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RESEARCH ARTICLE

Finite Element Analysis of Warm Deep Drawing Process for Pyramidal Cup of AA1070 Aluminum Alloy

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Abstract

In this present work, a statistical approach based on Taguchi techniques and finite element analysis were adopted to determine the influence of sheet thickness, temperature, coefficient of friction and strain rate on the formability of cups from AA1070 aluminum alloy using warm deep drawing process. The successful pyramidal cups of 1.5mm blank thickness with zero damage were obtained with operating conditions of 300^{o}C, temperature; 0.05, coefficient of friction; and 500, strain rate.

INTRODUCTION

Many investigations have been carried out to obtain an optimal blank shape that can be deformed into the near-net shape. Chung et al. (1997) have proposed a direct design method based on an ideal forming theory to get an initial blank shape. Toros et al. (2008) have developed an analytical model to evaluate deep drawing process at elevated temperatures and under different blank holder pressure (BHP) and identified that temperature, punch speed, BHP, and friction are the main factors that influence formability. Chennakesava Reddy et al. (2012) 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^{o}C. Chennakesava Reddy et al. (2012) in another 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. Reverse super plastic blow forming of a Ti-6Al-4V sheet has been simulated using finite element method to achieve the optimized control of thickness variation (Chennakesava Reddy, 2006). The strain hardening rate and fracture toughness are usually affected by strain rate and temperature. Chennakesava Reddy (2011) has used Taguchi technique which can save the cost of experimentation to optimize the extrusion process of 6063 aluminum alloy. Industrial pure aluminum cannot be heat strengthened, through increased intensity of cold deformation, the only form of heat treatment is annealing. The strength of 1070 aluminum can be improved by small addition of different amount of borax. 1070 aluminum alloy is highly resistant to chemical corrosion and has good crack resistance. 1070 is being widely used in less demanding on the strength of the product, such as chemical equipment, sheet metal processing parts, deep drawing or spinning hollowware, welding parts, heat exchangers, bell surface and disk, plate, kitchenware, decorations, utensils and other reflective

The objective of the present work is to optimize the warm deep drawing process of AA1070 aluminum alloy using Taguchi technique for the pyramidal cups. In this present work, a statistical approach based on Taguchi and ANOVA techniques was adopted to determine the merit of each of the process parameter on the formability of deep drawn pyramidal cup. All the experimental results have been verified using D-FORM software.

1. Materials and Methods

AA1070 aluminum alloy was used to fabricate deep drawing cups. The tensile and yield strengths of this alloy are 110 MPa and 75 MPa respectively. The Poisson's ratio is 0.33. The percent elongation is 12. The control parameters are those parameters that a manufacturer can control the design of the product, and the design of process. The levels chosen for the control parameters were in the operational range of AA1070 aluminum alloy 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 OA matrix is given in table 2.

1.1 Design and fabrication of deep drawn pyramidal cups

The initial dimensions of the pyramidal cup without corner and edge radii are shown in figure 1. The blank size was calculated by equating the surface area of the finished drawn cup with the area of the blank. The blank dimensions are obtained by:

$$(l_1 + l_2 + b_1 + b_2)h_2 + l_2 b_2 = l_b b_b \quad (1)$$

where l_1 and l_2 are the top and bottom lengths of the pyramidal cup respectively; h_1 and h_2 are the height and slant heights of cup respectively; b_1 and b_2 are top and bottom widths of the cup respectively.

In the present work, the dimensions of the cup are as follows:

Cup top length, $l_1 = 60$ mm

Cup top width, $b_1 = 40$ mm

Slant angle, $\alpha = 6$ degrees

Height of the cup, $h_1 = 75$ mm

The slant height, h_2 of the pyramidal cup is given by the following expression:

$$h_2 = \frac{h_1}{\cos\alpha} \quad (2)$$

The bottom length, l_2 of the pyramidal cup is given by the following expression:

$$l_2 = l_1 - 2x \quad (3)$$

The bottom width, b_2 of the pyramidal cup is given by the following expression:

$$b_2 = b_1 - 2x \quad (4)$$

where, $x = h_2 \times \sin\alpha$

In order to avoid wrinkling in the pyramidal cup, the blank must be given corner radius, r_c which can be expressed as follows:

$$r_c = \sqrt{r_{cp}^2 + 2r_{cp}h_1 - 1.41 r_{cp} r_{ep}} \quad (5)$$

where, r_{cp} is the punch side corner radius and r_{ep} is the punch edge radius.

