# Formability Analysis of 6063 Al Alloy for Deep Drawn Cylindrical Cups with Constant and Progressive Blank Holding Force

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***Abstract***

*In this present work, a statistical approach based on Taguchi techniques and finite element analysis were adopted to determine the influence of temperature, strain rate coefficient of friction and blank holder velocity on the formability of cylindrical cups from 6063 Al alloy using warm deep drawing process. The successful conical cups of 1.5mm blank thickness were obtained with operating conditions of 300oC, 0.1 $s^{-1}$, strain rate temperature; 0.1, coefficient of friction; and 0.13 $mms^{-1}$, blank holder velocity.*

**Keywords** — *6063 Al alloy, cylindrical cups, formability, finite element analysis, Taguchi, temperature, strain rate, coefficient of friction, blank holder velocity.*

## I. INTRODUCTION

Due to its lightweight and medium strength and high corrosion resistance, 6063 Al alloy is very attractive in many architectural applications. This is typically used in intricate extrusions. T4 tempered 6063 Al alloy is also finding applications in hydroformed tube for chassis. Deep drawing is a metal forming process for shaping flat sheets into cup-shaped products. The deep drawing process depends not only on the workpiece material, but also on the condition at the die-workpiece interface, the mechanics of plastic deformation and blank holding mechanism [1] - [3].

The friction at die punch-sheet interface must be adequately high to confirm that the sheet follows the movement of the die punch. The friction at the blank holder-sheet and bottom die-sheet interfaces must not be too high, because a high friction leads in fracture due to requirement of higher punch forces [4], [5]. The plastic deformation of the workpiece material is influenced by strain, strain rate and temperature [6] - [8]. Most of the aluminium alloys do not show the sudden bend in their stress strain curve but a gradual transition from elastic to plastic state [9] - [11]. At higher strain rates the flow stress of material increases leading to higher loads on the equipment [12] – [14]. In the case of hot deep drawing, the re-crystallization is present along with strain hardening and strain rate effect. High temperatures reduce the flow stress of sheet material, which results in low deforming forces [15] - [17]. The blank holding force (BHF) must be controlled to prevent the occurrence of tearing or wrinkling during deep drawing of cups [18] - [20]. Not enough of a BHF inclines to cause wrinkling of the drawn cup, but excessive BHF causes tears. The modern drawing presses have hydraulic blank holders [21], [22]. In this paper, the application of constant and progressive blank holding force is considered during drawing operations.

The objective of the present work was to optimize the warm deep drawing process of 6063 aluminium alloy using Taguchi technique for the cylindrical cups. The chosen process parameters, which could influence the formability of 6063 Al alloy, were temperature of sheet material, coefficient of friction between die-sheet material interfaces, strain rate and blank holder velocity. In this present work, a statistical approach based on Taguchi and ANOVA techniques was implemented to assess the worth of each process parameter on the formability of deep drawn cylindrical cups from 6063 Al alloy. The warm deep drawing process was executed using D-FORM software.

## II. FINITE ELEMENT MODELLING

The finite element modelling and analysis was carried using D-FORM 3D software. The circular sheet blank was created with desired diameter and thickness. The cylindrical top punch and cylindrical bottom hollow die were modeled as shown in Fig. 1 with appropriate inner and outer radius and corner radius as found in earlier publications. The clearance between the punch and die was calculated using Eq. (1).

$$\text{Clearance, } c_d = t \pm \mu\sqrt{10t} \quad (1)$$

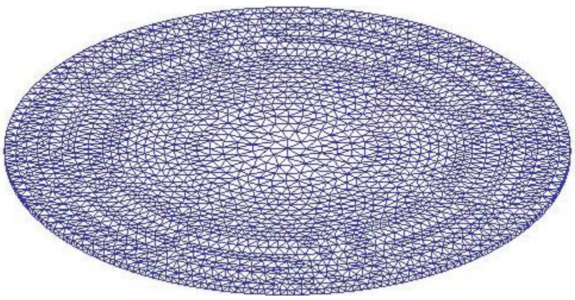


**Fig. 1: Discretization of sheet material.**

The sheet blank was meshed with tetrahedral elements as shown in Fig. 1. The modeling parameters of deep drawing process for all the trails were as follows:

Number of elements for the blank: 12805
Number of nodes for the blank: 4676

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 (FEA) was chosen to find the effective stress, effective strain, surface expansion and damage of the cup. The formability of the cylindrical was determined using major and minor strains [15], [16]. The finite element analysis was performed using D-FORM 3D software according to the design of experiments. The formation of cylindrical cup at various steps during simulation is shown n Fig. 2.

