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Simulation and Parametric Optimisation of Conical Cups in Warm Deep Drawing of Monel 400 at Elevated Temperatures

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Abstract

In this present work, a statistical approach based on Taguchi and Analysis of Variance techniques and Finite Element Analysis have been adopted to determine the degree of importance for each of the process parameter on the formability of conical cup using warm deep drawing process. The process parameters that were used are punch velocity, coefficient of friction, temperature and sheet thickness. Simulation results shows that the temperature and coefficient of friction have found to influence the quality of drawn conical cups. The major parameter which could influence the damage of cups is the punch velocity and coefficient of friction. It is observed that the drawn conical cups of sheet thickness more than 1mm have achieved the required shape with less wrinkle formation with no shearing occurred.

Keywords: Warm deep drawing, Monel 400, sheet thickness, ANOVA, D-Form, Thinning, Co-efficient of friction.

1. INTRODUCTION

The deep drawing process is often a combination of stretch forming and deep drawing. During stretch forming, the blank material will be shaped by the punch but squeezed between drawing die and the punch. The material flows under biaxial stress and strain, in the process the cup will be shaped with the reduction of blank thickness. Parts produced by hot forming are characterized by high strength, complex shapes.

Many investigations have been carried out to obtain an optimal blank shape that can be deformed into the accurate shape. Toros et al. [1] have developed an analytical model to evaluate deep drawing process at elevated temperatures and under different blank holder pressure and identified that temperature, punch speed, BHP, and friction are the main factors that influence the formability. Chennakesava Reddy et al. [2] have carried out the experimental characterization on the warm deep drawing process of extra-deep drawing (EDD) steel. The results of the experimentation conclude that the extent of thinning at punch corner radius is lower in the warm deep-cup drawing process of EDD steel at 200˚C. Chennakesava Reddy et al. [3] performed an experiment using 2014T6 Aluminum alloy and concluded that parameters influence the deformed cup shape and wrinkle formation is less in thick sheets. Chennakesava Reddy et al. [4] The AA1050–H18 sheets were used for the superplastic deep drawing of the conical cups. The strain rate by itself has a significant effect on the effective stress and the height of the conical cup drawn. Martins et al. [5] presented the analysis of different heating methods frequently used in laboratory scale and in the industrial practice to heat blanks at elevated temperatures. Lin and Yang et al. [6] used ANOVA as one of the methods to determine the influence of a drawing punch with a micro-ridged surface on the deep drawing of stainless steel. Reddy et al. [7] has used Taguchi technique which can save the cost of experimentation to optimize the extrusion process of 6063 aluminum alloy. Dilmec and Arap et al. [8] also indicated the implementation of ANOVA to determine the coefficient of friction as one of the most critical parameters that affects the deep drawing process for flange and radius regions.

The objective of the present work is to optimize the warm deep drawing process of MONEL 400 Nickel-copper based super alloy using Taguchi technique for the conical cups. In this present work, a statistical approach based on Taguchi and ANOVA techniques was adopted to determine the optimum of each of the process parameter on the formability of deep drawn conical cups. All the experimental results have been verified by using D-FORM 3D software.

2. MATERIALS AND METHODS

Monel 400 is a nickel-copper alloy is a solid-solution alloy that can be hardened only by cold working. It has high strength and toughness over a wide temperature range and excellent resistance to many corrosive environments. The operating temperature of these materials ranges from 150°C up to almost 1500°C. The levels chosen for the control parameters were in the operational range of Monel 400 using deep drawing process. Each of the four control parameters was studied at three levels. The chosen control parameters are summarized in table 1. The orthogonal array (OA), L9 was selected for the present work. The parameters were assigned to the various columns of O.A. The assignment of parameters along with the orthogonal array matrix is given in table 2.

Table 1: Control Parameters and Levels

Factors	Symbol	Level-1	Level-2	Level-3
Punch velocity(mm/sec)	A	2	3.5	5
Co-efficient of friction (μ)	B	0.2	0.3	0.4
Temperature(˚C)	C	600	700	800
Thickness(mm)	D	0.8	1.0	1.2

Table 2: Orthogonal Array (L9) and control parameters

Trail 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

2.1 Design of Deep drawing conical cups

The blank size was calculated by equating the surface area of the finished drawn cup with the area of the blank. The blank diameter, D is given by:

$$\boldsymbol{D = \sqrt{d_2 + (d_1 + d_2)\sqrt{(d_1 - d_2)^2 + 4h^2}}} \quad (1)$$

Where d_1 *and* d_2 are the top and bottom diameters of the cup and h is the height of the cup.