The top and bottom dimensions of the punch are equal to the top and bottom dimensions of the cup. The height of the punch is the height of the cup. The drawing punch must have corner radius exceeding one-tenth of the cup top length. The radius joining the bottom to the sides, r_{ep} generally ranges from three to eight times the blank thickness (t). In the present work, the corner and edge punch radii are taken as below:

$$r_{cp} = l_1/5 \text{ and } r_{ep} = 5t \quad (6)$$

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

$$\text{Clearance, } c_d = t \pm \mu\sqrt{10t} \quad (7)$$

where μ is the coefficient of friction.

The top length of the die is obtained from the following equation:

$$l_{d1} = l_1 + 2c_d \quad (8)$$

The bottom length of the die is obtained from the following equation:

$$l_{d2} = l_2 + 2c_d \quad (9)$$

The top width of the die is obtained from the following equation:

$$b_{d1} = b_1 + 2c_d \quad (10)$$

The bottom width of the die is obtained from the following equation:

$$b_{d2} = b_2 + 2c_d \quad (11)$$

The height of the die is the height of the cup.

The corner radius of the die is obtained by the addition of clearance to the punch corner radius. The edge radius of the die is eight times the blank thickness.

1.2 Finite element analysis

The finite element modeling and analysis was carried using D-FORM 3D software. The rectangular sheet blank was created with desired dimensions. The pyramidal top punch, blank and bottom hollow die were modeled as shown in figure 2 with appropriate inner and outer dimensions using UNIGRAPHICS software. The clearance between punch and die was calculated using Eq. (7). The sheet blank was meshed with tetrahedral elements (Chennakesava, 2008). The modeling parameters of deep drawing process for trail were as follows:

Number of elements for the blank: 7088
Number of nodes for the blank: 2472
Top die polygons: 604
Bottom die polygons: 1096.

The pyramidal cup operation during different steps is shown in figure 3. 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. 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 D-FORM 3D software according to the design of experiments for the purpose of validating the results of experimentation.

2. Results and Discussion

Two trials were carried out with mesh sizes for each experiment.

2.1 Influence of control factors on effective Stress

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 D, strain rate, all by itself contributes 78.64% towards the variation. The temperature (B) contributes over a one-fifth (19.95%) of the total variation observed. The effect of blank thickness (A) and C (coefficient of friction) give negligible variation on the effective tensile stress.

The influence of control factors on the effective stress is shown in figure 4. The effective stress of the pyramidal cups is found to be minimum of 79.45MPa at temperature of 300°C as shown in figure 4(a). The effective stress decreases with an increase of strain rate as shown in figure 4(b). The effective stresses induced in the pyramidal cups under different trial conditions are shown in figure 5. The equivalent stresses induced in the trials 1, 2, 5, 6, 7 and 9 are 138.26MPa, 100.29MPa, 111.09MPa, 115.02MPa, 143.57MPa and 110.51MPa respectively. The equivalent stress induced in the trial 4 is 76.80MPa. The equivalent stresses induced in the trials 3 and 8 are 41.76MPa and 26.37MPa respectively. The pyramidal cups are successful with trials 3 and 8. Even though the equivalent stress induced in the trial 4 is 76.80MPa, the pyramidal cup is failed due to very low temperature of 30°C (room temperature).

2.2 Influence of control factors on height of pyramidal cup

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, strain rate, contributes a two-third (66.23%) towards the variation. The blank thickness (A), temperature (B) and coefficient of friction (C) tender 13.80%, 13.68% and 5.99% respectively of variation on the cup height.

