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HIGH TEMPERATURE AND HIGH STRAIN RATE SUPERPLASTIC DEEP DRAWING PROCESS FOR AA5049 ALLOY CYLINDRICAL CUPS

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ABSTRACT

In this present work, the formability of high temperature and high strain rate deep drawing process were estimated for the cylindrical cups using Taguchi technique and finite element analysis. The process parameters were temperature, strain rate, coefficient of friction and blank holder velocity. The formability limit diagrams were developed for all the trials. The AA5049 alloy sheets were used for the deep drawing of the cylindrical cups. The formability of the cups was excellent for the temperature of 500ºC and strain rate of 10 s^{-1}.

KEYWORDS: AA5049 alloy, high temperature, high strain rate, superplastic deep drawing process, coefficient of friction, cylindrical cups, forming limit diagram.

INTRODUCTION

All sheet metal forming processes follow after permanent plastic deformation resulting in change of the material properties and therefore it is necessary to determine the extent to which a material can further be deformed under high temperature and high strain rate. Several researches have been accepted to boost the superplastic properties of aluminum alloys. During cup drawing process, the significance of process parameters such as temperature, coefficient of friction, strain rate and blank holder velocity was explored for 1050 [1], 1070 [2], 1080 [3], 1100 [4], 2014 [5], 2017 [6], 2024 [7], 2219 [8] and 5083 [9] aluminum alloys. The deep drawing process was also carried out for Al-Mg alloy [10], Ti-Al-4V alloy [11], EDD steel [12] and gas cylinder steel [13]. Forming limit diagram (FLD) has been fruitfully developed from the strains obtained from the finite element analysis [6, 7, 8].

The importance of the present work was to get suitability of AA5049 alloy for high temperature and high strain rate superplastic (HTHSR) deep drawing process. The exploration was concentrated on the process parameters such as temperature, strain rate, coefficient of friction and blank holder velocity. The design of experiments was carried out using Taguchi technique. The HTHSR superplastic deep drawing process was executed using the finite element analysis software explicitly D-FORM 3D.

MATERIALS AND METHODS

In the present work, AA5049 alloy was used to manufacture cylindrical cups. The levels chosen for the controllable process parameters are summarized in table 1. Each of the process parameters was examined at three levels. The orthogonal array (OA), L9 was selected to carry out finite element analysis (FEA). The assignment of parameters in the OA matrix is given in table 2.

Table 1. Control parameters and levels

Factor	Symbol	Level–1	Level–2	Level–3
Temperature, ^{0}C	A	300	400	500
Strain rate, 1/s	B	1	5	10
Coefficient of friction	C	0.10	0.15	0.20

BH velocity, mm/s	D	0.4	0.5	0.6

The cylindrical sheet blank was created with desired diameter and thickness using CAD tools. The cylindrical top punch, cylindrical bottom hollow die and movable blank holder were also modeled with correct inner and outer radii and corner radius. In the present work, moving blank die was used to hold the blank at a predefined speed unlike to the punch speed (figure 1). The contact between blank/punch and die/blank were coupled as contact pair. The mechanical interaction between the contact surfaces was assumed to be frictional contact and modelled as Coulomb's friction model [14].

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

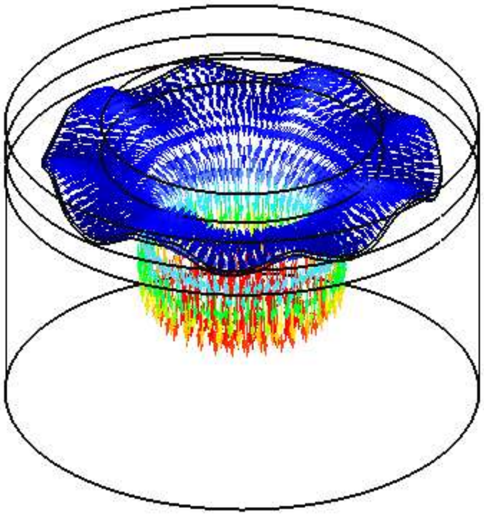

Figure 1. Cylindrical cup drawing with movable blank holder die.

