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Parametric Optimization of Monel 400 Cold Deep Drawn Cylindrical Cups

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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 cylindrical cup using cold deep drawing process. The process parameters that were used are punch velocity, coefficient of friction, strain rate, displacement per step.Simulation results shows that the punch velocity and the displacement per step have found to influence the quality of drawn conical cups.

Keywords: Cold deep drawing, Monel 400, punch velocity, coefficient of friction, strain rate, cylindrical cups, formability.

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.

Many investigations have been carried out to obtain an optimal blank shape that can be deformed into the accurate shape. The effect of stress decreases with increase of blank thickness, the effective stress decreases with increase in temperature [1]. The effective stress was increased with an increase in the punch velocity. A material that undergoes higher punch velocity experiences higher punch forces. The use of a high punch velocity can lead to rupture of the sheet material. The damages in the cups was decreased with increase of strain rate [2]. The effective stress decreases with an increase in displacement per step, this displacement is an account of plastic deformation of Inconel 600[3]. High friction is present at die punch sheet interface. Low friction must be present at blank holder, sheet and die interface because a high friction will lead to fracture due to requirement of higher punch force [4]- [5]. The volume of the cup increases with an increase in temperature, the wrinkle formation on the cup reduces with an increase in temperature due to softening of blank material [6]. Reddy et al. in their work have simulated that the cup drawing process with an implicit finite element analysis. The effect of local thinning on the cup drawing has been investigated. The thinning is observed on the vertical walls of the cup. The strain is maximum at the thinner sections. [7]. Bhargavi et al. optimized the process parameters of cold deep drawing of Inconel 600 conical cups as the thickness increases the cup height increases due to the availability of material for deformation [8]. Nithinsai et al. simulated for optimization of Nickel 201 conical cups observed Greater the coefficient of friction higher would be the surface expansion ratio. The cup height was higher when the coefficient of friction was 0.15[9]. Effective stress decreases with increase in temperature. This is owing to the softening of the alloy with increase in temperature. With an increase in punch velocity, the stress induced in the cup decreases [10]. As the thickness increases damage factor of Monel 400 conical cups decreases [11]. On the cup drawing process using an implicit finite element analysis, the thinning is observed on the vertical walls of the cup with high values of strain at the thinner sections. In the finite element simulations, a forming limit diagram (FLD) has been successfully applied to analyze the fracture phenomena by comparing the strain status.

In the present work, the formability of cold deep drawing process was evaluated during the fabrication of Monel 400 cylindrical cups. The investigation was focused on the process parameters such as punch velocity, coefficient of friction, displacement per step and strain rate. The design of experiments was carried out using Taguchi technique and the warm deep drawing process was executed using the finite element analysis software namely D-FORM 3D.

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 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 table1. The orthogonal array (OA), L9 was selected for the present work. The parameters were assigned to the various columns of OA. 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	B	0.1	0.15	0.2
Strain rate , 1/s	C	1	10	100
Displacement per step	D	0.5	0.75	1

Table 2: L9 Orthogonal Array and Control parameters

Trial	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 Fabrication of Deep Drawn Cups

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

$$D = \sqrt{d^2 + 4dh} \quad \text{for } d/r > 20 \tag{1}$$

$$D = \sqrt{d^2 + 4dh} - 0.5r \quad \text{for } 20 > d/r > 15 \tag{2}$$

$$D = \sqrt{d^2 + 4dh} - r \quad \text{for } 15 > d/r > 10 \tag{3}$$

$$D = \sqrt{(d - 2r)^2 + 4d(h - r) + 2\pi r(d - 0.7r)} \quad \text{for } d/r < 10 \tag{4}$$

where d is the mean diameter of the cup (mm), h is the cup height (mm) and r is the corner radius of the die (mm).

The force required for drawing depends upon the yield strength of the material σ_y, diameter and thickness of the cup:

Drawing force, $F = \pi dt\ [D/d - 0.6]\sigma_y$ (5)

where D is the diameter of the blank before operation (mm), d is the diameter of the cup after drawing (mm), t is the thickness of the cup (mm) and σ_y is the yield strength of the cup material (N/mm^2). The drawing punch must have a corner radius exceeding a minimum of three times the blank thickness (t). However, the punch radius should not exceed a quarter of the cup diameter (d).

