Parametric Optimization of Warm Deep Drawing Process of 1100 Aluminum Alloy: Validation through FEA

Thirunagari Srinivas, A. Chennakesava Reddy

Abstract— In this present work, a statistical approach based on Taguchi and Anova techniques and fininte element analysis were 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 paprameters were thickness of balnk, temperature, coefficient of friction and strain rate. The experimental results were validated using a finite lement software namely D-FORM. The Erichsen deep drawing test was conducted to study the formation of wrinkles in the cups. The thickness of sheet, temperature, coefficient of friction and strain rate would influence the effective stress. The major parameter which could influence the effective strain, the volume of the cup is the thickness of sheet. The damage in the cups was at high coefficient of friction, strainsrate and temperature. The formation of wrinkles was less with high coefficient of friction anfd with thick sheets.

Index Terms— warm deep drawing, 1100 aluminium, sheet thickness, temperature, strain rate, coefficient of friction, wrinkles,damage.

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1 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. [1] have proposed a direct design method based on an ideal forming theory to get an initial blank shape. But real forming conditions such as blank holder force, friction force, tool geometry are not considered. Shehata et al. [2] have demonstrated the formability can be improved using differential temperature rather than a uniform temperature rise. Finch et al. [3] investigated the effect of warm forming on drawbility of both rectangular and circular cups from annealed and hardened aluminum sheet alloys. The results indicated significant improvement in the drawability in terms of cup height at a temperature of about 150^{0}C even for the precipitation hardened alloys (like 2024-T4 and 7075-T6). Toros et al. [4] have developed an analytical model to evaluate deep drawing process at elevated temperatures and under different blank holder pressure (BHP) and identified that blank temperature, punch speed, BHP, and friction are the main factors that influence formability. Jeyasingh et al. [5] 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. [6] 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^{0}C. Reddy et al. [8] in their 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. 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 [9]. Reddy [10] has used taguchi technique which can save the cost of experimentation to optimize the extrusion process of 6063 alumimium alloy.

1100 aluminium alloy is mechanically strongest alloy in the series of 1xxx. At the same time, it keeps the benefits of being relatively lightly alloyed (compared to other series), such as high electrical conductivity, corrosion resistance, and workability. This alloy is commercially pure aluminum with excellent forming characteristics. Forming, either hot or cold, is readily accomplished with this alloy. In the annealed condition the alloy can be cold worked extensively without an intermediate anneal. This alloy is commonly used in spun holloware, fin stock, heat exchanger fins, dials and name plates, cooking utensils, decorative parts, giftware, rivets and reflectors, and in sheet metal work.

The objective of the present work is to optimize the warm deep drawing process of 1100 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.

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2 Materials and Methods

1100 aluminium alloy was used to fabricate deep drawin cups. The tensile and yield strengths of this alloy are 110 and 105 MPa respectively. The elastic modulus is 70-80 GPa. The poisson's ratio is 0.33. The percent elongation is 12. The shear strength is 69 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 1100 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.

TABLE 1
Control Parameters and Levels

Factor	Symbol	Level–1	Level–2	Level–3
Thickness, mm	A	0.40	0.80	1.50
Temperature, ^{0}C	B	30	300	500
Coefficient of Friction	C	0.02	0.05	0.08
Strain rate	D	100	500	1000

The orthogonal array (OA), L_9 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

2.1 Fabrication of Deep Drawn Cups

The blank size was calculated by equating the surface area of the finished drawn cup with the area of the blank. The diameter 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/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).

$3t$<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 would reduce the pressure area between the blank and the blank holder. 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)

The sheets of 1100 aluminium alloy were cut to the required blank size. The blank specimens were heated in a muffle furnace to the desired temperature as per the design of experiments. The blank pressure was caluculated using equ (5). The cups were fabricated using hydrolically operated deep drawing machine as shown in figure 1.

Fig. 1. Deep drawing machine (hydraulic type).