The influence of control factors on the cup height is shown in figure 6. The cup height of the pyramidal cups increases with an increase of blank thickness 6(a). The cup height of the pyramidal cups is minimum of 53.35mm at temperature of 300°C as shown in figure 6(b). The coefficient of friction of 0.075 gives the cup height of 64.39mm as shown in n figure 6(c). The strain rate of 100 imparts the cup height of 47.22mm as shown in figure 6(d). The height of the pyramidal cups under different trial conditions are shown in figure 7. For the pyramidal cups drawn with trials conditions of 1, 2, 5, 6 and 7, the cup heights are 44.61mm, 42.76mm and 41.32mm, 48.59mm and 50.55mm respectively. For the pyramidal cups drawn with trials conditions of 3, 4, 8 and 9, the cup heights are 78.34, 76.47mm, 76.19mm and 75.26mm respectively. The trials of 3, 4, 8 and 9 have reached the target height of 75mm.

2.3 Influence of control factors on damage of pyramidal cup

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 D, strain rate, over a one-third (32.63%) of the total variation. The blank thickness (A), temperature (B) and coefficient of friction (C) contribute 22.10%, 23.58% and 21.67% respectively on the variation of the cup damage.

The effect of control factors on the damage of cup are shown in figure 8. The damage of cups increases with an increase of the blank thickness as shown in figure 8(a). The damage of the cups decreases with an increase of temperature as shown in figure 8(b). The damage of cups is lowest for the coefficient of friction of 0.075 as shown in figure 8(c). The biggest damage of the cups is observed with the strain rate of 100 as shown in figure 8(d). The damage of the pyramidal cups under different trial conditions are shown in figure 9. For the pyramidal cups drawn with trials conditions of 1, 2, 5, 6, 7 and 9, the damage of cups are 6.38%, 2.51%, 4.99%, 8.97%, 55.07% and 5.37% respectively. Even though the trial condition of 9 gives the target height of 75mm there is tearing on the topside edge of the pyramidal cup. For the pyramidal cups drawn with trials conditions of 3, 4 and 8, the damage of cups are 0.06%, 0.12% and 0% respectively. The biggest damage is observed with trial conditions of 7 on account of room temperature (30^{o}C), strain rate (100) and high coefficient of friction (0.1) deep drawing process. For the damage of the pyramidal cups drawn with operating conditions of trial 1, the reasons are owing to room temperature deep drawing process. The cups drawn with conditions of trials 2 and 6 are failed due to strain rate of 100. The high coefficient of friction results in the damage of cups drawn with operating conditions of trial 5. The forming limit diagram, as shown in figure 10, shows that the cups drawn with trials 1, 2, 4, 5, 6, 7 and 9 have wrinkles. It is also observed from figure 5 that the Von Mises stresses for the cups drawn under trials 1, 2, 4, 5, 6, 7 and 9 exceed the yield strength of the material, thus these cups undergo the plastic deformation. For the remaining cups the von Mises stress is less than the yiled strength (75 MPa) of the material.

3. Conclusions

The successful pyramidal cups with zero damage of 1.5mm blank thickness were obtained with operating conditions of 300^{o}C, temperature; 0.05, coefficient of friction; and 500, strain rate. The successful pyramidal cups of 1.0mm blank thickness were obtained with operating conditions of 500^{o}C, temperature; 0.1, coefficient of friction; and 500, strain rate. The factors which cause the damage of cups have been found to be room temperature operation of deep drawing, high coefficient of friction, and low strain rate.

Acknowledgment

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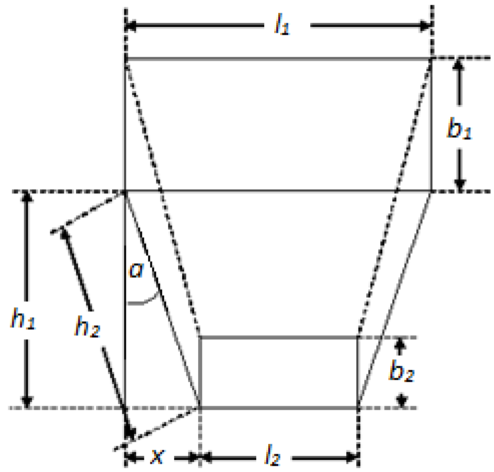

Figure 1: Initial dimensions (without corner & edge radii) of the pyramidal cup.

