Homogenization and Parametric Consequence of Warm Deep Drawing Process for 1050A Aluminum Alloy: Validation through FEA

A. Chennakesava Reddy

A. Chennakesava Reddy, Professor, Department of Mechanical Engineering, JNT University, Hyderabad-500 085, India

Abstract: ***In this present work, a statistical approach based on Taguchi Techniques and finite element analysis were adopted to determine the parametric consequence 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 experimental results were validated using a finite element software namely D-FORM. The sheets used for the deep drawing process homogenized to improve the drawability of 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 stress, height of the cup, damage in the cup were the thickness of sheet, strain rate, clearance, radius of the die and temperature. The homogenization at 500^{0}C for 16 hours could improve the drawability of the cups.***

Keywords: 1050A, warm deep drawing, thickness, temperature, coefficient of friction, strain rate, finite element analysis, homogenization

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 drawability 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. [7] in another work have simulated that the cup drawing process with an implicit finite element analysis. The effect of local thinning on the cup drawing has been investigated. The thinning is observed on the vertical walls of the cup. 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 [8]. Reddy [9] has used Taguchi technique which can save the cost of experimentation to optimize the extrusion process of 6063 aluminum alloy.

Grain boundary nucleation has been frequently observed and it plays a dominant role in recrystallization kinetics when the initial grain size is small, or at lower strains [10]. The second inhomogenity refers to the fact that the deformation microstructures varies from grain to grain because of the initial crystallographic texture. As a result, the nucleation sites for recrystallization in deformed grains with different orientations are different [11]. Each as-deformed grain will recrystallize at a rate that depends on its size as well as initial orientation with respect to the deformation field depending on the accumulation of the stored energy. Although many investigators have developed mathematical models to predict the temperature distribution and the strain distribution of the slab during hot rolling [12], very few publications paid attention to the deformation history and the variation of the strain rate pattern during hot rolling, which have been recognized as two important parameters for hot deformation. In practical hot rolling conditions, where the nominal strain rate ranges from 0.1 to 100 /s, the yield stress characteristics of the material are strain rate rather than strain dependent. 1050 aluminum alloy is not heat treatable. It is difficult to deep draw and to have minimum wall thickness of less than 1 mm. accordingly, it is expensive to produce and makes it difficult to exploit the combination of high strength and thin wall thickness. Aluminum alloy 1050 is a popular grade of aluminum for general sheet metal work where moderate strength is required as shown in figure 1. Alloy 1050 is known for its excellent corrosion resistance, high ductility and highly reflective finish. Applications - Alloy 1050 is typically used for: chemical process plant equipment, food industry containers, architectural flashings, Lamp reflectors, and cable sheathing.

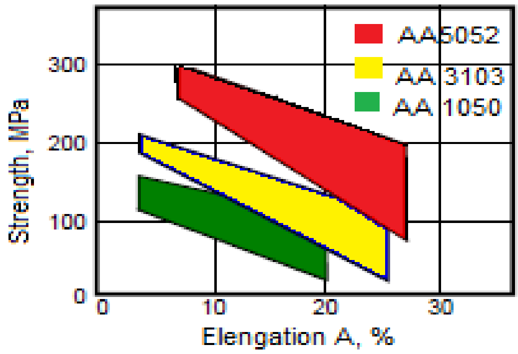

Figure 1: Application of 1050 in sheet metal work (strength perspective).

The objective of the present work is to optimize the warm deep drawing process of 1050A aluminum alloy taking the advantage of homogenization using Taguchi technique. In this present work, a statistical approach based on Taguchi 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. An effort was also made to correlate the Microstructural evolution of warm drawn 1050A aluminum alloy subjected to a series of homogenization treatments.

2. Materials and Methods

1050A aluminum alloy was used to fabricate deep drawing cups. The tensile and yield strengths of this alloy are 100 and 85 MPa respectively. The elastic modulus is 71 GPa. The Poisson's ratio is 0.30. The percent elongation is 12. The shear strength is 60 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 1050 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	0.80	1.00	1.20
Temperature, ^{0}C	B	300	400	500
Coefficient of Friction	C	0.20	0.30	0.40
Strain rate	D	0.1	10	100

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. 1050 aluminum alloy sheets were subjected to a homogenization treatment in a laboratory air furnace with controlled heating rates. All the sheets were annealed at 300, 400 and 500°C for a period of 8 hrs. Microstructural examination of the annealed samples was also carried out using optical microscope.

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 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/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 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, $c = t + \mu\sqrt{10t}$ (9)

The sheets of 1050A aluminum 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 calculated, as in (5). The cups were fabricated using hydraulically operated deep drawing machine as shown in figure 1.