$3t < \text{Punch radius} < d/4$ (6)

Figure 1. Deep drawing machine (Hydraulic type).

For smooth flow of material, the die edge should have generous radius preferably four to six times the sheet thickness but never less than three times the blank thickness because lesser radius would impede material flow while excess radius would increasethe pressurearea between the blank and the blank holder, and would cease to be under blank pressure. The corner radius of the die can be calculated from the following equation:

$$r = 0.8\sqrt{(D-d)t} \tag{7}$$

The drawing ratio is roughly calculated as

$$DR = D/d \tag{8}$$

The material flow in drawing may contribute to some flange thickening and thinning of walls of the cup which is inevitable. The space for drawing the cup is kept bigger than the sheet thickness which is called die clearance.

$$\text{Clearance, } c = t + \mu\sqrt{10t} \quad (9)$$

The sheets of Monel 400 alloy were cut to the required blank size. The blank pressure was calculated, as in (5). The cups were fabricated using a hydraulically controlled deep drawing machine.

2.2 Finite Element Modelling and Analysis

The finite element modelling and analysis was doneusing DEFORM 3D software. The circular sheet blank was modelled with the required diameter and thickness. The cylindrical top punch and cylindrical bottom hollow die weremodelled with relevant inner and outer radius and corner radiususing equation (7). Using equation (9) the clearance between the punch and die was calculated. The sheet blank was meshed with tetrahedral elements as shown in figure 2. Themodelling parameters of deep drawing process were as follows:

Number of elements for the blank: 14475 tetrahedron

Number of nodes for the blank: 4991

Top die polygons: 9120

Bottom die polygons: 9600

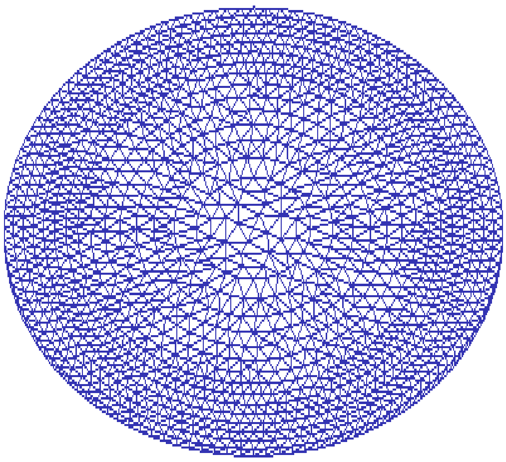

Figure 2: Discretization of sheet material.

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 carried out using D-FORM 3D software according to the design of experiments.

3. RESULTS AND DISCUSSION

For the ANOVA (analysis of variance) the Fisher's test (*F* = 3.01) was carried out on all the parameters (A, B, C and D) at 90% confidence level.

3.1 Influence of control factors on Effective Stress

Table 3 gives the ANOVA 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) contributed 41.82% of variation, theFactor B (Coefficient of Friction) 24.26% of variation, Factor C (strain rate)32.7% of variation and D (Displacement per step) 1.22% of variation on the effective stress.

Table 3: ANOVA summary of the EffectiveStress

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	1706	1402	2229	116652.66	1	116652.66	3888422.09	41.82
B	1702	1506	2129	67652.66	1	67652.66	2255088.72	24.26
C	1694	2184	1459	91216.66	1	91216.66	3040555.40	32.7
D	1843	1702	1792	3397.99	1	3397.99	113266.34	1.22
e				0.03	4	0.01	0.33	-1.11E-15
T	6945	6794	7609	278920.00	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.

