Experimental and Finite Element Studies on Formability of Low Carbon Steel Sheets using Deep Drawing

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Abstract

One of the commonly used metal forming processes is deep drawing, in which circular blanks are converted into a cup or shell with good surface finish. In this paper, the forming characteristics of Deep Draw Steel (DDS), a low-carbon steel with many engineering and automotive applications, is investigated by deep drawing. The forming limit diagram is a useful concept in favor of characterizing the formability of sheet metal. The present work is aimed to investigate the limiting draw ratio (LDR) and the forming limit diagram during forming for the various punch strokes is examined. The experimental findings such as thickness distribution and thinning limit of the formed cup are compared with the simulation results. Good correlation was obtained between the finite element predicted results and experimental results. Experimental Results shows that best forming characteristic were found at a punch stroke of 50 mm with LDR value of 2.2. Finite Element Analysis model was built using Abaqus/Standard 6.10-1. Von Mises stress distribution for the best forming conditions was analyzed using simulation results.

Keywords: formability, metal forming, deep drawing, limiting drawing ratio, punch stroke, forming limit diagram

I. INTRODUCTION

The most commonly used metal forming process is deep drawing, which converts the blanks into a cup or shell with good surface finish without the initiation of cracks (*O.A. Sokolova, 2012*). Successful deep drawing depends on many factors such as material type, geometry, punch feed, blank temperature, binder pressure etc (*H. Monajati, 2010*). Even one of these factors if not controlled properly can cause failure during forming. The defects during deep drawing include wrinkling in the flange, wrinkling in the wall, tearing, surface scratches etc. Hence while analyzing the formability characteristics of steel or alloy sheets; it is essential to deep draw the blanks with proper working conditions to avoid defects (*V. Uthaisangsuk, 2008*).

Deep draw quality steel sheets formed through deep drawing have extensive industrial applications such as automotive body applications, petrol tanks, compressor shells, truck frames and wheel rims etc(*C. Capdevila, 2006*). However during deep drawing the steel sheets are subjected to large strains in order to obtain the final shape. Consequently the sheets may experience tearing or cracking during the process and it becomes imperative to study their formability characteristics.

Many researchers have conducted formability tests to improve the formability characteristics of steels both at normal and at elevated temperatures (*D Ravi Kumar, 200: Swadesh Kumar Singh, 2010:* Claudio Garcia, 2006: V. Uthaisangsuk, 2007). Still formability studies on deep drawability of steels under varying stroke lengths have not been discussed in detail. Therefore this paper deals with the formability characteristics of deep draw quality steel at various operating conditions. FEM Simulation has been done and the simulated results are compared with experimental findings.

II. EXPERIMENTAL PROCEDURE

Production of thin walled parts with complicated shapes like automotive panels and structural parts is easy through deep drawing. To evaluate the deep drawability of steel sheets Limiting Drawing Ratio tests were conducted in a 80 T hydraulic press at room temperature. The experimental setup is shown in Fig 1. After the experiments, the Drawing Ratio (DR) and Limiting Drawing Ratio (LDR) were calculated by the following formulas

Draw ratio : D_o / d_o ------ (1)

Limiting draw ratio : $D_{o\,max} / d_o$ ----- (2)

Fig. 1. Experimental Test Rig

The material used for the present study is Low carbon deep drawing steel sheet of thickness 0.8 mm. Circular blanks of various diameters (d_0) ranging from 90 mm to 114 mm were cut from the purchased material at intervals of 2 mm by shearing operation. The characteristics of the parent material are listed in Table I.

