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Influence of Process Parameters of Single Point incremental Deep Drawing Process for Truncated Pyramidal Cups from 304 Stainless Steel using FEA

T. Santhosh Kumar, V. Srija, A. Ravi Teja, A. Chennakesava Reddy

Abstract— For 304 stainless steel sheet, the single point incremental deep drawing process has been simulated using finite element analysis software code and Taguchi experimental planning. The process parameters are blank thickness, step depth, tool radius and coefficient of friction for the truncated pyramidal cups. It has been found that the step depth and tool radius are highly influential in controlling the formability of cups.

Index Terms— single point incremental deep drawing process, 304 stainless steel , truncated pyramidal cups, blank thickness, tool radius, step depth, coefficient of friction.

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1 Introduction

SINGLE point incremental (SPI) deep drawing is a forming process in which the sheet is clamped along its edges and a hemispherical headed tool is moved along required path so that it presses the sheet locally along the path. It suffers from some disadvantages such as long processing time, poor dimensional accuracy due to bending of the sheet near clamped edges. The process is very flexible and can be carried out on a computer numerical control (CNC) milling machine. The path of the tool is controlled by a part program generated using computer aided manufacturing (CAM) software. The conventional superplastic forming is accepted at low strain rates, in general about 10^{-4} – 10^{-3} s^{-1} and high forming temperatures. In a series of reseaarch on deep drawing process, abundant explorations have been convinced to boost the superplastic properties of materials such as AA1050 alloy [1], AA1070 alloy [2], AA1080 alloy [3], AA1100 alloy [4], AA2014 alloy [5], AA2017 alloy [6], AA2024 alloy [7], AA2219 alloy [8], Ti-Al-4V alloy [9], EDD steel [10], gas cylinder steel [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 ISF process [12-13].

The present work was to predict formability of single point incremental deep drawing 304 stainless steel sheet. The investigation was to optimize the process parameters such as blank thickness, step depth, coefficient of friction and tool radius. The design of experiments was carried out using Taguchi technique. The single point incremental deep drawing was implemented using the finite element analysis software code namely ABAQUS.

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2 Materials and Methods

In the present work, AA304 stainless steel was used to make truncated pyramidal cups. The levels chosen for the controllable process parameters are summarized in table 1. 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). The obligation of parameters in the OA matrix is given in table 2.

Table 1
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 2
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 finite element modeling and analysis was established using ABAQUS software [14]. The rectangular sheet blank was created with desired diameter and thickness using CAD tools. The sheet was meshed with S4R shell elements [15] as shown in fig.1. The cylindrical single point tool was also modeled with appropriate inner and outer radius and corner radius using CAD tools (Fig. 1). The mechanical interface between the contact surfaces was implicated to be frictional contact and modeled as Coulomb's friction model [7, 8]. In the present work, profile tool path technique was used as shown in fig.2. In profile tool path, tool moves in one plane till it reaches to its initial point. Thereafter it moves vertically downward direction by specified step depth. After reaching to next plane tool continues its motion in the same direction as that of earlier cycle. This process continues till the complete geometry is formed.

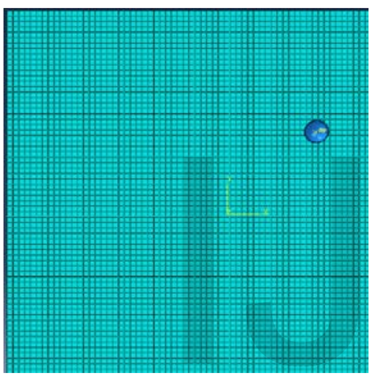

Fig. 1. Modeling of sheet and single point tool.

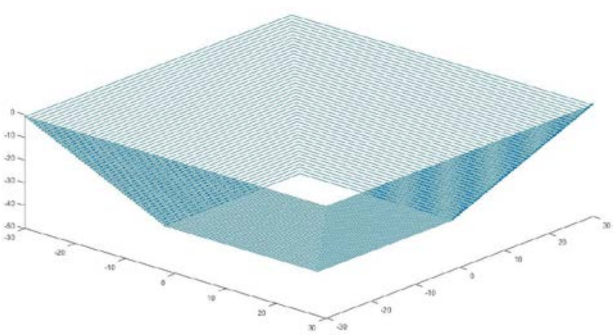

Fig. 2. Profile tool path.

