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Parametric Optimization of Warm Deep Drawing Process of 2014T6 Aluminum Alloy Using FEA

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ABSTRACT— In this present work, a statistical approach based on Taguchi and Anova techniques and fininte element analysis have been adopted to determine the degree of significance of each of the process parameter on the formability of cup using warm deep drawing process. The process paprameters were thickness of balnk, temperature, coefficient of friction and strain rate. The thickness of sheet and temperature decrease the effective stress while the coefficient of friction and strain rate increase it. The height of cup increases with an increase in the warm drawing temperature. The damage in the cups was at high coefficient of friction. The formation of wrinkles was less with high coefficient of friction anfd with thick sheets.

Index Terms— 2014T6, warm deep drawin process, thickness, temperature, coefficient of friction, strain rate, damage.

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1 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. [1] 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. [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 2000C. Reddy et al. [3] 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. Reverse superplastic blow forming of a Ti-6Al-4V sheet has been simulated using finite lement method to achieve the optimized control of thickness variation [4]. A statistical approach based on Taguchi techniques and finite element analysis has been adopted 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 [5].

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Aluminium alloy 2014 is a copper based alloy with very high strength. 2014 aluminium 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. Aluminium 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 aluminium 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.

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

2 Materials and Methods

2014T6 aluminium alloy was used to fabricate deep drawin cups. The tensile and yield strengths of this alloy are 483 and 414 MPa respectively. The elstic modulus is 72.4 GPa. The poissoon'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

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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.

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

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:

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

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

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

$D = \sqrt{(d-2r)^2 + 4d(h-r) + 2\pi r(d-0.7r)}$ for 2d/r < 10 (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, $F_d = \pi dt[D/d - 0.6]\sigma_y$ (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/mm²).

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).

$3t$<Punch radius < $d/4$ (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:

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

The drawing ratio is roughly calculated as

DR = D/d (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.

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

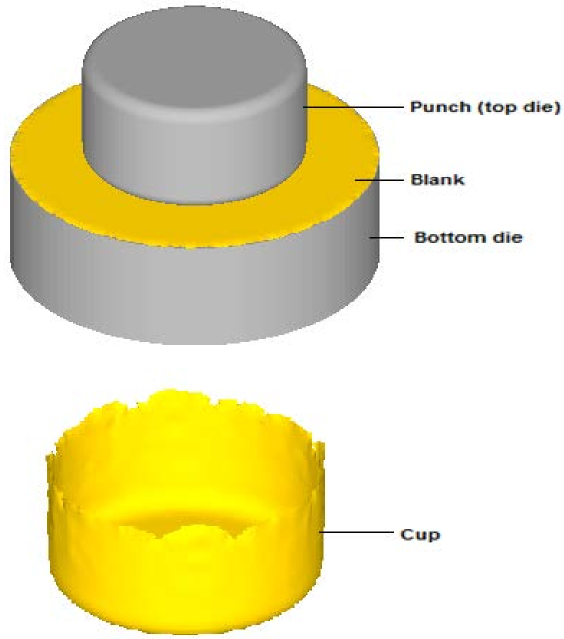

Fig. 1. Deep drawing operation using D-FORM 3D software.

3 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 [6]. The clearance between the punch and die was calculated using equ (9). The sheet blank was meshed with tetrahedral elements [7]. 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.

4 Results 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 aluminium alloy are shown in figure 2. They are almost equal in nature tested at room temperature using hydralically operated universal tensile testing (UTM) machine.

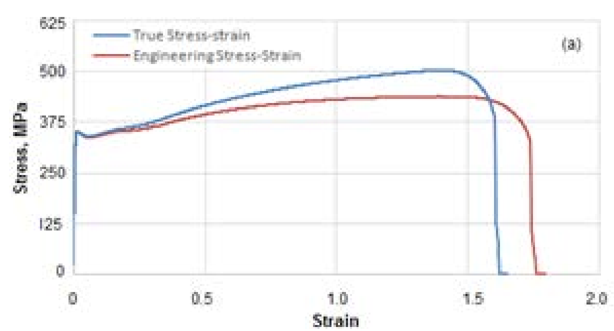

Fig. 2. Tensile stress-strain curves of sheet thickness 1.2 mm.

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 52.13% of variation, B (temperature) assists 27.56% of variation, C (coefficient of friction) influences 9.20% of variation and D (strain rate) contributes 10.77% of variation on the effective tensile stress.