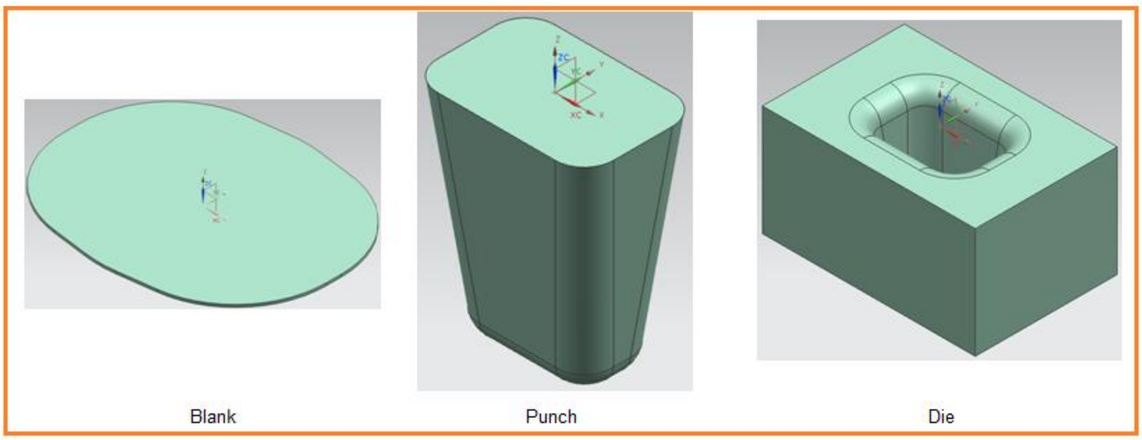

Figure 2: Blank, punch and die

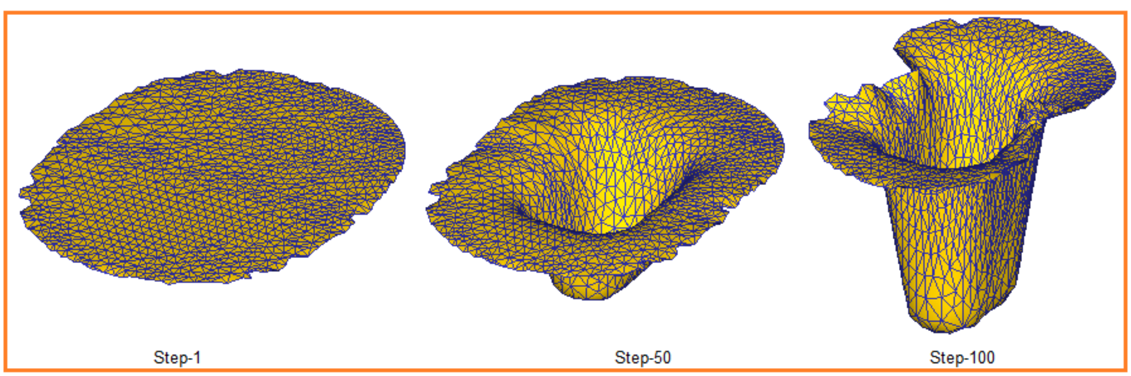

Figure 3: Pyramidal cup drawing at different steps.

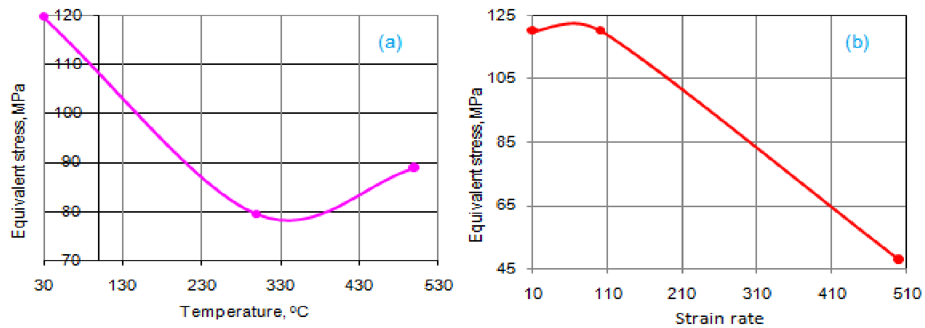

Figure 4: Effect of control factors on the effective stress.