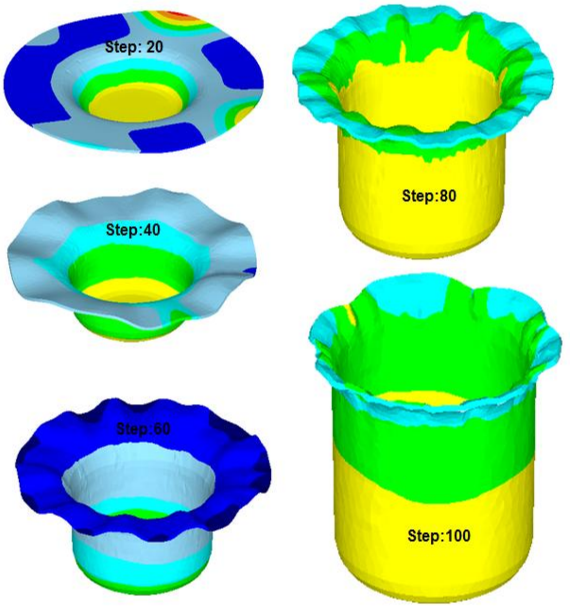



**Fig. 2: Formation of cylindrical cup at different steps of FEA simulation.**

**TABLE 1**
**PROCESS PARAMETERS AND LEVELS**

| Factor | Symbol | Level–1 | Level–2 | Level–3 |
|---|---|---|---|---|
| Temperature, $^{0}$C | A | 300 | 400 | 500 |
| Strain rate, 1/s | B | 0.1 | 0.5 | 1.0 |
| Coefficient of friction | C | 0.10 | 0.15 | 0.20 |
| BH velocity, mm/s | D | 0.13 | 0.17 | 0.20 |

The analysis of deep drawing was carried out as per the design of experiments using Taguchi techniques. The process parameters and their levels are given Table-1. The orthogonal array (OA), L9 was selected for the current project work. The parameters were assigned to the various columns of OA. The assignment of parameters along with the OA matrix is given in Table 2. The material properties of 6063 Al alloy are as follows:

Ultimate tensile strength: 241 MPa
Tensile yield strength: 214 MPa
Elongation at break: 12%
Modulus of elasticity: 68.9 GPa
Shear strength: 152 MPa
Thermal conductivity: 200 W/m-K
Coefficient of thermal expansion: 25.6 μm/m-$^{o}$C

**TABLE II**
**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 |

## III. RESULTS AND DISCUSSION

The results obtained from the finite element analysis are divided into stress values developed in the sheet material during formation of the cup, surface expansion of sheet material, damage of the cups and formability of the cups.

### *A. Influence of Process Parameters on von Mises Stress*

The percent contributions of A, B, C and D are, respectively, 33.55%, 6.77%, 27.45% and 32.23% towards variation in the von Mises stress (Table 3). This indicates that the most influential process parameters are temperature, coefficient of friction and Blank holder (BH) velocity.

**TABLE III**
**ANOVA SUMMARY OF THE TEMPERATURE DISTRIBUTION**

| Source | Sum 1 | Sum 2 | Sum 3 | *SS* | *v* | *V* | *P* |
|---|---|---|---|---|---|---|---|
| A | 744.00 | 1015.00 | 827.00 | 12852.67 | 2 | 6426.33 | 33.55 |
| B | 790.00 | 900.00 | 896.00 | 2594.67 | 2 | 1297.33 | 6.77 |
| C | 728.00 | 977.00 | 881.00 | 10514.00 | 2 | 5257.00 | 27.45 |
| D | 705.00 | 946.00 | 935.00 | 12344.67 | 2 | 6172.33 | 32.23 |
| E | | | | 0.00 | 0 | | 0.00 |
| T | 2967.00 | 3838.00 | 3539.00 | 38306.00 | 8 | | 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.*

