ISSN- 2394-5125 VOL 07, ISSUE 16, 2020

PARAMETRIC IMPORTANCE OF WARM DEEP DRAWING PROCESS FOR MONEL 400 CYLINDRICAL CUPS: VALIDATION THROUGH FEA

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ABSTRACT: In this present work, a statistical approach based on Taguchi techniques and finite element analysis were adopted to determine degree of each parameter that is punch velocity, coefficient of friction, temperature, thickness on the formability of cups from Monel 400 using warm deep drawing process. The results obtained from finite element software namely D-FORM were validated experimentally. The influence of temperature on the deformation behavior of material and the drawing loads which is required to draw the component was studied.

Keywords: Deep drawing, Monel 400, cylindrical cups, Sheet thickness, Coefficient of friction, punch velocity, damage.

1. Introduction: In sheet metal forming a thin sheet is subjected to a plastic deformation using forming tools to get the designed shape. During this process if the process parameters are not selected properly the blank sheet develops some defects. Therefore, it is very important to optimize the process parameters to reduce the defects in the parts and to minimize the production cost. Deep drawing process at room temperature, especially of high strength/low formability material has serious difficulties because of the large amount of deformations revealed and high flow stresses of the materials mentioned. Experimental [1] investigation of cup drawing was carried out to study of stresses and strains at warm drawing environments. In the finite element simulations, AC Reddy has done warm deep drawing process for different materials AA2618 alloy, AA3003 alloy, AA5052 alloy, 2017T4 Aluminium Alloy at elevated temperatures [2-9]. Optimization of the process parameters such as strain rate, temperature, friction coefficient, etc., was accomplished based on their degree of importance on the sheet metal forming characteristics. In fact, the metallic material is subjected to large irreversible deformation in sheet forming processes. This leads to high strain localization zones and then internal or superficial micro-defects (ductile damage). This damage causes quality problems such as necking and fracture, leading to process interruptions.

The objective of the present work is to optimize the warm deep drawing of Ni 201 alloy using Taguchi techniques for the cylindrical cups. In the present work, a statistical approach based on Taguchi and ANOVA techniques were adopted to determine the merit of each of the process parameter on the formability of deep drawn cylindrical cups. All the experiments results have been verified using D-form software.

2. Materials and Methods

Monel 400 was used to fabricate cylindrical cups. The levels chosen for the control parameters were in the operational range of Monel 400 using deep warm drawing process.

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The chosen control parameters are summarized in table 1. The orthogonal array (OA), L9 was selected for the present work. The assignment of parameters along with the OA matrix is given in table 2.

Table 1: Control Parameters and Levels

Factor	Symbol	L1	L2	L3
Punch Velocity	A	2	3.5	5
Coefficient of friction	B	0.2	0.3	0.4
Temperature	C	600	700	800
Thickness	D	0.80	1.00	1.20

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 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:

$$\text{Drawing force, } F = \pi dt\,[D/d - 0.6]\sigma_y \tag{5}$$

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).

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

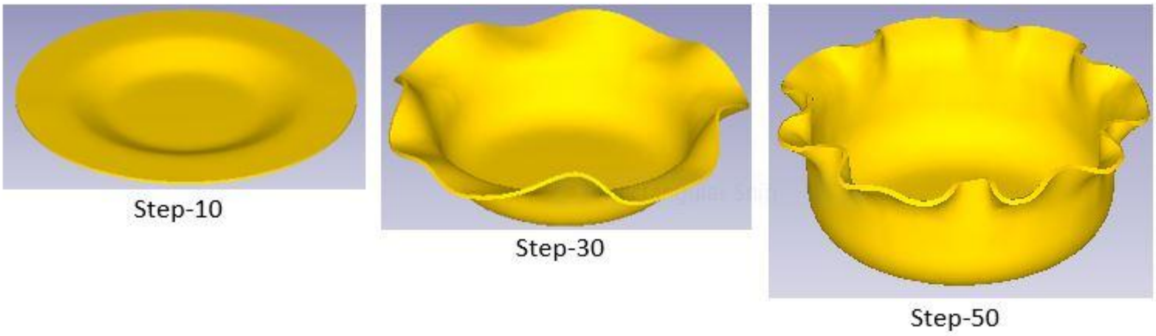

Figure 1: Cup Drawing at Different Steps

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 increase the pressure area 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

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

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.