3 Results and Discussion

The sheet was discretized with S4R quadratic elements (5625) as shown in Fig. 2. The cylindrical tool was assumed to be rigid body. But, the tool was allowed to rotate about its axis. The tool was also given three translatory motions along z-direction to facilitate step depth and along x- and y-directions to define 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 atleast 90% of confidence. Hence, the process parameters which had an absolute Fisher's ratio larger than 3.4579 were believed to influence the average value for the forming characteristic under null hypothesis, parameters which had Fisher's ratio less than 3.457 were believed to have no effect on the average.

2.1 Effect of Process Parameters on Effective Stress

To reduce variation in the effective stress, the relative powers of process parameters are summarized in table 3. The adequacy of the finite element analysis was exceptional as the percent contribution due to error was zero. In table 3, the percent contribution indicates that the parameter B, step depth, all by itself contributes the most toward the variation in the effective stress: almost 40%. The sheet thickness (A) influences nearly one-third of the total variation (32.3%) observed in the effective stress. The tool radius (C) tenders 21.92% of the total variation in the effective stress. The coefficient of friction (D) contributes only 5.69% of the total variation in the effective stress.

Table 3
ANOVA summary of the effective stress

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	1494.2	1558.5	1523.6	690.76	1	690.76	276303.98	32.3
B	1485.7	1555.4	1535.2	857.37	1	857.37	342947.97	40.09
C	1505.4	1555.5	1515.4	468.67	1	468.67	187467.98	21.92
D	1510	1535.1	1531.2	121.63	1	121.63	48651.99	5.69
e				0.01	4	0.0025	1.00000	0
T	4422.25	4953.60	5084.25	2138.44	8			100

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.

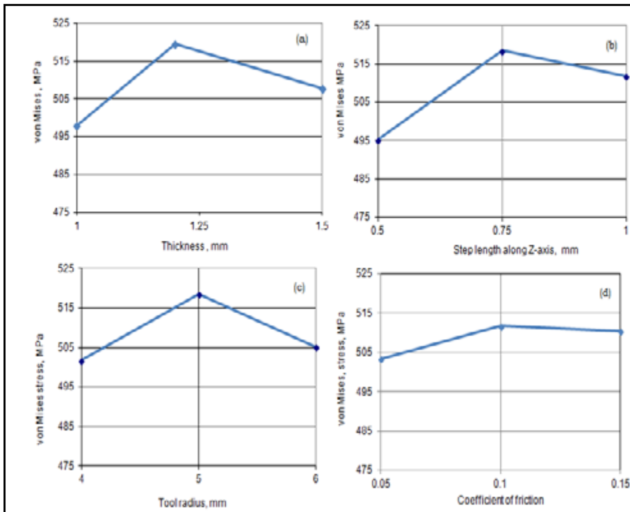

Fig. 3. Effect of process parameters on von effective stress.

Fig. 3(a) presents the effective stress induced in 304 stainless steel during incremental deep drawing process as a function of blank thickness. The effective stresses were, respectively, 498.07 MPa, 519.50 MPa and 507.87 MPa at 1.0 mm, 1.2 mm and 1.5 mm blank thicknesses. Fig. 3(b) describes the effective stress as a function of step depth. The effective stress increased with the increase of step depth initially from 0.50 to 0.75 mm and then it decreases slightly from 0.75 to 1.0 mm. The effective stress is high for tool radius of 5 mm as showed in Fig 3(c). Fig. 3(d) describes the effective stress as a function of coefficient of friction. The effective stress increases with the increase of coefficient of friction. The principal stresses S_{11}, S_{22} and shear stress S_{12} are shown in figs. 4, 5 and 6, respectively. The compressive stresses induced in the blank sheet are higher in number than the tensile stresses. The deformation based on compression for the strain less than 3.0 and it is tensile for the strain greater than 3.0. The shear stress developed in the blank sheet is nearly 50% of S_{11}. The stress distribution is nearly the same along the center-line of the cup in all the trails.