TABLE 3
ANOVA summary of the effective stress

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	1497	1249	1179	9307.11	2	4653.55	182.56	52.13
B	1415	1334	1176	4924.78	2	2462.39	96.60	27.56
C	1249	1290	1386	1648.11	2	824.05	32.33	9.2
D	1396	1271	1258	1935.45	4	483.86	18.98	10.77
Error				25.49	7	3.64	0.14	0.34
T	5557	5144	4999	17840.94	17			100

Note: SS is the sum of square, v is the degres 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.

The influence of thickness on the effective stress is shown figure 3. The effective stress of the cups decreases from 249.50 to 196.50 MPa with increasing thickness of sheet. This is practical as the denominator component of 'stress = force/area' increases the stress value decreases. The effective stress decreases from 235.83 to 196.00 MPa with increasing temperature from 300 to 500^{0}C (figure 4). 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 maximum forming load is found to decrease from 48KN to 34KN over the working temperature range 300^{0}C<T< 500 ^{0}C for sheet thickness of 0.8 mm (figure 5). The maximum forming load is found to decrease from 51KN to 30KN over the working temperature range 300^{0}C<T< 500 ^{0}C for sheet thickness 1.0 mm (figure 6). The maximum forming load is found to decrease from 59KN to 38KN over the working temperature range 300^{0}C<T< 500 ^{0}C for sheet thickness of 1.2 mm (figure 7).

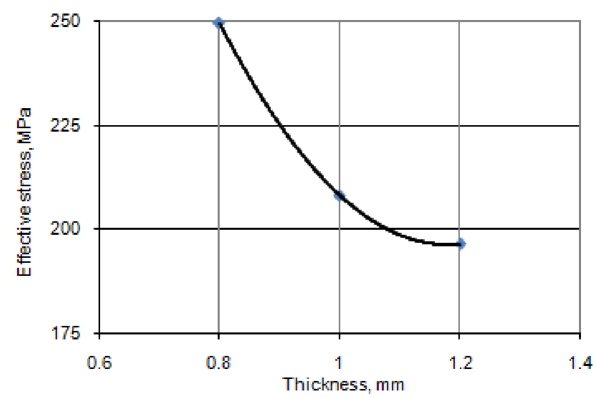

Fig. 3. Influence of sheet thickness on the effective stress.

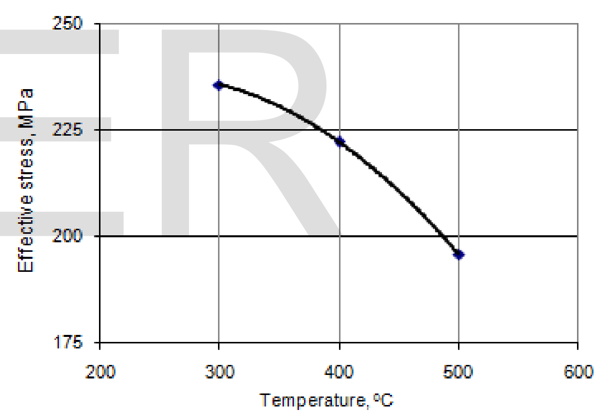

Fig. 4. Influence of temperature on the effective stress.

The influence of coefficient of friction on the effective stress is shown in figure 8. 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 frictional shear stress is directly proportional to the friction coefficient as shown in figure 9. The effect of friction is highly significant as it varies from 0.3 to 0.4. As shown in figure 10 the absolute shear stress increases from 111 to 127 MPa as the coefficient of friction changes from 0.3 to 0.4 for the sheet thickness of 0.8 mm.

The influence of strain rate on the effective stress is shown in figure 11. It is observed that the effective stress decreases with an increase in the strain rate. The test condtions (treat no. 3) of thickness, 0.80 mm, temperature, 500^{0}C, coefficient of friction, 0.4 and strain rate, 50 has yielded the effective stress of 233 MPa with wrinkles. Kobayashi and Dodd [8] proposed

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the following equation with a term for temperature softening:

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

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

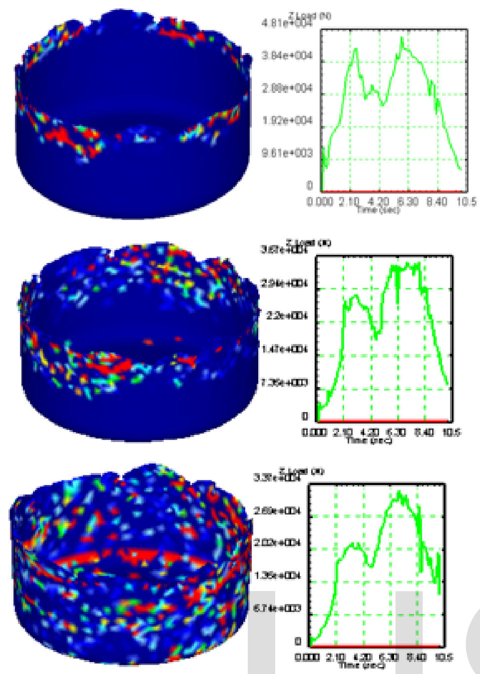

Fig.5. Load applied for trails 1, 2 & 3 of sheet thickness 0.8 mm.

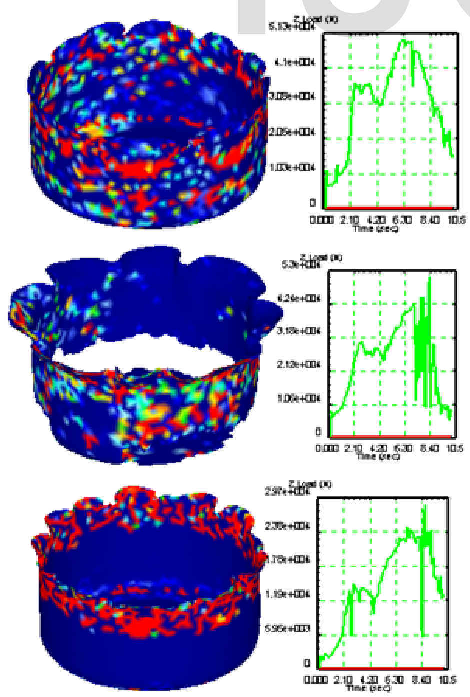

Fig. 6. Load applied for trails 4, 5 & 6 of sheet thickness 1.0 mm.

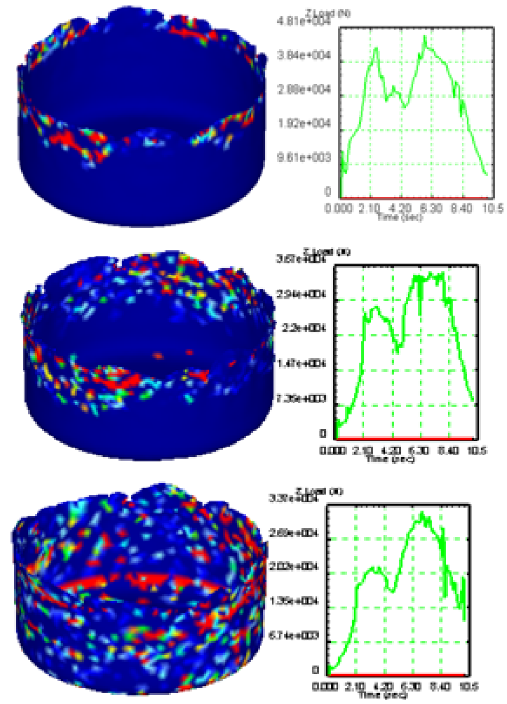

Fig. 7. Load applied for trails 7, 8 &9 of sheet thickness 1.2 mm.

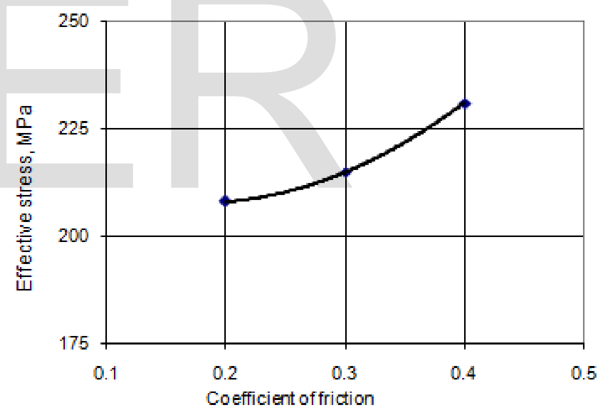

Fig. 8. Influence of friction coefficient on the effective stress.