Corner radius of drawing punch must exceed 3 times of the blank thickness (t). Although, the punch radius should not be greater than one-fourth the cup diameter (d).

$$3t < \text{punch radius} < d/4 \quad (2)$$

The punch radius r_p , mm is expressed as:

$$\boldsymbol{r_p = \frac{12t+d}{8}} \quad (3)$$

Where *t* is thickness of sheet and *d* is mean diameter i.e.$\left(\frac{d_1+d_2}{2}\right)$

For uniform material flow, the die radius should be ideally 4 to 6 times the blank thickness (t) but under any circumstances, it must be never less than 3 times the thickness of the sheet. Lesser is the radius; higher would be the obstruction to the material flow whereas surplus radius would lower the pressure area between blank and blank holder.

The corner radius r_d , mm of the die can be calculated from the following equation:

$$r_d = 0.8\sqrt{(D-d)t} \quad (4)$$

where D is blank diameter (mm), d is mean diameter (mm) and t is thickness (mm).

In deep drawing, the material flow may exhibit thickening of the flange and thinning of walls of the cup. To this avoid this problem, some space must be created by modeling die diameter greater than punch diameter. This space is called die clearance.

$$\text{Clearance, } c_d = t \pm \mu\sqrt{10t} \quad (5)$$

where μ is the coefficient of friction.

The top diameter of the die d_{d1} is obtained from the following equation:

$$d_{d1} = d_1 + 2c_d \quad (6)$$

The bottom diameter of the die d_{d2} is obtained from the following equation:

$$d_{d2} = d_2 + 2c_d \quad (7)$$

By adding clearance to the punch corner radius, corner radius of the die is obtained. The edge radius of the die is eight times the blank thickness

2.2 Finite Element Analysis

The finite element modeling and analysis was carried using D-FORM 3D software. The circular sheet blank was created with desired diameter and thickness. The conical top punch, bottom hollow die was modeled as shown in figure1 with appropriate inner and outer radius and corner radius using UNIGRAPHICS NX 12.0 software. The clearance between the punch and die was calculated using Eq. (4). The sheet blank was meshed with tetrahedral elements (Chennakesava, 2008)[9]. The modeling parameters of deep drawing process for each trail were as follows:

Number of elements for the blank: 8961

Number of nodes for the blank: 3103

Top die polygons: 1088

Bottom die polygons: 2188.

The contact between blank and punch, die and blank holder were coupled as contact pair. The mechanical interaction between the contact surfaces was assumed to be frictional contact as shown in fig 1. The finite element analysis was chosen to find the effective stress, height of the cup, and damage of the cup. The finite element analysis was conceded to run using DEFORM 3D software according to the design of experiments for the purpose of validating the results of experimentation.

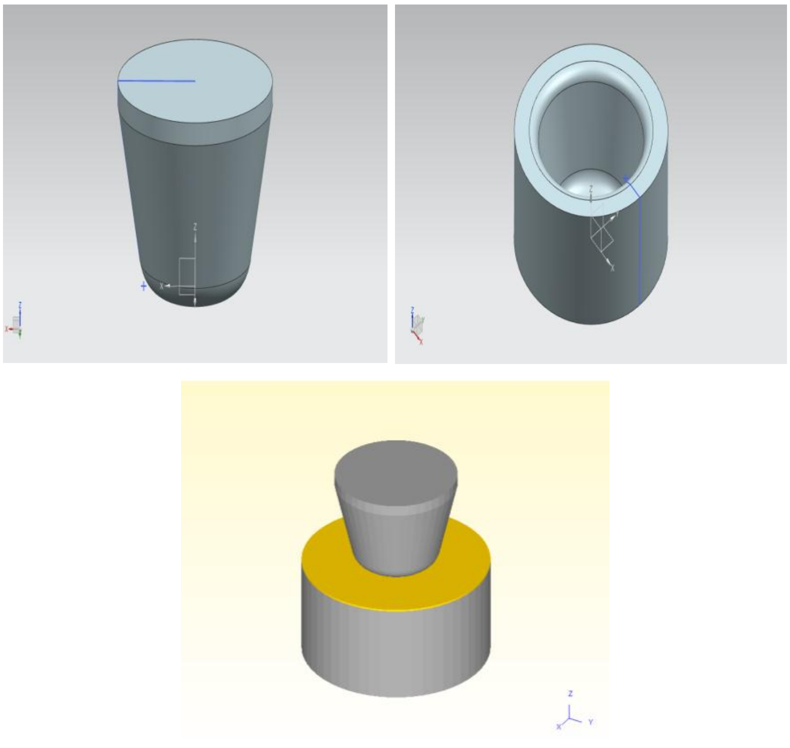

Figure 1: Conical punch, Die and Interaction with the blank

3. RESULTS AND DISCUSSION

3.1 Influence of control factors on Effective stress on conical cups

Table 3 gives the ANOVA (analysis of variation) summary of raw data. The Fisher's test column establishes all the parameters (A, B, C and D) accepted at 90% confidence level. The percent contribution indicates that the factor C, Temperature, all by itself contributes almost (82.91%) towards the variation. The thickness (D) contributes the (8.97%) of the total variation observed. The punch velocity (A) supports (5.09%) of variation, and coefficient of friction (B) gives (3.02%) of variation on the effective stress.

