Parametric Merit of Warm Deep Drawing Process for 1080A Aluminium Alloy: Validation through FEA

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ABSTRACT— In this present work, a statistical approach based on Taguchi and Anova techniques and fininte element analysis were adopted to determine the merit of sheet thickness, temperature, coefficient of friction and temperature on the formability of cups from 1080A aluminium alloy using warm deep drawing process. The experimental results were validated using a finite element 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 and strain rate would influence the effective stress. The major parameter the volume of the cup was the thickness of sheet. The damage in the cups were occurred in thin sheets, high coefficient of friction, high strain rate and high temperature.

Index Terms— warm deep drawing, 1080A aluminium, sheet thickness, temperature, strain rate, coefficient of friction, wrinkles,damage.

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 1500C 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 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 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]. The strain hardening rate and fracture toughness are usually affected by strain rate and temperature. Reddy [10] has used taguchi technique which can save the cost of experimentation to optimize the extrusion process of 6063 alumimium alloy. Industrial pure aluminum can not be heat strengthened, through increased intensity of cold deformation, the only form of heat treatment is annealing. 1080 is highly resistant to chemical attack and weathering. It is easily worked and welded. This is excellent for chemical processing equipment and other uses where product purity is important, and for metal pressings of all types where ductility is critical also, it is a soft workable alloys having high purity which gives excellent corrosion resistant.

The objective of the present work is to optimize the warm deep drawing process of 1080A aluminium alloy using taguchi technique. 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 cup. All the experimental results have been verified using D-FORM software.

2 MATERIALS AND METHODS

1080A aluminium alloy was used to fabricate deep drawing cups. The tensile and yield strengths of this alloy are 120 and 80 MPa respectively. The elastic modulus is 70 GPa. The poisson's ratio is 0.33. The percent elongation is 8. The control pa-

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rameters 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 1080A 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:

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

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

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

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

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:

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:

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

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 1080A 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).

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

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- Erichsen deep drawing test

The Erichsen deep drawing test (figure 2) was conducted for testing the deep drawing quality and ear forming tendency on 1080A 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: 6767 tetrahedron
Number of nodes for the blank: 2375
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.

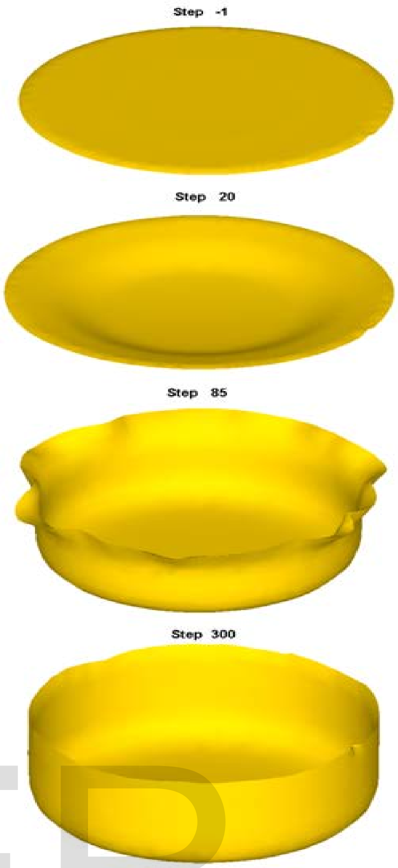

Fig. 3. Deep drawing operation using D-FORM 3D software.

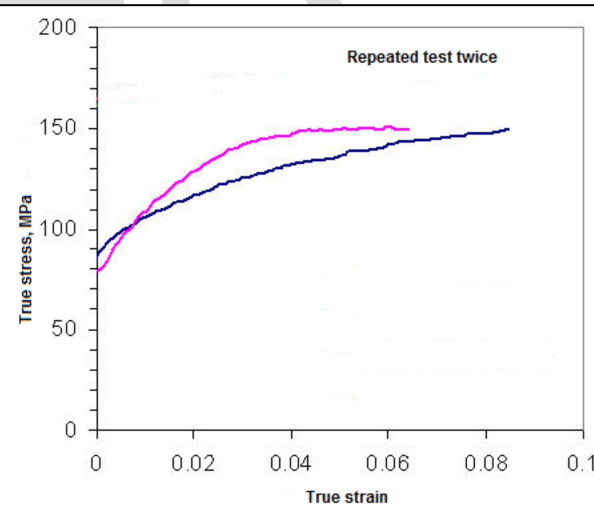

Fig. 4. 1080A aluminum alloy tensile stress-strain curves.