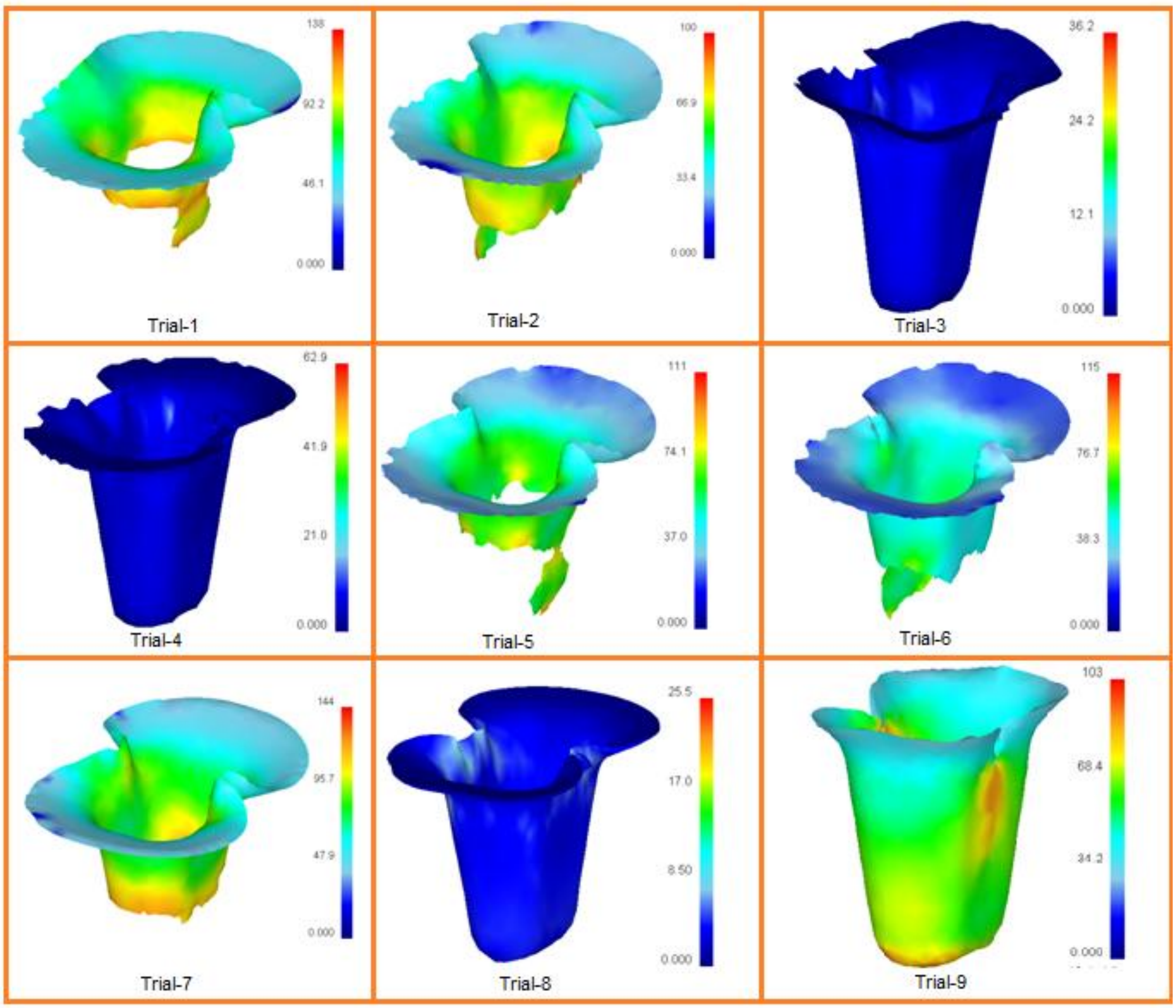

Figure 5: Effective stress in pyramidal cups under different operating conditions.