$$\text{Clearance, } c = t + \mu\sqrt{10t} \tag{9}$$

The sheets of Monel 400 alloy were cut to the required blank size. The blank specimens were heated in a muffle furnace to the preferred temperature as per the design of experiments. The blank pressure was calculated using necessary equation. 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 done using DEFORM 3D software. The circular sheet blank was modelled with the required diameter and thickness. The cylindrical top punch and cylindrical bottom hollow die were modelled with relevant inner and outer radius and corner radius using equation (7). Using equation (9) the clearance between the

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punch and die was calculated. The sheet blank was meshed with tetrahedral elements as shown in figure 2. The modelling 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

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

3. Results and Discussion

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) contributed5.18% of variation, the Factor B (Coefficient of Friction) 2.31% of variation, C (Temperature) 89.93% of variation and D (Sheet Thickness) 2.58% of variation on the effective stress.

Table 3: ANOVA summary of the Effective Stress

Factor	S1	S2	S3	SS	v	V	F	P
A	394.30	384.61	458.74	1082.39	1	1082.39	65476.32	5.18
B	395.75	443.59	398.31	482.95	1	482.95	29214.78	2.31
C	583.68	406.00	247.96	18805.36	1	18805.36	1137580.52	89.93
D	411.77	384.47	441.41	540.54	1	540.54	32698.54	2.58
e				-0.02	4	0.00	0.00	0.00
T	1785.49	1618.68	1546.42	20911.22	8			100.00

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.

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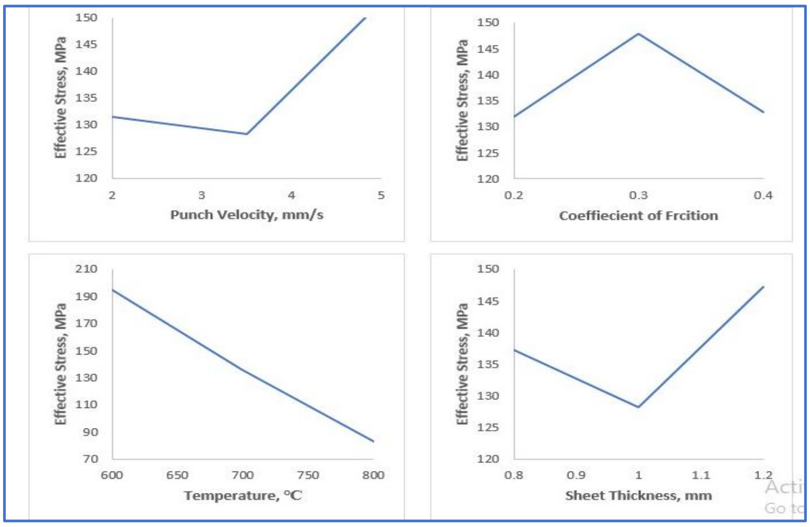

Figure 3: Influence of Process parameters on Effective Stress

The effective stress increases with increase in punch velocity. The effective stress decreases from 194.5Mpa to 82.65MPa with increasing temperature from 600 to 800°C (figure 3c). This is owing to the softening of material with an increase in the temperature. The maximum forming load decreases as the working temperature is increased. The effective stress of the cups decreases with increasing thickness of sheet. This is practical as the denominator component of 'stress = force/area' increases the stress value decreases.

3.2 Influence of control factors on Effective Strain

Table 4 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 would indicate that the factor A (Punch Velocity) contributed 9.46% of variation, Factor B (Coefficient of Friction) 4.30% of variation, C (Temperature) 24.08% of variation and D (Sheet Thickness) 62.50% of variation on the effective strain.

Table 4: ANOVA Summary of Strain Effective

Factor	S1	S2	S3	SS	v	V	F	P
A	4.29	4.58	5.63	0.33	1	0.33	27.17	9.46
B	4.37	5.29	4.85	0.15	1	0.15	12.35	4.30
C	3.60	5.81	5.09	0.84	1	0.84	69.15	24.08
D	6.90	4.02	3.58	2.18	1	2.18	179.47	62.50
e				-0.01	4	0.00	0.00	-0.34
T	19.17	19.71	19.15	3.49	8			100.00

The effective strain decreases with an increase in the thickness of blank sheet as shown in figure 4d. The characteristic equation that describes superplastic behaviour is usually written as $\sigma = K\dot{\epsilon}^{m}$, where σ is the flow stress, K is a material constant, έ is the strain rate and m is the strain-rate sensitivity index of the flow stress. The m-value is a function of the forming parameters, such as the strain rate and the temperature, and is also connected with the microstructural characteristics.