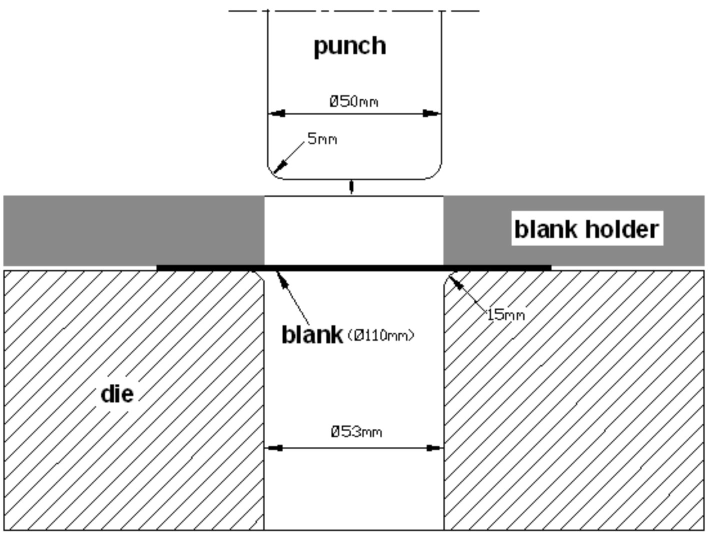

Fig. 2. Dimensions of the tools for deep drawing process.

TABLE I
Characteristics of cold rolled Deep Draw Steel

Properties	Unit	Value
Yield Strength	MPa	190
Tensile Strength	MPa	275
Young Modulus	MPa	205
Min Elongation	%	42
Thickness	mm	0.8

The tool and blank dimensions are shown in Figure2 and input values are listed in table II.

TABLE II
Input values of the deep drawing process.

Input Values	Punch Stroke(d), mm			
	d = 30	d = 30	d = 40	d = 50
Blank Hold Force, kN	100	120	140	160
Punch Load, kN	300	320	340	360
Punch Velocity, mm/sec	2	2	2	2

III. FINITE ELEMENT SIMULATION

Trial and error method of parameter optimizations involve lot of expenditure and loss of time. To overcome this problem process modeling through computer simulation has been introduced(S. V. S. NarayanaMurty, *2003*). Finite Element Method is used in many forming operations to optimize the various input parameters and produce defect free components. By adopting FEM the chances of re-designing of tools for making defect free products can be minimized (*T.W Kua*, *2002*). Many commercial codes are available for Finite Element Analysis in metal forming such as ABAQUS, DYNA-3D etc (T Meindersa, *2000: Kazunari Shinagawa, 1991: Ghader Faraji,2012:* J.P. Fan, 2006).

A. Description of the Model

The Finite element analysis in the present work was done using Abaqus/Standard 6.10-1. Initially the structural material of various parts of the models namely blank, blank holder, die and punch were assembled in the pre processor with exact specifications. The geometry of parameters used in the analysis are listed in Table III. To model the blank, die, blank holder and punch, 2D elements were created with 4 nodes.

TABLE III
Tool and material geometry

Sl. No	Parameter	Geometry size (mm)
1	Blank Thickness (t)	0.8
2	Blank Diameter (D_0)	90- 114 at intervals of 2 mm
3	Punch Diameter (d_p)	50
4	Punch Travel (L)	50
5	Die Profile Radius (r)	15
6	Die cavity Diameter (D_d)	53