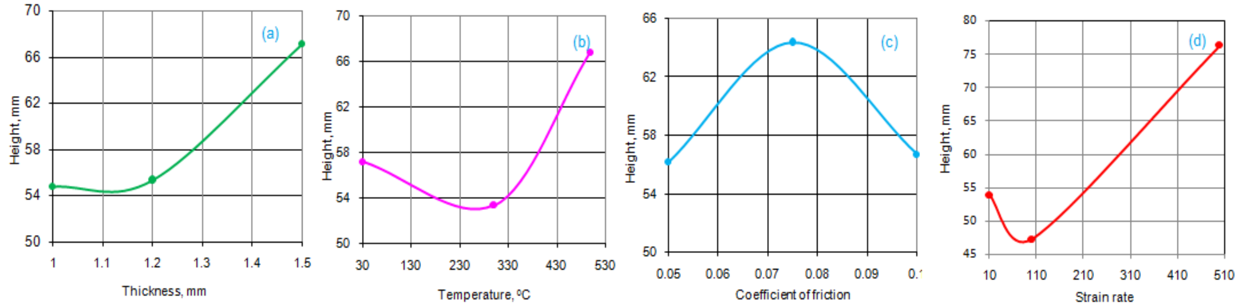

Figure 6: Effect of control factors on the cup height.

