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RESEARCH ARTICLE

Finite Element Analysis of Warm Deep Drawing Process for 2017T4 Aluminum Alloy: Parametric Significance Using Taguchi Technique

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Abstract

In this present work, a statistical approach based on Taguchi and ANOVA techniques and finite element analysis have been adopted to determine the degree of importance of each of the process parameter on the formability of cup using warm deep drawing process. The process parameters were thickness of blank, temperature, coefficient of friction and strain rate. The temperature and strain rate have been found to influence the quality of deep drawn cups. The major parameter which could influence the damage of cups is the strain rate.

INTRODUCTION

Ductility is an essential property of material for its formability. This is not absolute constant for a metal or alloy under all conditions. The same material may show different formability in different forming processes. A large number of alloys show super-plastic properties at different temperatures and grain sizes. Jeyasingh et al. (2008) have carried out investigations on failures of hydroforming deep drawing processes. The punch deforms the blank to its final shape by moving against a controlled pressurized fluid, which acts hydrostatically via a thin rubber diaphragm. As a result of the controllable backup pressure, a favorable pressure path, with respect to the punch travel, can be sought in order to delay the premature failures. The failure by rupture results from an excessive fluid pressure, while wrinkling results from insufficient fluid pressure. The range of pressure in between these two boundaries, give the working zone. 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 2000C. Reddy (2012) in his 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. Reverse superplastic blow forming of a Ti-6Al-4V sheet has been simulated using finite element method to achieve the optimized control of thickness variation (Reddy, 2006). A statistical approach based on Taguchi techniques and finite element analysis has been adapted to deter-mine the parametric consequence on the formability of cup using warm deep drawing process. The process parameters are thickness of blank, temperature, coefficient of friction and strain rate (Reddy, 2015).

Aluminum alloy 2014 is a copper based alloy with very high strength. 2014 aluminum alloy is often used in the aerospace industry. Other applications include military vehicles, bridges, weapons manufacture and structural applications. 2014 is the second most popular of the 2000-series aluminum alloys, after 2024 aluminum alloy. It is commonly extruded and forged. Aluminum alloy 2014A is available in bar, sheet, strip, plate, wire, tube, drawn tube, forging stock and rivet stock.

The objective of the present work is to optimize the warm deep drawing process of 2014A aluminum alloy using Taguchi technique. In this present work, a statistical approach based on Taguchi and ANOVA techniques was adopted to determine the degree of importance of each of the process parameter on the formability of deep drawn cup. All the experimental results have been verified using D-FORM software.

1. Material and Methods

2014T6 aluminum alloy was used to fabricate deep drawn cups. The tensile and yield strengths of this alloy are 483 and 414 MPa respectively. The elastic modulus is 72.4 GPa. The Poisson's ratio is 0.33. The percent elongation is 13. The shear strength is 290 MPa. 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 2014T6 aluminum alloy using deep drawing process. Each of the three 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.

The blank size 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:

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

$$D = \sqrt{d^2 + 4dh} - 0.5\text{r} \quad \text{for 20 < d/r < 20} \qquad (2)$$

$$D = \sqrt{d^2 + 4dh} - \text{r} \quad \text{for 15 < d/r < 10} \qquad (3)$$

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

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:

$$\text{Drawing force, } F_d = \pi \text{dt}[D/d - 0.6]\sigma_y \qquad (5)$$

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 punches must have corner radius exceeding three times the blank thickness (t). However, the punch radius should not exceed one-fourth the cup diameter (d).

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

For smooth material flow the die edge should have generous radius preferably four to six times the blank thickness but never less than three times the sheet thickness because lesser radius would hinder material flow while excess radius 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:

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

The drawing ratio is roughly calculated as

$$\text{DR} = D/d \qquad (8)$$

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.

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

2. Finite Element Modeling and 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 cylindrical top punch, cylindrical bottom hollow die were modeled with appropriate inner and outer radius and corner radius (Chennakesava, 2008). The clearance between the punch and die was calculated using equ (9). The sheet blank was meshed with tetrahedral elements (Chennakesava, 2009). The modeling parameters of deep drawing process were as follows:

Number of elements for the blank: 6725 tetrahedron
Number of nodes for the blank: 2307
Top die polygons: 9120
Bottom die polygons: 9600

The initial position of the die, punch, blank holder is shown in figure 1. 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, effective strain, volume 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.