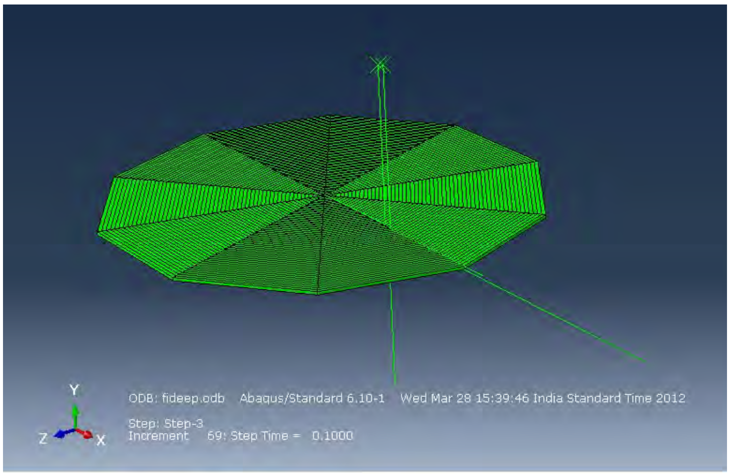

Fig 3. Blank at initial configuration

The initial configuration of the blank is illustrated in Fig 3. During deep drawing process the sheet is subjected to radial stress as the blank is forced into the die cavity and compressive stress due to the blank holder pressure. In addition the flange of the sheet is subjected to wrinkles due to the hoop stress developed in circumferential direction.

The load applied on the sheet material was modeled as a disseminated load on blank holder and blank contact surfaces. The co-efficient of friction between contact surfaces has an important effect during forming process. Hence it should be assigned before initiating the process(Bilgin Kaftanoglu, 1973). The value of friction co efficient between blank and the punch was taken as 0.125 and that of for the blank and blank holder was taken as 0.05. The punch velocity was maintained at 2 mm/sec.

The movement of the punch was defined using a pilot node located at the nose of the punch. This node was also used to obtain the contact pressure during the simulation. The depth variations of the cup after 30 mm punch stroke (d) are illustrated in Fig 4. The contact pressure of the punch on the blank material during the simulation process for the various punch strokes is illustrated in Figure 5 (a-d).