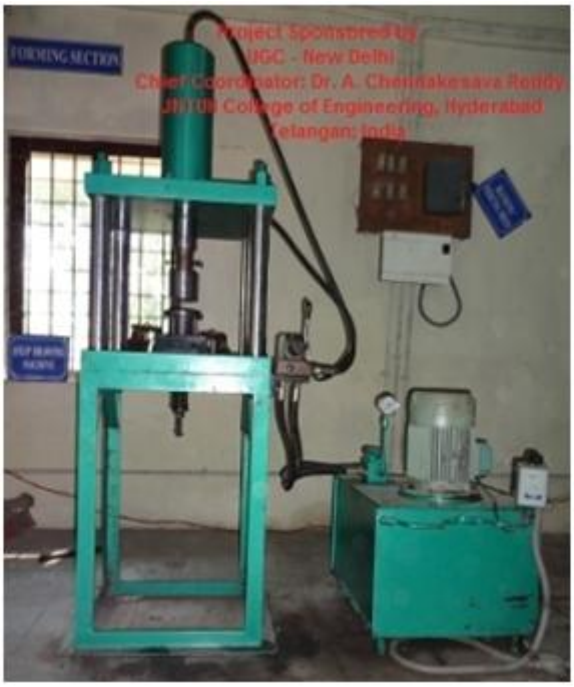

Figure 2: Deep drawing machine (hydraulic type).

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 [13]. The clearance between the punch and die was calculated as in (9). The sheet blank was meshed with tetrahedral elements [14]. The modeling parameters of deep drawing process were as follows:

Number of elements for the blank: 21980 tetrahedron
Number of nodes for the blank: 7460
Top die polygons: 9120
Bottom die polygons: 9600

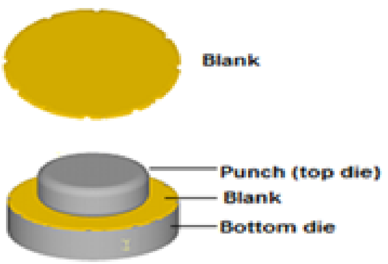

Figure 3: Initial position die, punch and

The initial position of the die, blank and punch 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.

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 true tensile strength decreases with an increase in the temperature due to softening as shown in figure 4.

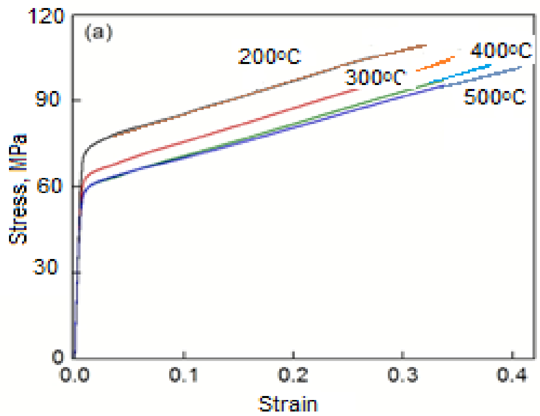

Figure 4: 1050A aluminum alloy rod, tensile stress-strain curves.

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 puts in 9.68% of variation, B (temperature) supports 41.60% of variation, C (coefficient of friction) influences 0.71% of variation and D (strain rate) contributes 47.73% 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	568.21	672.16	618.61	900.75	2	450.38	43.52	9.68
B	741.03	582.13	535.84	3860.96	2	1930.48	186.56	41.60
C	625.10	630.52	603.37	68.80	2	34.40	3.32	0.71
D	752.74	549.17	557.08	4432.39	4	1108.10	107.09	47.73
Error				10.35	7	1.48	0.14	0.28
T	2687.08	2433.99	2314.90	9273.25	17			100.00

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.

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 ^{0}C.

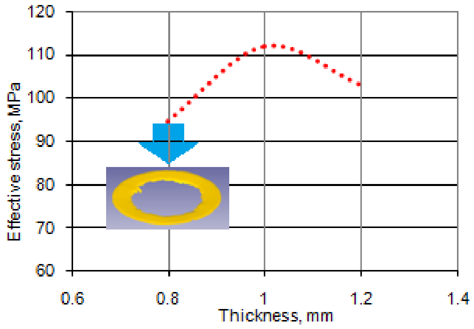

Figure 5: Influence of sheet thickness on the effective stress.

The influence of thickness on the effective stress is shown figure 5. The effective stress of the cups increases from 94.70 to 112.03 MPa with increasing thickness of sheet from 0.8 to 1.0 mm. This was on account of any early tear of sheet at applied deep drawing force in the case of thickness less than 1.0 mm. However the effective stress decreases from 112.03 to 103.10 MPa decreases with increasing thickness of sheet from 1.0 to 1.2 mm. This is practical as the denominator component of ‘stress = force/area’ increases the stress value decreases.