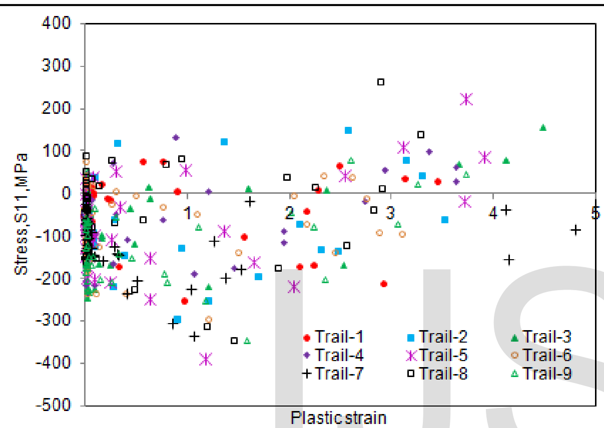

Fig. 4. Effect of process parameters on S_{11}.

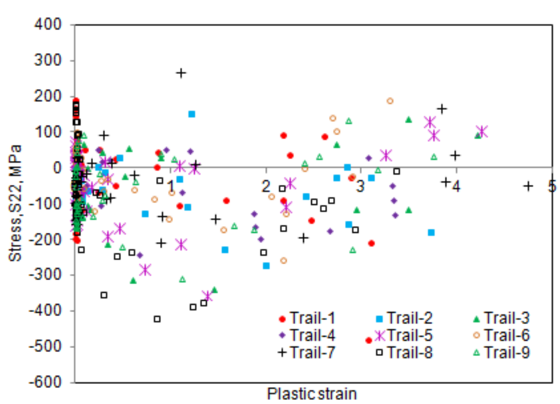

Fig. 5.Effect of process parameters on S_{22}.

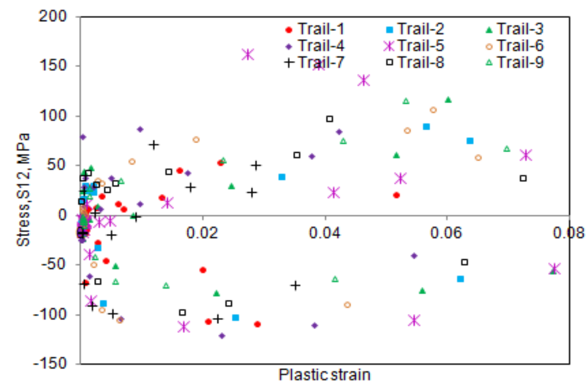

Fig.6. Effect of process parameters on S_{12}.

2.2 Effect of Process Parameters on Strain Rate

The relative influences of process parameters are summarized in table 4. In table 4, the percent contribution indicates that the parameter, coefficient of friction (D), all by itself accords 38.43% of the total variation in the strain rate. The step depth (B) commits to a quarter of the total variation (24.08%) observed in the strain rate. The blank thickness (A) doles 16.63% of total variation in the strain rate. The tool radius (C) dispenses 20.92% of the total variation in the strain rate. Of all nine results, only one result is higher than the average strain rate. Hence, all process parameters would dominant in controlling the strain rate.

TABLE 4
ANOVA SUMMARY OF THE STRAIN RATE

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	14.582	9.409	8.694	6.89	1	6.89	2014.76716	16.63
B	15.36	8.77	8.555	9.98	1	9.98	2918.34198	24.08
C	15.052	9.022	8.611	8.67	1	8.67	2535.27305	20.92
D	16.5	7.517	8.668	15.93	1	15.93	4658.23525	38.43
e				-0.01368	4	-0.00342	1.00000	0
T	61.494	34.718	34.528	41.45632	8			100

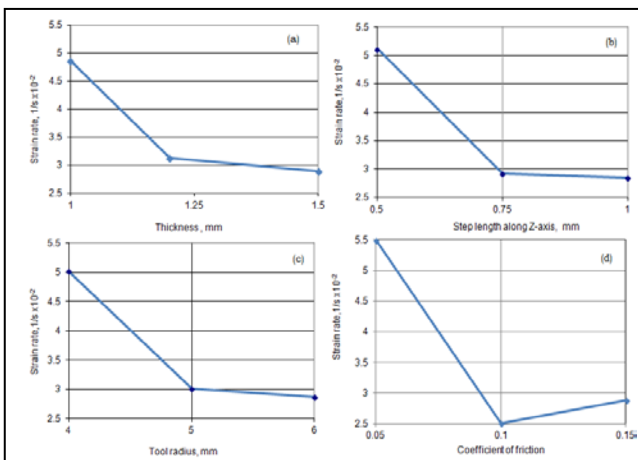

Fig.7. Effect of process parameters on strain rate.