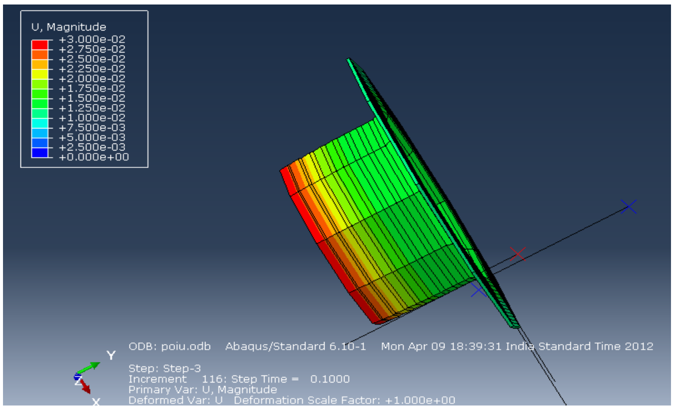

Fig. 4. Depth variations of the cup after 30mm punch displacement

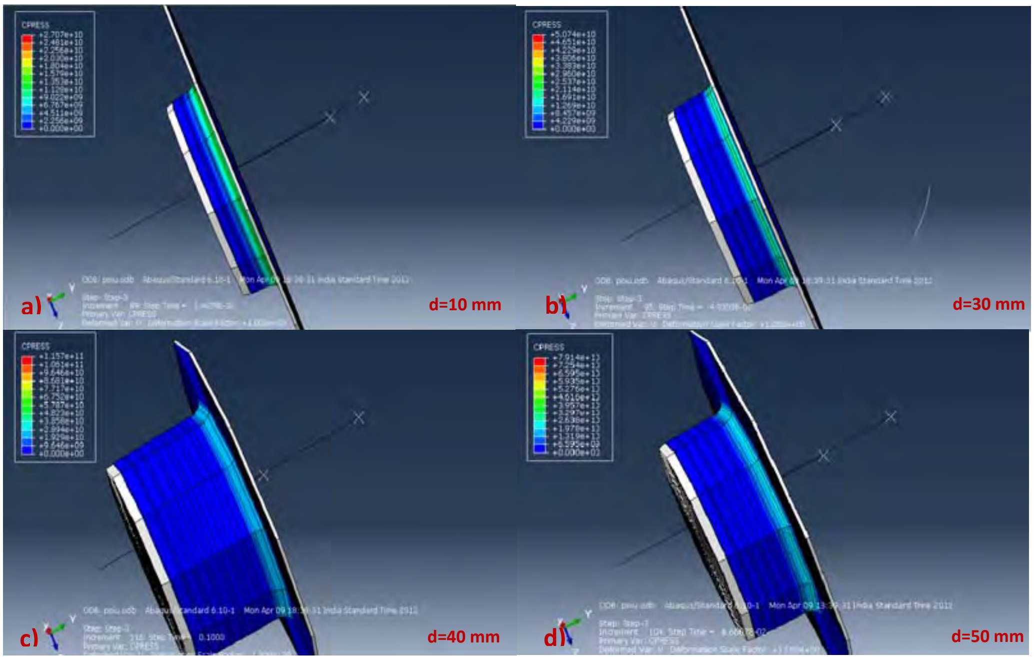

Fig. 5. (a - d) Contact Pressure of the Blank for various punch strokes (d)

IV. RESULTS AND DISCUSSION

The formability of the sheet is indicated by Liming Drawing Ratio (LDR). It is the ratio of maximum blank diameter that can be formed into cup without the flange to the diameter of the punch. The blanks of progressively increasing diameters (D_o) are drawn into cups using a punch of diameter d_p. The maximum diameter of the blank (D_{0max}) just before the first defect occurs is used to find the LDR value. This LDR value determines the deep drawability of the material (*Yoshihiro Yazawa, 2003*). Figure 6 shows the array of cups formed at different punch strokes with a blank thickness of 0.8 mm and punch radius of 5 mm

Fig. 6. Array of cups at different punch strokes

Hence the Liming Drawing Ratio (LDR) for the specimen considered was calculated as 2.2. Figure 7 (a-d) shows the cups formed at different punch strokes with a blank diameter of 110 mm with thickness of 0.8 mm.