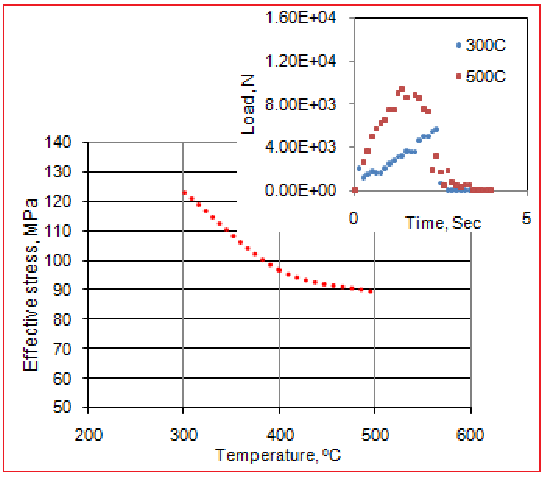

Figure 6: Influence of temperature on the effective stress.

The effective stress decreases from 123.51 to 89.31 MPa with increasing temperature from 300 to 500^0C (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. For instance the maximum forming load was found to decrease from 8.5 KN to 5.8 KN over the working temperature range 300^0C<T< 500 ^{0}C for 0.8mm thick sheet. This kind of decreasing trend of load was also observed for 1.0 and 1.2 mm thick sheets too.

The influence of friction coefficient on the effective stress was found to be negligible. The influence of strain rate on the effective stress is shown in figure 7. It is observed that the effective stress increases with an increase in the strain rate.

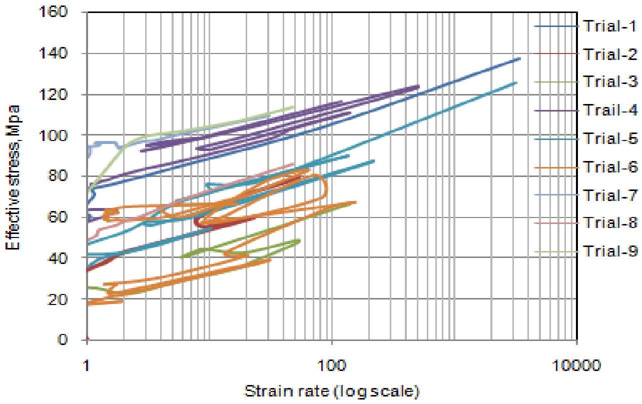

Figure 7: Influence of strain rate on the effective stress.

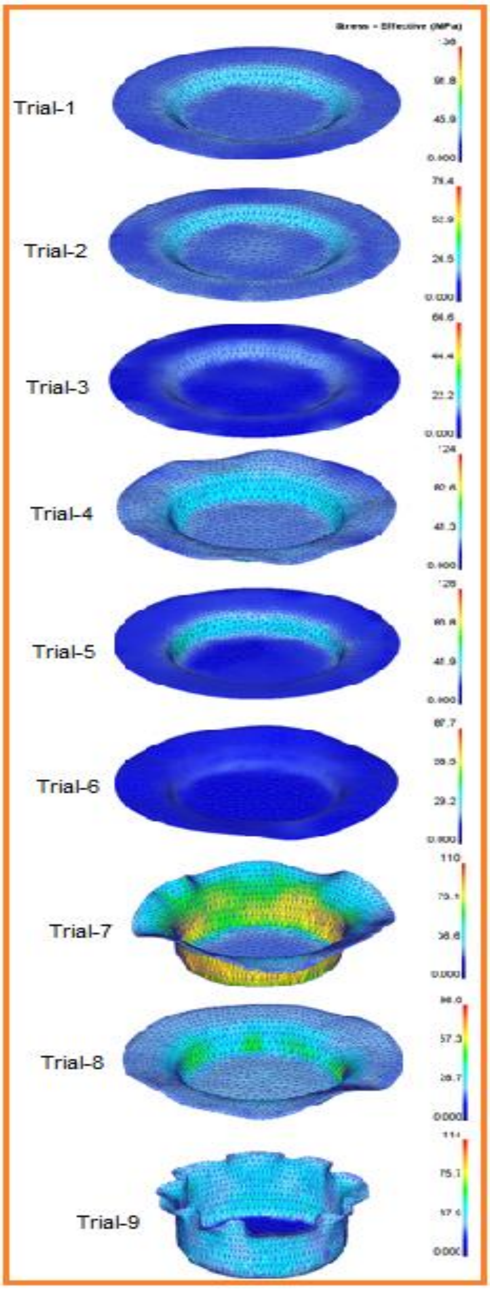

Figure 8: Influence of process parameters on the effective stress.