Table 3: ANOVA summary of effective stress

Factor	Sum 1	Sum 2	Sum 3	SS	*v*	*V*	*F*	*P*
A	457.60	400.70	390.60	869.84	1	869.84	28994.67	5.09
B	384.60	436.70	427.60	516.24	1	516.24	17208.00	3.02
C	526.00	472.00	250.90	14164.57	1	14164.57	472152.33	82.91
D	408.70	467.60	372.60	1533.04	1	1533.04	51101.33	8.97
Error				0.03	4	0.01	0.33	0.01
T	1776.90	1777.00	1441.70	17083.72	8			100.00

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

The influence of punch velocity on effective stress is shown in fig 2(a). The effective stress is decreasing from 152.53Mpa to 130.2Mpa as the punch velocity increases from 2 to 5mm/s. the effective stress is increases to 145.56Mpa with the increase of friction from 0.2 to 0.3 and then later on decreases with the increase of friction as shown in fig 2(b). Influence of temperature on effective stress is shown in fig 2(c) and the effective stress is decreasing from 175.33Mpa to 83.63Mpa as the temperature increases from 600˚C to 800˚c. Effective stress got influenced by sheet thickness as shown in fig 2(d), effective stress increases from 136.23Mpa to 155.86Mpa with the increase of sheet thickness from 0.8 to 1.0mm and then further it gets decreased to 124.2Mpa from thickness 1.0 to 1.2mm.

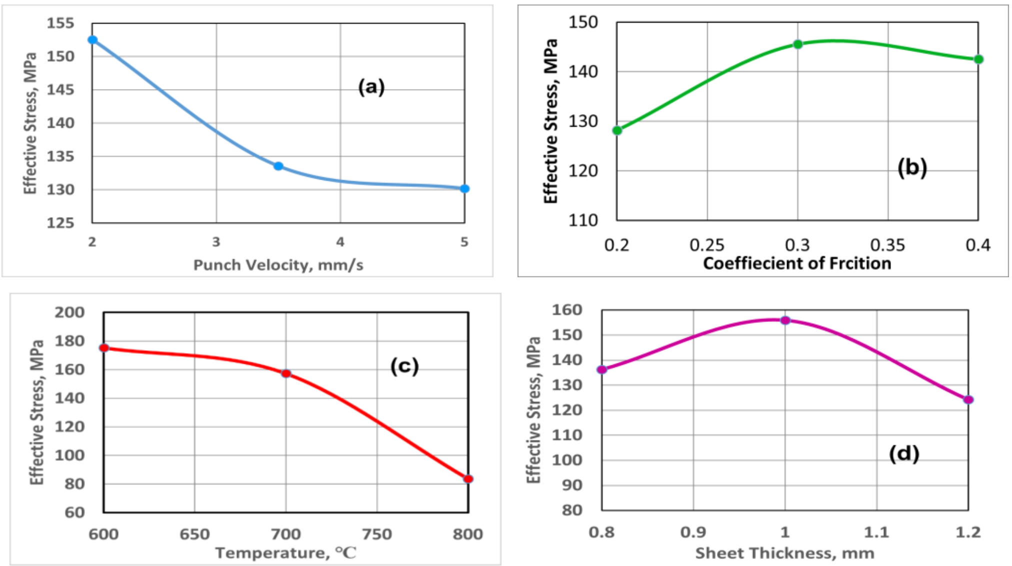

Figure 2: Effect of control parameters on effective stress

The FEA results of effective stress are shown in figure 3 for various test conditions as per the design of experiments. Effective stress found in the trail conditions 1, 3, 4, 5, 7, 8 and 9 are 176Mpa, 86.6Mpa, 127Mpa, 82.7Mpa, 81.6Mpa, 159Mpa and 150Mpa respectively, which are less than the yield strength of the 195Mpa. The trail conditions of 2 and 6 exhibits the effective stress near to the yield strength of 195Mpa and 191Mpa in the results and this is due to effect of working temperature and friction induced in the blank.