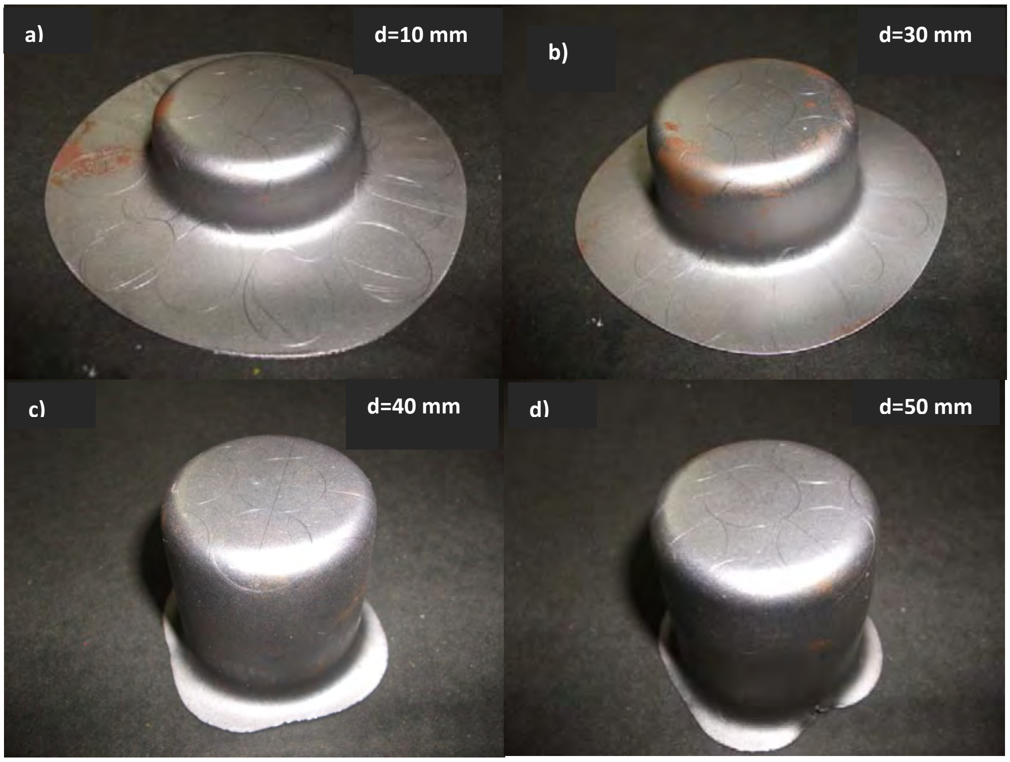

Fig. 7. (a-d) Formed cup at different punch strokes (d) with LDR of 2.2

Based on the major and minor strain values obtained by the LDR test, the Forming Limit Diagram was constructed and analyzed. The experimental and simulation results such as thickness distribution, thinning limit and Von Mises stress distribution for the formed cup with a LDR value of 2.2 are discussed in detail.

A. Forming Limit Diagram

Figure8 illustrates the blank before deep drawing process. Sheet metal can be deformed only to a certain level before fracture. This can be determined using the forming limit diagram. The forming limit diagram (FLD) shows the limit of success of the sheets as a function of major and minor strains. It serves as an important guideline to evaluate the

formability of sheets (*L. Wang, 2006*). The major and minor strains can be calculated from the deformation of the circles drawn on the surface of the blanks.