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2.2 Conduction of Tests

The following tests were conducted on the materials used in the present work:

- Tensile test to find true stress-true strain curve
- Volume of the deep drawn cups
- Thickness of deep drawn cups
- Inspection of fracture and wrinkle formation on the cups
- Erichsen deep drawing test

The Erichsen deep drawing test (figure 2) was conducted for testing the deep drawing quality and ear forming tendency on 1100 aluminium alloy sheet. The test consisted of forming an indentation by pressing a punch with a spherical end against a test piece clamped between a blank holder and a die, until a through crack appears. The depth of the cup was measured.

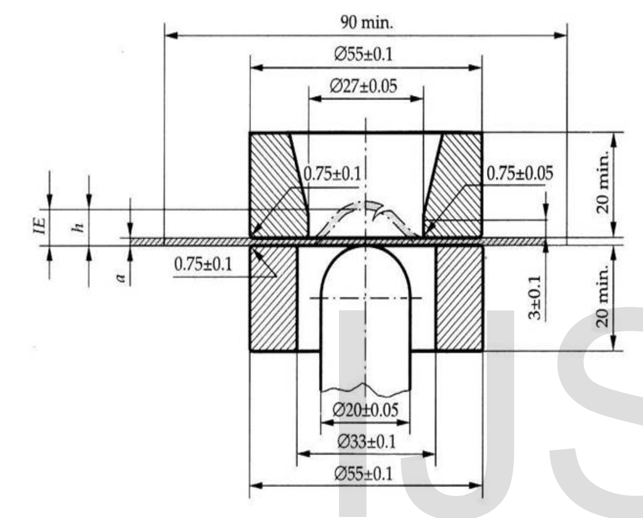

Fig. 2. Erichsen deep drawing tester.

Note: *a* is the thickness of the sheet, *h* is the depth of the indentation during the test and *IE* is the Erichsen cupping index.

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 [10]. The clearance between the punch and die was calculated using equ (9). The sheet blank was meshed with tetrahedral elements [11]. 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 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, 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.

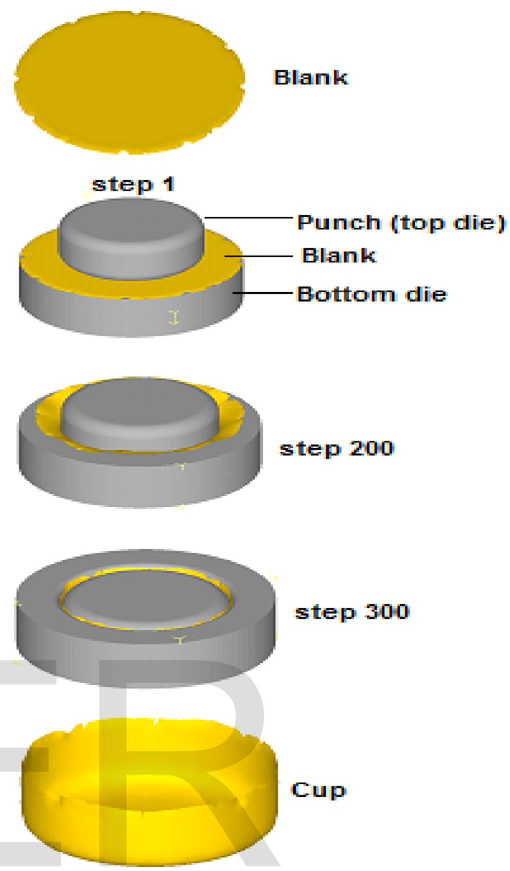

Fig. 3. Deep drawing operation using D-FORM 3D software.