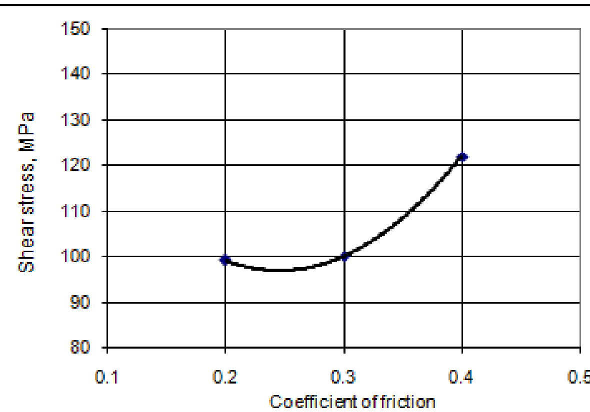

Fig.9. Influence of strain rate on the effective stress.

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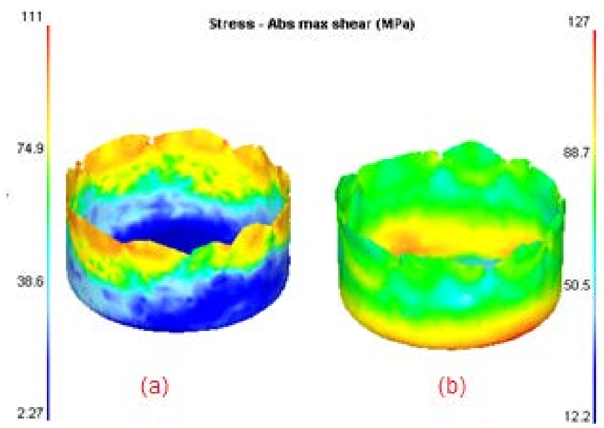

Fig. 10. Influence of friction on the shear stress stress.

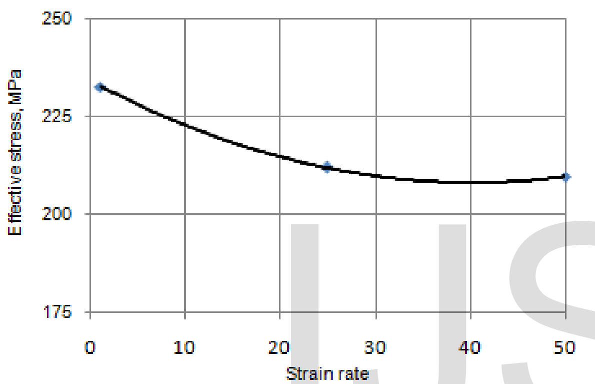

Fig. 11. Influence of strain rate on the effective stress.

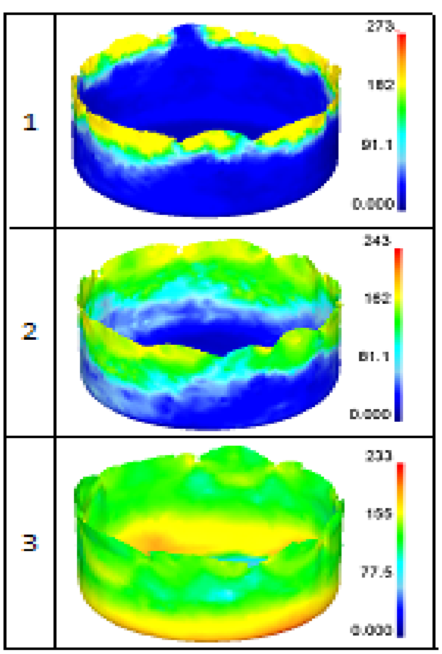

Fig.12. Influence of process parameters on the effective stress (sheet thickness 0.8 mm).

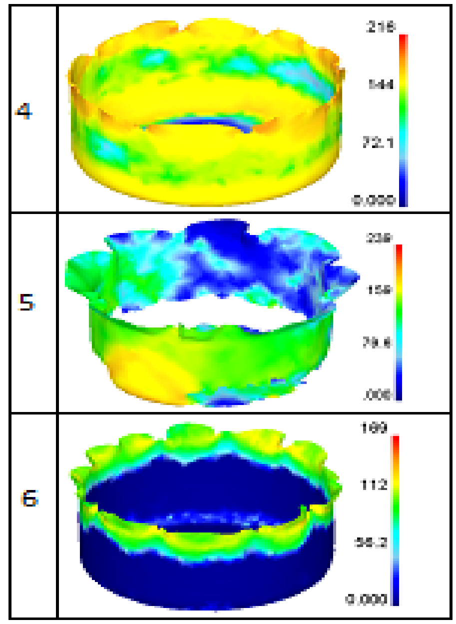

Fig.13. Influence of process parameters on the effective stress (sheet thickness 1.0 mm).