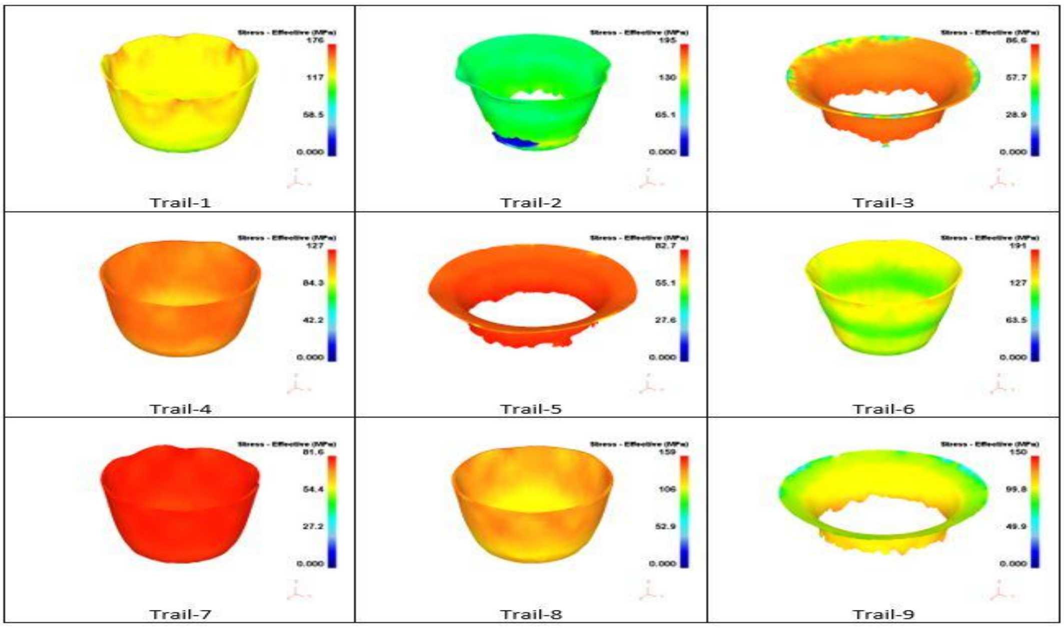

Figure 3: Effective Stresses of all the experiments

3.2 Influence of control factors on Height of conical cups

Table 4 gives the ANOVA (analysis of variation) summary of raw data. The Fisher's test column establishes all the parameters (A, B, C and D) accepted at 90% confidence level. The percent contribution indicates that the factor D, sheet thickness, contributes more than half of (57.89%) towards the variation. The factor Temperature (C) contributes the (14.89%) of the total variation observed. The punch velocity (A) contributes (14.21%) of variation and sheet thickness (D) contributes (13.21%) of variation on the cup height.

Table 4: ANOVA summary of height of the cups

Factor	Sum 1	Sum 2	Sum 3	SS	*v*	*V*	*F*	*P*
A	120.60	103.80	102.50	67.95	1	67.95	6795.00	14.21
B	120.20	103.60	103.10	63.13	1	63.13	6313.00	13.21
C	120.90	103.00	103.00	71.20	1	71.20	7120.00	14.89
D	85.50	121.50	119.90	275.77	1	275.77	27577.00	57.69
Error				0.01	4	0.00	0.00	0.00
T	447.20	431.90	428.50	478.06	8			100.00

The influence of punch velocity on the height of the drawn cups is shown in fig 4(a), and the height of cups is highest of 40.2mm at initial velocity of 2mm/s and then progressively decreases till the punch velocity 3.5mm/s, further variation in cup height is very small as velocity increases. The cup height decreases as the friction value increases from 0.2 to 0.4 as shown in fig 4(b). Influence of temperature on height of cups is shown in fig 4(c), at temperature of 600˚C the cup height is 40.3 and then cup height gets decreases till the temperature of 700˚C and it remained constant as temperature increases to 800˚C.The influence of thickness on the height of cup drawn is shown in figure 4(d). The height of cup increases with an increase in the thickness of blank from 0.8 to 1.0mm. This is obvious that the enough material is available to deform under the given parameters, and it achieves the target height.