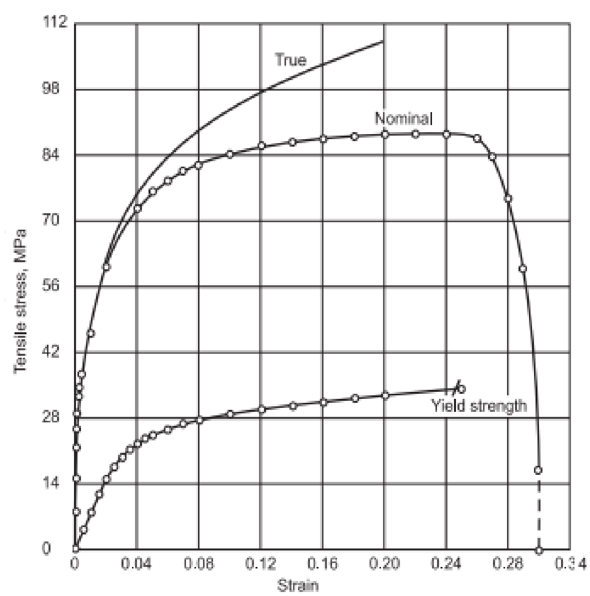

Fig. 4. 1100-O aluminum alloy rod, tensile stress-strain curves.

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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 specifications of the tensile test specimen are diameter, 12.7 mm and gage length 203.2 mm. The properties are as follows: nominal tensile strength, 84.8 MPa, true tensile strength, 103 MPa, nominal yield strength (0.2% offset), 33 MPa, elongation (in 50.8 mm), 30.0% and reduction of area, 88%. A log-log plot of the stress-strain curve would yield a slope (n) of 0.22 in the area of uniform plastic deformation (figure 4).

3.1 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 24.67% of variation, B (temperature) assists 61.74% of variation, C (coefficient of friction) influences 2.91% of variation and D (strain rate) contributes 10.17% 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	654.42	533.42	464.37	3084.96	2	1542.48	95.66	24.67
B	687.90	577.58	386.73	7738.71	2	3869.36	239.97	61.94
C	528.03	535.29	588.89	368.31	2	184.15	11.42	2.91
D	494.71	540.26	617.25	1278.89	4	319.72	19.83	10.17
Error				16.13	7	2.3	0.14	0.31
T	2365.07	2186.54	2057.25	12486.99	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.

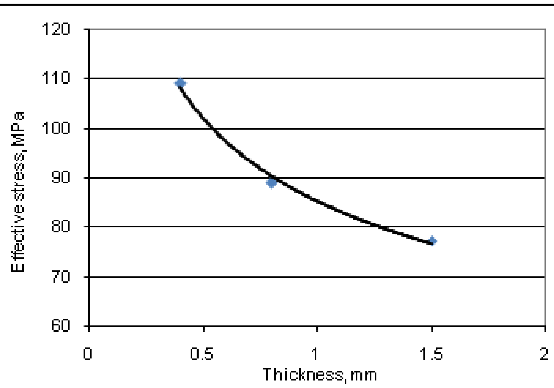

Fig. 5. Influence of sheet thickness on the effective stress.

The influence of thickness on the effective stress is shown figure 5. The effective stress of the cups decreases from 109.07 to 77.40 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 114.65 to 64.46 MPa with increasing temperature from 30 to 5000C (figure 6). 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 12KN to 4KN over the working temperature range $100^0C<T<500\ ^0C$.

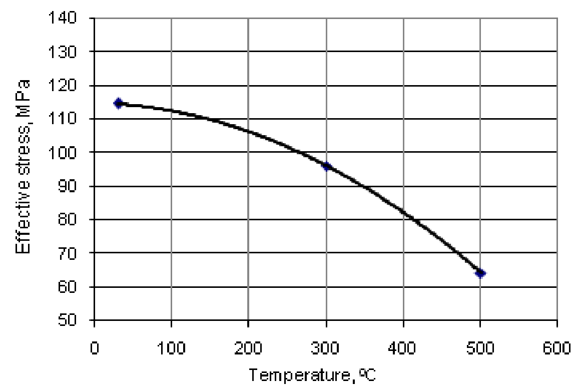

Fig. 6. Influence of temperature on the effective stress.