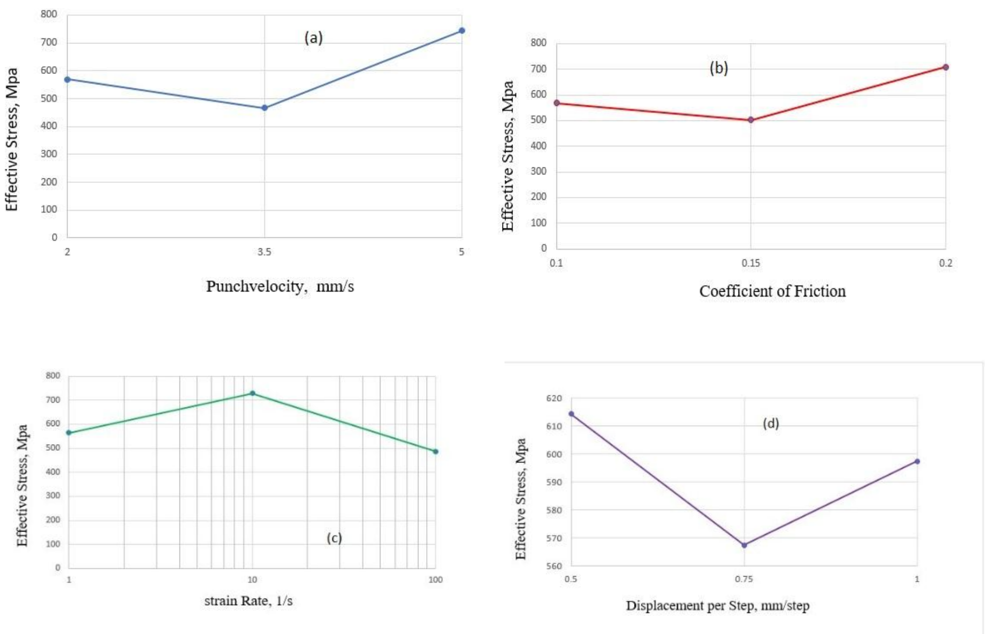

Figure 3: Influence of Process parameters on Effective Stress

The effective stress was increased with an increase in the punch velocity (figure 3a). A material that undergoes higher punch velocity experiences higher punch forces. The use of a high punch velocity can lead to rupture of the sheet material. The effective stress increases with increase in friction is shown in figure 3b. Increase in coefficient of friction can lead to increase in normal pressure which results in increase in stress.

The influence of strain rate on the effective stress is shown in figure 7. It is observed that the effective stress increases with an increase in the strain rate. Lee and Yeh [13] made some experiments to determine dynamic relation between yield strength and deformation of steel alloy. Obtained results showed that yield strength is magnifying with increasing of strain rate or decrease of the temperature. the equivalent stressis low when displacement per step is 0.75 as shown in figure 3d.Figure 4 presents the punch force evolution with the punch displacement, considering anisotropic and isotropic behaviour of the blank, respectively. Some oscillations in the predicted punch force evolution due to the relation between the blank discretization and the isotropic behaviour of the material. Globally, there is always a surface layer of nodes entering or leaving contact with the tools, leading to a globally smoother evolution, presenting more oscillations.

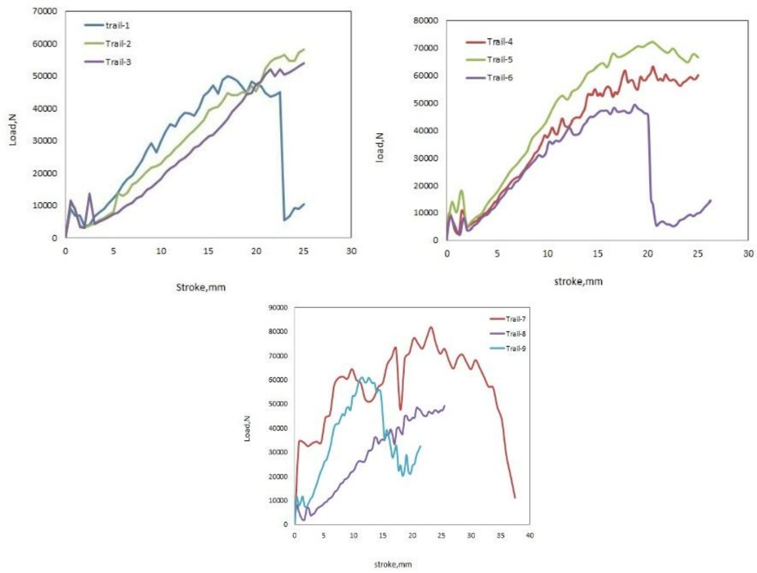

Figure 4: Punch force evolution with the punch displacement

3.2 Influence of Process Parameters on Surface Expansion Ratio

The ANOVA summary of surface expansion ratio is given in table 4. The punch velocity (A) would contribute 13.6% towards the variation observed in the surface expansion ratio. The coefficient of friction contributes 16.32% the strain rate was insignificant on the surface expansion ratio. The displacement per step contributed 65.29% towards the total variation in the surface expansion ratio.

