Study the effect of elevated dies temperature on aluminium and steel round deep drawing

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Abstract. Round deep drawing operation can only be realized by expensive multi-step production processes. To reduce the cost of processes while expecting an acceptable result, round deep drawing can be done at elevated temperature. There are 3 common problems which are fracture, wrinkling and earing of deep drawing a round cup. The main objective is to investigate the effect of dies temperature on aluminium and steel round deep drawing; with a sub-objective of eliminate fracture and reducing wrinkling effect. Experimental method is conducted with 3 different techniques on heating the die. The techniques are heating both upper and lower dies, heating only the upper dies, and heating only the lower dies. 4 different temperatures has been chosen throughout the experiment. The experimental result then will be compared with finite element analysis software. There is a positive result from steel material on heating both upper and lower dies, where the simulation result shows comparable as experimental result. Heating both upper and lower dies will be the best among 3 types of heating techniques.

1. Introduction
Deep drawing of cylindrical cups for improvement has been investigated from time to time. Hosford et al. [1] said that the principal strain in the plane of the sheet is positive and the other is negative. The major failure of deep drawing is by plastic instability in tension rather than fracture. Limit drawing ratio (LDR) is being focused in any researches related to deep drawing. For scenario when the blank diameter is too large, the force must be transmitted by the wall will be excessive. To prevent wrinkling in the flange, hold-down force must be applied during deep drawing process. Park et al. [2] have carried out research on the improvement of formability for elliptical deep drawing process. According to them, the punch and die corner radii play an important role in influencing formability of elliptical deep drawing process. Besides punch and die corner radii, lubricant condition, working speed, blank-holding force, friction force and the clearance will affect the results. Stretching will be involved in sheet metal forming, but drawing or various combinations of processes took part in deformation. In Jiang et al. [3] paper, counter pressure deep drawing device which is Nakamura’s idea has been used. Sheet was placed into a chamber, the inside oil was pressurized. Deep drawing is a complex forming process which includes almost all the parts of a cup. This involves tension (cup wall), bending (punch and die corners) and compression at cup flange. Zeng et al. [4] stated that the stress and strain

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distributions in regions over the punch and die are quite different in deep drawing of a round blank by a cylindrical punch. There are biaxial tensile stresses over the punch head, which act to thinning the material. There are radial tensile stresses over the die, where the compressive stresses are generated during drawing process.

A sheet forming process at elevated temperature technique which is first introduced by “American Aerospace Industry” is being considered [5]. Moon et al. [6] have studied tool temperature control to increase deep drawability of aluminium 1050 sheet. This study is to examine the possibilities of increasing limiting drawing ratio through the tool temperature, where the limit drawing ratio of conventional deep drawing process is limited. Aluminium sheet strength will decrease when it is heated and after it is cooled, the strength will increased.

Deep drawing operation for complex part geometries can only be realized by expensive multi-step production processes. To overcome this problem, deep drawing can be done at elevated temperature. In this way the formability of sheet metal can be improved significantly, and the number of necessary production steps can be reduced. Palumbo et al. [5] have investigated the warm deep drawing of magnesium alloy sheet to form cylindrical cups. They have combined experimental method and Finite Element Method to complete their research. As a result, the limit drawing ratio of deep drawing for material Magnesium Alloy is 2.6 at 170°C. When the die is heated to 250 °C, the limit drawing ratio has been increased to 3.1. By heating up the die for deep drawing process, there are aims that hope to be achieved.