3. Result and Discussion

The experiments were scheduled on random basis to accommodate the manufacturing impacts (like variation of temperature, pressure). Two trials were carried out for each experiment. The true tensile-true strain and engineering stress-strain of 2014T6 aluminum alloy are shown in figure 2. They are almost equal in nature tested at room temperature using hydraulically operated universal tensile testing (UTM) machine.

4.1 Influence of Process Parameters 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 thickness parameter, A contributes 25.43% of variation, B (temperature) assists 37.37% of variation, C (coefficient of friction) influences 2.34% of variation and D (strain rate) contributes 34.72% of variation on the effective tensile stress.

The influence of thickness on the effective stress is shown figure 3a. The effective stress of the cups increases from 176.33 to 235.17 MPa with increasing thickness of sheet from 0.8 to 1.2 mm. The effective stress decreases from 234.62 to 154.50 MPa with increasing temperature from 300 to 400^0C (figure 3b) and later on it increases from 154.50 to 201.33 MPa for increase of temperature from 400 to 500^0C. This is owing to the softening of material with an increase in the temperature from 300 to 400^0C. For an increase in the temperature from 400 to 500^0C the enhancement of stress is due to the formation of precipitates as shown figure 4. Also the maximum forming load decreases as the working temperature is increased. The maximum forming load is found to decrease from 51KN to 10KN over the working temperature range 300^0C<T< 500 ^{0}C for sheet thickness of 0.8 mm. The maximum forming load is found to decrease from 14KN to 9KN over the working temperature range 300^0C<T< 500 ^{0}C for sheet thickness 1.0 mm). The maximum forming load is found to decrease from 37KN to 7KN over the working temperature range 300^0C<T< 500 ^{0}C for sheet thickness of 1.2 mm (figure 5).

The influence of coefficient of friction on the effective stress is shown in figure 3c. The influence of friction on the effective stress is very less as compared other parameters. However, the effective stress increases with an increase in coefficient of friction. According to Coulomb's friction model ($\tau_f = \mu p$ where τ_f is the frictional shear stress, p the internal pressure and μ the coefficient of friction). The influence of strain rate on the effective stress is shown in figure 3d. It is observed that the effective stress decreases with an increase in the strain rate. The flow stress is a function of strain hardening, strain rate sensitivity and temperature (Kobayash and Dodd, 1989) as given below:

$$\sigma = \sigma_0 \epsilon^n \dot{\varepsilon}^m (1 - \beta\Delta T) \qquad (10)$$

where σ is the flow stress, ε the strain, n the work-hardening coefficient, $\acute{\varepsilon}$ the strain rate, m the strain-rate sensitivity index, T the temperature and σ_o and β are constants.

For sheet thickness of 0.8 mm the maximum induced stress is 239 MPa. For sheet thickness of 1.0 mm the maximum induced stress is 189 MPa. For sheet thickness of 0.8 mm the maximum induced stress is 284 MPa (figure 6).

3.2 Influence of Process Parameters on Height of Cup

The ANOVA summary of the height of cup is given in table 4. The Fisher's test column ascertains all the parameters (A, B, C, D) accepted at 90% confidence level influencing the variation in the elastic modulus. The major contribution (50.23%) is of thickness of blank sheet towards variation in the height of up. The effects of temperature, coefficient of friction and strain rate are 16.01%, 8.34% and 25.33% respectively towards variation in the height of cup.

The influence of thickness on the height of cup drawn is shown in figure 7a. The height of cup increases with an increase in the thickness of blank. This is obvious that the sufficient material is available to deform under the applied load. At temperature 300^0C the height of cup drawn is 41.48 mm. At temperature 400^0C the height of cup drawn is 30.30 mm. At temperature 300^0C the height of cup drawn is 44.02 mm (figure 7b). The reduction of cup height drawn is due to failure of the blank material at 400^0C due to transition phase from metastable to stable precipitates of $CuAl_2$. By quenching and then reheating an Al-2017 alloy, a fine dispersion of precipitates forms within a grain. These precipitates are effective in hindering dislocation motion and, consequently, increasing alloy hardness (and strength). This process is known as precipitation hardening, or age hardening. The yield strength and ductility decrease with the precipitation heat. The height of the cup drawn decreases with an increase in the coefficient of friction from 0.2 to 0.4 as shown in figure 7c. While the height of the cup drawn increases with increase in the strain rate as shown in figure 7d. The flow stress of the sheets obeys the function of strain rate, strain and temperature.