The strain rate ratio would decrease with an increase in the

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blank thickness, step depth, tool radius and coefficient of friction as illustrated in Fig. 7. The average maximum strain rate was in the range of 0.05 - 0.055 s^{-1} [8, 9]. The strain rate values indicate the superplastic deforming during the SPI deep drawing of 304stainless steel.

2.3 Effect of Process Parameters on Thickness Reduction

In table 5, the percent contribution indicates that the parameter C, tool radius, all by itself contributes the most toward the variation in the thickness reduction: almost 72.69%. The sheet thickness (A) controls 5.12% of the total variation observed in thickness reduction. The step depth (B) carries 7.39% of the total variation in the thickness reduction. The coefficient of friction (D) gives only 14.80% of the total variation in the thickness reduction.

TABLE 5

ANOVA SUMMARY OF THE THICKNESS REDUCTION

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	232.20	228.58	229.20	2.5	1	2.5	7200.00	5.12
B	229.12	228.23	232.63	3.61	1	3.61	10396.80	7.39
C	222.00	231.68	236.30	35.51	1	35.51	102268.80	72.69
D	229.87	226.77	233.35	7.23	1	7.23	20822.40	14.8
e				0.001389	4	0.000347	1.00	0
T	913.18	915.27	931.48	48.85139	8			100

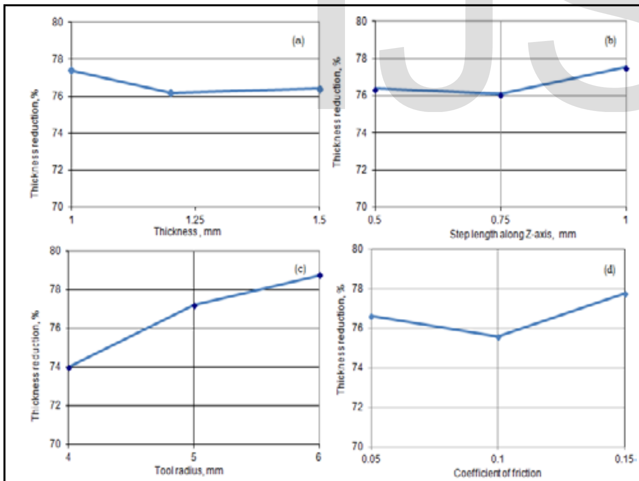


Fig.8. Effect of process parameters on thickness reduction.

As seen from Fig. 8, the reduction of thickness decreases with increase of blank thickness (Fig. 8a); it increases with increase of step depth (Fig. 8b) and tool radius (Fig. 8c). Except at 0.1 value of coefficient of friction,the reduction of thickness increases with increase of coefficient of friction. The variation of thickness was considered at the center-line of the deformed cup as shown in Fig. 9. As observed from Fig. 10, the majority of thickness reduction takes place in the walls of the cup but not in the flange or bottom of the cup. The elements located at the mid regions of the walls are elongated higher than those present at the top and bottom of the cup walls.

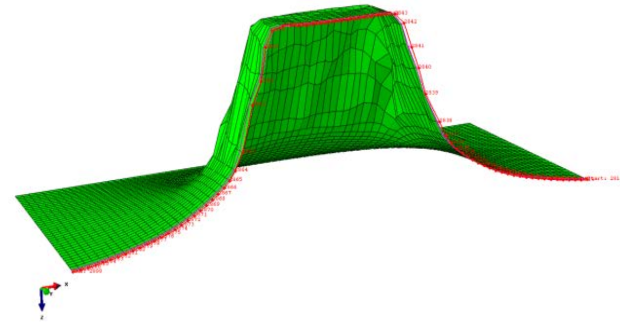


Fig.9. Location of thickness reduction in the deformed cup.