- To increase limit drawing ratio
- To reduce fracture effect (including wrinkling effect and earing effect)
- To increase the depth of the drawn cup

Zeng et al. [4] have focused on the wrinkling at elevated temperature and the comparison with cold forming in deep-drawing operations. They use a theoretical model to predict the critical conditions of wrinkling at room temperature and elevated temperature. Ambrogio et al. [7] have studied the formality extension in deep drawing when superimposing a thermal gradient. They have combined effect of a thermal heater and air-cooling nozzle in their experiment. Raju et al. [8] have done a research on influence of variables in deep drawing AA 6061 sheet. The die shoulder radius has major influence followed by blank holder force and punch nose radius on the thickness distribution of the deep drawn cup of AA 6061 sheet. Hosford et al. [9] stated that most of the sheet forming operations, the deformation is characterized by biaxial stretching instead of drawing. Failure in stretching operations normally occurs by the development of a sharp localized neck on the surface. The usual procedure for determining experimentally forming limit diagrams involves marking sheets photographically with a circle grid. This may involve leaving a dyed film on the surface or lightly etching the grid into the surface. The width strain increases as the specimen width increases. Full width specimens produce conditions close to balanced biaxial tension and very narrow specimens produce conditions close to uniaxial tension. In the case of drawing, the sheet metal is pulled on one direction, with the perpendicular direction unrestrained. Thus, as the material stretches in one direction it actually contracts in the other direction. This is what happens during the formation of a beer or soda can – a cylindrical punch is pressed into a piece of sheet metal that is unrestrained or only partly restrained along the edges. In this case we have positive major strain and negative minor strain. This study will focus on aluminium and steel blank specimen preparation and fabricate a deep drawing part with various die temperature [10,11]. Using an experimental-numerical method, the most efficient heating positioning and the most suitable way of performing the deep drawing process was evaluated using data from the numerical model and experimental activity. Experiments on heating die for deep drawing process will used to determine increasing limit drawing ratio of cup. This study will cover up metal forming of steel and aluminium sheet metal and forming limit diagram by using circle grid analysis (CGA).
2. Methodology

Methodology used in this research will be discussed in this section. Figure 1 shows the complete set up of this work. A dies has been attached to a single acting hydraulic cylinder. It has a 101kN cylinder capacity, with 105mm stroke that will press the sheet material downward when forming the cup. The cylinder is controlled by a hydraulic pump. It has power source of AC220V and a 330W motor, which allowed providing 70MPa pressure. The temperature of the dies is controlled by temperature controllers, which provide heating up the die and thermocouple type K as temperature feedback when they are connected. The heater capacity is 200W and temperature can be varying with 1°C of difference. For deep drawing simulation, ANSYS workbench software is used to run the deep drawing simulations.

![Figure 1: Set up for experiment](image)

2.1. Procedures

In conducting the experiments, following procedure are used.

1. Experiment started with preparation of aluminum blank. Pre-run is being tested starting with a circle aluminium blank, diameter 65, 70, 75 and 80 mm.
2. After the suitable diameter is selected, 36 pieces of aluminum blank with same diameter is prepared for experiment.
3. Each aluminum blank is sketched with a 10mm diameter inscribe circle for circle grid analysis (CGA) result. A grid of circles of specific diameter is drawn to the surface of the aluminum blank. The drawing process deforms the circles, stretching the diameters in one direction (the major strain) and compressing the diameters in the other direction (the minor strain). The difference between the major and minor diameters from the original diameter is the amount of strain.
4. The experiment will be conducted in 3 different parameters:
   a) Heating upper dies
   b) Heating lower dies
   c) Heating both upper and lower dies
5. The aluminum blank is placed in between upper and lower dies with a support of blank holder, followed by operation of hydraulic pump and hydraulic cylinder pressing the upper dies downward to form a cylindrical cup.
6. The changes in shape of circle grid are being measured and recorded in tabulate form. Results are discussed and analyzed.
7. The experiment is repeated with steel blank from step 1 to 6.