RESULTS AND TABLES

The modeling parameters of deep drawing process were as follows:
Number of tetrahedron elements for the blank: 7948
Number of polygons for top die: 9120
Number of polygons for bottom die: 9600
Number of polygons for moving blank die: 960

A. Influence of process parameters on effective stress

The ANOVA (analysis of variance) summary for the effective stress is given in table 3. For the ANOVA analysis, the effective stresses at failure were considered. It is observed that the percent contribution indicates that process parameter A, temperature, all by itself contributes the most toward the variation observed in the effective stress: 53.49%. The effort was focused on those trials having results that were very similar results and having technical appeal. Six results were higher than the average value (356.06 MPa) of effective stress. The results would fall into groups of 2/3 of the effective stress (one strong factor). Even though strain rate, coefficient of friction and BH velocity would assure statistically the Fisher's test, the strongest process parameter is temperature controlling the effective stress. Figure 2a presents the effective stress induced in AA5049 alloy during cup drawing process as a function of temperature. Whether the temperature was 300ºC or 400ºC, the effective stress was unaffected to a large extent. The effective stress decreased drastically for the change of temperature from 400ºC to 500ºC (figure 2a). The increase in the coefficient of friction lessened the effective stress induced in the cups (figure 2b). Figure 2c expresses the effective stress as a function of BH (blank holder) velocity. In the present work, the blank holder was allowed to move along with the punch but at different velocities. The effective stress was, respectively, 363.56 MPa, 329.53 MPa and 375.08 MPa at 0.4 mm/s, 0.5 m/s and 0.6 mm/s. The BH velocity of 0.5 m/s was found to be optimistic as it would consistent with the punch velocity. The effective stress decreased with the increase of temperature as observed from all results (figure 3).

Table 3. ANOVA summary of the effective stress

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	1121.52	1139.3	943.68	7800.56	1	7800.56	10203269	53.49
B	1027.39	1101.5	1075.62	942.69	1	942.69	1233055	6.46
C	1135.39	1052.6	1016.54	2475.98	1	2475.98	3238625	16.98
D	1090.68	988.60	1125.23	3364.72	1	3364.72	4401112	23.07
e				0.00	4	0.00	0.00	0.00
T	4488	5531	45543	108644	8			100

Note: SS is the sum of square, v is the degrees of freedom, V is the variance, F is the Fisher's ratio, P is the percentage of contribution and T is the sum squares due to total variation.

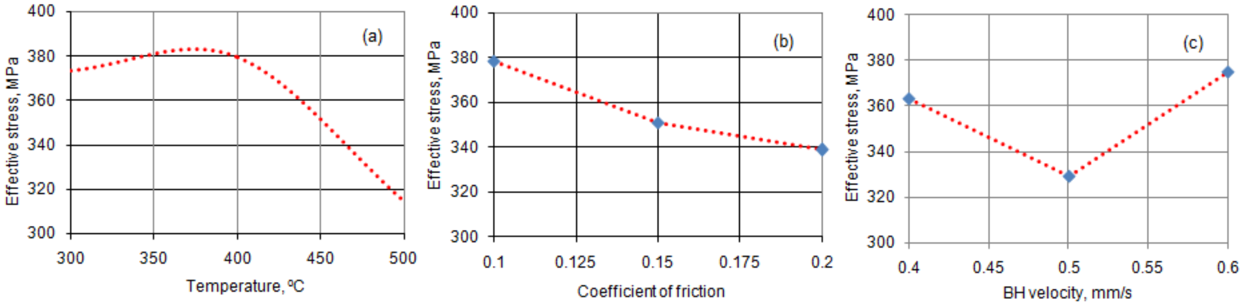

Figure 2. Effect of process parameters on the effective stress.