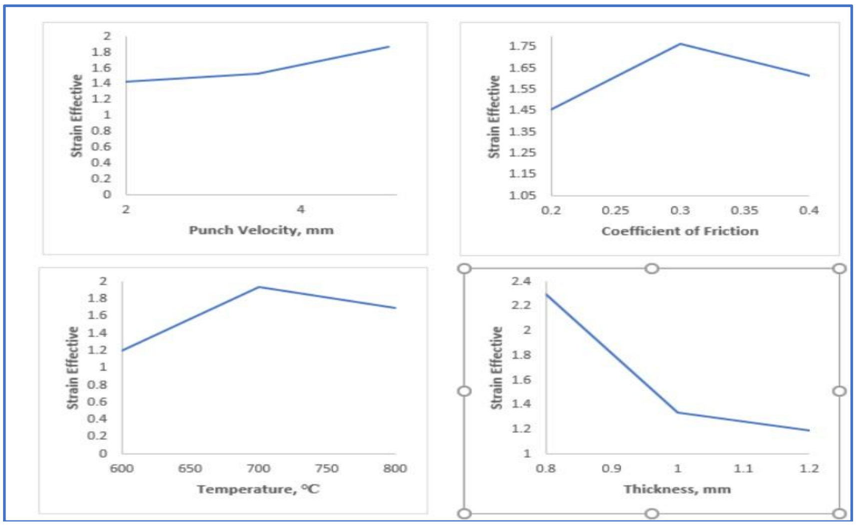

Figure 4: Influence of control parameters on Strain Effective

3.3 Influence of control factors on Cup Height

The ANOVA summary of height of the cup is given in table 5. The Fisher's test column ascertains the parameters A, B, C and D accepted at 90% confidence level influencing the variation in influencing the variation in the elastic modulus. The major contribution (49.80%) is of thickness of blank sheet towards variation in the height of up. The effects of temperature, coefficient of friction are 24.90% each towards variation in the height of cup.

Table 5: ANOVA Summary of Cup Height

Factor	S1	S2	S3	SS	v	V	F	P
A	75.35	75.48	75.32	0.00	1	0.00	0.00	0.00
B	75.35	75.32	75.48	0.01	1	0.01	62.72	24.90
C	75.57	75.32	75.26	0.01	1	0.01	62.72	24.90
D	75.25	75.55	75.35	0.02	1	0.02	125.44	49.80
e				0.00	4	0.00	0.00	0.40
T	301.51	301.67	301.41	0.04	8			100.00

The cup height increases 25.1mm to 25.16mm with increase in coefficient 0.2 to 0.4 of friction. Cup height is decreases with increase in temperature because of the softening of material easily breaks. The influence of thickness on the height of cup drawn is shown in figure 5d. The height of cup increases with an increase in the thickness of blank up to 1mm. This is obvious that the sufficient material is available to deform under the applied load

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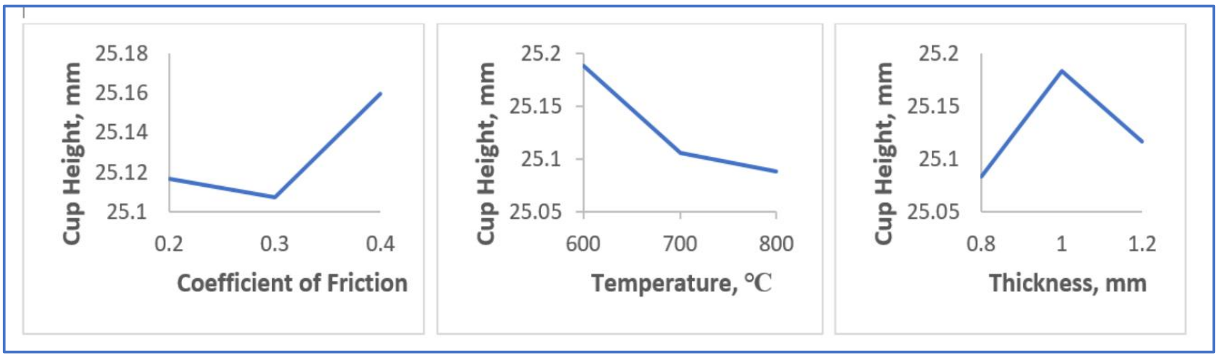