Table 1 shows the experimental design for both for aluminium and steel deep drawing. There are 12 set of experiments were formulated in this study.

| Experiment | Upper die (°C) | Lower die (°C) |
|------------|----------------|----------------|
| 1          | 25             |                |
| 2          | 50             |                |
| 3          | 75             |                |
| 4          | 100            |                |
| 5          | 25             | 25             |
| 6          | 50             | 50             |
| 7          | 75             | 75             |
| 8          | 100            | 100            |
| 9          | 25             | 25             |
| 10         | 50             | 50             |
| 11         | 75             | 75             |
| 12         | 100            | 100            |
3. Result and Discussion

From figure 2, there is a huge wrinkling effect at the edge of the cup and fracture did occur after the drawing process. Thus, first test is conducted with 80mm diameter. From figure 2, the wrinkling effect at the edge of drawn cup did not improved but getting worst compared to 75mm aluminium blank. This led to a direction where bigger diameter of aluminium plate will produce more wrinkles. Same case happened where the bottom of cup cracked. Next, aluminium plate diameter is reduced and run the third test.

![Figure 2 Test run aluminium plate with (a) 80 mm diameter and (b) 75 mm diameter (c) 70 mm diameter and (d) 60 mm diameter](image)

From figure 2, test run of aluminium plate with 70mm diameter have gained improvement compared to 75 test run where wrinkling area is reduced and crackling problem has been eliminated. While for the test run of aluminium plate with 65mm diameter, the drawn cup did not crack, and the wrinkling are is being reduced to minimum. This is quite satisfied and the 65mm diameter will be used as constant for whole experiment.

3.1. Heating upper die

First stage of experiment is to heat the upper die at various elevated temperature as explain in table 1. Figure 3 shows the graph of aluminium sheet elongation against temperature for heating the upper die. At 25°C, the value of major elongation is 11.68mm. It is then increased by 0.42mm to 12.10mm at temperature 50°C. As the temperature of upper die increase, the value of major elongation decreases to 12.02mm at 75°C and 11.93mm at 100°C. At 25°C of heating upper die, the value of minor elongation is 8.86mm. It only shows some decreasing of 0.04mm to 8.82mm at temperature of 50°C and continue to decrease to 8.75mm at 75°C. The value suddenly changes direction of increase to 8.79mm when the upper die is heated to 100°C.
Figure 3: Elongation against temperature for heating upper die (aluminium blank)

Figure 4 is a graph showing elongation of steel plate deformation against temperature for heating only the upper die. The elongation of circle grid is calculated, resulting major elongation of 12.22mm and minor elongation of 8.86mm, when upper die is heated up to 50°C. By heating up the upper die to 75°C, the steel blank is placed at the center of die and punched down with a support of blank holder. The elongation of circle grid is calculated, resulting major elongation of 12.32mm and minor elongation of 8.79mm. When the upper die is heated up to 100°C, the repeated experiment get 3 values which is then calculated to get the average major elongation of 12.32mm and minor elongation of 8.72mm.

Figure 4 Elongation against temperature for heating upper die (steel blank)
3.2. Heating lower die

The elongation of major and minor axes has been measured and tabulated, resulting major elongation and minor elongation. From the graph shown in Figure 5, the elongation against temperature for heating lower die is obtained. At 25°C, the value of major elongation is 11.68mm. As the lower die being heated to 50°C, the value of major elongation increases to 12.28mm was recorded. But, a slight drop occurred at 75°C which make the value 12.25mm. Just when the die temperatures reach 100°C, the value of major elongation hits the lowest point which is 11.19mm. At 25°C, the value of minor elongation is 8.86mm. It is then increased by 0.17mm to 9.03mm when the die temperature is 50°C. The value decreases to 8.74mm at temperature 75°C and hits the lowest point which is 8.62mm when the lower die reaches 100°C.

| Temperature | Major Elongation | Minor Elongation |
|-------------|------------------|------------------|
| 25°C        | 11.68            | 8.86             |
| 50°C        | 12.28            | 9.03             |
| 75°C        | 12.25            | 8.74             |
| 100°C       | 11.19            | 8.62             |

Figure 5: Elongation against temperature for heating lower die (aluminium blank)