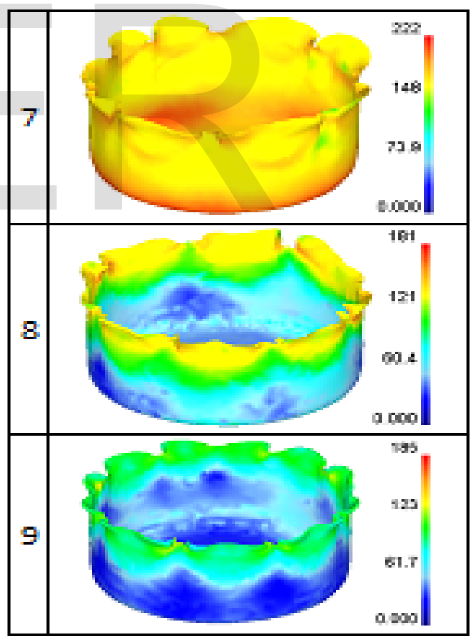

Fig.14. Influence of process parameters on the effective stress (sheet thickness 1.2 mm).

For sheet thickness of 0.8 mm the maximum induced stress is 273 MPa (figure 12). For sheet thickness of 1.0 mm the maximum induced stress is 239 MPa (figure 13). For sheet thickness of 0.8 mm the maximum induced stress is 222 MPa (figure 14).

4.2 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,

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D) accepted at 90% confidence level influencing the variation in the elastic modulus. The major contribution (46.40%) is of thickness of blank sheet towards variation in the height of up. The effects of temperature, coefficient of friction and strain rate are 30.49%, 13.36% and 9.14% respectively towards variation in the height of cup.

TABLE 4
ANOVA summary of the height of cup

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	225.9	267.6	270.3	206.54	2	103.27	90.59	46.4
B	277.5	239.4	246.9	135.8	2	67.9	59.56	30.49
C	259.8	264.6	239.4	59.68	2	29.84	26.18	13.36
D	263.4	242.1	258.3	41.24	4	10.31	9.04	9.14
Error				1.14	7	0.16	0.14	0.61
T	1026.6	1013.7	1014.9	444.4	17			100

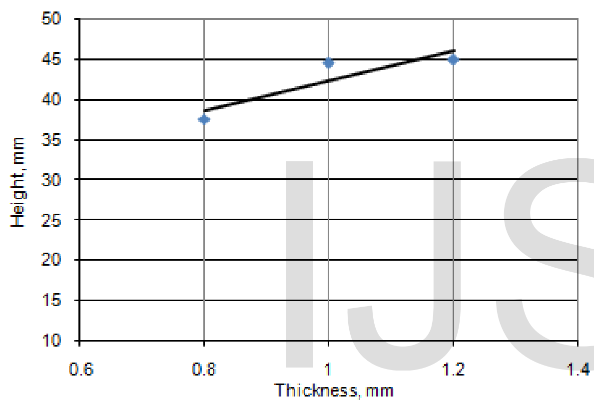

Fig. 15. Influence of thickness on the height of cup.

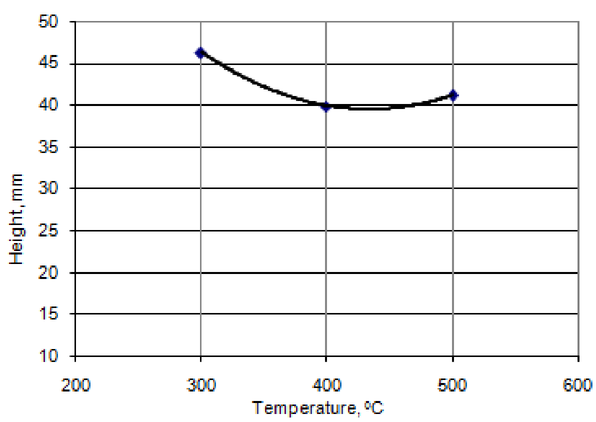

Fig. 16. Influence of temperature on the height of cup.