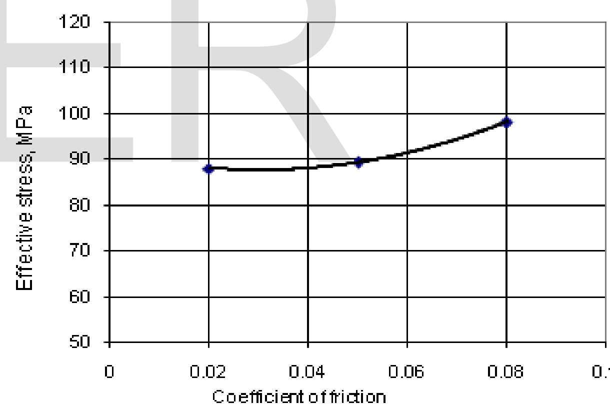

Fig. 7. Influence of friction coefficient on the effective stress.

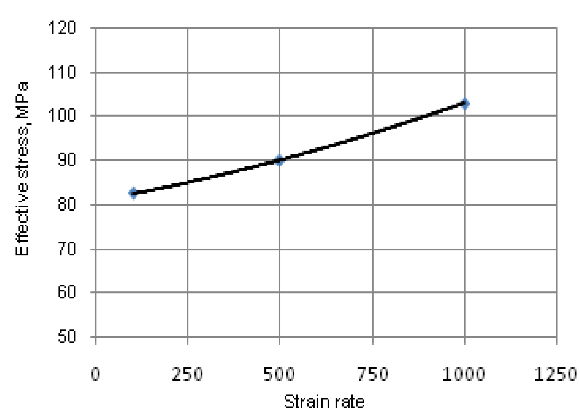

Fig. 8. Influence of strain rate on the effective stress.

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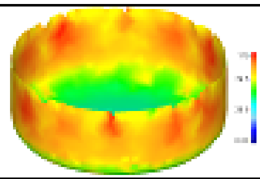
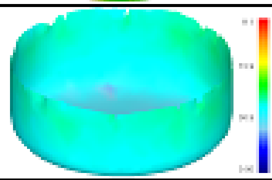
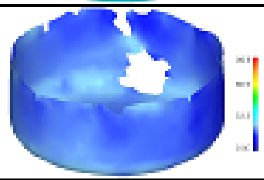
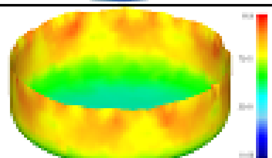
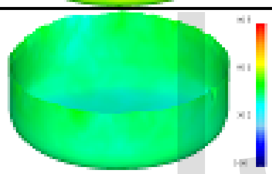
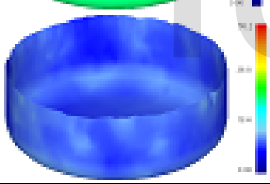
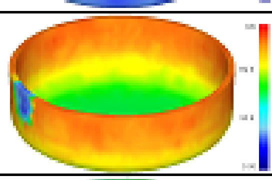
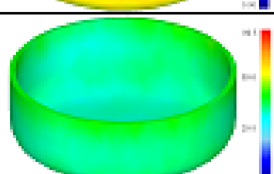
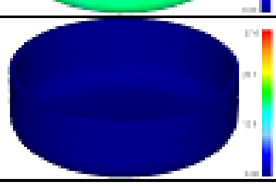
Treat No.	FEA results	Maximum Effective stress, MPa
1		119.00
2		111.00
3		99.80
4		119.00
5		90.50
6		55.20
7		105.00
8		89.50
9		37.60

Fig. 9. Influence of process parameters on the effective stress.

The influence of coefficient of friction on the effective stress is shown in figure 7. The influence of friction on the effective stress is very less as compared to 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. The influence of strain rate on the effective stress is shown in figure 8. It is observed that the effective stress increases with an increase in the strain rate. Lee and Yeh [12] 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 FEA results of effective stress are shown in figure 9. The test condtions (treat no. 3) of thickness, 0.40 mm, temperature, 500^{0}C, coefficient of friction, 0.08 and strain rate, 1000 has yielded the effective stress of 99.80 MPa with fracture on the wall of cup. Kobayashi and Dodd [13] proposed the following equation with a term for temperature softening:

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

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 σ_o and β are constants.