Fig. 3 presents the von Mises stress established in 6063 Al alloy during cup drawing process as a function of temperature and strain rate. It is observed that the von Mises stress is found to be higher at 400°C than that at 300°C and 500°C. As observed from Fig. 4, for trials 1, 2 and 3, the von Mises stress is lower than that of other trials. Also, for trials 4, 5 and 6 the von Mises stress is higher than that of remaining trials. After deep drawing operation, heated to 300°C, 400°C and 500°C temperatures used in this work shows tendency of equiaxial grains, representing the end of the recovery process, followed by processes of recrystallization of the alloy. The presence of precipitations of $Mg_2Si$ and β-$Al_5FeSi$ influences the size of grains, avoiding the excessive growth of grain. The majority of the grains are slightly elongated, indicating the sustained presence of plastic deformation in deep drawing. At 500°C temperature, a superposition of events (precipitation kinetics and grain growth processes) is likely to occur with the possibly formation of precipitates that will lead to reduction of ductility [23], [24].

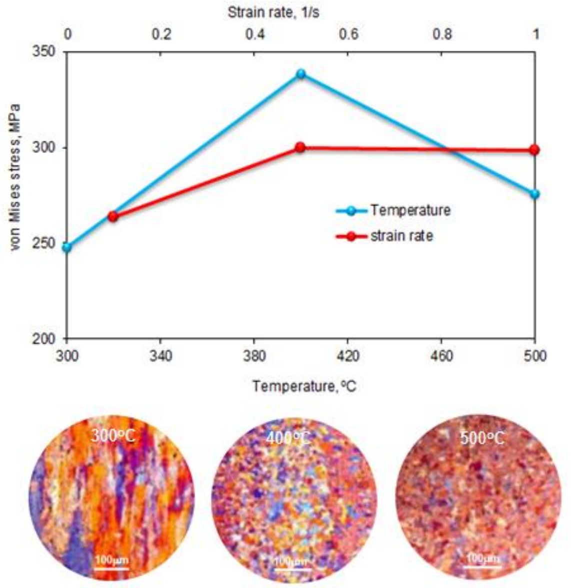



**Fig. 3: The von Mises stress as a function of temperature and strain rate.**

The von Mises stress increases with increasing strain rate up to 0.1 $s^{-1}$ as shown in Fig. 5. Strain hardening is a result of plastic deformation, a permanent change in shape to ensue cylindrical cup. An increase in the von Mises stress is effective for the change in the strain rate up to 0.1 s- 1and it is nearly constant above 0.1 s-1 of strain rate. Fig. 6 describes the von Mises stress as a function of COF (coefficient of friction) and blank holed (BH) velocity. It is observed that the von Mises stress increases with increase of COE and BH velocity, respectively, from 0.1 to 0.15 and 0.13 to 0.17 mm/s. In deep drawing process, friction initiates from sliding contact between the tool and the blank sheet. As the blank holding force was maintained constant and progressive in this work, the BH velocity could increase von Mises stress to avoid the formation of wrinkles in the flange area of the cup. The change in BH velocity from 0.17 to 0.20 does not bring any change in the von Mises stress.

The FEA results of von Mises stress as a function of von Mises strain are shown in Fig. 7 for various test conditions as per the design of experiments. For trials 1, 2 and 3, the maximum values of von Mises stresses for trails 1, 2 and 3 are, respectively, 127, 327 and 290 MPa. For trials 4, 5 and 6, the maximum values of von Mises stresses for trails 4, 5 and 6 are, respectively, 377, 305 and 333 MPa. For trials 7, 8 and 9, the maximum values of von Mises stresses are, respectively, 286, 268 and 273 MPa. In all the cases except for trail 1, the von Mises stress exceeds the ultimate tensile strength (241 MPa) of 6063 Al alloy. This indicates the occurrence of fracture in all the cups except the cup drawn from the trail 1 conditions. The sudden drop of punch load curve for trials 2, 3, 4, 5, 6, 7, and 9 are on account of fracture of sheet blank without complete formation of the cups as shown in Fig. 8. However, the plastic deformation is continued till the formation of cups for trial 1 conditions.