3.4 Influence of Process Parameters on Damage of Cup

The ANOVA summary of specific wear rate 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 the impact strength. The major contribution on the damage of cups is the strain rate (90-.4%) only. The effect of other variables is negligible.

The damage in the cups decreases with an increase in the strain rate as shown in figure 8. It is observed from figure 9 that the trials 1, 2, 3, 5, 6 and 7 have resulted with damage in the cups. The cups of 0.8 mm thick sheets have experienced the damage with the three strain rates. The cups under trail 5 and 6 of 1.0 mm thick sheets have experienced the damage with strain rates of 1and 25 mm/mm/s respectively. The cup drawn (trial 7) with 1.2 mm thick sheet has qualified the damage with strain rate of 25 mm/mm/s. Trial 9 also results in the damage (folding) with strain rate of 1 mm/mm/s. The cups drawn under trail conditions of 4 and 8 have zero damage with strain rate of 50 mm/mm/s.

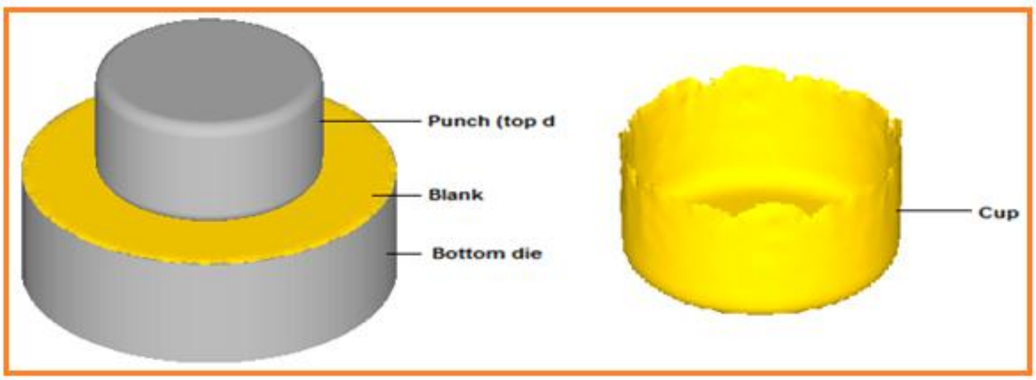

Figure 1: Deep drawing operation using D-FORM 3D software.