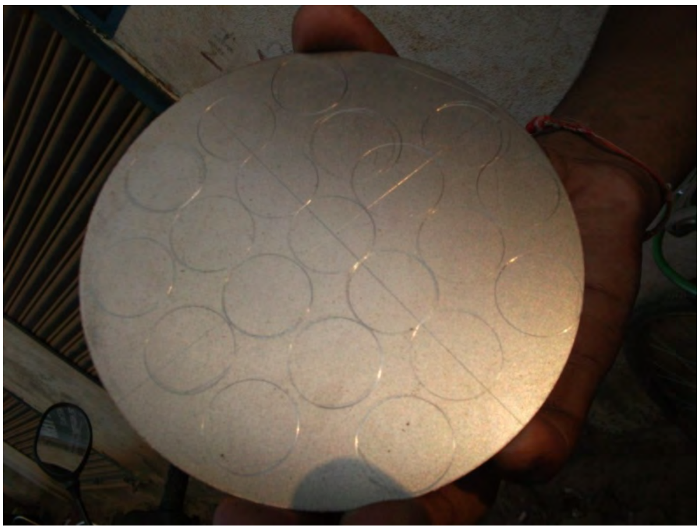

Fig. 8. Blank with circle grids

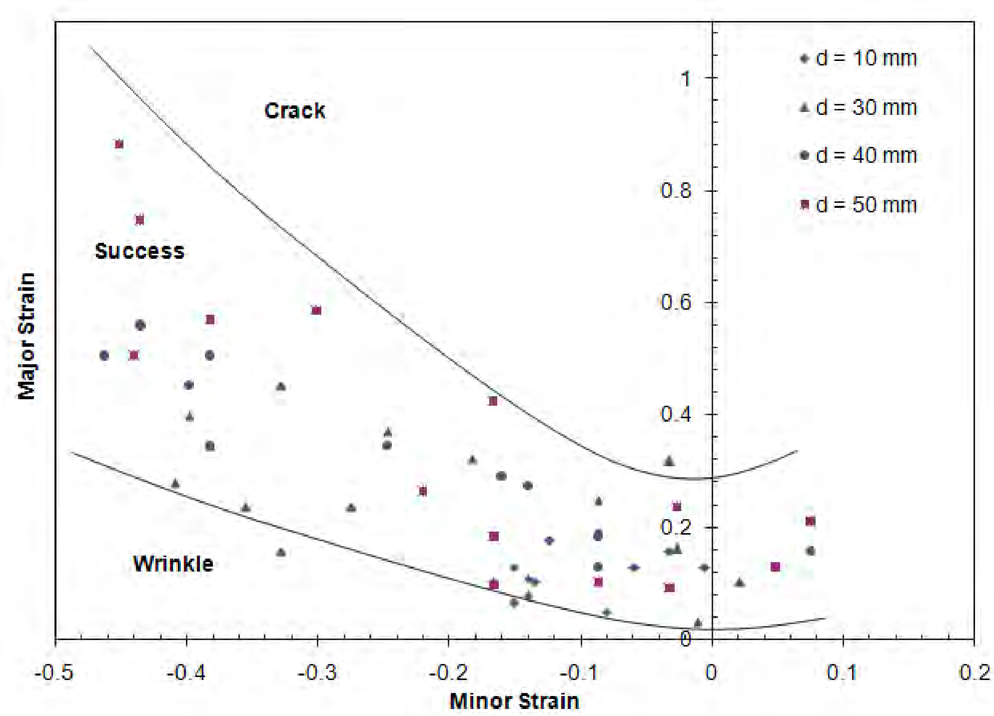

Fig. 9. Forming limit diagram of low carbon deep draw steel for various strokes (d)punch

The forming limit diagram of steel sheets was drawn for the various punch strokes by plotting the minor strain along the abscissa and major strain along the ordinate. In the FLD, higher the forming limit curves, better the formability. The strain percentages of the deformed grids were in the range

from simple tension region to the biaxial stretch region. Based on the grid ratios, two types of forming limit curve (FLC) are formed namely Upper FLC and lower FLC. The upper FLC is based on fracture grids and lower FLC is based on wrinkle grids. The minor strain value varies from –0.46 to 0.8 and major strain varies from 0.20 to 0.88. By drawing the curve which separates the safe region and unsafe region of the formed cup, the forming conditions of the sheet can be selected accordingly. Fig 9 shows the forming limit diagram of the low carbon steel sheet for various punch strokes. In this study the best forming characteristics were obtained at a punch stroke of 50 mm and blank diameter of 110 mm.

B. Thickness Distribution of the formed cup

Thickness is one of the key characteristics of the formed sheet metal, as it is not uniform at all surfaces of the deep drawn part (Mark Colgan, 2003). Generally its value is low at punch radius and outside die corner whereas it is high at the flange area. The objective of better forming is to reduce thickness variations between thinning and thickening of the part formed. Figure10 shows the locations along the surface of the cup at which thickness was measured.