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, 126 MPa, true tensile strength, 154 MPa, nominal yield strength (0.2% offset), 83 MPa, and elongation (in 50.8 mm), 8.0% A log-log plot of the stress-strain curve would yield a slope (n) of 0.21 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, and D) accepted at 90% confidence level. The percent contribution indicates that the thickness parameter, A contributes 25.01% of variation, B (temperature) assists 59.50% of variation, and D (strain rate) contributes 13.92% 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	753.93	689.57	489.76	6325.09	2	3162.55	649.07	25.01
B	879.99	585.92	467.36	15044.10	2	7522.05	1543.81	59.50
C	650.33	607.90	675.03	384.23	2	192.12	39.43	1.51
D	532.01	733.60	667.65	3521.60	4	880.40	180.69	13.92
Error				4.87	7	0.70	0.14	0.06
T	2816.25	2616.98	2299.80	25279.89	17			100.00

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.

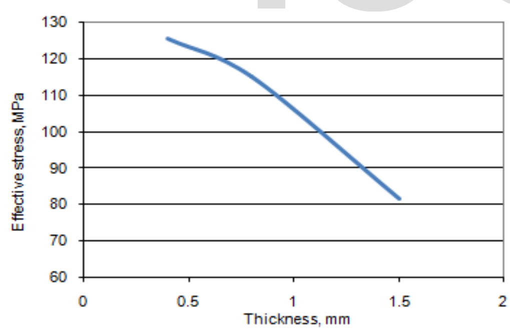

Fig. 5. Influence of sheet thickness on the effective stress.

The influence of thickness on the effective stress is shown figure 5. The effective stress of the cups decreases from 125.66 to 81.63 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 146.66 to 77.89 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 13KN to 5KN over the working temperature range 100⁰C<T< 500 ⁰C.

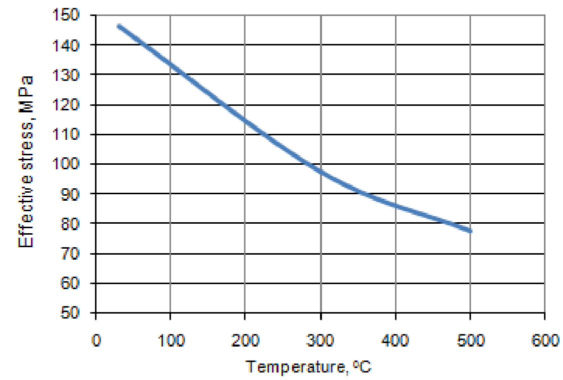

Fig. 6. Influence of temperature on the effective stress.

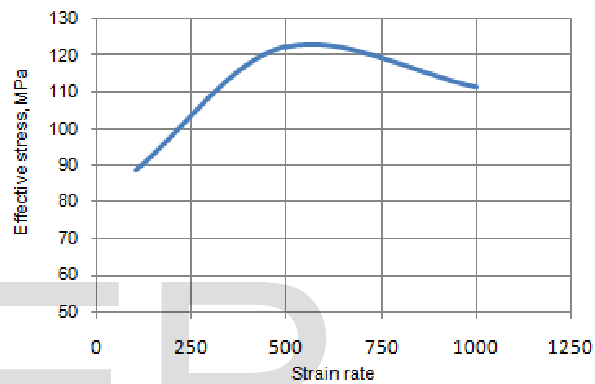

Fig. 7. Influence of strain rate on the effective stress.

The influence of strain rate on the effective stress is shown in figure 7. It is observed that the effective stress (122.27 MPa) is maximum at the strain rate of 500 s^{-1}.