The FEA results of effective stress are shown in figure 8 for various test conditions as per the design of experiments. It was found that the trail- 9 could give big cup as compared to the rest of test conditions with maximum effective stress of 114 MPa. The effect of temperature softening in the cups is shown in figure 9. Kobayashi and Dodd [15] proposed the following equation with a term for temperature softening:

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

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. It was proved from the results obtained from the present work that the major dominant parameters were the temperature and the strain rate which could influence the effective stress of the cups during the deep drawing process.

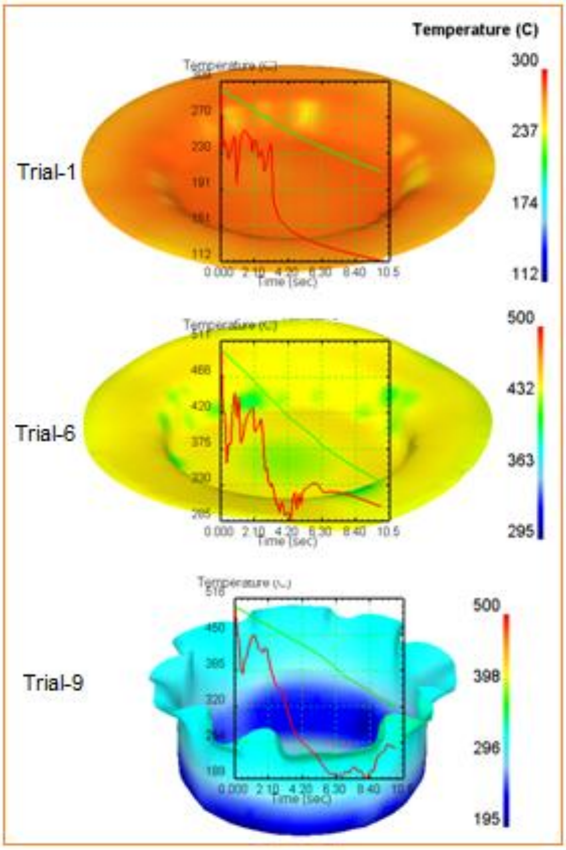

Figure 9: Temperature softening

Table 4: ANOVA summary of the height of cup

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	63.27	97.09	192.14	1488.09	2	744.05	546.53	68.28
B	117.78	95.13	139.59	164.74	2	82.37	60.50	7.54
C	83.23	142.52	126.75	314.33	2	157.17	115.45	14.41
D	143.93	114.64	93.93	210.37	4	52.59	38.63	9.62
Error				1.36	7	0.19	0.14	0.15
T	408.21	449.38	552.41	2178.89	17			100

4.3 Influence of process parameters on height of cup

The ANOVA summary of cup height is given in table 4. 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 68.28%of variation, temperatures influences 7.54% of variation, coefficient of friction contributes 14.41% of variation and strain rate controls 9.62% of variation.

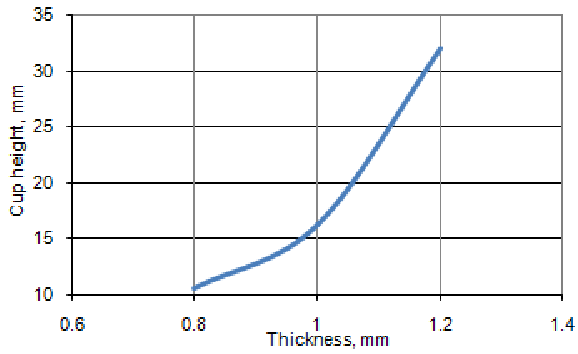

Figure 10: Influence of sheet thickness on the height of cup.

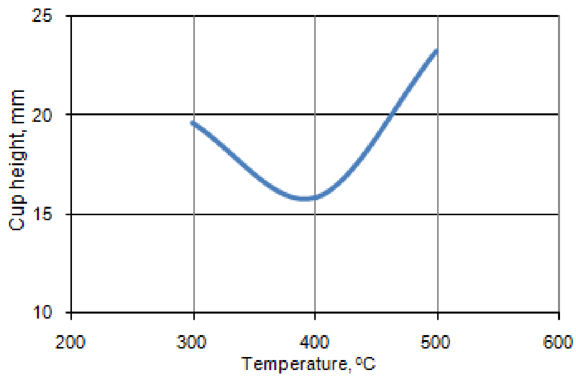

Figure 11: Influence of temperature on the height of cup.