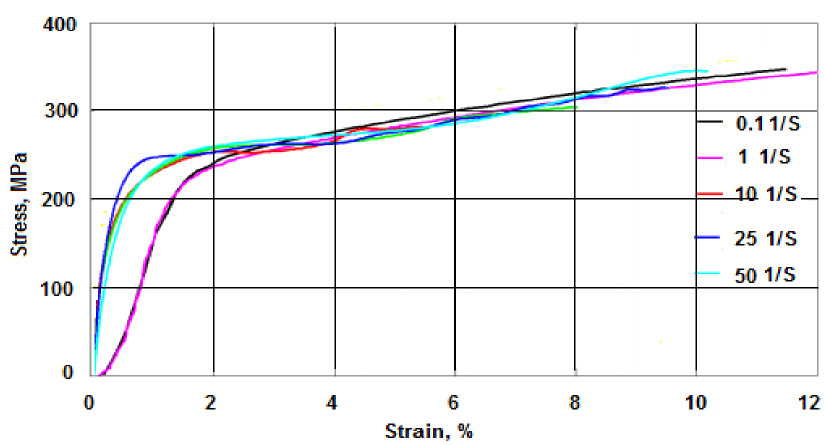

Figure 2: tensile stress-strain curves of 2024T6 aluminum alloy

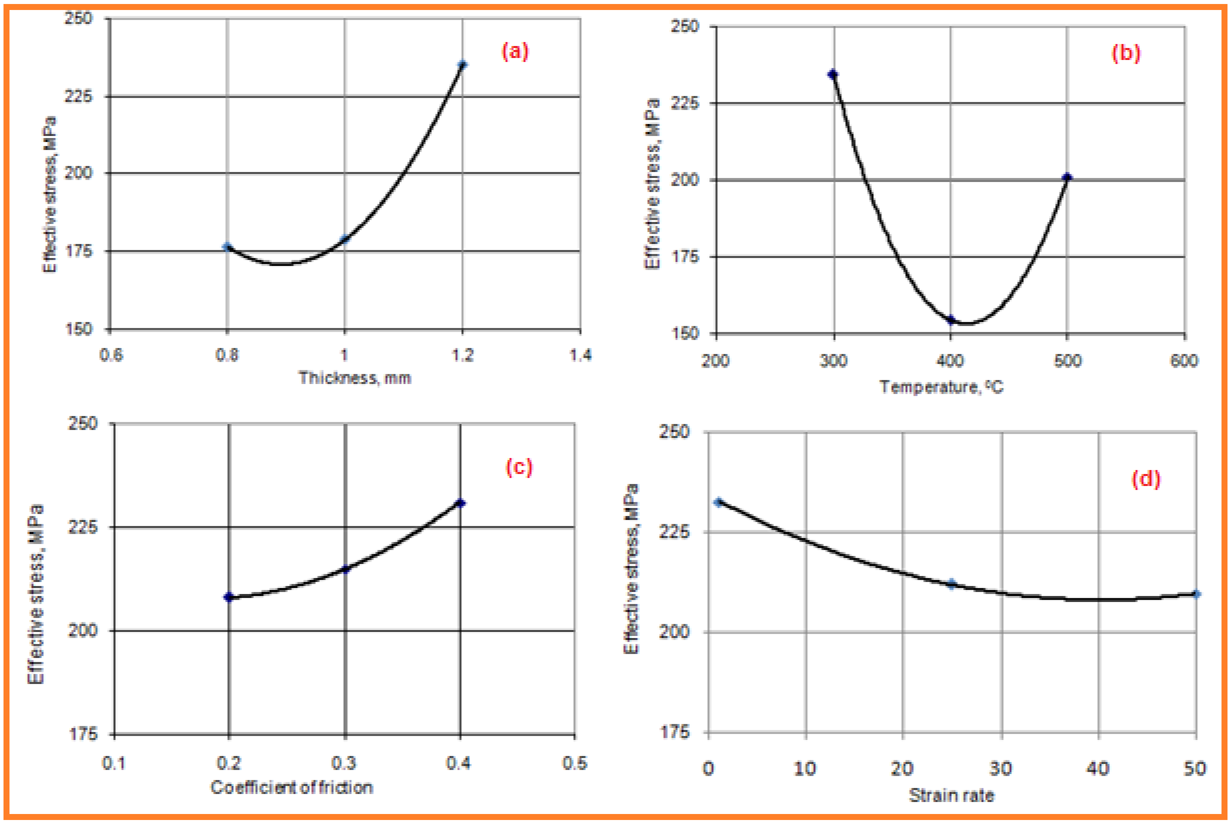

Figure 3: Influence of Process parameters on the effective stress.

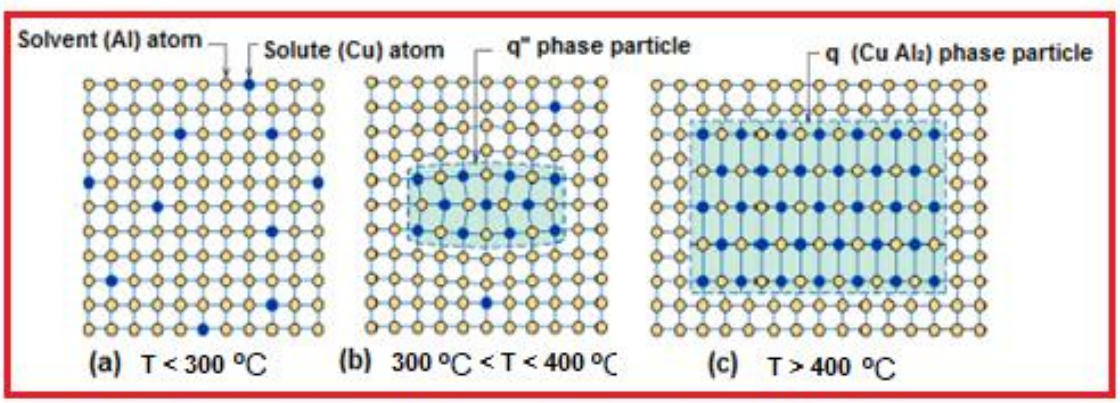

Figure 4: Influence of temperature on formation of precipitates: (a) super saturated solid solution, (b) transition q" precipitate phase and (c) equilibrium q phase.