The FEA results of effective stress are shown in figure 8. The test condtions (treat no. 1, 2 &3) of thickness, 0.40 mm have yielded the effective stresses of 145, 125 and 105 MPa respectively with fracture in the cups. In all the cases the thickness, strain rate and temperature have played a dominant role. Kobayashi and Dodd [13] proposed the following equation with a term for temperature softening:

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

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 K and β are constants.

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 contributions 24.91% 34.95% are of sheet thickness and temperature towards variation in the effective strain. The other influencial parameters are coefficient of friction (19.50%) and strain rate (21.20%).

The effective strain decreases with an increase in the thickness of blank sheet as shown in figure 9 where as it increases with with increase of temperature, coefficient of friction and strain rate. The characteristic equation that describes super-

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plastic behavior is usually written as $\sigma = K\dot{\epsilon}^m m$, [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 13. The failure of cups under treat ments 1, 2 and 3 were on account of thickness and temperature dependency for the fracture strain was evidently strain rate sensitive.

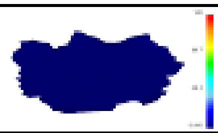
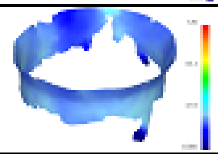
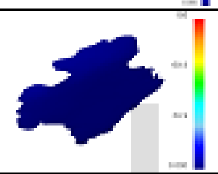
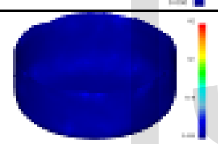
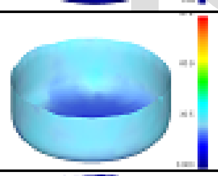
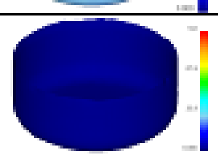
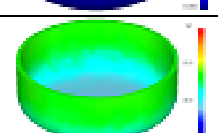
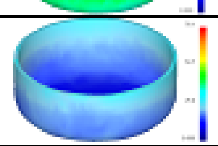
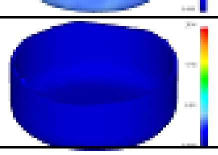
Treat No.	FEA Results	Maximum Effective Stress, MPa
1		148.00
2		125.00
3		105.00
4		152.00
5		91.40
6		102.00
7		141.00
8		76.10
9		26.40

Fig. 8. Influence of process parameters on the effective stress.

TABLE 4

ANOVA summary of the effective strain

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	40.87	16.40	12.47	78.95	2.00	39.48	86.91	24.91
B	11.44	14.35	43.95	107.88	2.00	53.94	118.74	34.05
C	12.27	18.98	38.49	61.84	2.00	30.92	68.07	19.5
D	15.45	14.64	39.65	67.33	4.00	16.83	37.05	21.2
Error				0.45	7.00	0.06	0.13	0.34
T	80.03	64.37	134.56	316.45	17.0 0			100

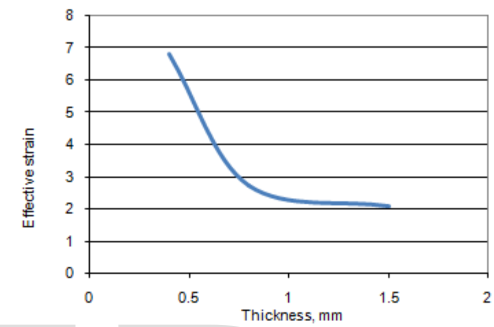


Fig. 9. Influence of thcikness on the effective strain.

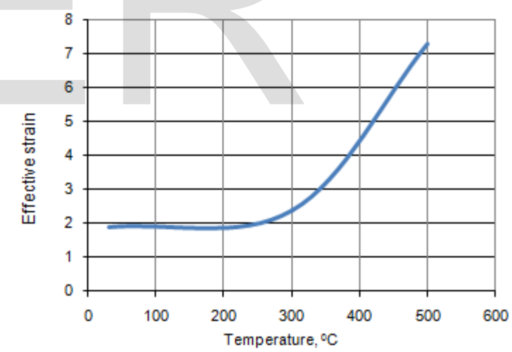


Fig. 10. Influence of temperature on the effective strain.