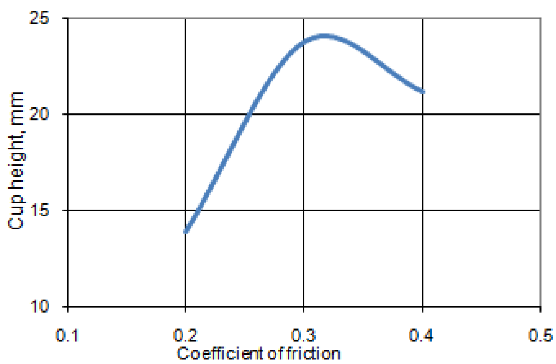

Figure 12: Influence of friction on the height of cup.

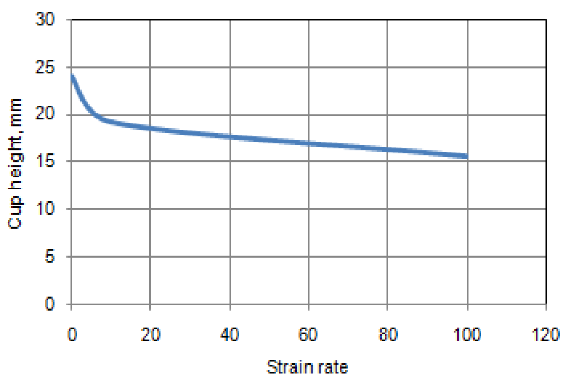

Figure 13: Influence strain rate on the height of cup.

The height of cup increases with an increase in the thickness of sheet as shown in figure 10. The height of the cup drawn at temperature 400^{0}C was short (figure 11). The height of the cup increases with an increase in the coefficient of friction from 0.2 to 0.3 and later on it decreases (figure 12). The height of the cup decreases with an increase in the strain rate (figure 13).

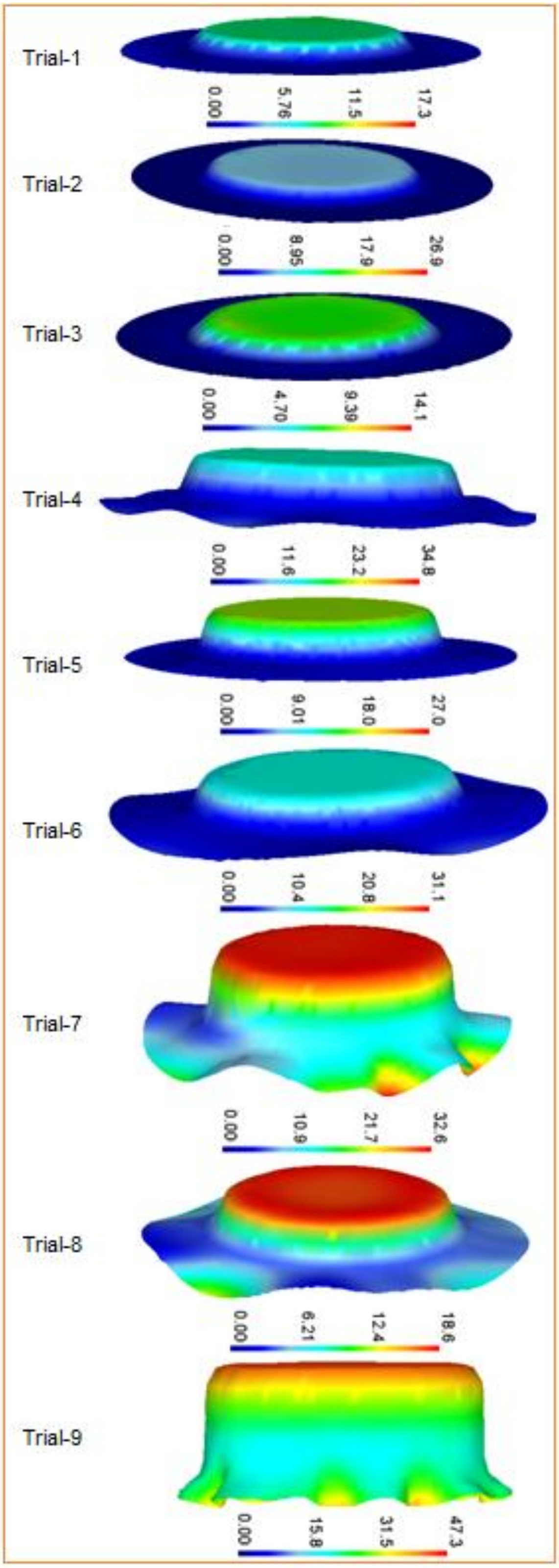

Figure 14: FEA results showing the heights of cups.

The FEA results of the cups drawn with different trials as per the design of experiments are shown in figure 14. The target height of the cup was 50 mm with diameter 100 mm. 95% of the expected cup height was reached with the trial 9.