Figure 5: Influence of control parameters on Cup Height

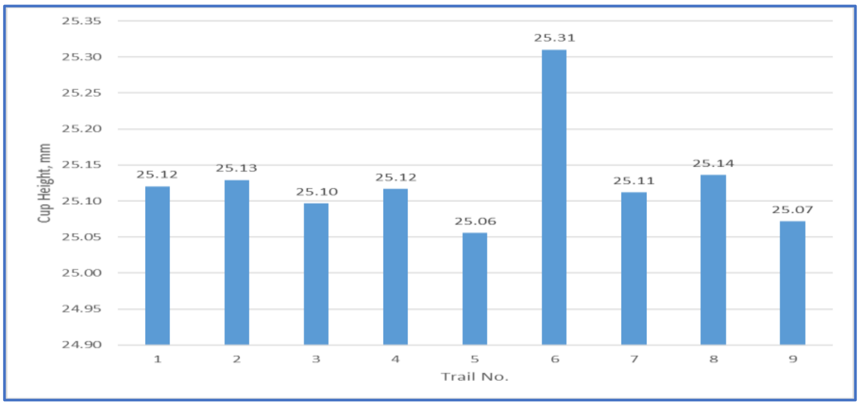

Figure 6: Cup height under different trials

3.4 Influence of control factors on Damage of Cup

The ANOVA summary of damage of cup is given in table 6. The Fisher's test column ascertains the parameters A, B, C and D accepted at 90% confidence level influencing the variation in the impact strength. The percent contribution would indicate that the thickness (D) of the sheet contributed 39.05% of the variation, temperature parameter (C) 42.6% of variation, coefficient of friction (B) 14.2% of variation and punch velocity (A) 3.55% of variation.

Table 6: ANOVA Summary of Damage of cups

	Factor	S1	S2	S3	SS	v	V	F	P
Punch Velocity	A	2.15	2.26	2.39	0.01	1	0.01	5.97	3.55
Coefficient of Friction	B	2.01	2.50	2.29	0.04	1	0.04	23.88	14.20
Temperature	C	1.77	2.47	2.55	0.12	1	0.12	71.65	42.60
Thickness	D	2.74	1.99	2.07	0.11	1	0.11	65.68	39.05
	e				0.00	4	0.00	0.00	0.60
	T	8.68	9.23	9.30	0.28	8			100.00

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The effect of thickness on the damage of cup is shown in figure6d. The damage decreases with an increase in the thickness of the sheet. The average distribution of the blank thinning increases with an increase in the blank thickness. Ironing can be defined as thinning of the blank at the die cavity. The main reasons for the damage of cups were due to ironing and the coefficient of friction. The clearance was obtained by the formula as in eq. (9).

In the case of friction between the piece and the tool, the increase of the coefficient of friction determines the wrinkling to reduce, but high values of the coefficient can cause cracks and material breakage. In the case of deep drawing, under the effect of the deformation force, the blank is subjected to a tangential compression stress and a radial extension stress. For instance, in the case of the thin sheets, although the radial extension stress of the flange is relatively high, the tangential compression stress can lead to the risk of its wrinkling, a risk which is very likely to appear when the difference between the outer diameters of the blank and the finished piece is big and the sheet thickness is small. It is observed that the damage in the cup increases with an increase in the coefficient of friction from 0.2 to 0.4. It was observed that if the friction forces are low, the wrinkling is more pronounced, but if the friction forces are too high the material can break.

The effect of control factors on the damage of cup are shown in figure 6. As the punch velocity increased the damage increases linearly as shown in figure 6(a). The damage of cups was highest for the coefficient of friction of 0.3 with a value of 0.83 as shown in figure 6(b). Then the damage factor reduced to a value of 0.76 at the coefficient of 0.3. The damage of the cups was found to be low at temperature of 600°C as shown in figure 6(c). The damage of cups was found to be high for the blank thickness of 0.8mm with a value of 0.9 and reduced rapidly for 1mm sheet with a value of 0.66.