The influence of thickness on the height of cup drawn is shown in figure 15. The height of cup drawn increases with an increase in the thickness of blank. This is obvious that the sufficient material is available to deform under the applied load

The height of cup drawn increases with an increase in the warm drawing temperature as shown in figure 16. At temperatue 300⁰C the height of cup drawn is 46.25 mm. At temperatue 400⁰C the height of cup drawn is 39.90 mm. At temperatue 300⁰C the height of cup drawn is 41.15 mm. This may be due to formation of hardening temperature at 400⁰C. By quenching and then reheating an Al-2014 alloy, a fine dispersion of precipitates forms within a grain (figure 17). 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 ductility decreases with the precipitation heat as shown in figure 18.

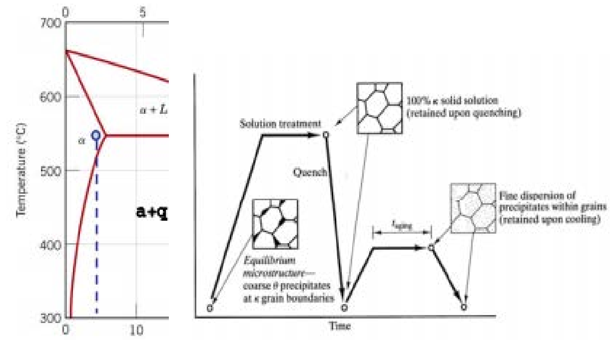

Fig. 17. Precipitation hardening.

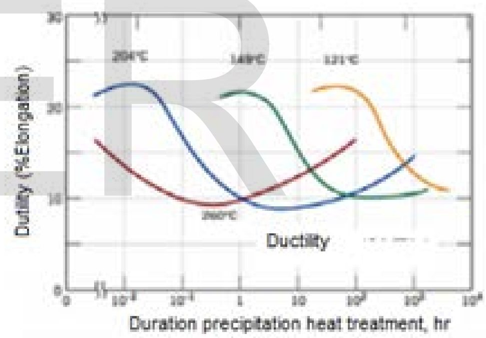

Fig. 18. Precipitation hardening characteristics of Al 2014 alloy.

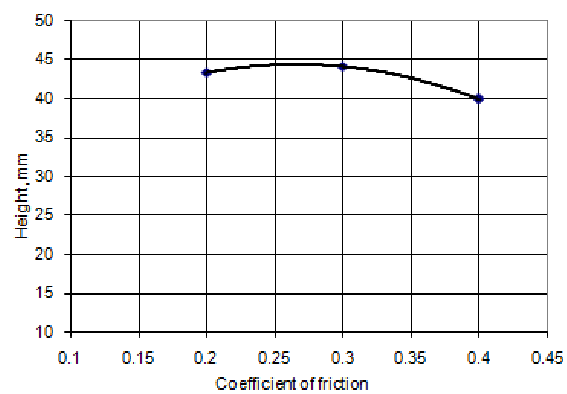

Fig. 19. Influence of friction on the height of cup.

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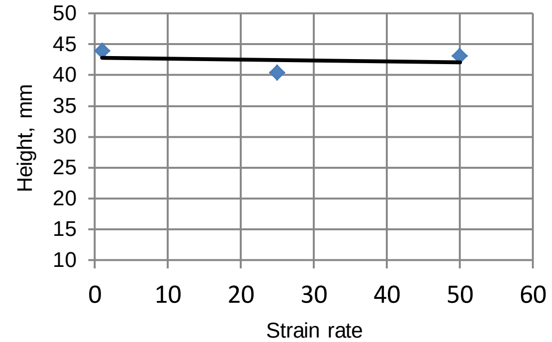

Fig. 20. Influence of strain rate on the height of cup.

As the coefficient of friction and strain rate increase the heightof the cup drawn decreases as shown in figure 19 &20.

4.3 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 percent contribution indicates that the thickness of the sheet only contributes half (23.44%) of the variation, parameter, T (temperature) aids 12.30% of variation, coefficient of friction contributes 44.86% of variation and strain rate contributes 19.10% of variation.