Table 4: ANOVA summary of the surface expansion ratio

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	4.32	4.55	4.85	0.05	1	0.05	6.56	13.6
B	4.22	4.72	4.78	0.06	1	0.06	7.88	16.32
C	4.57	4.68	4.47	0.01	1	0.01	1.31	2.72
D	5.24	4.46	4.03	0.24	1	0.24	31.51	65.29
e				0.01	4	0	0.00	2.07
T	18.35	18.42	18.12	0.37	8			100

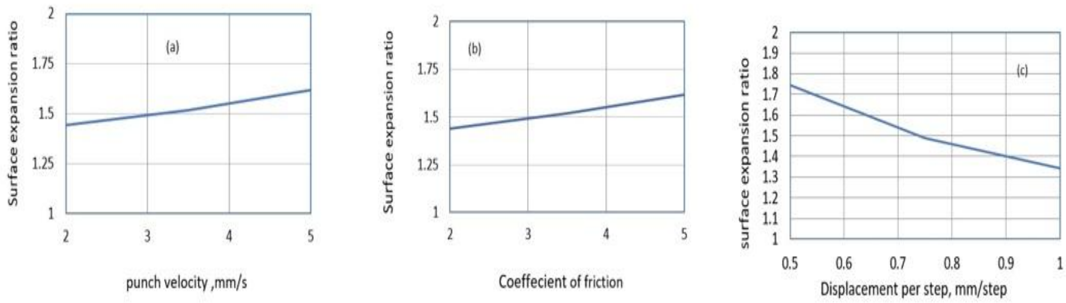

Figure 5: Influence of process parameters on the surface expansion ratio: (a) punch velocity, (b) coefficient of friction, (c) displacement per step on the effective stress.

The surface expansion ratio increases with increase in punch velocity shown in figure 5a. in the deep drawing process plastic deformation occurs. As the plastic deformation is irreversible, the cup retains its shape. As the punch velocity increases, the retaining of the cup shape increases due to irreversible plastic deformation. The surface expansion ratio increases with increase in friction as shown in figure 5b. the surface expansion ratio high for friction coefficient value 0.2 due to stretch formation. Surface expansion ration decreases with increase in displacement per step.the strain rate does not have very low influence on the surface expansion ratio.

3.3 Influence of control factors on Cup Height

The ANOVA summary of cup height is given in table 5. The displacement per step contributing(97.48%) the major role in cup height. Remaining other parameters have negligible influence on the cup height.

Table 5: ANOVA Summary of Cup Height

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	114.14	115.23	107.91	10.40	1	10.40	2941.68	0.98
B	113.30	114.77	109.21	5.53	1	5.53	1564.18	0.52
C	113.32	108.04	115.91	10.74	1	10.74	3037.85	1.01
D	72.77	112.99	151.52	1033.61	1	1033.61	292360.98	97.48
e				0.00	4	0.00	0.00	0.01
T	413.53	451.03	484.55	1060.28	8			100.00

The cup height would decrease with an increase in the punch velocity (figure 5a). The coefficient of friction decreases with increasing of punch velocity. Due to severe friction there may be thinning or failure of the side wall in drawn cup at the flange area. The cup height would increase with an increase in the coefficient of friction as shown in figure 5b. The major influential characteristic of the material is the ductility which depends upon the strain rate. For the strain rate $100s^{-1}$, the cup height was highest. At higher rates of strain, the flow stress of material increases leading to higher loads on the equipment. For the trials 3, 4and 8, the cup heights are 51 mm, 50 mm and 50 mm respectively as shown in figure 6. The lowest cup heights were 25 mm and 20 mm for trials 1 and 9 respectively. the cup height increases with increase of displacement per step as shown in figure 5d.