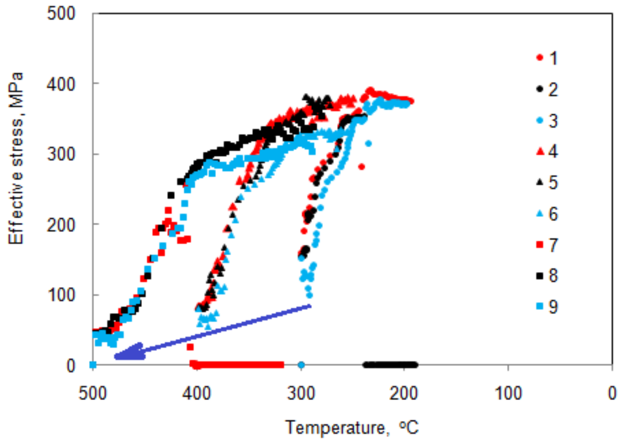

Figure 3. Influence of temperature on the effective stress induced in all trials.

The FEA results of effective stress are shown in figure 4 for various test conditions as per the design of experiments. For trials 1, 2 and 3, the temperature was 300°C and other process parameters were varied as mentioned in tables 1 and 2. The safe (means without fracture) effective stresses for trails 1, 2 and 3 were, respectively, 361 MPa, 353 MPa and 350 MPa (figure 4a). For trials 4, 5 and 6, the temperature was 400oC and other process parameters were as stated in tables 1 and 2. The effective stresses for trails 4, 5 and 6 were, respectively, 353 MPa, 381 MPa and 331 MPa (figure 4b). For trials 7, 8 and 9, the temperature was 500°C and other process parameters were as designed in tables 1 and 2. The effective stresses for trails 7, 8 and 9 were, respectively, 204 MPa, 367 MPa and 295 MPa (figure 6c).

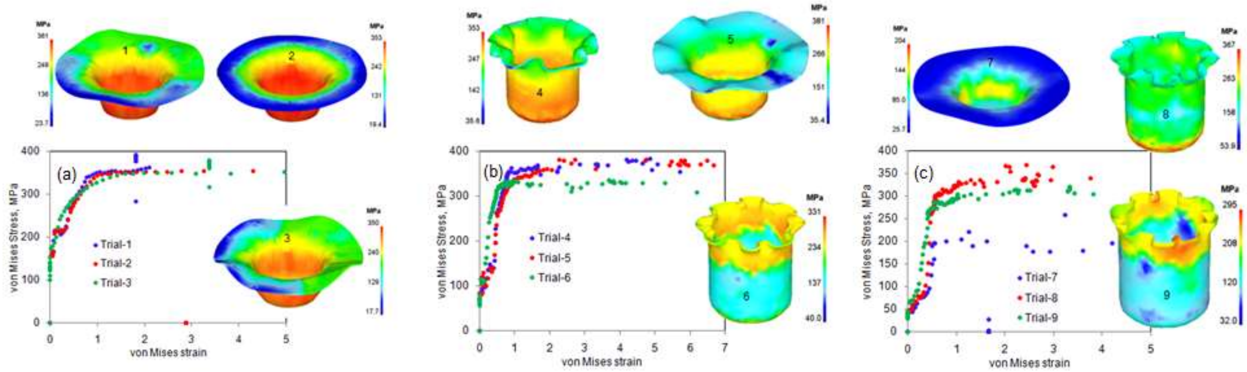

Figure 4: Effect of process parameters on the safe effective stress.

B. Forming limit diagrams and damages in the cups

The ANOVA summary for the damage in the cups is given in table 4. For the ANOVA analysis, the damages at failure were considered. It is observed that the percent contribution signifies that the process parameter A, temperature, all by itself commits 50.87% toward the variation observed in the damage. Only two results were above the mean value of damage in the cups. The results would fall into groups of 1/3 of the damages (two strong factors). Hence, at least two process parameters would manipulate damage in the cups. The strongest one is the temperature and the second one could be either strain rate or coefficient of friction as the percent contributions of strain rate and coefficient of friction were nearly equal.

Table 4. ANOVA summary of the damage factor.