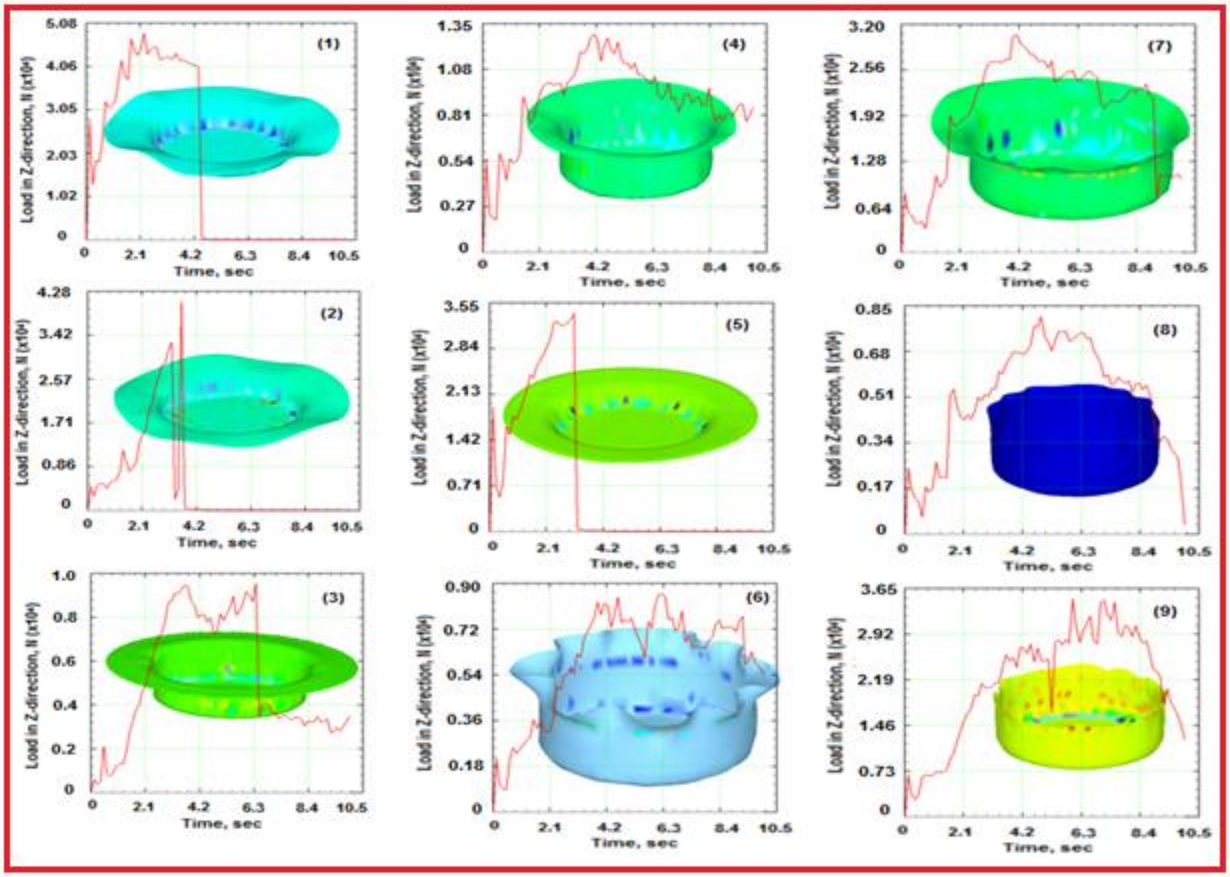

Figure 5: Load applied during cup drawing operations for trails 1 to 9.