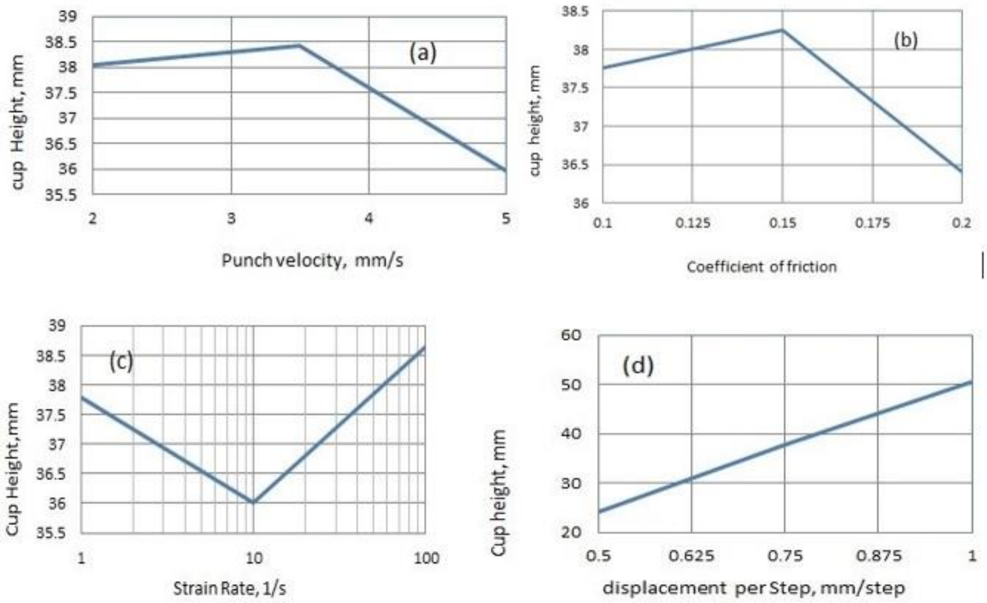

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Figure 5: Influence of control parameters on Cup Height

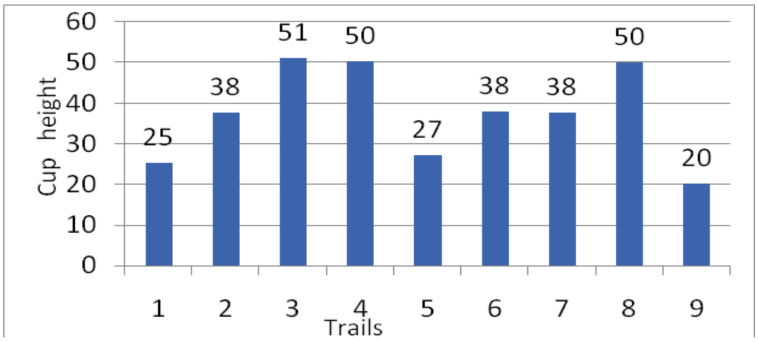

Figure 6: Cup height under different trials

3.4 Influence of control factors on Damage of Cup

The ANOVA summary of damage of cups is given in table 6. When the Fisher's test was applied to ascertain the influence of process parameters it was found that the punch velocity (A) contributes 28.33%, coefficient of friction(B) contributes21.25%, and the strain rate(C)contributed 24.99% and displacement per step contributes18.38% of the variation in the damages of cups drawn.

Table 6: ANOVA Summary of Damage of cups

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	2.60	1.40	12.60	25.20	1	25.20	8.29	28.33
B	2.80	2.10	11.70	19.09	1	19.09	6.28	21.25
C	2.60	12.20	1.80	22.32	1	22.32	7.34	24.99
D	11.30	2.70	2.60	16.62	1	16.62	5.47	18.38
e				3.04	4	0.76	0.25	7.05
T	19.30	18.40	28.70	86.27	8			100.00

The damage factor in the cups is defined as follows:

$$D_f = \int \frac{\sigma_1}{\sigma_{es}} d\varepsilon \qquad (10)$$

where, σ_1 is the tensile maximum principal stress; σ_{es} is the effective stress; and $d\varepsilon$ is the effective strain increment.The damage in cups increases with increase in punch velocity (Figure6a). The damage of the cup increases with an increase in friction figure 6b. the friction between the work piece and the tool reduce the wrinkle formation but very large friction causes failure of the cup which results in the increase in damage of the cup. how ever the cup damage increases with increase in strain rate figure6c. the damage of the cup is high for the strain rate of 100, 1/s having the damage factor value of 7.64. damage factor decreases with increasing displacement per step. The damage factor for different trials are shown in the figure8. The trial 9 has the maximum damage factor of 10.4 and the trial 5 has the zero damage factor.