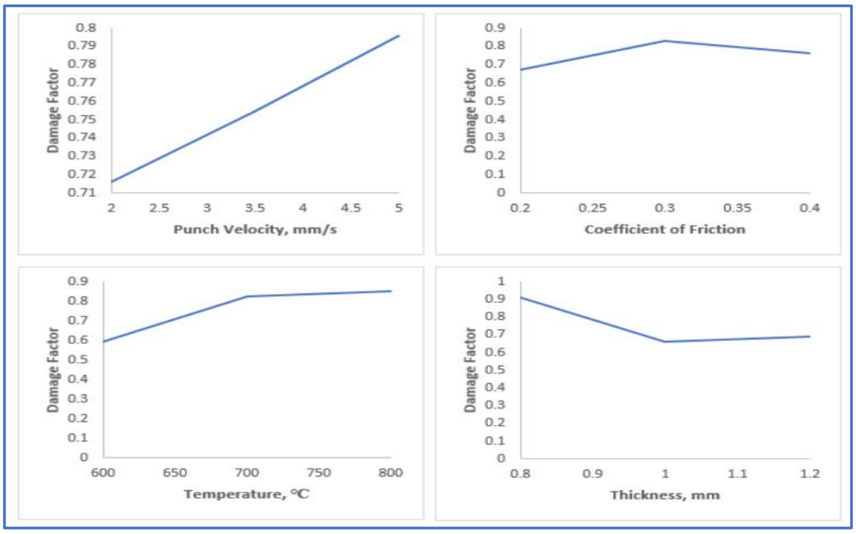

Figure 6: Influence of control parameters on Damage of cup

The damage of the cups under different trial conditions are shown in figure7. Figure 8 depicts the forming limit diagram of Monel 400 with 0.8mm sheet thickness. the trials 1, 5 and 9 were most damaged on account of biaxial tension and compression induced in the blank material as shown in figure 8. Less damage was observed in the trials 3, 4 and 8 except wrinkles due more compressive stresses as shown in figure 10. The cylindrical cups drawn under trials 2, 6 and 7 with sheet thickness 1mm were damaged due to uniaxial tension and stretching as shown in figure 9. Highest damage occurred in trial 5 due to low temperature and least sheet thickness.