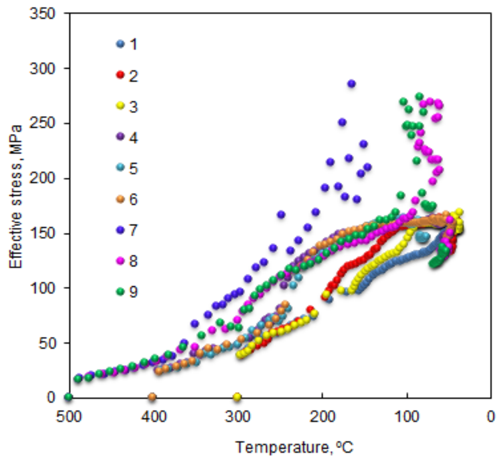



**Fig. 4: Effect of temperature on von Mises stress for all trials.**

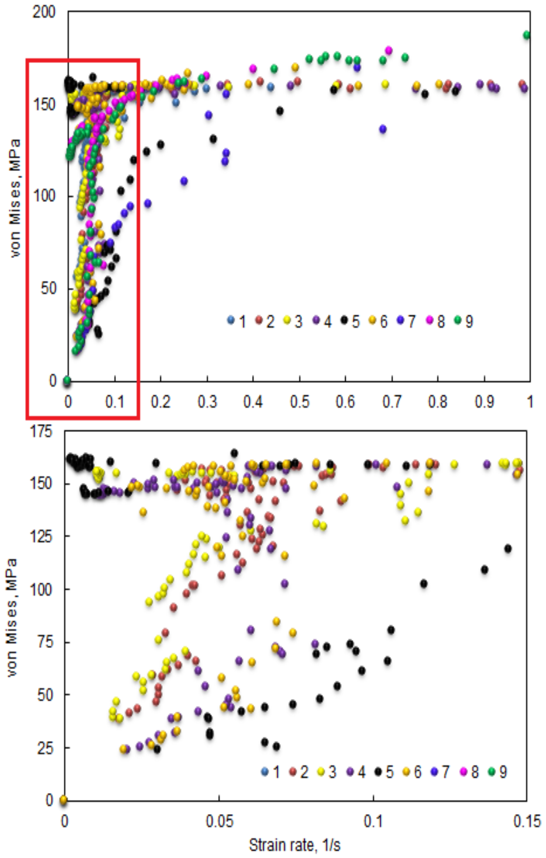



**Fig. 5: Effect of strain rate on von Mises stress for all trials.**

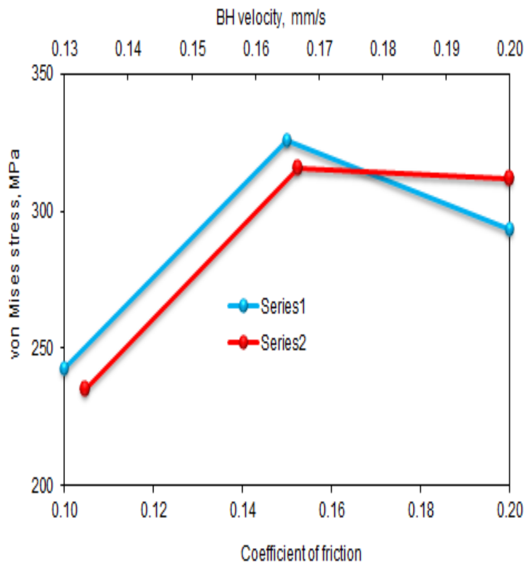



**Fig. 6: The von Mises stress as a function of COF and BH velocity.**

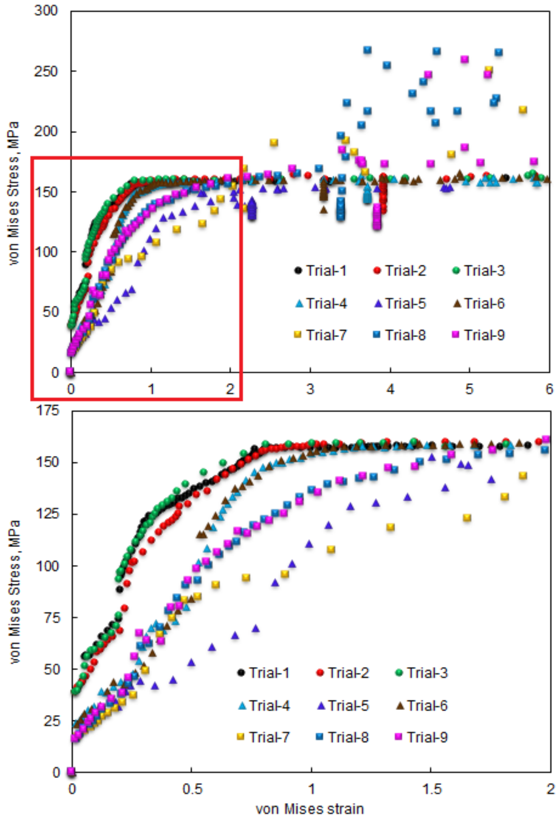



**Fig. 7: Effect of von Mises strain on the von Mises stress.**

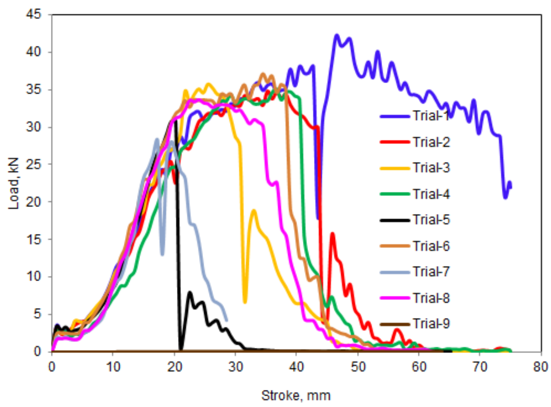



**Fig. 8: Applied load as a function punch stroke.**

### *B. Influence of Process Parameters on Surface Expansion Ratio*

In the cup drawing process, the plastic deformation in the surface is highly predominant than in the thickness. As per the ANOVA summary of surface expansion ratio given in Table 4., the process parameters A, B, C and D attribute, respectively, 26.58%, 21.51%, 28.66% and 22.15% respectively towards variation in the surface expansion ratio. The effect of all the process parameters is nearly the same.

TABLE IV
ANOVA SUMMARY OF VON MISES STRESS

| Source | Sum 1 | Sum 2 | Sum 3 | *SS* | *v* | *V* | *P* |
|---|---|---|---|---|---|---|---|
| A | 36.45 | 6.43 | 10.19 | 178.32 | 2 | 89.16 | 26.58 |
| B | 9.16 | 9.23 | 34.68 | 144.33 | 2 | 72.16 | 21.51 |
| C | 6.57 | 9.26 | 37.24 | 192.30 | 2 | 96.15 | 28.66 |
| D | 3.7 | 12.08 | 35 | 148.60 | 2 | 74.30 | 22.15 |
| e | | | | 7.39 | 0 | | 0 |
| T | 55.88 | 37.00 | 117.11 | 670.96 | 8 | | 100.00 |