The required flow stress is less than 99.80 for treat no.3. At higher rates of strain the flow stress of material increases leading to higher loads on the equipment.

TABLE 4
ANOVA summary of the effective strain

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	20.48	14.25	3.98	23.12	2	11.56	351.86	96.93
B	12.59	12.40	13.73	0.17	2	0.09	2.74	0.71
C	12.44	12.51	13.77	0.2	2	0.1	3.04	0.84
D	12.41	12.27	14.04	0.33	4	0.08	2.44	1.38
Error				0.033	7	0	0	0.14
T	57.91	51.43	45.52	23.853	17			100

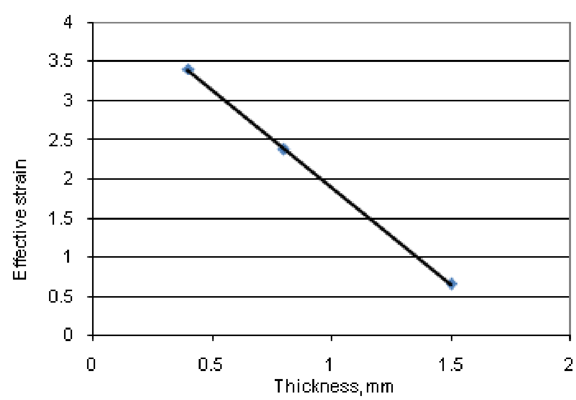


Fig. 10. Influence of thickness on the effective strain.

3.2 Influence of Process Parameters on Effective Strain

The ANOVA summary of the effective strain 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. However, the major contribution (96.93%) is of thickness of blank sheet towards variation in the effective strain. The influence of other factors is negligible.