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	8.26	31.92	7.26	129.86	1	129.86	554.47	50.87
B	23.99	16.71	6.73	50.07	1	50.07	213.79	19.60
C	5.93	21.58	19.92	49.28	1	49.28	210.41	19.29
D	14.94	10.08	22.41	25.74	1	25.74	109.90	10.06
e				0.23	4	0.06	0.26	0.18
T	53.12	80.28	56.33	255.18	8			100

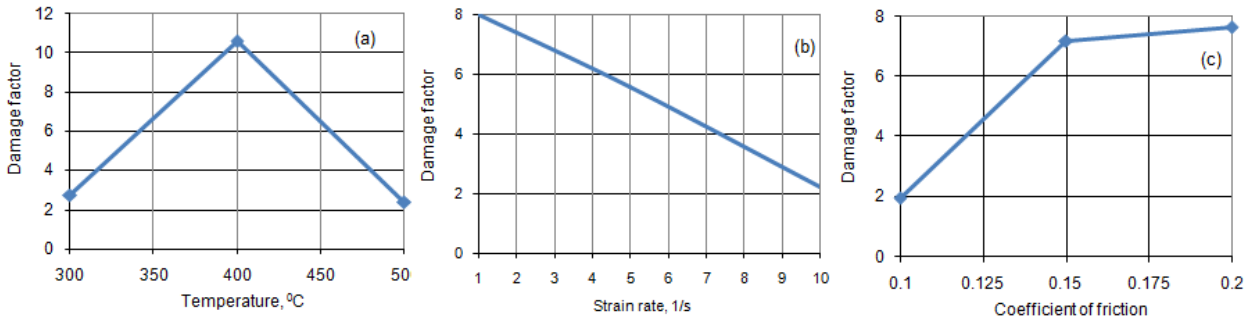

Figure 5: Effect of temperature on the damage of cups.

Figure 5a demonstrates the effect of temperature on the damage of cups. The damage of cups was highest at the temperature of 400ºC; it was least at 500ºC. The damage in the cups decreased with the increase of strain rate (figure 5b) while it increased with the increase of friction coefficient (figure 5c).

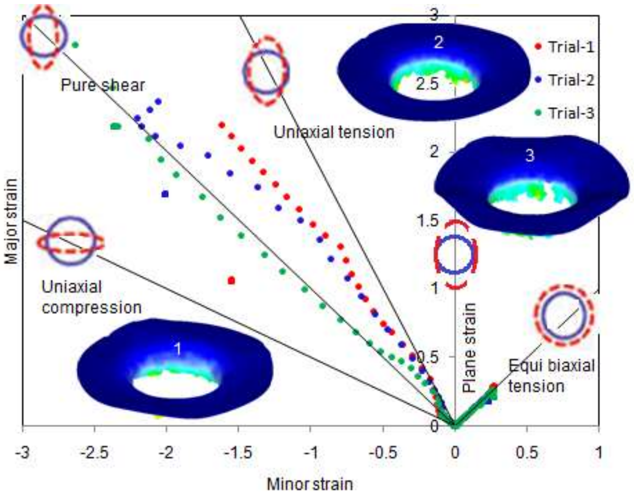

Figure 6. Forming limit diagram with damage in the cups drawn at temperature 300ºC.

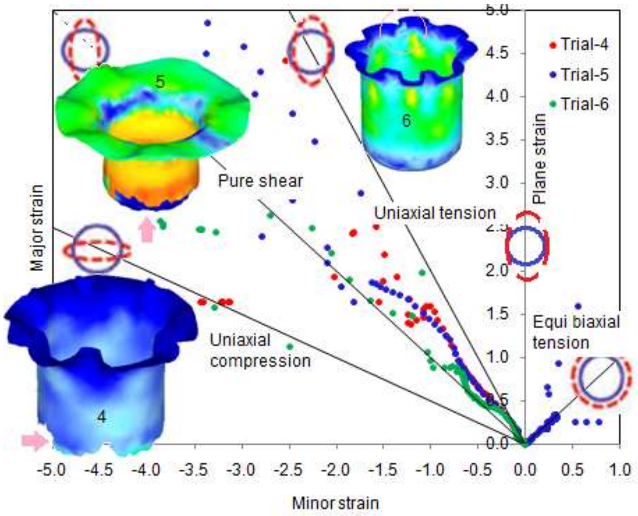

Figure** 7. **Forming limit diagram with damage in the cups drawn at temperature 400°C.