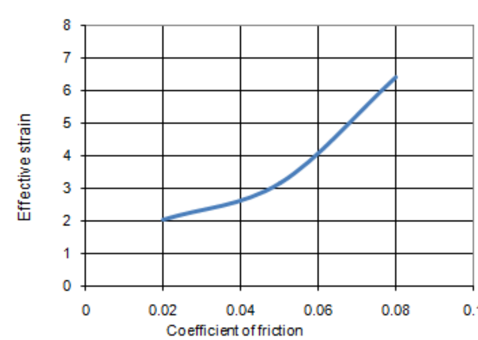


Fig. 11. Influence of friction on the effective strain.

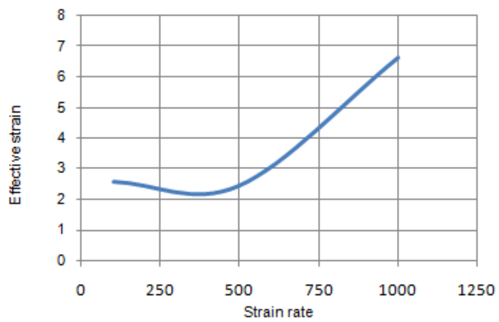


Fig.12. Influence of strain rate on the effective strain.

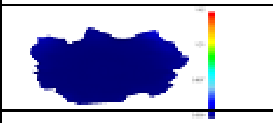
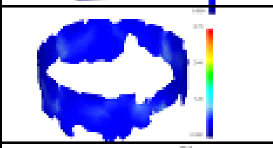
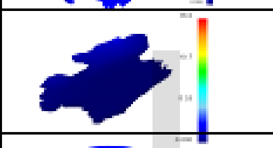
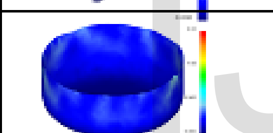
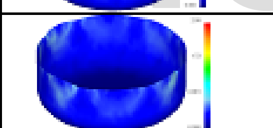
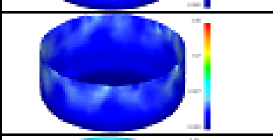
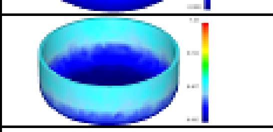
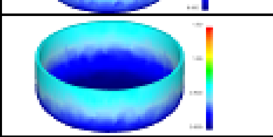
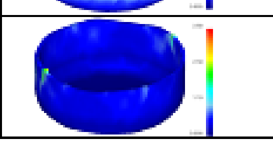
Treat No.	FEA Results	Maximum Effective Strain
1		1.82
2		3.73
3		16.00
4		2.83
5		2.58
6		2.96
7		1.22
8		1.50
9		3.58

Fig. 13. Influence of process parameters on the effective strain.

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 rest of the parameters has negligible influence of variation. The volume of cup increases with an increase in the thickness of sheet as shown in figure 14.

TABLE 5
ANOVA summary of the volume of cup

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	15969	32025	59957	165164802	2	82582401	186293	100
B	35985	36009	35957	219	2	109	0	0
C	35947	36003	36002	347	2	174	0	0
D	35972	36019	35960	318	4	79	0	0
Error				443	7	63	0	0
T	123873	140055	167877	165166130	17			100

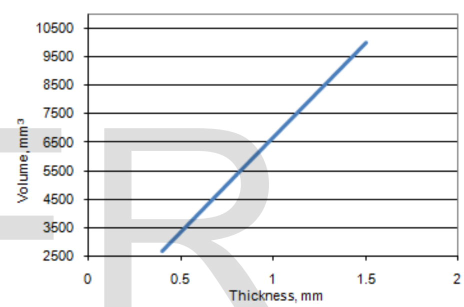


Fig. 14. Influence of thickness on the volume.