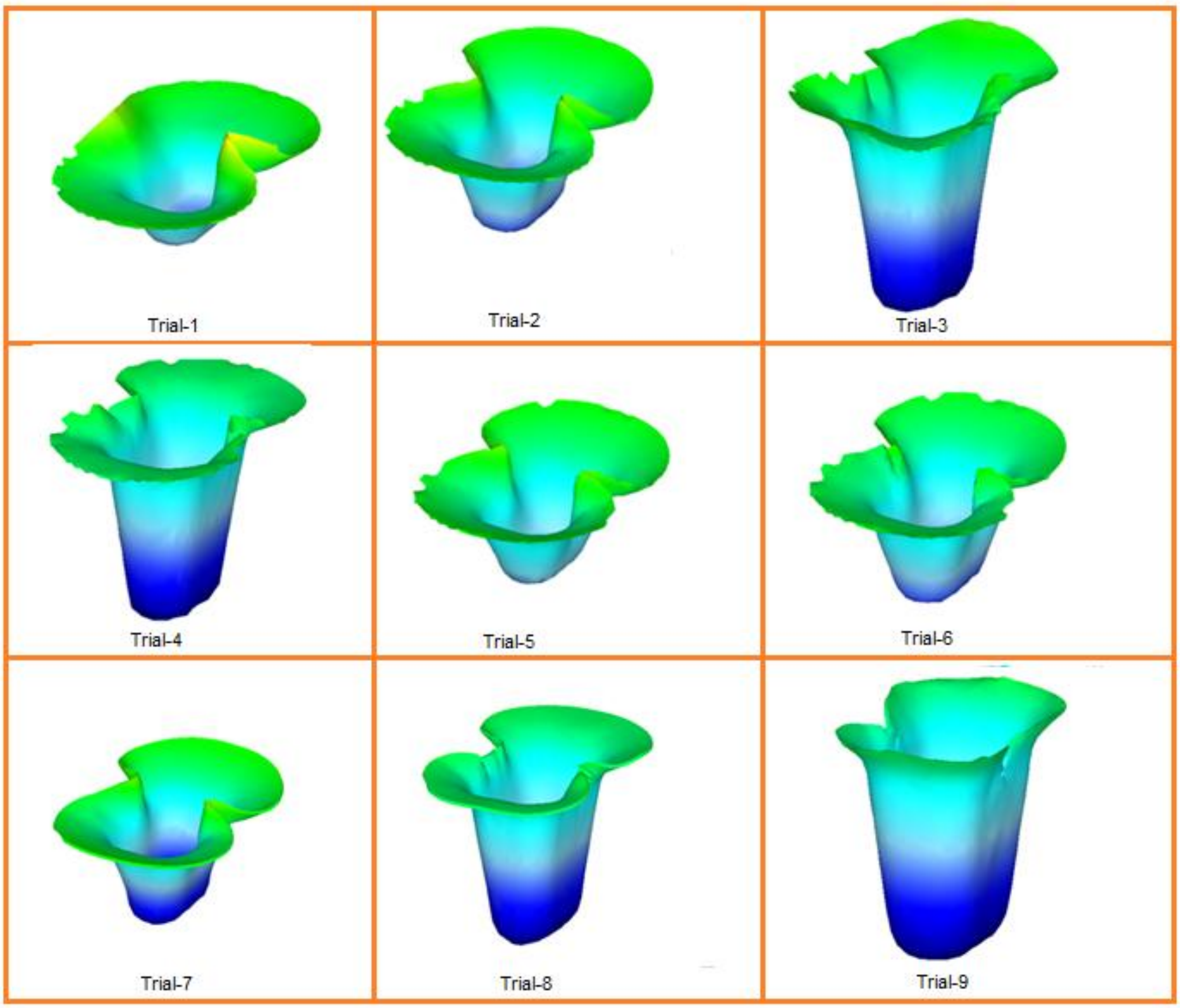

Figure 7: Heights of pyramidal cups under different operating conditions.

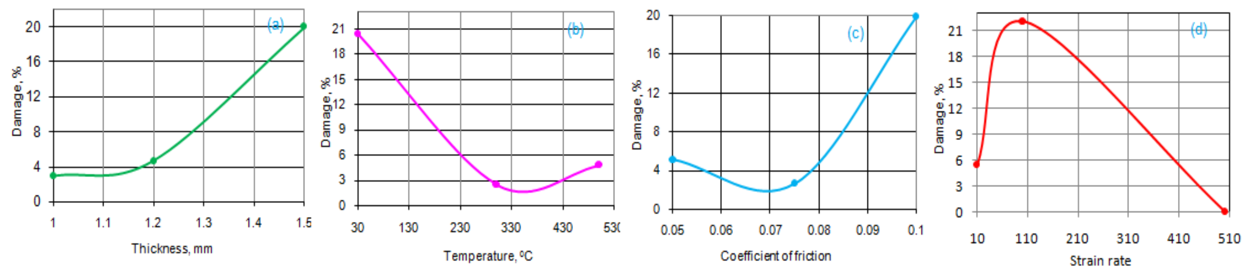

Figure 8: Effect of control factors on the cup damage.