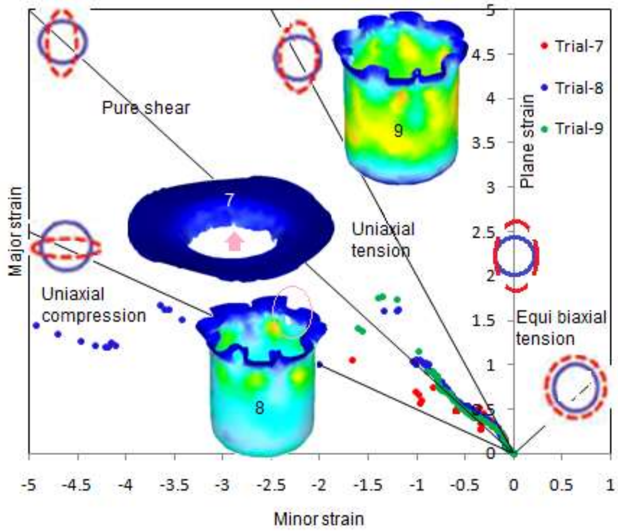

Figure 8. Forming limit diagram with damage in the cups drawn at temperature 500°C.

Figure 6 illustrates the forming limit diagram (FLD) with damages in the cylindrical cups drawn from AA5049 alloy sheets at temperature 300°C. The cylindrical cups drawn under trials 1, 2 and 3 were ruptured because of pure shear. Figure 7 illustrates the forming limit diagram and damages in the cups drawn from AA5049 alloy sheets with trials, 4, 5 and 6 at temperature 400°C. Cups drawn on trial 4 were fractured due to uniaxial compression. Cups drawn from trials 5 were fractured due to uniaxial and equi-biaxial tensions. The fracture in the cups was noticed in the flange area on account of uniaxial compression. Figure 8 shows the forming limit diagram (FLD) with damages in the cylindrical cups drawn from AA5049 alloy sheets at temperature 500°C. Cups drawn from trial 7 were fractured owing to uniaxial compression. Cups drawn under trial 8 were fractured in the flange region due to compression. Cups drawn under trial 9 did not have any fracture.

The heights of the cups drawn under various trails are shown in figure 9. Even though the cup heights were high for trails 6 and 8, the damage was detected in the flange area. The maximum height of the cup was for trail 9. The deep drawing conditions of the trail 9 were:

- Temperature = 500°C
- Strain rate = 10 s^{-1}

- Coefficient of friction = 0.15
- Blank holder velocity = 0.4 mm/s.

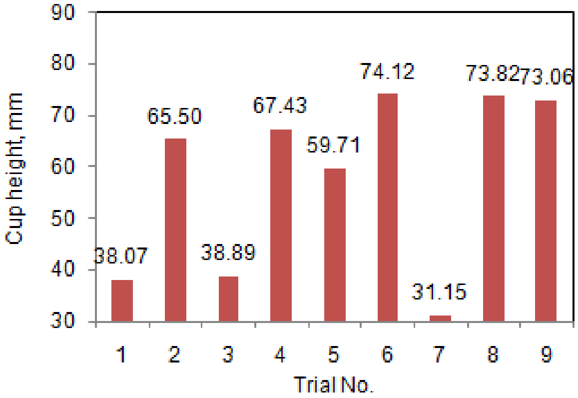

Figure 9. Cup heights of all trails.

CONCLUSION

The effective stress decreases with the increase of temperature. The damage in the cups decreases with the increase of stain rate. The optimum strain rate and temperature were, respectively, 10 s^{-1} and 500°C. Therefore, AA5049 alloy has been found to yield successful cups at high temperature and high strain rate.

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