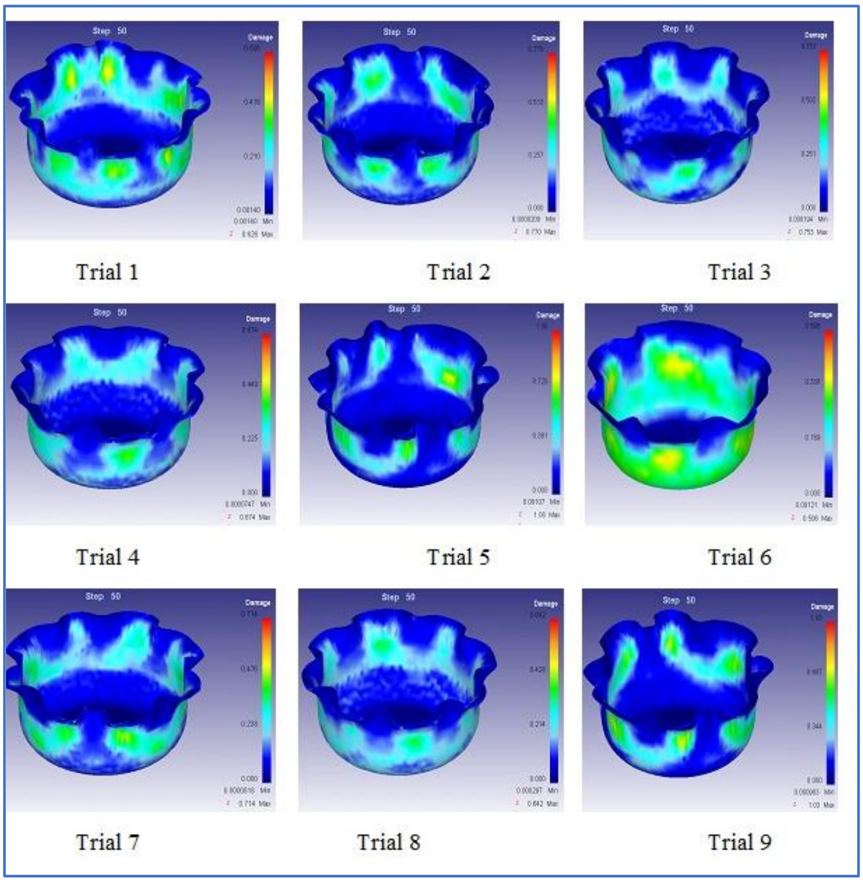

Figure 7: Damage of the cup under different operating conditions

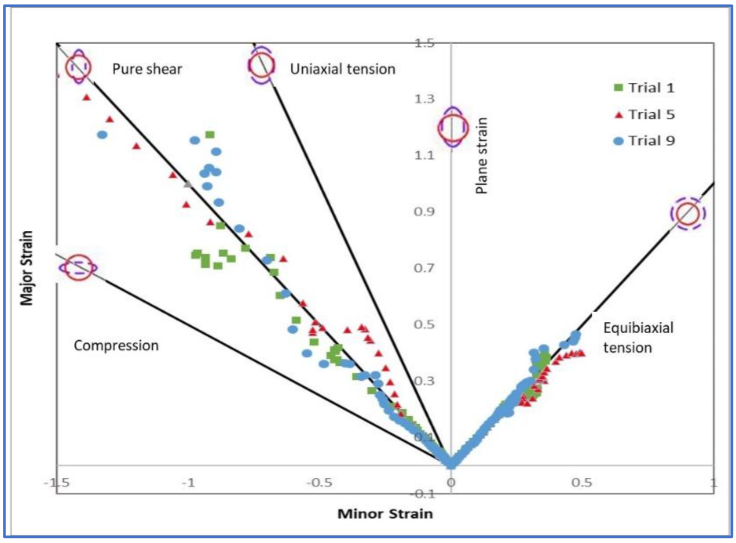

Figure 8: Forming Limit Diagrams for 0.8mm sheet thicknesses

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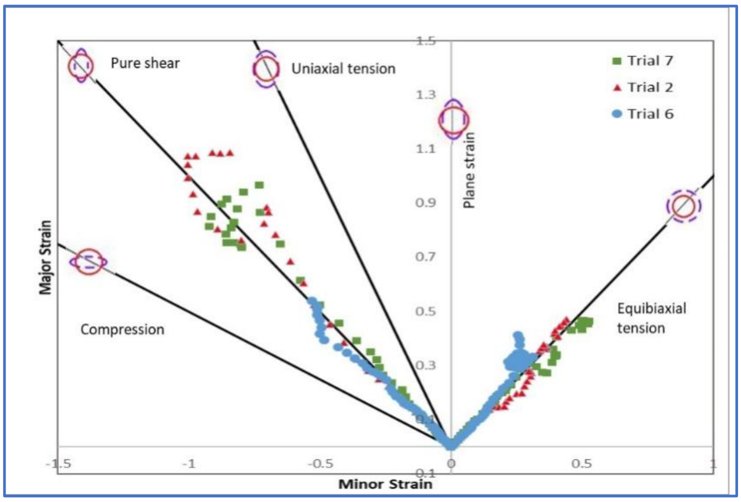

Figure 9: Forming Limit Diagrams for 1mm sheet thicknesses

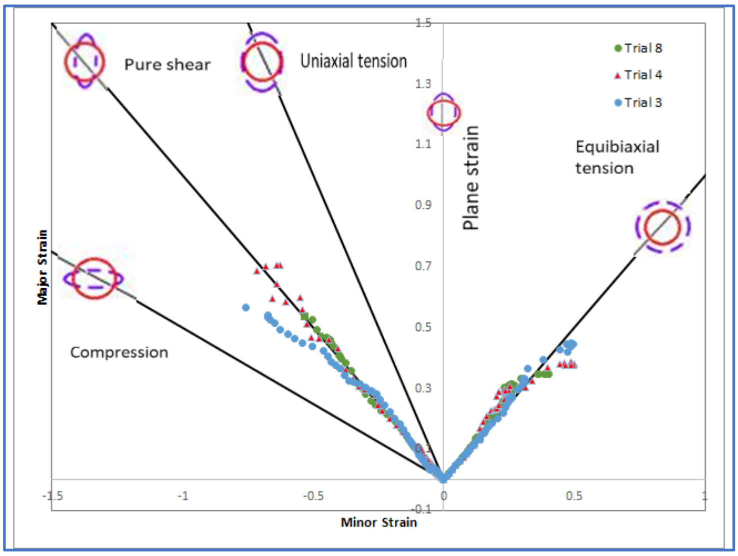

Figure 10: Forming Limit Diagrams for 1.2 mm sheet thicknesses

Figure 11: The successful deep drawn cup

4. Conclusion

The major process parameters which could the influence the deep drawing capability of Monel-600 cylindrical cups, were blank thickness and temperature. The damage of the cups

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was found to be less with the sheet thickness of 1mm. Effective stress continuously decreased with increase in temperature. Effective strain was found to be less with 1mm sheet and with 0.4 coefficient of friction. The cup with punch velocity 3.5mm/s, coefficient of friction 0.4, temperature 600 °C and sheet thickness 1.1mm was found to be best drawn cup.

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