TABLE 5
ANOVA summary of the damage of cup

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	42.64	55.8	8.743	196.48	2	98.24	97.52	23.44
B	19.36	54.34	33.483	103.23	2	51.62	51.24	12.3
C	22.55	10.743	73.89	375.72	2	187.86	186.48	44.86
D	59.653	16.56	30.97	160.42	4	40.11	39.815	19.1
Error				1.007	7	0.14	0.14	0.3
T	144.23	137.44	147.08	836.85	17			100

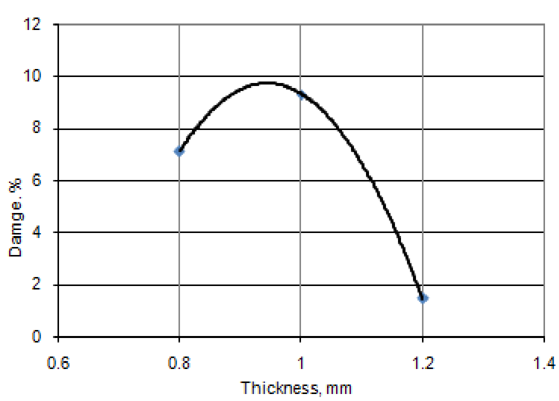

Fig. 21. Influence of thickness on the damage of cup.

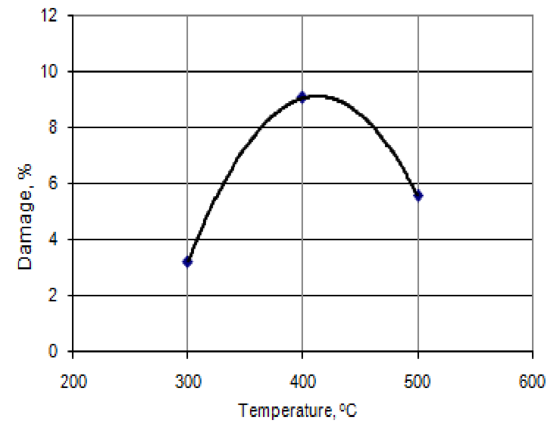

Fig. 22. Influence of temperature on the damage of cup.

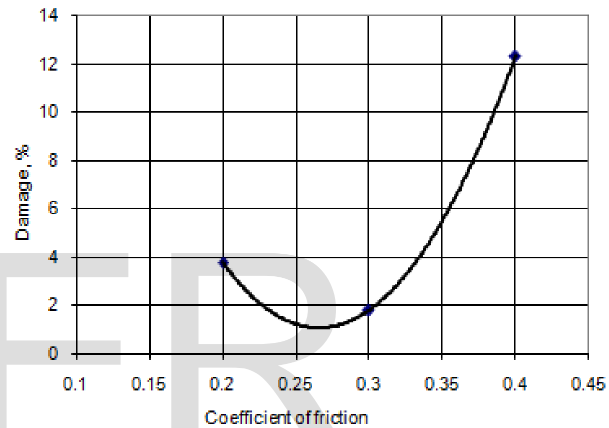

Fig. 23. Influence of friction on the damage of cup.

The effect of thickness on the damge of cup is shownin figure 21. The damage is found to be maximum with 1.0 mm thickness of the sheet. Also, there are wrinkling defects with 0.8 mm thickness sheets. The damage is very less with 1.2 mm thickness sheets. At 400^{0}C temperature the damage is found to be maximum because of reduction in the yield strength and the ductility (figure 22). 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 [9]. 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 from figure 23 that the damage is low with coefficientt of friction of 0.3. It is 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.

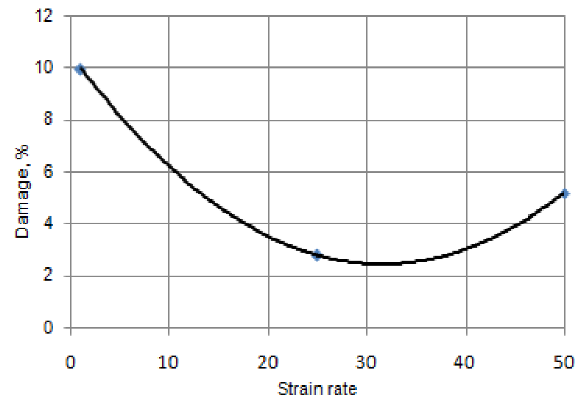

Fig. 24. Influence of strain rate on the damage of cup.