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 (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 (28.40%) of the variation, parameter, T (temperature) aids 36.65% of variation, coefficient of friction contributes 15.97% of variation and strain rate contributes 18.73% of variation.

TABLE 6
ANOVA summary of the damage of cup

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	55.69	13.59	4.79	246.70	2	123.35	131.50	28.40
B	3.11	10.88	60.09	318.26	2	159.13	169.64	36.65
C	13.41	12.41	48.25	138.86	2	69.43	74.02	15.97
D	4.42	21.37	48.28	163.02	4	40.76	43.45	18.73
Error				0.94	7	0.13	0.14	0.25
T	76.63	58.25	161.40	867.78	17			100.00

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The effect of thickness on the damge of cup is shown in figure 15. The damage decreases with an increase in the thickness of the sheet. As the temperature increases the damage increases (figure 16) 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]. The effect of coefficient of friction on the damage of cups is shown in figure 17. As the friction increases the damage also increases. The damage in the cups increases with an increase in the strain rate as shown in figure 18.

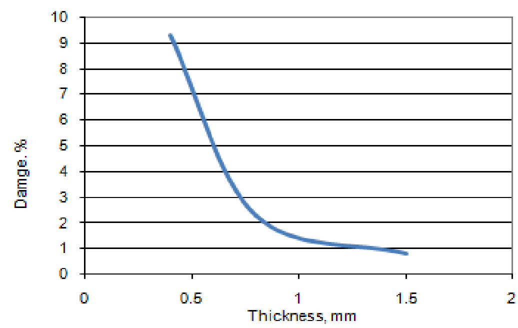


Fig. 15. Influence of thickness on the damage of cup.

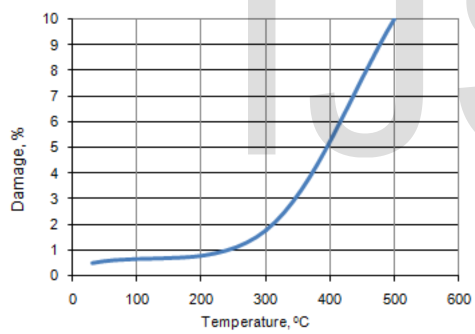


Fig. 16. Influence of temperature on the damage of cup.

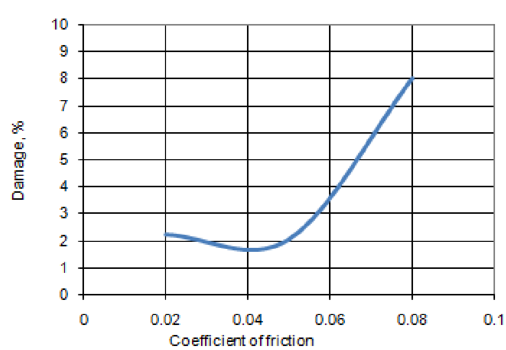


Fig. 17. Influence of friction on the damage of cup.

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 (figure 19a), 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 17 that the damage in the cup increases with an increase in the coefficient 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.

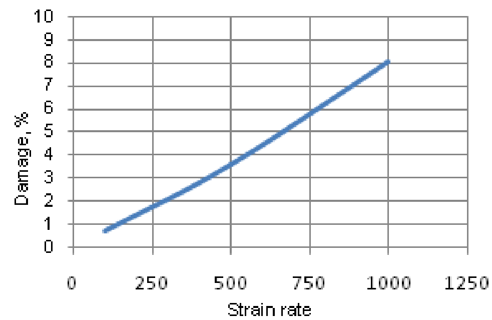


Fig. 18. Influence of strain rate on the damage of cup.