4.4 Influence of process parameters on damage of cup

The ANOVA summary of damage of cups 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 cup height. The percent contribution indicates that the thickness of the sheet only contributes half (28.77%) of the variation, parameter, B (temperature) aids 17.43% of variation, coefficient of friction (c) contributes 18.04% of variation and strain rate (D) contributes 35.74% of variation.

Table 6: ANOVA summary of the damage of cup

Source	Sum 1	Sum 2	Sum 3	*SS*	*v*	*V*	*F*	*P*
A	126.94	447.64	16.87	16695.56	2	8347.78	1441.42	28.77
B	155.79	388.32	47.34	10116.78	2	5058.39	873.44	17.43
C	131.20	62.37	397.88	10467.91	2	5233.96	903.76	18.04
D	484.96	42.98	63.51	20744.03	4	5186.01	895.48	35.74
Error				5.79	7	0.83	0.14	0.02
T	898.89	941.31	525.60	58030.07	17			100.00

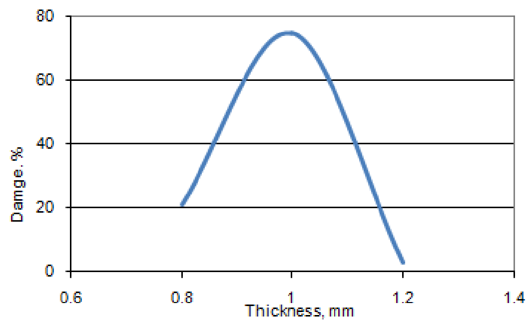

Figure 15: Influence of thickness on the damage of cup.

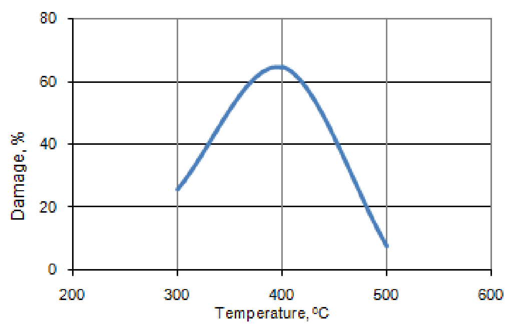

Figure 16: Influence of temperature on the damage of cup.

The effect of thickness on the damage of cup is shown in figure 15. The damage decreases with an increase in the thickness of the sheet. The average distribution of the blank thinning increases with an increase in the blank thickness. Ironing can be defined as thinning of the blank at the die cavity. The main reasons for the damage of cups were due to ironing and the coefficient of friction. The clearance was obtained by the formula as in eq. (9).

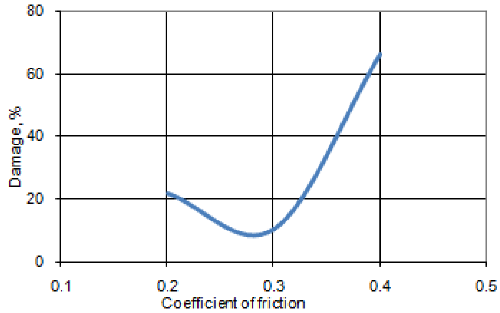

Figure 17: Influence friction on the damage of cup.

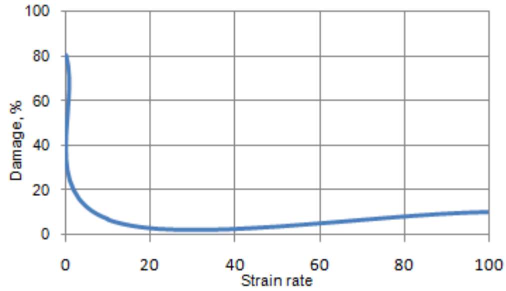

Figure 18: Influence of strain rate on the damage of cup.

As the temperature increases the damage is also increases (figure 16) because of softening of the material. 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 [16]. 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 17 that the damage in the cup increases with an increase in the coefficient of friction from 0.3 to 0.4. 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. The optimum value of friction coefficient could be 0.3.

The damage in the cups decreases with an increase in the strain rate from 0.1 to 10 as shown in figure 18. The damages were 81, 7 and 11 for the strain rates of 0.1, 10 and 100 respectively. It is clearly observed from figure 19 that the damage in the cup for trials 1 to 60 was due to high coefficient of friction, low thickness of sheet and low strain rate. It was also observed that the thinning occurs near the die radius. For trials 7 to 9 the damage was occurred at the punch radius. The large die radius can cause wrinkling to the part while the smallest radius can cause fracture or breaking the part due to the high stresses.

4.5 Influence of homogenization

The sheet metal blank has an inherent grain structure, so the stresses can vary depending on the design of the die and the orientation of the grain. Adjusting the grain in an asymmetrical design to minimize the compound of grain stresses and the general stresses of the deep draw process is something to take into consideration.