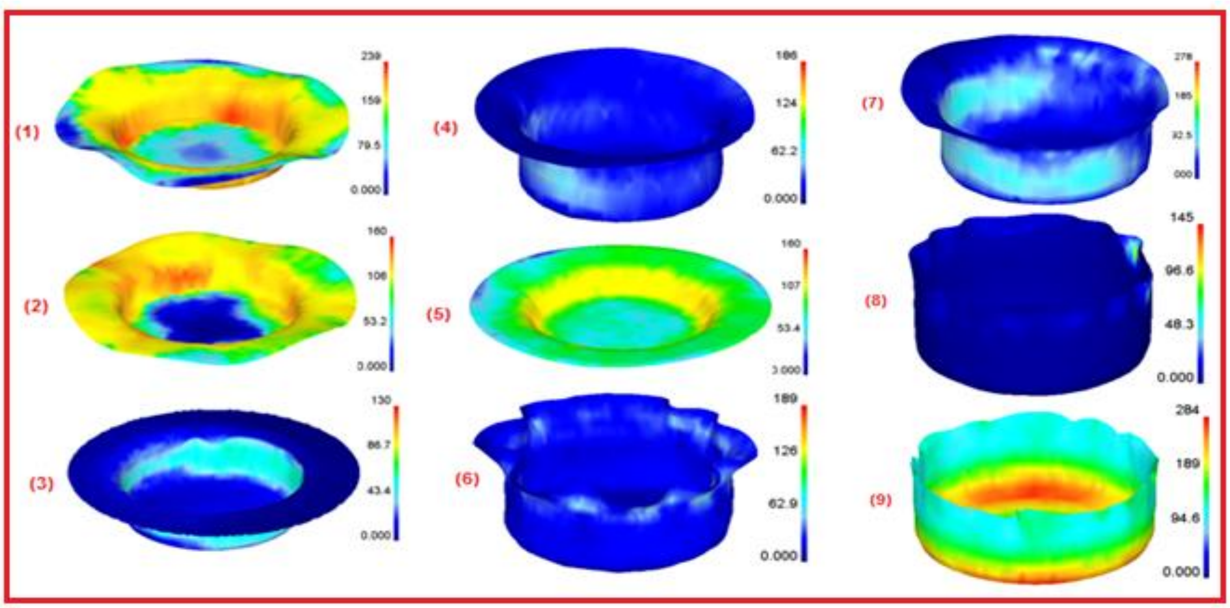

Figure 6: Influence of process parameters on the effective stress.

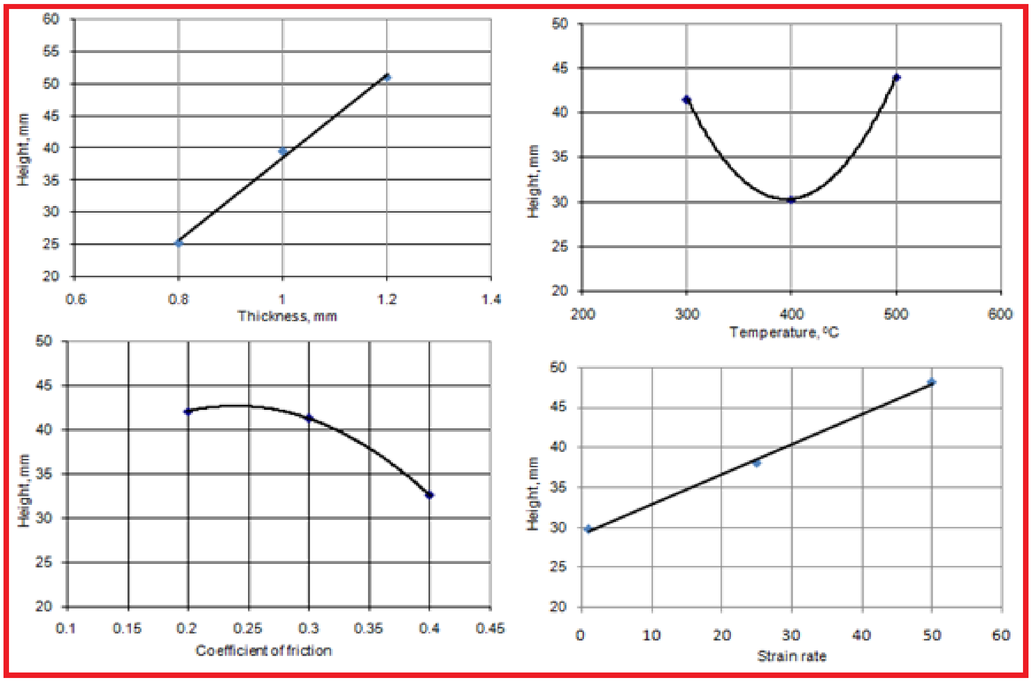

Figure 7: Influence of thickness on the height of cup.