Fig. 19. Experimentally drawn cups

It is clearly observed from figures 19a, (figure 20-1), 19b (figure 20-2) & 19c (figure 20-3) that the damge in the cup was due to low thickness of sheet, high temperature, high coefficent of friction and high strain rate. The result of figure 19a (figure 20-1) was due to thickness, 0.40 mm of the sheet metal. The result of figure 19b (figure 20-2) was due to temperature (300^0C) and strain rate (500). The result of figure 19c (figure 20-3) was due to temperature (500^0C), high friction coefficient (0.08) and strain rate (1000). Very good quality of cup with test conditions of treatment 8 (figure 20-8) was resulted (figure 19d). This is also proved with the FEA results as seen in figure 20. The damage was observed with treat number 1, 2 &3. With test conditions of treatment 1, 2 & 3 the damages were20.42, 12.37 and 23.70 respectively. In these cases it was also observed that heavy thinning was occured near the punch radius.

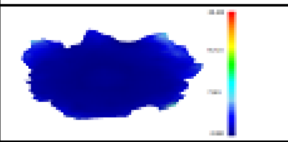
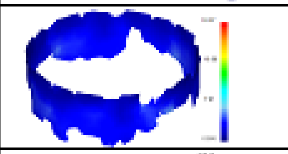
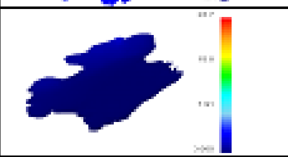
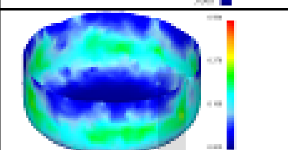
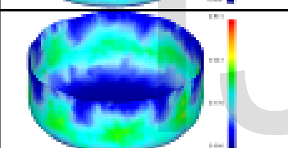
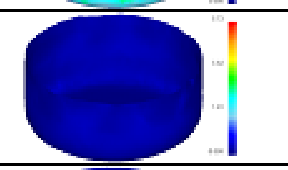
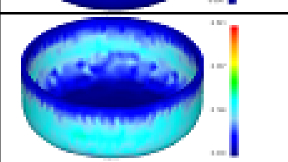
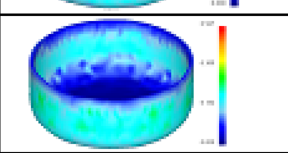
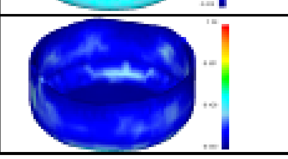
Treat No.	FEA Results	Damage
1		20.42
2		12.37
3		23.70
4		0.56
5		0.51
6		5.73
7		0.58
8		0.55
9		1.28

Fig. 20. Influence of process parameters on the damage of cups

The effect of temperature on the results of the Erichsen deep drawing test is shown in figure 21. The volume of the cup increases with an increase in the temperature. From figure 22a, 22b &122c it was observed that 0.40 mm sheets at room temperature, at 300⁰C and at 500⁰C show cleavage which was an indication of the damage and the formationn of wrinkles in the cups. From figure 22d there was an indication of forming wrinkles at room temperature for 0.80 mm thick sheets. No wrinkles (figure 22f) were formed at 500⁰C temperature for 1.50mm thick sheets.

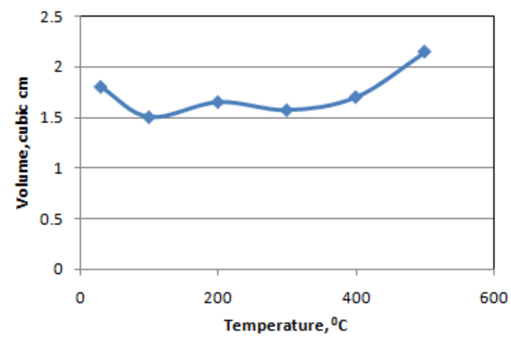


Fig. 21. Influence of temperature on the volume

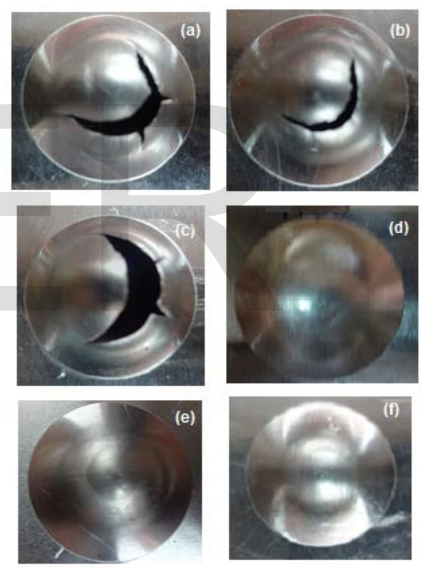


Fig. 22. Cups drawn on Erichsen deep drawing tester.