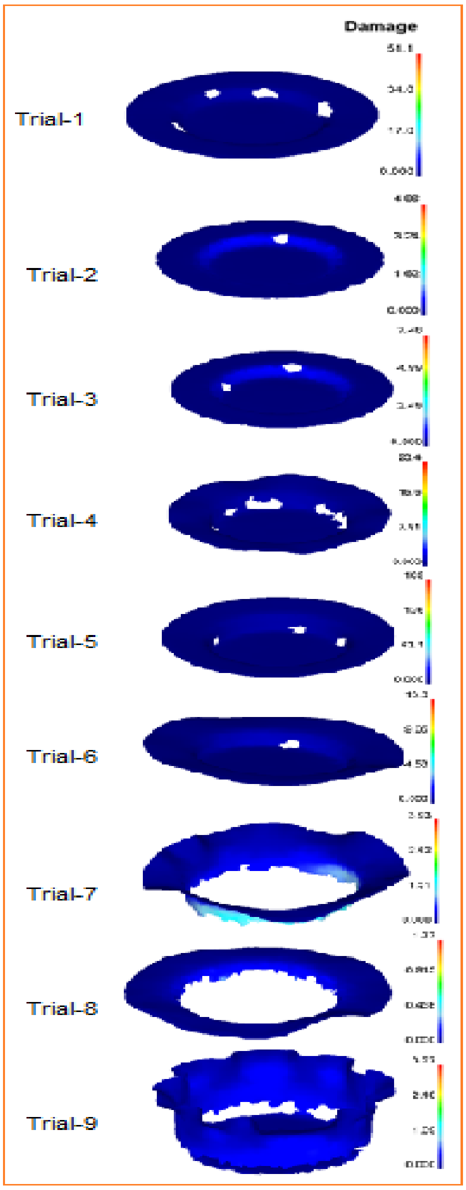

Figure 19: Influence of process parameters on the damage of cup.

Figure 20a shows the microstructure of 1050A aluminum alloy before homogenization. The microstructure contains more intermetallics in number and smaller in size compared to the bulk. The optical micrographs in figure 20b & c show the particle distribution and the grain structures at the surface for homogenized 1050A aluminum alloy at 500^0 C for 16 hours. A deformed layer of approximately 200 microns is clearly seen after deep drawing in the sheet at 300^0C without homogenization of 1050A aluminum alloy. The second phase particles are aligned with the deep drawing direction forming colonies of clusters. In the case of inhomogenized sample, those clusters of intermetallics would in turn results in recrystallized grain growth in the deep drawing direction since those clusters inhibit the growth in the normal direction. The discrepancy in grain size was related to the concentration gradients developed during deep drawing at low temperatures. The concentration gradients are totally eliminated in figure 20c. This can be attributed to the coarsening and/or precipitation of second phase particles out of the supersaturated zone forming potential nuclei for particle stimulated nucleation.

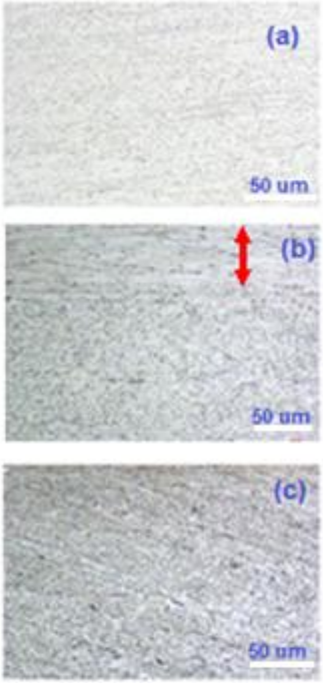

Figure 20: Effect of homogenization on grain structure.

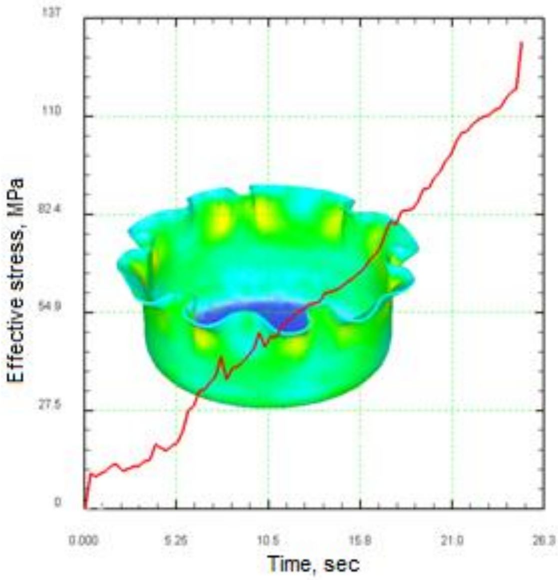

Figure 21: Effective stress in the successful cup.