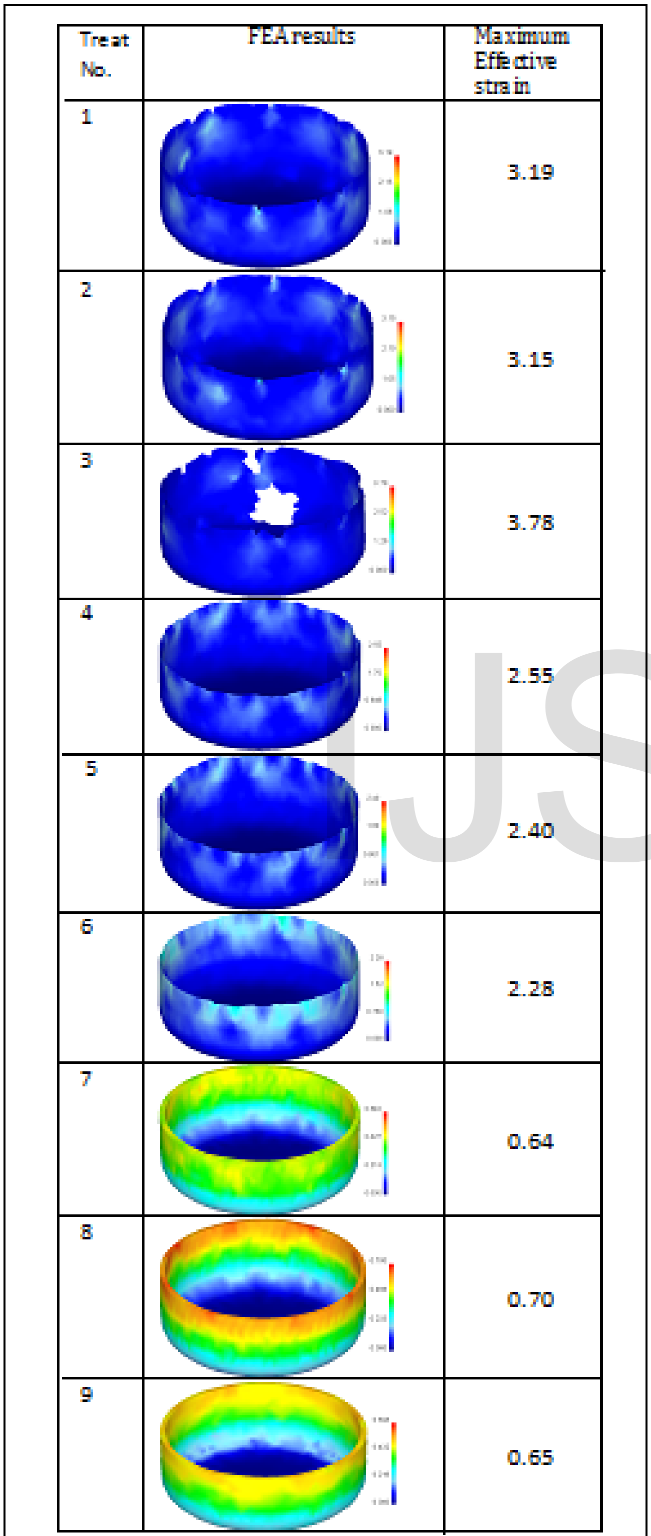


Fig. 11. Influence of process parameters on the effective strain.

The effective strain decreases with an increase in the thickness of blank sheet as shown in figure 10. The characteristic equation that describes superplastic behavior is usually written as $\sigma = K\epsilon^{m}m$, [14] where σ is the flow stress, K is a material constant, $\dot{\epsilon}$ 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. The FEA results of effective stress are shown in figure 11. The failure of cup fabricated under test conditions of treat no.3 was due to the high effective strain of 3.78. It is seen that the temperature dependency for the fracture strain is evidently strain rate sensitive.

3.3 Influence of Process Parameters on Volume of Cup

The ANOVA summary of volume is given in table 5. The Fisher's test column ascertains all the parameters (A, B, C, and D) accepted at 90% confidence level influencing the variation in the flexural strength. The percent contribution indicates that thickness of sheet gives 100%of variation and rests of the factors have negligible influence of variation. The volume of cup increases with an increase in the thickness of sheet as shown in figure 12.

TABLE 5
ANOVA summary of the volume of cup

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	15918	31836	59868	165043564	2	82521782	9173565	100
B	35888	35863	35871	53.45	2	26.72	2.97	0
C	35866	35868	35889	53.95	2	26.97	2.99	0
D	35871	35890	35862	68.69	4	17.17	1.91	0
Error				8.99	7	1.29	0.14	0
T	123545	139460	167491	165043749	17			100

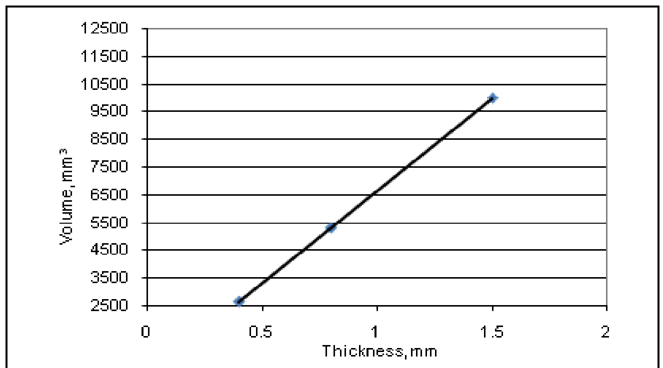


Fig. 12. Influence of thickness on the volume of cup.

3.4 Influence of Process Parameters on Damage of Cup

The ANOVA summary of specific wear rate is given in table 6. The Fisher's test column ascertains the parameters (t, T, u and s) 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 (50.11%) of the variation, parameter, T (temperature) aids 14.94% of variation, coefficient of friction contributes 17.04% of variation and strain rate contributes 17.90% of variation.