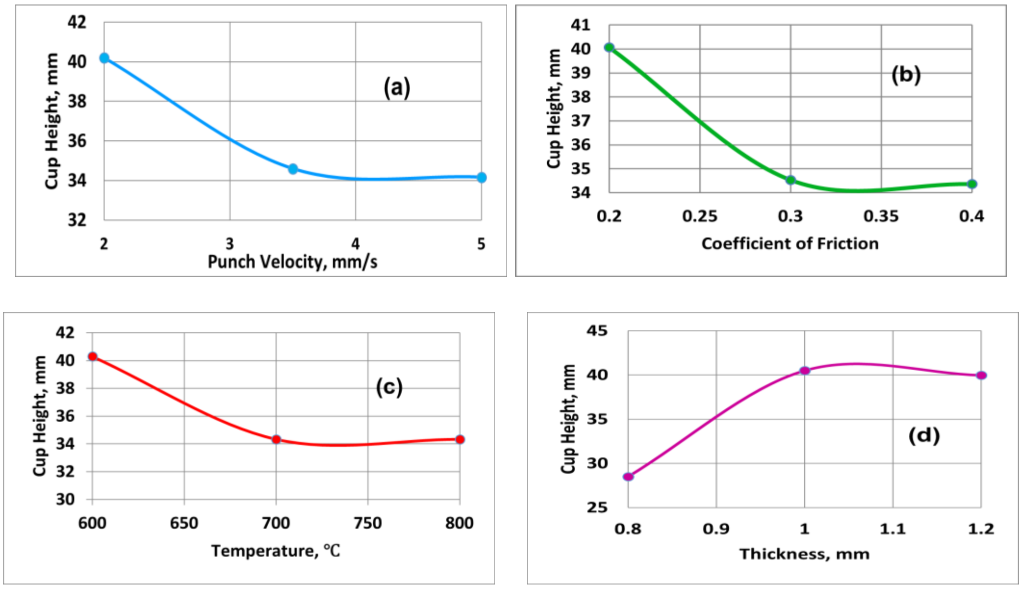

Figure 4: Effect of control parameters on height of cups

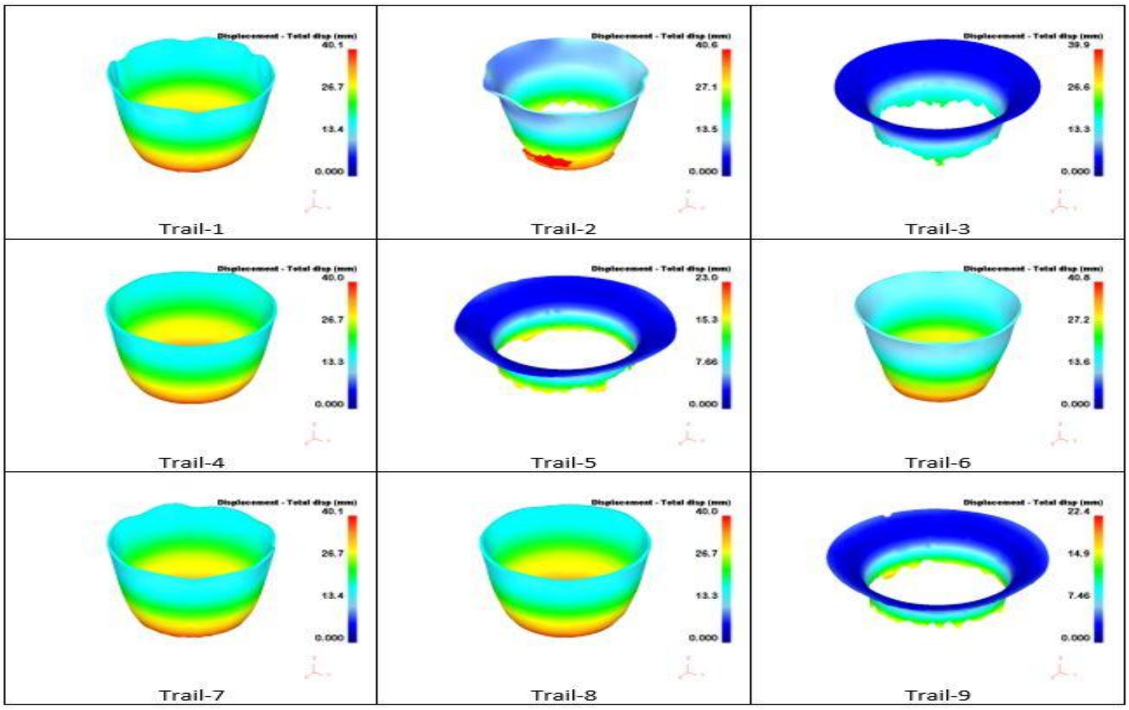

Figure 5: Drawn cup heights of all experiments

The FEA results of cup height are shown in figure 5 for various test conditions as per the design of experiments. The obtained cup height for trail conditions of 1, 4, 6, 7 and 8 are 40.12mm, 40.03mm, 40.79mm, 40.09mm and 40.05mm. Height of the sheared cup trails are 2, 3, 5 and 9 are 40.59mm, 39.95mm, 22.99mm and 22.37mm as shown in fig 6. Even though the trial conditions 2 and 3 gives the target height of 40.59mm and 39.95mm, but there is tearing on the bottom corner side of the conical cup as shown in trail 2 of fig 5. Drawn cup under trail 3 gets completely sheared in trail 3 of fig 5, for both these trail condition the major factor that had influenced is high temperature and higher friction value. Heights of the drawn conical cups for each conducted trail are shown in the fig 6.