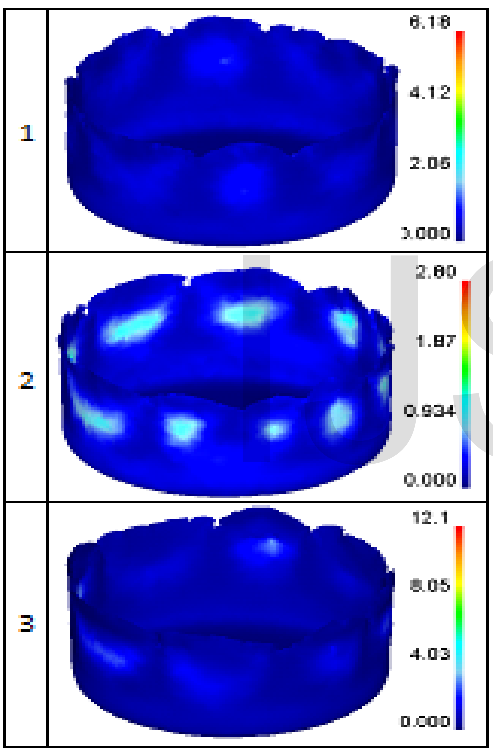

Fig.25. Influence of process parameters on the effective stress (sheet thickness 0.8 mm).

The damge in the cups decreases with an increase in the strain rate from 1 to 25 and increases for the strain rate above 50 as shown in figure 24. From figure 25 it is noticed the formation wrinkles with sheet thickness of 0.8 mm. It is clearly observed from figure 26(5) that the damge in the cup was due to precipitates at 400^{0}C temperature and high coefficent of friction (0.4). The damage is observed with treat number 5. It is also observed that the thinning occurs near the punch radius for sheet thickness of 1.2 mm as shown in figure 27. The predicted von misses stresses reach their maximum value at the point near to where the greatest amount of thinning takes place, (i.e.) just above the punch radius on the sidewall.

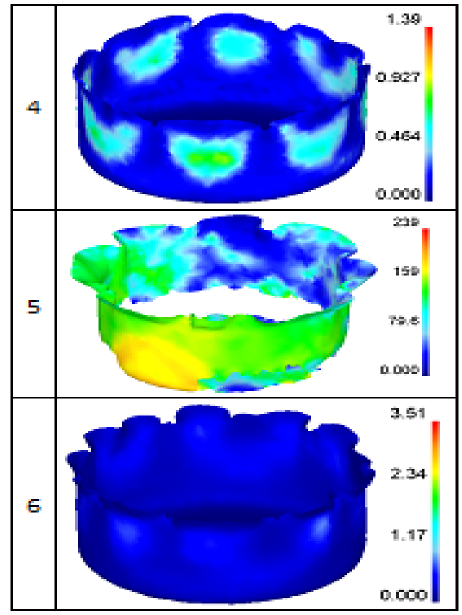

Fig.26. Influence of process parameters on the effective stress (sheet thickness 1.0 mm).

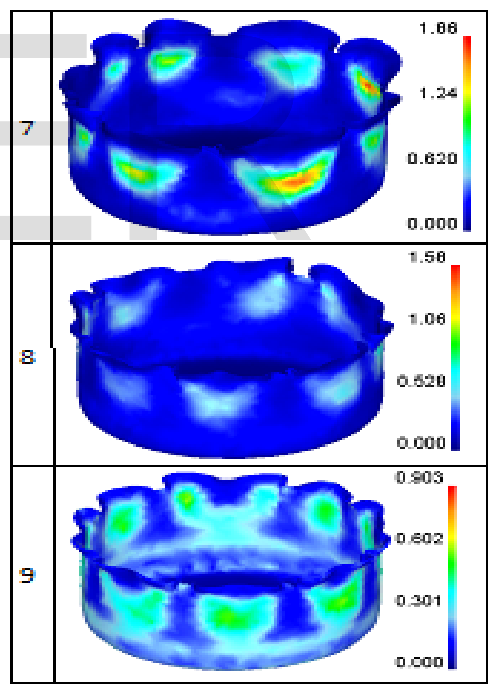

Fig.27. Influence of process parameters on the effective stress (sheet thickness 1.2 mm).

5 Conclusions

The thickness of sheet, temperature, coefficient of friction and strain rate influence the effective stress. The damage in the cups is less with thick sheets and it is at high coefficient of friction, strainsrate and temperature. The formation of wrinkles is less with high coefficient of friction and with thick sheets.

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