TABLE 6
ANOVA summary of the damage of cup

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	15918	31836	59868	165043564	2	82521782	9173565	100
B	35888	35863	35871	53.45	2	26.72	2.97	0
C	35866	35868	35889	53.95	2	26.97	2.99	0
D	35871	35890	35862	68.69	4	17.17	1.91	0
Error				8.99	7	1.29	0.14	0
T	123545	139460	167491	165043749	17			100

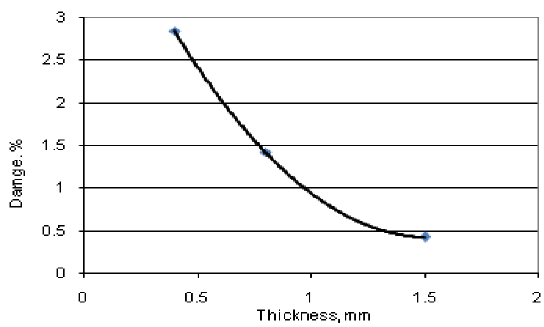


Fig. 13. Influence of thickness on the damage of cup.

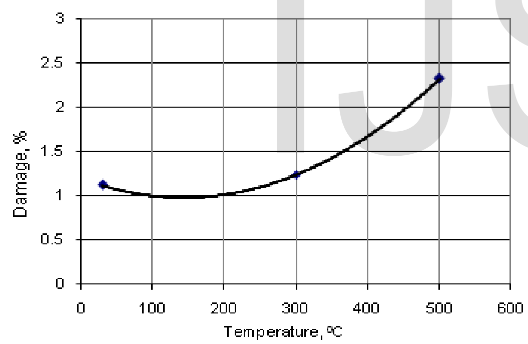


Fig. 14. Influence of temperature on the damage of cup.

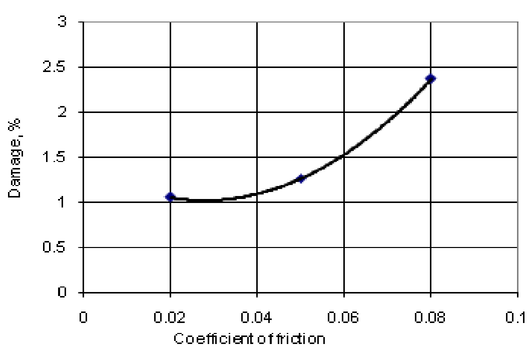


Fig. 15. Influence of friction on the damage of cup.

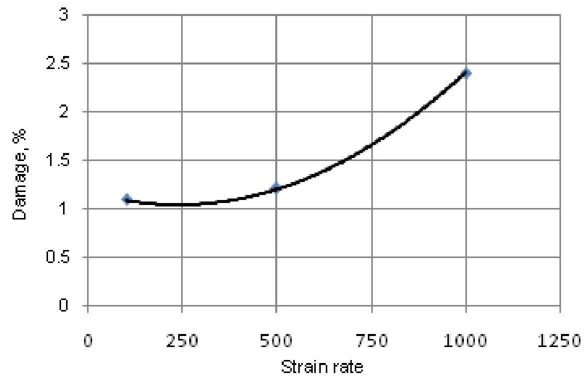


Fig. 16. Influence of strain rate on the damage of cup.

Fig. 17. Influence of thickness on the damage of cup

The effect of thickness on the damge of cup is shownin figure 13. The damage decreases with an increase in the thickness of the sheet. As the temperature increases the damage is also increases (figure 14) because of softening of the material. In the case of friction between the piece and the Dies, the increase of the coefficient of friction determines the wrinkling to reduce, but high values of the coefficient can cause cracks and material breakage [12]. 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 form figure 15 that the damage in the cup decreases with an increase in the coeffi-

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cientt of friction. 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.