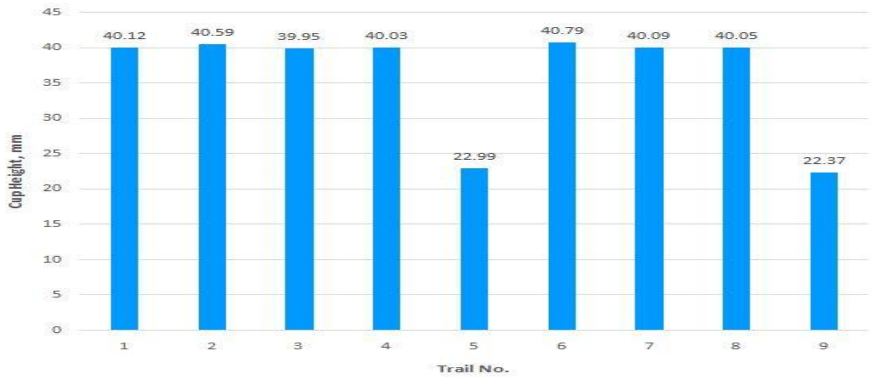

Figure 6: Height of cups under different trails

3.3 Influence of control factors on Damage of conical cups

Table 5 gives the ANOVA (Analysis of variation) summary of raw data. The Fisher's test column establishes all the parameters (A, B, C and D) accepted at 90% confidence level. The percent contribution indicates that the factor A, punch velocity, nearly one-third (30.54%) of the total variation. The coefficient of friction (B) contributes (23.91%) of the total variation observed. The factor (C) temperature shows a (23.69%) of total variation observed, and factor (D) sheet thickness gives (21.56%) of variation on the cup damage.

Table 5: ANOVA summary of Damage of cups

Factor	Sum 1	Sum 2	Sum 3	SS	*v*	*V*	*F*	*P*
A	66.40	4.69	4.15	853.82	1	853.82	-173294.09	30.54
B	2.00	61.19	12.05	668.62	1	668.62	-135705.30	23.91
C	2.28	61.05	11.91	662.47	1	662.47	-134457.07	23.69
D	6.12	60.00	9.12	611.21	1	611.21	-124053.18	21.86
Error				0.00	4	0.00	0.00	0.00
T	76.81	186.93	37.22	2796.12	8			100.00

The influence of punch velocity on the damage of the cups is shown in fig 7(a), the damage is higher at the initial velocity of 2mm/s and then decreases as the punch velocity increases. The damage increases with the increase of the friction to 0.3 as shown in fig 7(b) and then later on damage decreases with the increase of friction. The influence of temperature on damage of cups is shown in fig 7(c), and we observe that the damage is higher at the temperature of 700˚ C, damage is lower at the temperatures of 600˚C and 800˚C respectively. The sheet thickness has a influence on damage of cups with the maximum damage is observed at the sheet thickness of 1.0mm as shown in fig 7(d), the damage is observed less at the thickness of 0.8 and 1.2mm.

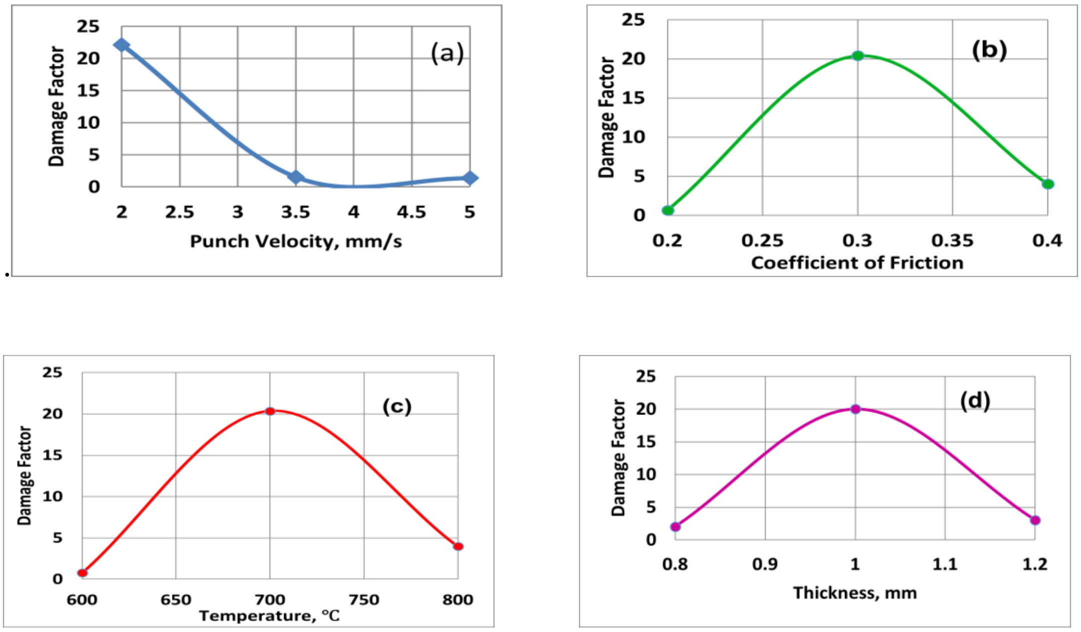

Figure 7: Effect of control parameters on Damage of cups

The FEA results of damage are shown in figure 8 for various test conditions as per the design of experiments. Damage of successful cups of trail conditions 1, 4, 6, 7 and 8 are 0.52%, 0.54%, 1.26%, 0.94% and 0.49% as shown in fig 8 and the damage for the sheared cups of trails 2, 3, 5 and 9 are 57.81%, 8.08%, 2.88% and 2.71%. The highest damage was observed at the trail condition 2 with damage of 57.81%, because the parameters of trail condition 2 are velocity (2mm/s), friction (0.3), temperature (700˚C) and sheet thickness (1mm), the next highest damage was observed in trail condition 3 of 8.81%. Damage for each trail is shown in fig 9 and in both the trail conditions of 2 and 3 the damage was higher because of higher temperatures and higher friction value. Trails under 0.8mm thickness are 1, 5 and 9, due to higher temperature the sheet can't withstand the drawing force, gets sheared and the damage is observed. As the thickness increases damage factor decreases also wrinkles as observed in trail 4 and 8 as shown in fig 8.