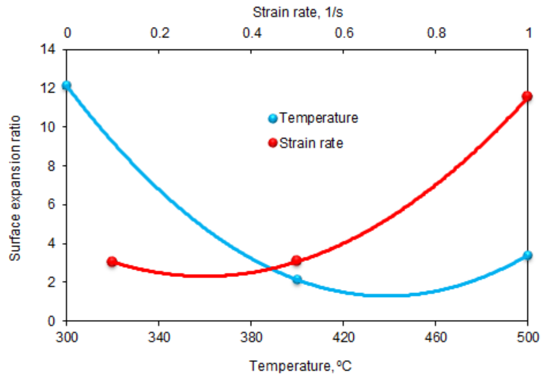



**Fig. 9: The surface expansion ratio as a function of temperature and strain rate.**

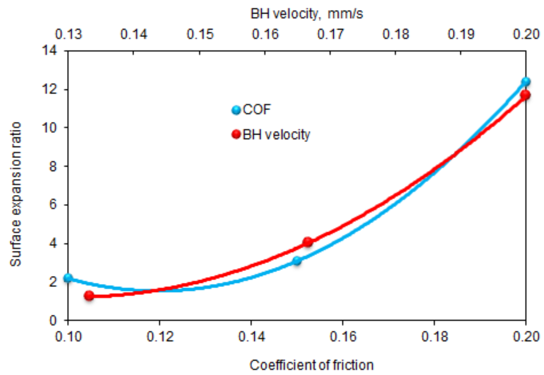



**Fig. 10: The surface expansion ratio as a function of COF and BH velocity.**

As the blank temperature from 300°C to 500°C the surface expansion ratio decreases as shown in Fig. 9. The reason is very unusual to understand. This is due to softening effect of the sheet material with increased temperature. The surface expansion ratio increases with an increase in the strain rate from 0.1 to 0.5 $s^{-1}$ owing to strain hardening of the sheet material during deep drawing process. As shown in Fig. 10, the surface expansion ration increases with an increase in the blank holder velocity from 0.13 to 0.20 mm/s and with an increase in the coefficient of fraction from0.1 to 0.2. With an increase in the BH velocity and the coefficient of friction, the sheet material is restrained for the free flow of the material resulting the expansion of sheet with the applied load and the punch movement. The FEA results of surface expansion ratio are mentioned in Fig. 11 for various test conditions as per the design of experiments. For the best quality of cup, the surface expansion ratio should be in the range of 1.5 to 1.7.

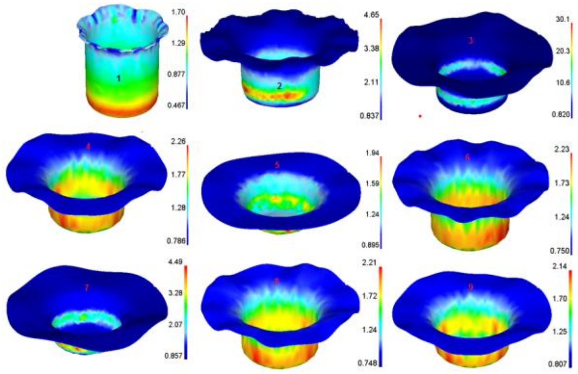


**Fig. 11: Effect of process parameters on the surface expansion ratio.**

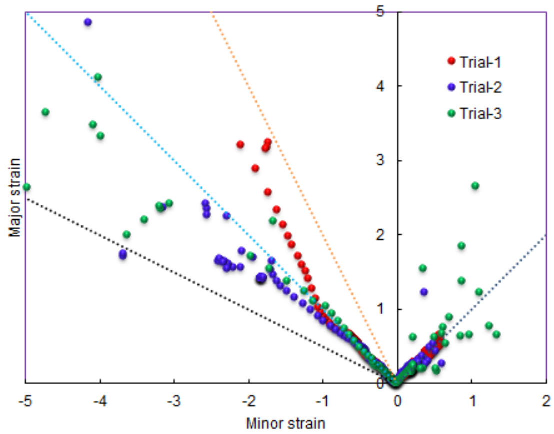



**Fig. 12: Forming limit diagram with damage in the cups drawn at temperature 300°C.**

### *C. Forming Limit Diagrams and Damages in the Cups*

Fig. 12 shows the forming limit diagram (FLD) for the cylindrical cups drawn from 6063 Al alloy sheets at temperature 300°C. The FLD for the cylindrical cup drawn under trial 1 experiences pure shear only. The FLD for the cylindrical cup drawn under trial 2 and 3 practices pure shear and equibiaxial tension and compression. Fig. 13 demonstrates the forming limit diagram for the cups drawn from 6063 Al alloy sheets with trials, 4, 5 and 6 at temperature 400°C. Cups drawn on trials 4 and 5 have damaged due to high uniaxial and equibiaxial tensions. For trial 6, the failure of the cup is due to high compression in the flange area of sheet material. Cups drawn from trials 7, 8 and 9 have damaged on account of high uniaxial tension in the walls of the cups as shown in Fig. 14.

