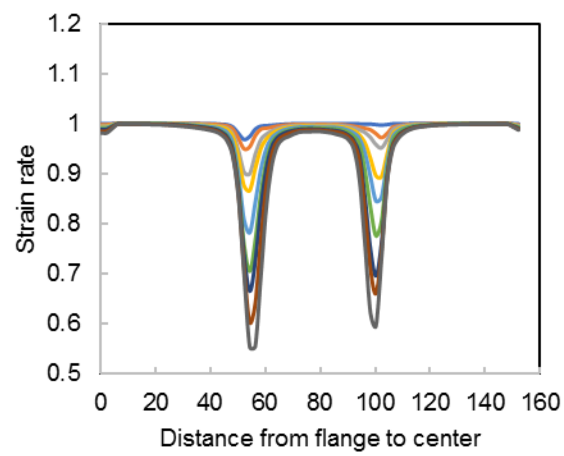


Fig. 13. Thickness variation along the walls of elliptical cup.

Figure 14 represents the formability diagrams for the 1 mm elliptical cups. In the very initial stages of forming the compressive stresses were predominant. But in the later stages of forming the formability limit diagrams of the cups are dominated by the uniaxial tensile stress.

The crack propagation (figure 15) in the elliptical cup is due to the high stress concentration on the minor axis side of the cup. Due to sudden increase in the radius of curvature of the shape the concentration of stress increases in that particular area which results in the thinning of the material and further elongation has resulted in the fracture of the cup. The tool path followed in the forming of the cup also influences the crack propagation and failure of the cup. The zigzag crack propagation path was triggered around the circumferential direction probably due to friction caused by rotation of the forming of the tool.

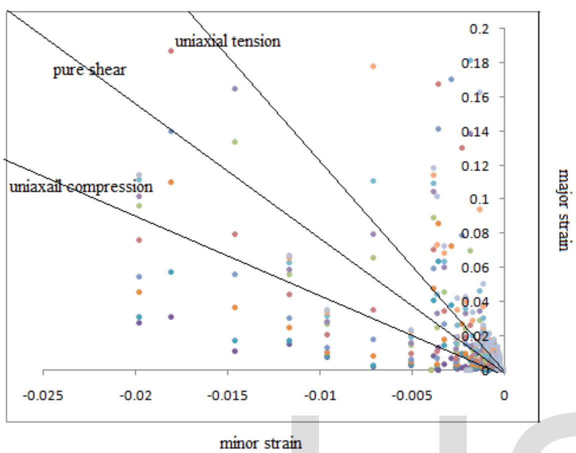


Fig. 14. Formability limit diagrams of (a) 1mm and (b) 1.2mm thick sheets.

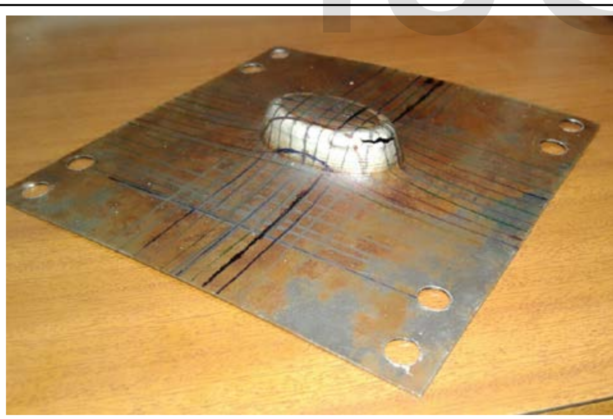


Fig. 15. Crack propagation in the elliptical cup.

4 Conclusion

In the present work, the finite element analysis and validation are successfully implemented for single point incremental forming process of SS304 sheet. Initially the shear and compressive stresses were dominating the formability of elliptical cup 304 stainless steel. At later stages tension is highly predominant on the minor axis side of the cup resulting in the fracture of the cup. The experimental strains obtained were larger than that of FEA this is because fracture in the cup this further indicates experimental strain is not within the allowable limits to form the cup. Another parameter which influences the forming of the cup is that the complexity of the shape. Due to sudden increase in the radius of curvature of the shape the concentration of stress increases in that particular area which results in the thinning of the material and further elongation has resulted in the fracture of the cup. It has been shown that tool path plays an important role in the final outcome and geometry accuracy of the path generated so tool path along with the features and features interaction can be used to improve the accuracy of features in the part produced by SPIF.

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