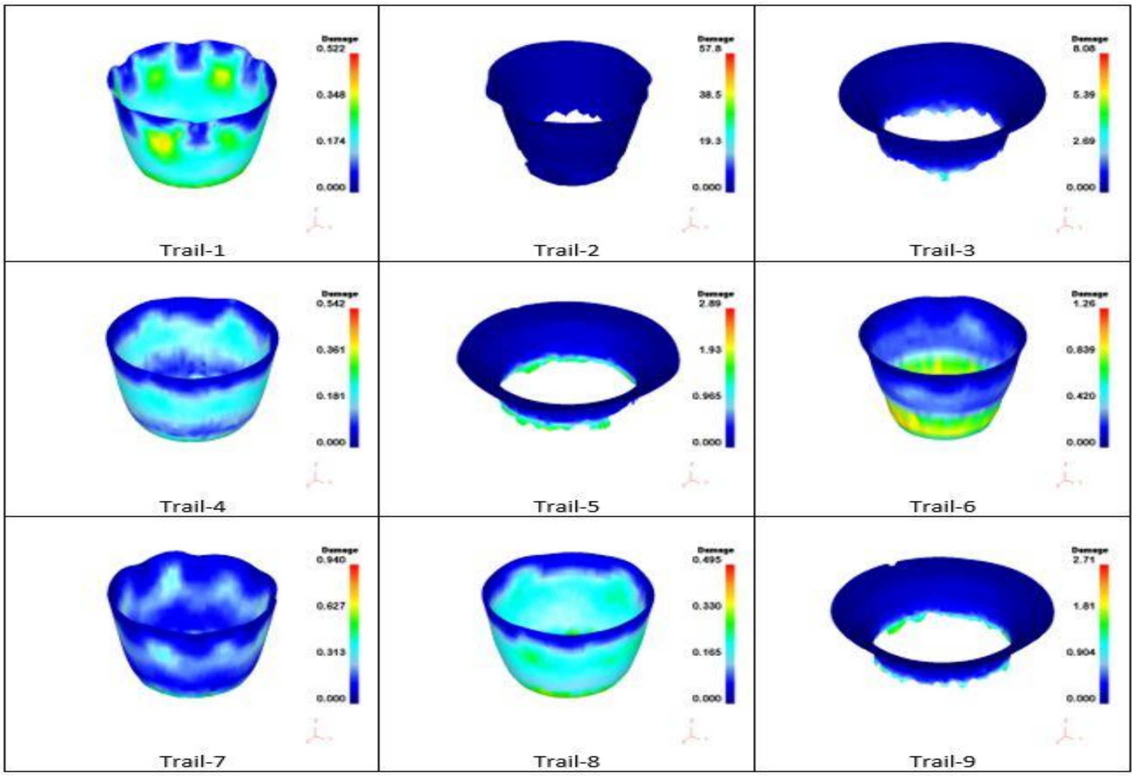

Figure 8: Damage of all the experiments

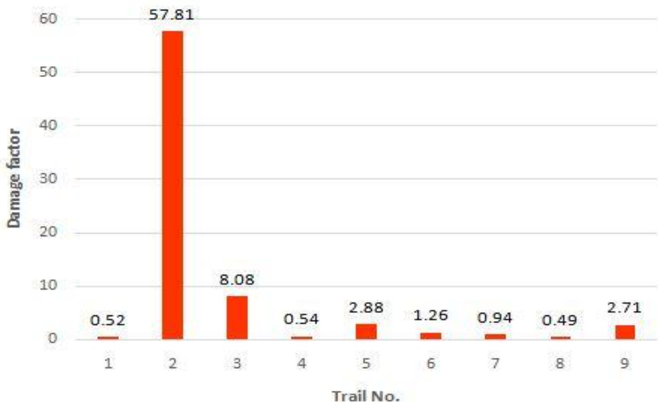

Figure 9: Damage of cups under different trails

3.4 Forming Limit Diagram

Fig 10 shows the forming limit diagrams of the conical cups for 0.8mm sheet thickness. The trail 5 and 9 are having higher damage and it because of shear and equibiaxial tension occurred in the blank. The conical cup drawn using trial 1 has less damage and it had wrinkles as the minor strain was double the major strain occurred in the blank material