Figure 9 depicts the forming limit diagram with damages in the cylindrical cups drawn from Monel 400 sheets of 0.8mm. The cylindrical cups drawn under trials 1 has wrinkle on the cup an account of uniaxial tension. In trial 3 we observed less damage. figure 10 depicts the forming limit diagrams of 1mm sheet thickness for the trials 4,5& 6. The trial 5 has zero damage factor but the entire cup is not formed successfully. Figure 11 depicts the forming limit diagrams of sheet thickness 1.2mm for trials 7,8 &9. the cups drawn under trial 9 were fractured due to compression at die corner radius (figure7).

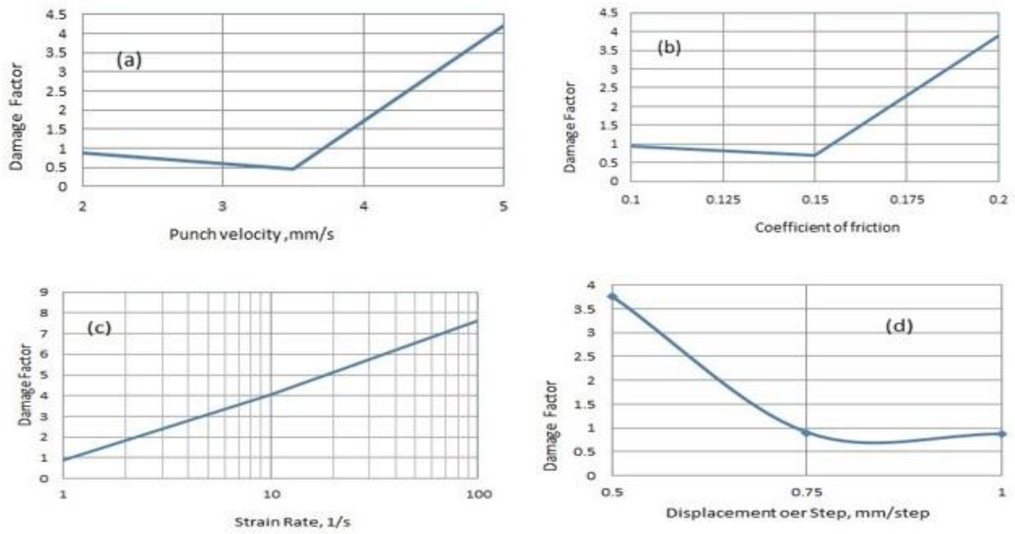

Figure 6: Influence of control parameters on Damage of cup

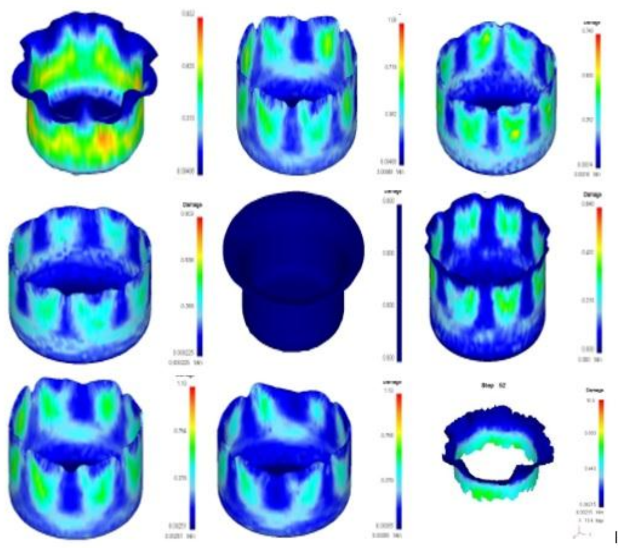

Figure 7: Damage of the cup under different operating conditions

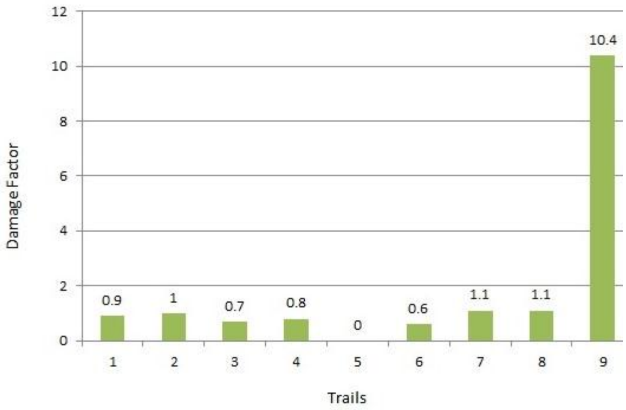

Figure 8: Cup damages under different trials.