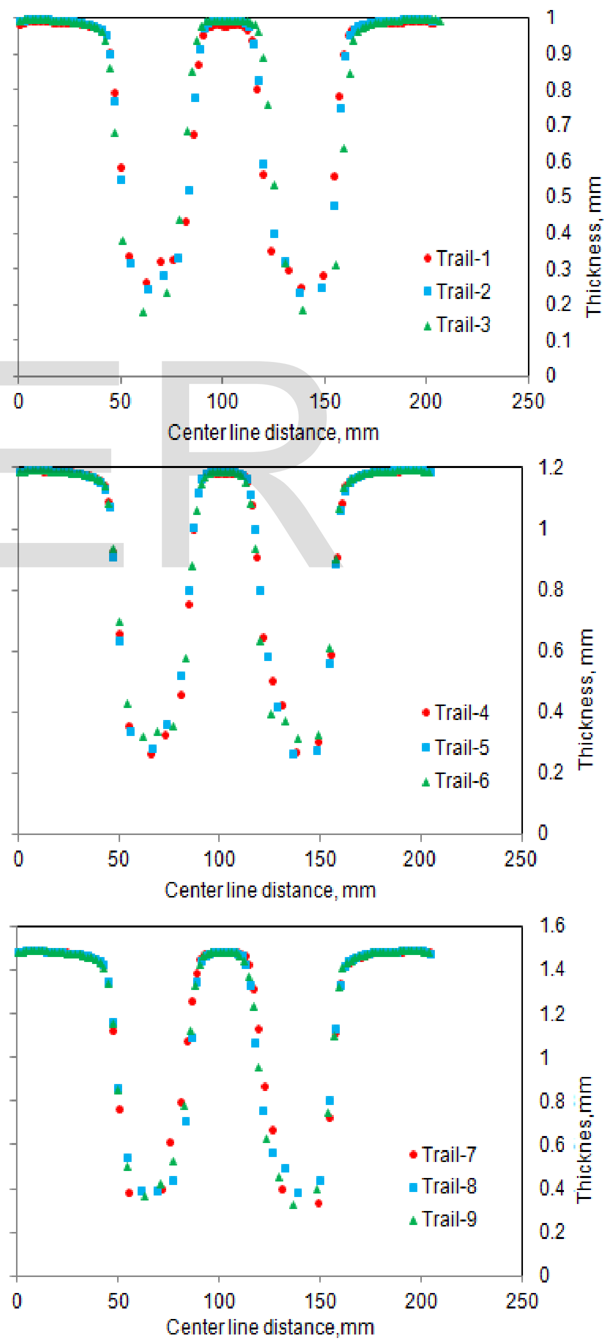


Fig.10. Effect of process parameters on thickness reduction.

2.4 Formability of SPI Deep Drawing Process

The formability diagrams of the cups are shown in Figs. 11, 12 and 13. Tension is highly dominated during the formation of blank sheet. For the trials 1, 2 and 3, the von Mises stresses are, respectively, 473.0 MPa, 521. 3 MPa and 499.9 MPa. For the trials 4, 5 and 6, the von Mises stresses are, respectively, 518.2 MPa, 521. 0 MPa and 519.3 MPa. For the trials 7, 8 and 9, the von Mises stresses are, respectively, 494.5 MPa, 513. 1 MPa and 516.0MPa. The safe tensile and compressive strain should be less than 0.2 to prevent the rupture in the cups.

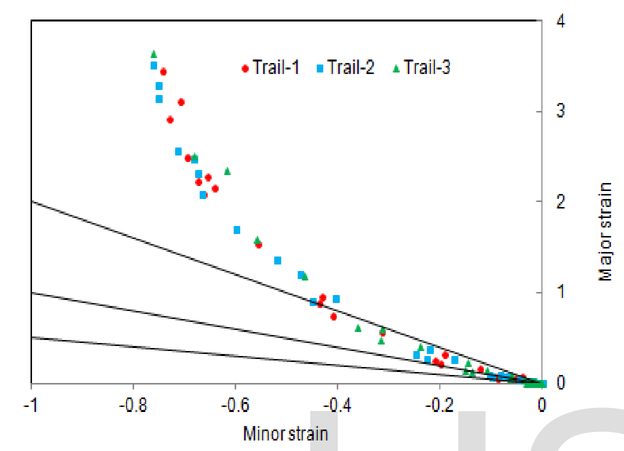


Fig.11. Forming limit diagram.