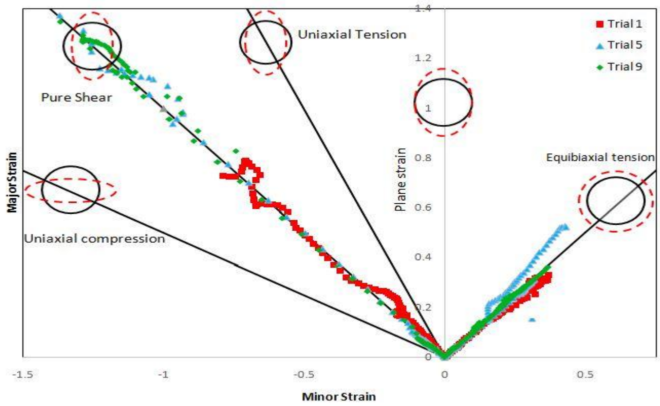

Figure 10: Forming limit diagram with damage of conical cups of 0.8mm sheet thickness

Fig 11 displays the forming limit diagram of damage on 1mm sheet thickness; drawn conical cup under trail 2 gets sheared mainly because of the pure shear and biaxial tension due to higher friction between punch and sheet. Trail 6 and 7 have obtained the conical cups with less wrinkles and has got equal amount of shear and uniaxial compression.

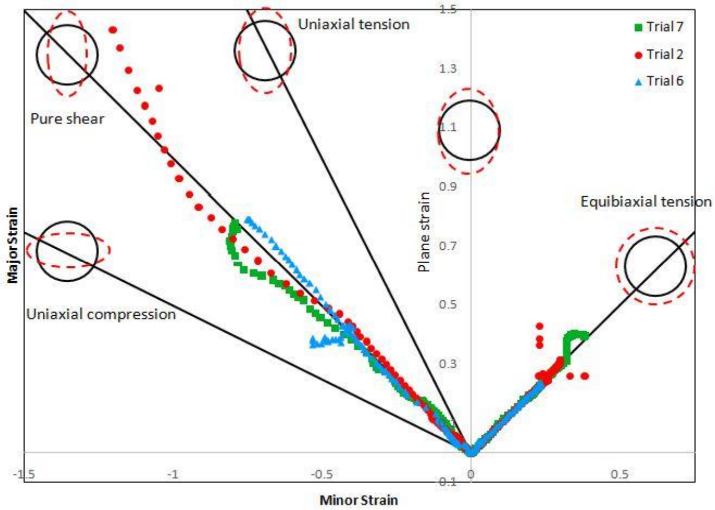

Figure 11: Forming limit diagram with damage of conical cups of 1.0mm sheet thickness

Fig 12 exhibits the forming limit diagram of damage on 1.2mm sheet thickness and only the trail condition 3 has huge influence of pure shear and equibiaxial tension on drawn cup thus it has led to torn of cup and the other trails 4 and 8 have the more major strain than minor strain.

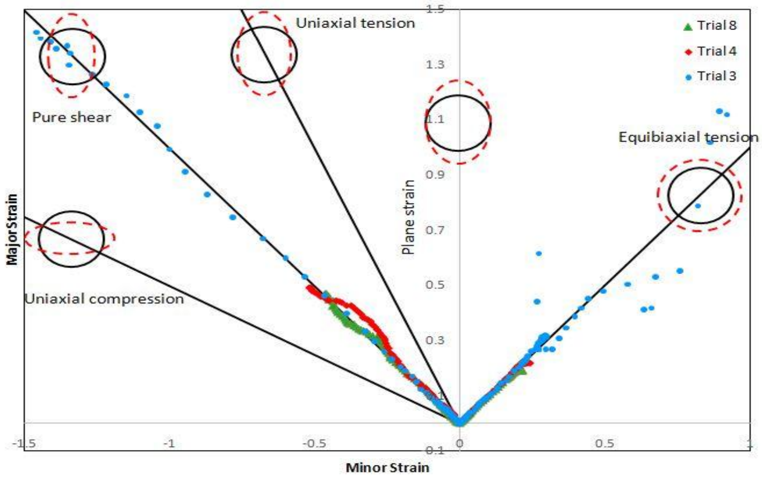

Figure 12: Forming limit diagram with damage of conical cups of 1.2mm sheet thickness

4. CONCLUSION

From the results of Finite Element Analysis, it is clearly observed that the successful drawn cups are obtained for trail condition of 8. The input parameter of temperature has got more influence on the effective stress. The other parameters like Sheet thickness, temperature and punch velocity are responsible for the influence on drawn cup height. Punch velocity and friction has got influence on the damage of the cups. Damage in the drawn cups is less with the higher thickness sheets and at higher temperature and friction. Wrinkles formation in the drawn cups is observed less with the higher friction value and increased sheet thickness.

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