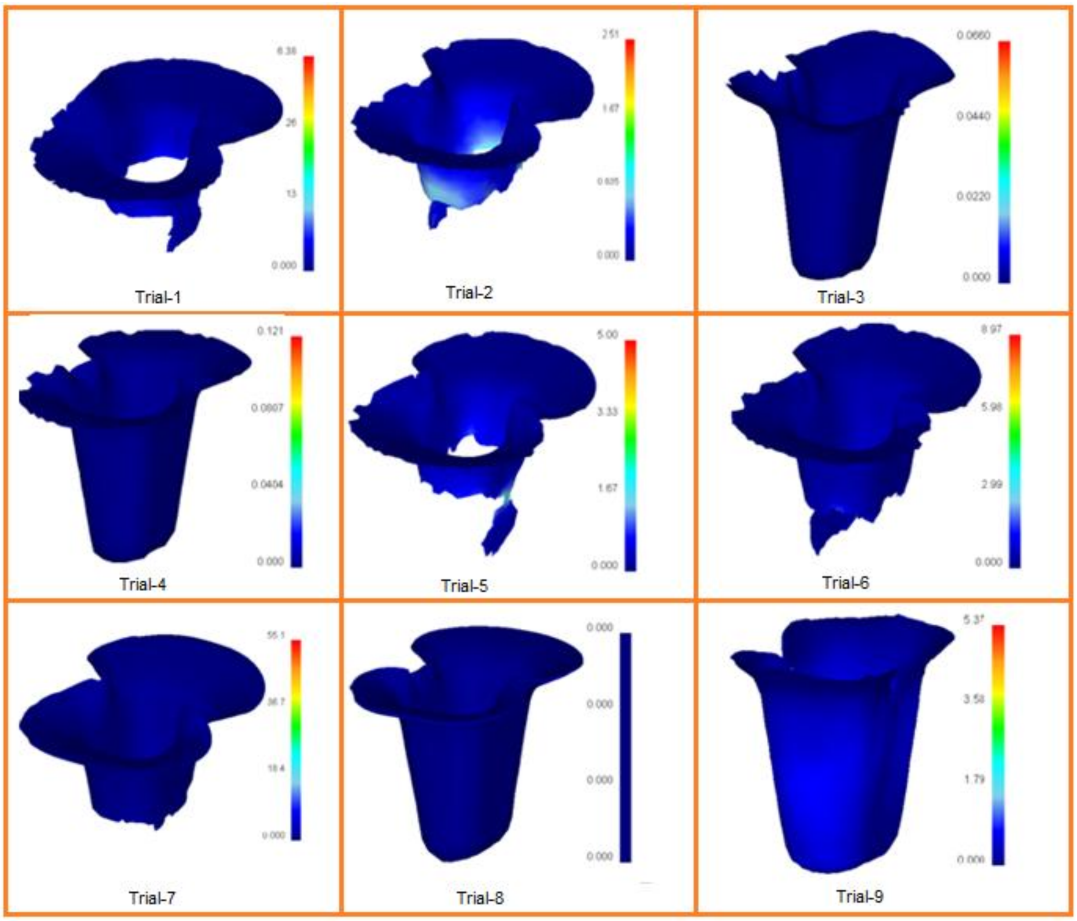

Figure 9: Damage in pyramidal cups under different operating conditions.

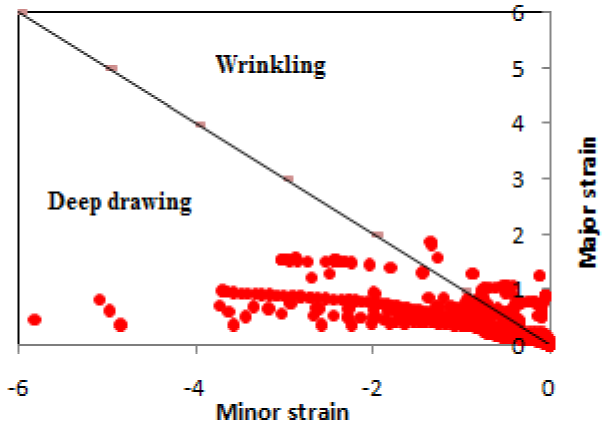

Figure 10: Forming limit diagram of cups

Table 1: Control Parameters and Levels

Factor	Symbol	Level–1	Level–2	Level–3
Thickness, mm	A	1.00	1.20	1.50
Temperature, ^{0}C	B	30	300	500
Coefficient of Friction	C	0.05	0.075	0.1
Strain rate	D	10	100	500

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

Table 3: ANOVA summary of the effective stress

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	562.8225	605.6051	558.7289	224.7	2	112.35	97.69565	0.84
B	717.2667	476.6946	533.1953	5274.98	2	2637.49	2293.47	19.95
C	557.3284	573.1151	596.713	130.96	2	65.48	56.93913	0.49
D	719.5375	720.2367	287.3823	20784.53	4	5196.13	4518.374	78.64
Error				8.051061	7	1.15	1	0.08
T	2556.955	2375.652	1976.019	26423.22	17			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.

Table 4: ANOVA summary of the pyramidal cup heights.

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	328.75	332.2	402.76	581.57	2	290.78	392.9459	13.8
B	342.85	320.11	400.75	576.24	2	288.12	389.3514	13.68
C	337.22	386.36	340.13	253.36	2	126.68	171.1892	5.99
D	322.7	283.34	457.67	2786.5	4	696.63	941.3919	66.23
Error				5.1561	7	0.74	1	0.3
T	1331.52	1322.01	1601.31	4202.826	17			100

Table 5: ANOVA summary of the pyramidal cup damages.

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	17.49	27.971	120.233	1065.46	2	532.73	10654.6	22.1
B	122.184	14.76	28.75	1136.97	2	568.49	11369.8	23.58
C	30.61	15.781	119.303	1044.62	2	522.31	10446.2	21.67
D	32.82	132.333	0.541	1573	4	393.25	7865	32.63
Error				0.340722	7	0.05	1	0.02
T	203.104	190.845	268.827	4820.391	17			100

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