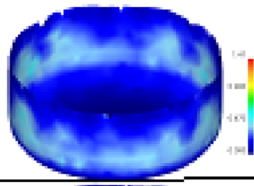
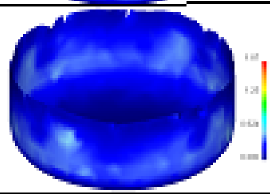
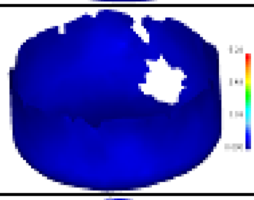
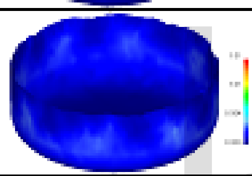
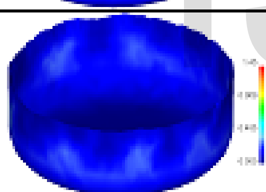
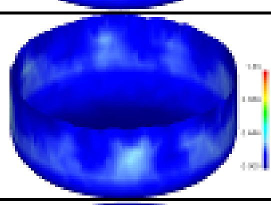
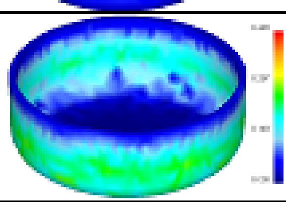
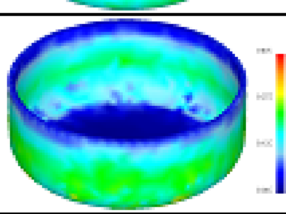
Treat No.	FEA results	Damage, %
1		1.41
2		1.87
3		5.23
4		1.51
5		1.45
6		1.33
7		0.45
8		0.41

Fig. 18. Influence of process parameters on the damage of cups

The damge in the cups increases with an increase in the strain rate as shown in figure 16. It is clearly observed from figure 17a that the damge in the cup was due to high temperature, high coefficent of friction, low thickness of sheet and high strain rate. This is also proved with the FEA results as seen in figure 18. The damage is observed with treat number 3. The damage is 5.23%. It was also observed that the thinning occurs near the punch radius. 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.

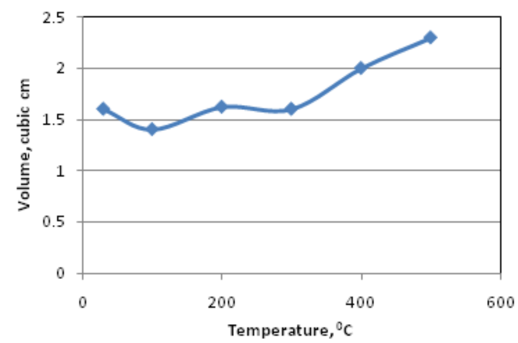


Fig. 19. Influence of temperature on the volume of cup

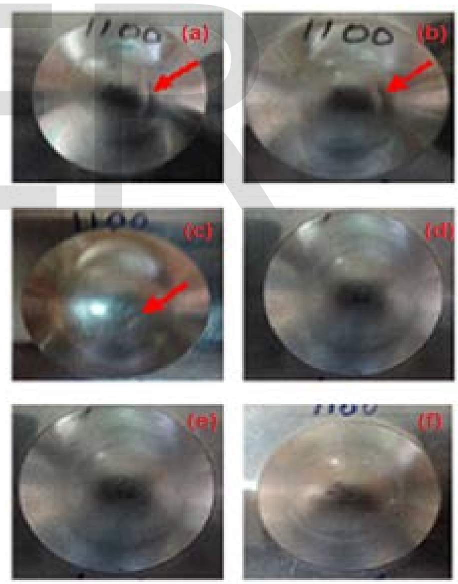


Fig. 20. Cups Drawn on Erichsen Deep Drawing Tester

The effect of temperature on the results of the Erichsen deep drawing test sis is shown in figure 19. The volume of the cup increases with an increase in the temperature. From figure 20a&b it is observed that 0.40 mm sheets at room temperature and at 500⁰C show cleavage which is an indication of the formationn of wrinkles in the cups. From figure 20c there is an indication of forming wrinkles at room temperature for 0.80 mm thick sheets. No wrinkles were formed at 500⁰C temperature for 0.80mm thick sheets. The wrinkles were not formed for thick (1.50mm) sheets of cups.

4 CONCLUSION

The thickness of sheet, temperature, coefficient of friction and strain rate influence the effective stress. The major parameter which can influence effective strain, volume of the cup is the thickness of sheet. The damage in the cups was less with thick sheets and it was more at high coefficient of friction, strains-rate and temperature. The formation of wrinkles is less with high coefficient of friction anfd with thick sheets.

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