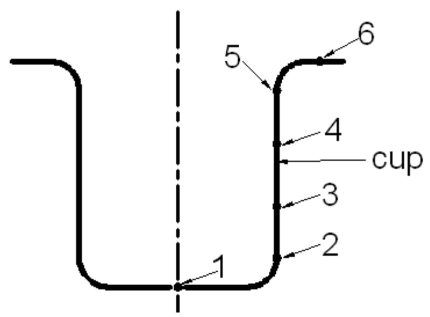

Fig. 10. Thickness measurement locations on the surfaces of the cup

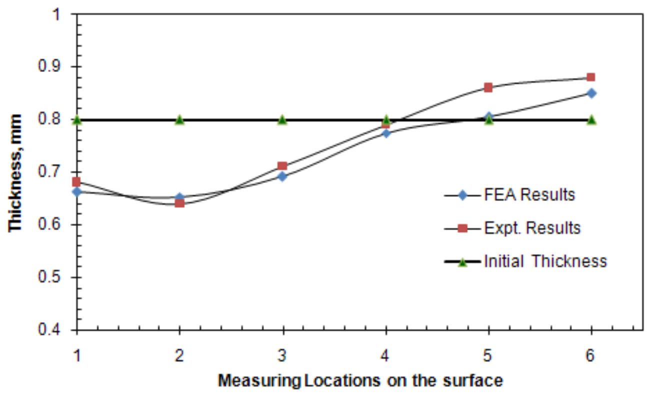

Fig. 11. Thickness distribution of the Blank and formed cup

Figure 11 compares the thickness distribution of blank material and formed cup at different locations. It also compares the actual thickness distribution with FEA predicted values. The greatest thinning limit of 0.64 mm occurs near the punch radius (refer location 2). The predicted von misses stresses reach their maximum value at the point near to where the greatest amount of thinning takes place, (i.e.) just above the punch radius on the sidewall. Table IV represents the comparison of experimental and FEA predicted values of thickness distribution of the cup drawn to a depth of 50 mm. The variations between the predicted and experimental thickness is nearly 2%. Thickness variations between thinning limit and thickening part during the experiment was found to be a maximum of 0.24 mm which may be considered good for a blank material of thickness 0.8 mm.

TABLE IV
Comparison of Thickness distribution FEA predicted and experiment values

Locations	1	2	3	4	5	6	Avg.	% of Variations
Experimental, mm	0.68	0.64	0.71	0.79	0.83	0.88	0.7550	2.05 %
FEA Predicted, mm	0.662	0.653	0.692	0.775	0.805	0.850	0.7395	

C. Von Mises stress Distribution of the formed cup

Von Mises criterion is a method for identifying whether a particular stress combination at a given location will cause failure. It is merely a function of the stress field at a point in the material and is equal to the octahedral effective stress. Its major relevance is to distinguish failure in ductile materials, i.e. if the Von Mises stresses are greater than the yield stress of the material then plastic strain is assumed to occur. Hence many researchers use Von Mises stress distribution to analyze the stress characteristics of the formed cup (*Ivaylo N. Vladimirov, 2010: Zhiying Chen, 2009*) .

The distribution of the von Mises stresses at various locations of sheets formed at room temperature is illustrated in Figure 12. The developed Von Mises stresses are minimum on the surface of the cup (20.54 MPa) and maximum nearer to the punch radius and die radius (186.4 MPa). The maximum stress values leads to maximum thinning limit of 0.64 mm.

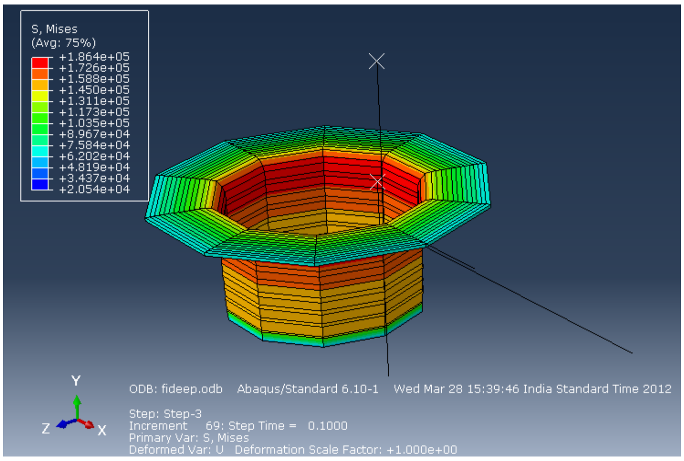

Fig. 12. Von Mises stress distribution of the Blank after 50mm punch stroke

V. CONCLUSIONS

Deep draw quality steel was subjected to forming at room temperature under various input conditions and results observed. From this the following conclusions can be drawn.

1. The maximum blank diameter of the sheet formed without cracks within the present experimental range was 110 mm and a limiting draw ratio of 2.2 was achieved.
2. The best forming characteristics were obtained at a punch stroke of 50 mm.
3. Thickness variations of the deep drawn steel sheet were less. The maximum thickness variation observed was only 0.24 mm.
4. Good correlation was obtained between the finite element predicted results and experimental results.
5. The developed Von Mises stresses are minimum on the surface of the cup (20.54 MPa) and maximum nearer to the punch radius and die radius (186.4 MPa).

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