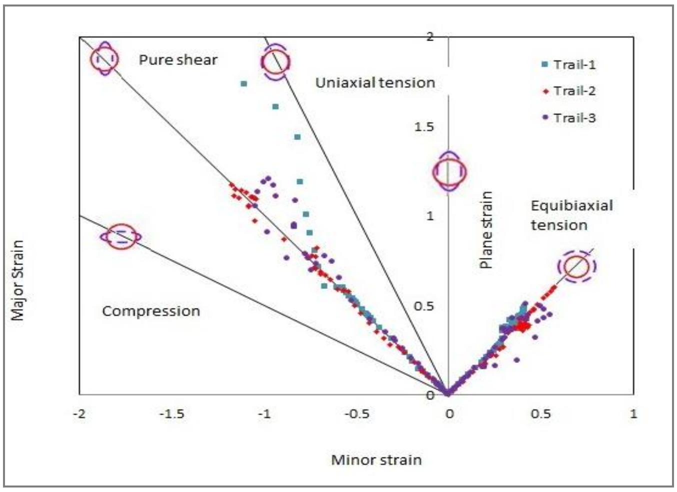

Figure 9: Forming Limit Diagrams for 0.8mm sheet thicknesses

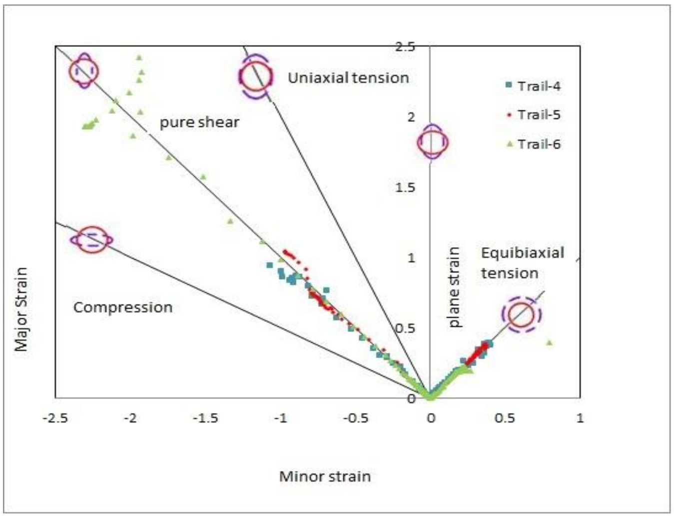

Figure 10: Forming Limit Diagrams for 1mm sheet thicknesses

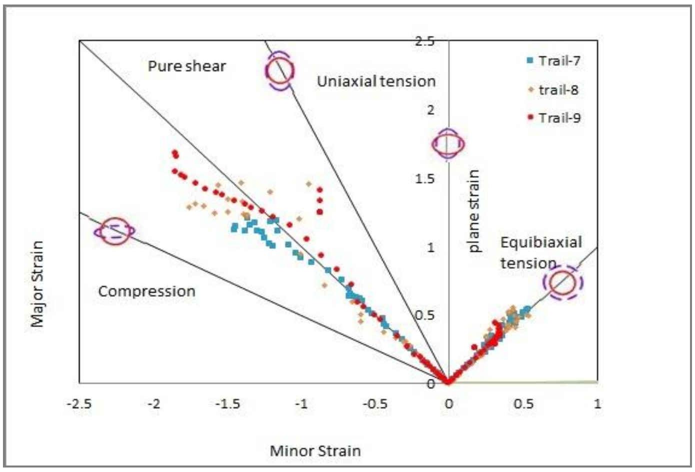

Figure 11: Forming Limit Diagrams for 1.2 mm sheet thicknesses

Figure 12: The successful deep drawn cup

4. CONCLUSION

In the present work, Monel 400 was used to fabricate cylindrical cups. The investigation was focused on the process parameters such as punch velocity, coefficient of friction, displacement per step and strain rate. The major process parameters which could the influence the deep drawing capability of Monel 400 cylindrical cups, were punch velocity and displacement per step. The effective stress was increased with an increase in the punch velocity. The equivalent stress was increased for coefficient of friction from 0.75–1. The trial 3 produces the successful cylindrical cup.

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