4.6 Successful cup

The optimum deep drawing conditions to get successful cup of height 50 mm and diameter 100 mm) are as follows:

- The clearance as in eq.(9) was modified to

$c = t + \mu\sqrt{12t}$ (11)

- Coefficient of friction – 0.25
- Temperature = 500^0C
- Strain rate = 25 s^{-1}
- Clearance
- The die radius as in eq.(7) was modified to

$r = 0.9\sqrt{(D-d)t}$ (12)

- The blank was homogenized at 500^0C for 16 hours before drawing into cups.

The maximum effective stress was 131 MPa (figure 21). The damage was 0.88% (wrinkling). The maximum, load in the z-direction was 20029.02 N (figure 22). The maximum height of the cup achieved was 50 mm (100% success) (figure 23 & 24).

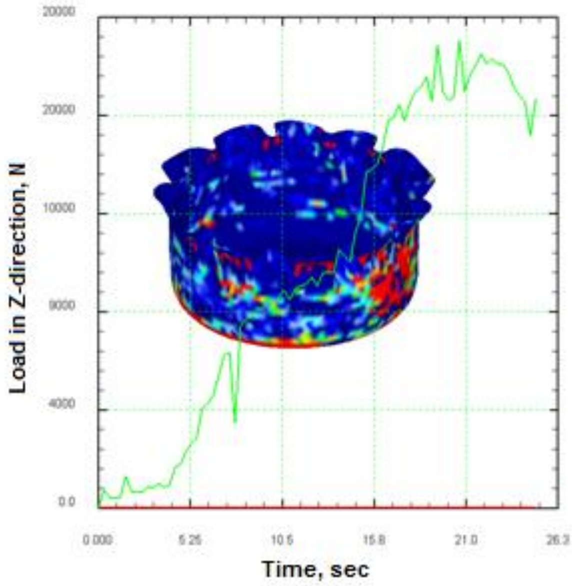

Figure 22: Load in z-direction on the successful cup.

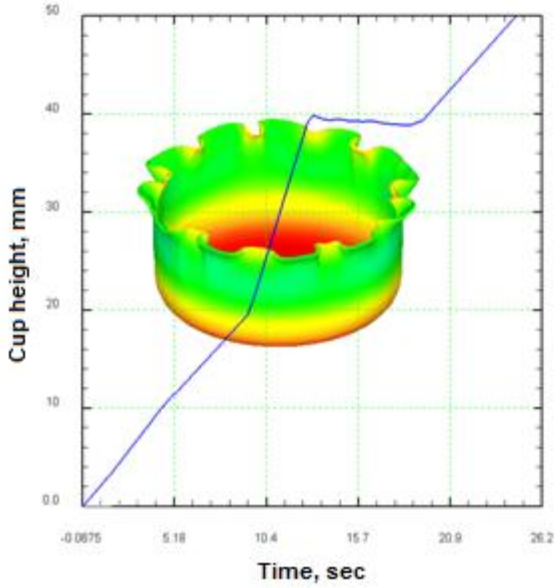

Figure 23: Height of the successful cup.

Figure 24: The successful deep drawn cup

5. Conclusions

The experimental and finite element analysis of warm deep drawing of 1050A aluminum alloy was carried out. It was observed that thickness of sheet, coefficient of friction temperature and strain rate were highly influence the required dimensional cup. The modification of equations for the die radius and the clearance and limiting the strain rate to 25s-1 could yield the best results. The homogenization of the sheet before deep drawing was precipitation of second phase particles out of the supersaturated zone forming potential nuclei for particle stimulated nucleation.

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Author Profile

Dr. A. Chennakesava Reddy, B.E., M.E (prod). M.Tech (CAD/CAM)., Ph.D (prod)., Ph.D (CAD/CAM) is a Professor in Mechanical Engineering, Jawaharlal Nehru Technological University, Hyderabad. The author has published 209 technical papers worldwide. He is the recipient of best paper awards ten times. He is recipient of Best Teacher Award from the Telangana State, India. He has successfully completed several R&D and consultancy projects. He has guided 14 Research Scholars for their Ph.D. He is a Governing Body Member for several Engineering Colleges in Telangana. He is also editorial member of Journal of Manufacturing Engineering. He is author of books namely: FEA, Computer Graphics, CAD/CAM, Fuzzy Logic and Neural Networks, and Instrumentation and Controls. Number of citations are 516. The total impact factors are 80.1246.His research interests include Fuzzy Logic, Neural Networks, Genetic Algorithms, Finite Element Methods, CAD/CAM, Robotics and Characterization of Composite Materials and Manufacturing Technologies.