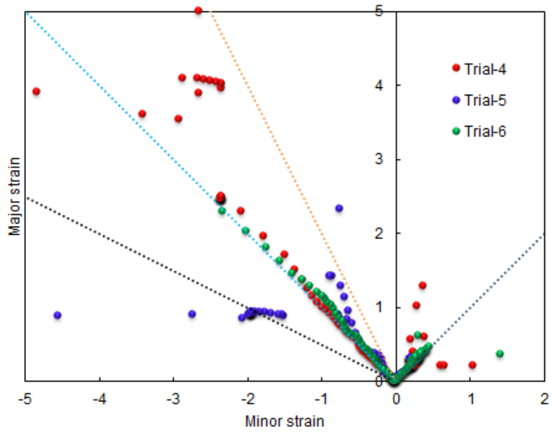



**Fig. 13: Forming limit diagram with damage in the cups drawn at temperature 400°C.**

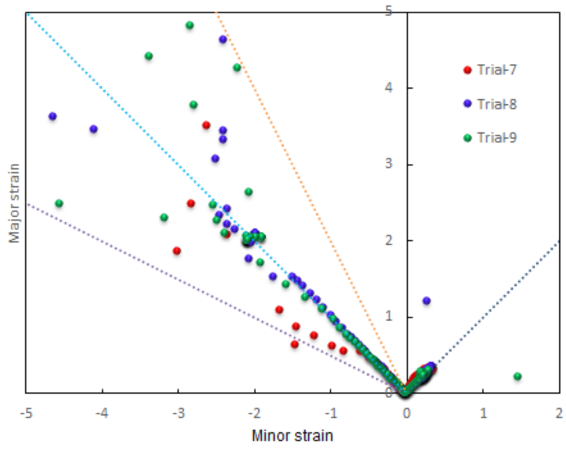
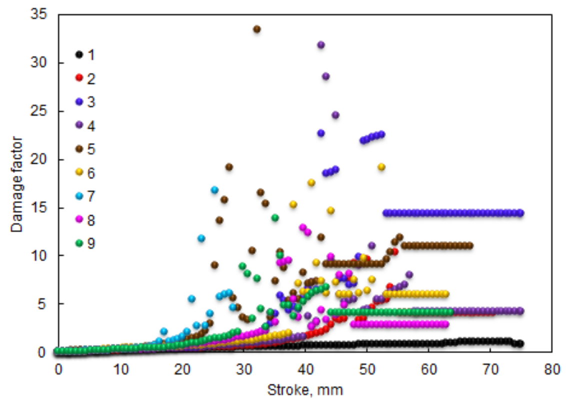



**Fig. 14: Forming limit diagram with damage in the cups drawn at temperature 500°C.**

In the present work, the critical value of the damage factor is defined as follows:

$$D_f = \int \frac{\sigma^*}{\sigma_{vm}} d\epsilon \quad (2)$$

where $\sigma^*$ is the tensile maximum principal stress, $\sigma_{vm}$ is the von Mises stress and $d\varepsilon$ is the effective strain increment. Fracture takes place when the damage factor has reached its critical value. The damage factors for all the trials are illustrated in Fig. 15. The least damage factor is associated with trail 1 of the design of experiments. Therefore, for the successful the optimum levels of the process variables are taken of trial 1 conditions of tables 1 and 2. The biggest damage can be seen in the cup drawn with trail 6 conditions as shwon in Fig. 16.



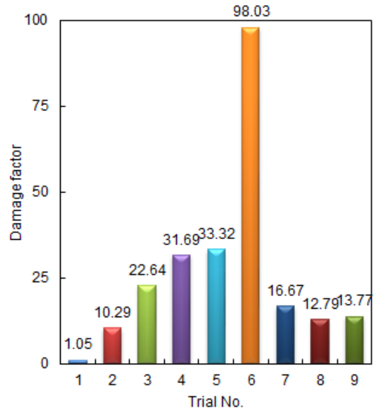




**Fig. 15: Damage factors under different trials.**

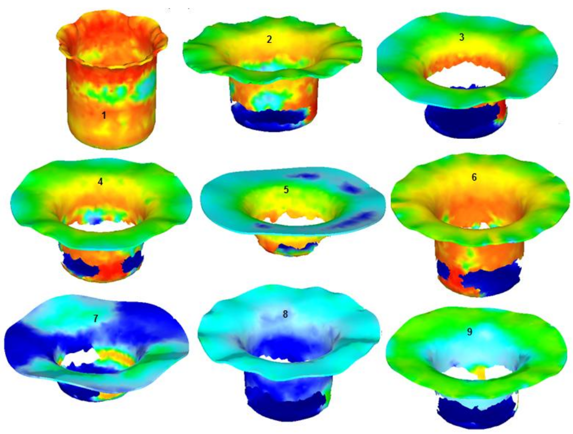


**Fig. 16: Damages of the cups drawn under different trials.**

## IV. CONCLUSIONS

In this paper, cylindrical cups of a 6063 Al alloy sheet have been formed numerically using D-FORM software. The von Mises stress was least at operating temperature of 300°C, strain rate of 1.0 $s^{-1}$, friction coefficient of 0.1 and blank holder velocity of 0.13 $mms^{-1}$. The whys and wherefores for the failure of cups were due to uniaxial tension, compression and stretching.

## ACKNOWLEDGMENT

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