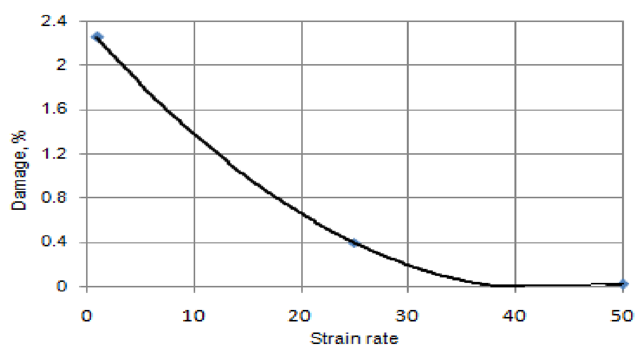

Figure 8: Influence of strain rate on the damage of cup.

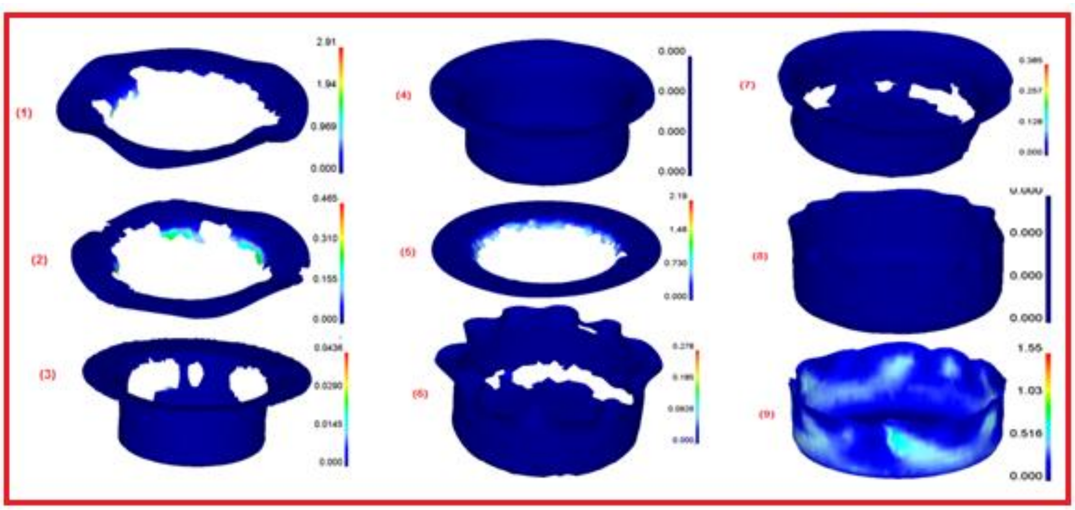

Figure 9: Influence of process parameters on the effective stress.

Table 1: Control Parameters and Levels

Factor	Symbol	Level–1	Level–2	Level–3
Thickness, mm	A	0.80	1.00	1.20
Temperature, ^{0}C	B	300	400	500
Coefficient of Friction	C	0.2	0.3	0.4
Strain rate	D	1	25	50

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	1058	1074	1411	13246.34	2	6623.17	210.39	25.43
B	1408	927	1208	19462.34	2	9731.17	309.12	37.37
C	1149	1251	1143	1228	2	614	19.50	2.34
D	1368	1255	920	18094.34	4	4523.58	143.70	34.72
Error				31.48	7	4.5	0.14	0.14
T	4983	4507	4682	52062.5	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 height of cup

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	151.4	237.2	306.2	2004.77	2	1002.39	696.10	50.23
B	248.9	181.8	264.1	639.26	2	319.63	221.96	16.01
C	252.3	247.3	195.2	333.33	2	166.67	115.74	8.34
D	178.4	228	288.4	1011.58	4	252.9	175.62	25.33
Error				1.44	7	0.21	0.15	0.09
T	831	894.3	1053.9	3990.38	17			100

TABLE 5: ANOVA summary of the damage of cup

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	6.9686	4.988	4.005	0.76	2	0.38	113.94	4.0
B	6.655	5.415	3.891	0.64	2	0.32	95.95	3.37
C	6.448	4.225	5.288	0.42	2	0.21	62.96	2.21
D	13.5	2.368	0.0946	17.16	4	4.29	1286.37	90.4
Error				0.00334	7	0	0	0.02
T	33.57	16.996	13.28	18.983	17			100

4 Conclusion

The formation of stable precipitate phase of $CuAl_2$ increases the effective stress induced in the cups during deep drawing process at elevated temperature. The damage in the deep drawn cups decreases with an increase in the strain rate.

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