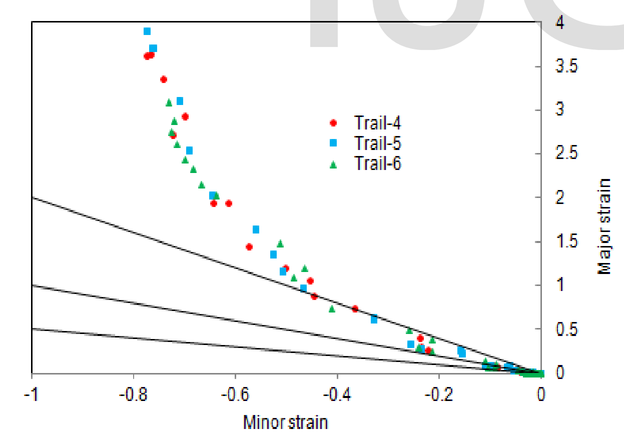
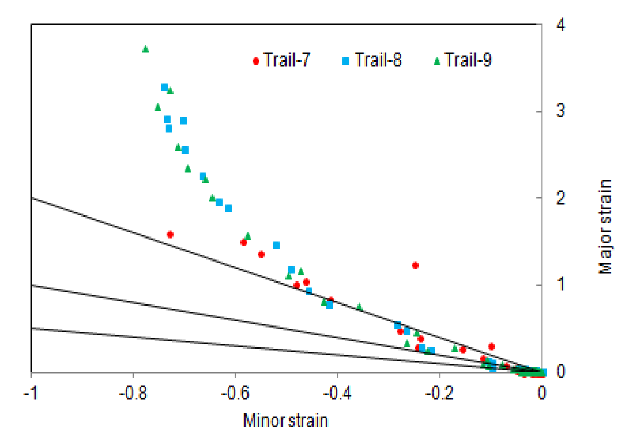


Fig.12. Forming limit diagram.



It is observed from Fig. 14 that the high stresses are induced at the bottom corners, along the edges of walls and at flange to wall change over sections in the deformed cups.

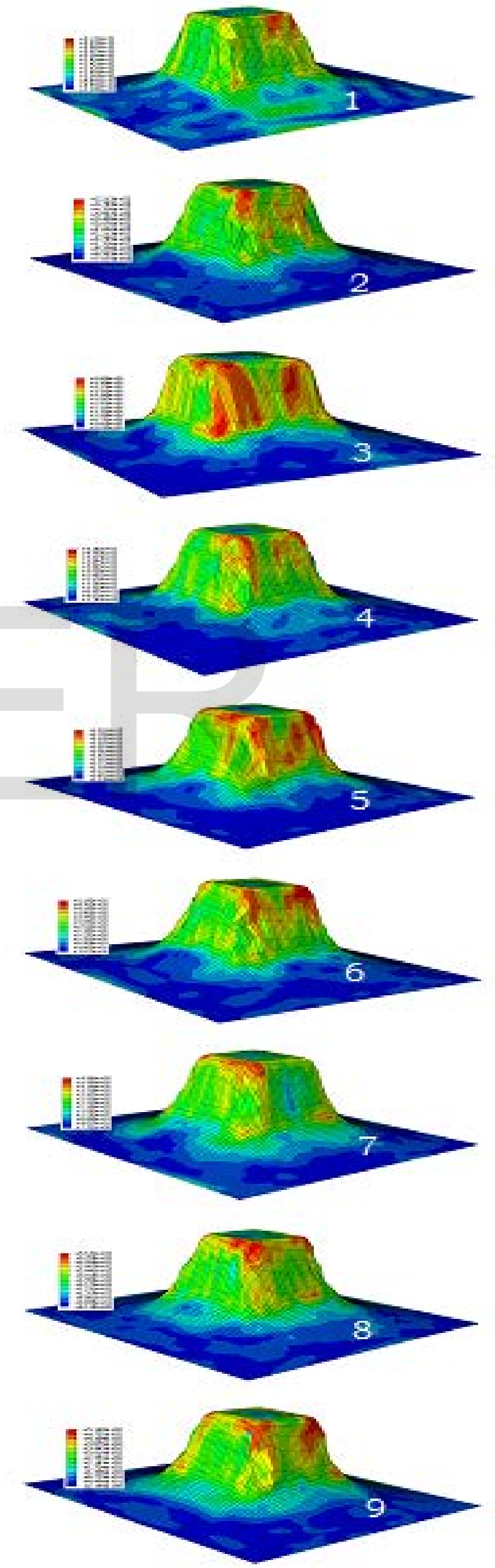


Fig.14. Raster images of von Mises stress in the cups.

4 CONCLUSION

In the present work, the finite element analysis and Taguchi techniques are successfully implemented to simulate single point incremental deep drawing process for the 304 stainless steel sheet. The major parameter, which influences the effective stress, is the step depth.The strain rate decreases with increase of process parameters chosen in the present work.The thickness reduction is greatly affected by the tool radius.The formability of the cups is dominated by the tensile behavior of 304 stainless steel.

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