4 Conclusion

The thickness of sheet, temperature, and coefficient of friction influence the effective stress. The major parameter which can influence volume of the cup is the thickness of sheet. The effective strain and the damage in the cups are affected by sheet thickness, temperature, coefficient of friction and strain rate. The damage in the cups was less in the thick sheets and it was more at high coefficient of friction, strain rate and temperature.

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REFERENCES

[1] K. Chung, F.Barlat and J.C. Brem, Blank shape design for a planar anisotropy sheet based on ideal forming design theory and FEM analysis, International Journal of Mechanical Sciiences, vol. 39, pp.617–633, 1997.

[2] F. Shehata, M.J. Painter, and R. Pearce., Warm forming of aluminium/magnesium alloy sheet, Journal of Mechanical Working Technology, vol .2, no.3, pp. 279-291, 1978.

[3] D.M. Finch, S.P. Wilson and J.E. Dorn, Deep drawing aluminium alloys at elevated temperatures. Part II. Deep drawing boxes, Transactions ASM, vol.36, pp. 290–310, 1946.

[4] S. Toros S, F.Ozturk and Ilyas Kacar, Review of warm forming of aluminum–magnesium alloys, Journal of Materials Processing Technology, vol.207, no.1-3, pp. 1–12, 2008.

[5] J.V.Jeysingh, B. Nageswara Rao , A. Chennakesava Reddy, Investigation On Failures Of Hydroforming Deep Drawing Processes, Materials Science Research Journal, vol.2, no.3&4, pp.145-168, 2008.

[6] A. Chennakesava Reddy ,T. Kishen Kumar Reddy, M. Vidya Sagar, Experimental characterization of warm deep drawing process for EDD steel, International Journal of Multidisciplinary Research & Advances in Engineering, vol.4, no.3, pp.53-62, 2012.

[7] A. Chennakesava Reddy, Evaluation of local thinning during cup drawing of gas cylinder steel using isotropic criteria, International Journal of Engineering and Materials Sciences, vol.5, no.2, pp.71-76, 2012.

[8] A. Chennakesava Reddy, Finite element analysis of reverse superplastic blow forming of Ti-Al-4V alloy for optimized control of thickness variation using ABAQUS, Journal of Manufacturing Engineering, vol.1, no.1, pp. 06-09, 2006.

[9] Chennakesava Reddy, Optimization of Extrusion Process of Alloy 6063 Using Taguchi Technique, International Journal of Multi- Disciplinary Research & Advances in Engineering, vol.3, no.2, pp.173-190, 2011.

[10] Chennakesava R Alavala, "CAD/CAM: Concepts and Applications," PHI Learning Pvt. Ltd., 2008.

[11] Chennakesava R Alavala, "FEM: Basic Concepts and Applications," PHI Learning Pvt. Ltd., 2008.

[12] W. Lee and G. W. Yeh, The plastic deformation behaviour of AISI 4340 alloy steel subjected to high temperature and high strain rate loading conditions. Journal of materials processing technology, vol. 71, pp. 224–234, 1997.

[13] H. Kobayash and B. Dodd, A numerical analysis for the formation of adiabatic shear bands including void nucleation and growth, International Journal of Impact Engineering, vol.8, pp.1-13, 1989.

[14] J. Hedworth, M.J. Stowell, The measurement of strain-rate sensitivity in superplastic alloys, Journal of Material Science vol.6, pp.1061–1069, 1971.

[15] A. Wifi and A. Mosallam, Some aspects of BHF schemes in deep drawing process, Journal of Achievements in Materials and Manufacturing Engineering vol. 24, no., pp.315-320, 2007.