Elongation of steel blank against temperature for heating the upper die is shown in Figure 6. When the lower die is heated to 50°C, the average major elongation is 12.45mm and the minor elongation is 8.80mm. For experiment of deep drawing steel blank with heating lower dies at 75°C. The experiment is repeated 3 times as it aims to get the average elongation value. The average major elongation is 12.41mm and the minor elongation is 8.79mm. The average major elongation of 12.00mm and average minor elongation of 8.77mm is calculated. The elongation is measured from circle grid on steel blank which deform after it is punched when the lower die is heated up to 100°C, Major elongation recorded at 12.41 mm and 8.77mm recorded for minor elongation.
3.3. Heating both upper and lower die

Figure 7 shows the graph of elongation of aluminium against temperature for heating both upper and lower dies. When heating both dies at 25°C of aluminium blank deep drawing, minor elongation is 8.86mm, while 11.68 mm is recorded for major elongation. At 50°C, when heating both dies, the average major elongation is 11.92mm while minor elongation is 8.75mm. For heating both dies at 75°C, the repeated experiments result in an average major elongation of 12.02mm and minor elongation of 8.75mm. Finally, at 100°C, the average major elongation of 11.06 mm and minor elongation of 8.70 mm was recorded.
For heating both upper and lower die of steel blank, the same procedure was applied. Figure 8 shows a graph of minor and major elongation recorded at various dies heating temperature. At 25°C, the value of major elongation is 11.78mm. It is then increased by 0.48mm to 12.16mm at temperature 50°C. The value continue to increase at 75°C which set a value of 12.59mm and reach the highest elongation value which is 12.64mm when the dies are heated up to 100°C. At 25°C, the value of minor elongation is 8.94mm. It experienced a drop of 0.06mm to 8.85mm when the temperature is 50°C. The minor elongations continue its drop to 8.82mm at 75°C and finally reach the lowest point which is 8.70mm when the die is heated up to 100°C.

3.4 Discussion on heating of dies

From Figure 9, the major strain of aluminium for heating both upper and lower dies sets the value of 0.168 when temperature is 25°C. The value increases to 0.192 at 50°C and 0.202 at 75°C. This proves that the increasing in limit drawing ratio which is similar to magnesium alloy plate done by Palumbo (2006). However, when the temperature reaches 100°C, the value drops to 0.160. This is due to the changing of aluminium strength when temperature increases and decreases. For the second parameter which is heating only the upper die, same case happen where the value of major strain increasing from 0.168 at 25°C to 0.210 at 50°C and lastly 0.202 at 75°C. When the die reaches 100°C, the value drops to 0.193 but is higher than the first parameter. For the third parameter which is heating only the lower die, the major strain value increases from 0.168 at 25°C to 0.228 at 50°C. But for temperature 75°C and 100°C, the value decreases to 0.215 and 0.119 respectively. Deep drawing shows the principal plane of a plate sheet is positive while the other side is negative, as what is said by Hosford [1]. Elevated temperature will affect the sign of principal plane. Changing sign of plate without changing the punching direction will shows different in collecting major strain data.
For figure 10, the major strain of steel for heating both upper and lower dies sets the value of 11.78mm at 25°C, followed by increment to 12.26mm at 50°C, 12.59mm at 75°C and 12.64mm at 100°C. As what have done by Palumbo (2006), the limit drawing ratio of magnesium alloy increased as temperature increased. For the second parameter which is heating only the upper die, the result is quite similar to first parameter but the major strain value become constant at 12.32mm when temperature is 75°C and 100°C. As temperature increases, the increment of major strain value decreases and it is lower than heating both upper and lower dies. For the third parameter which is heating only the lower die, the major strain value increases from 11.78mm at 25°C to 12.45mm at 50°C. But for temperature 75°C and 100°C, the value decreases to 12.41mm and 12.00mm respectively.
3.5 ANSYS Simulation

Figure 11 shows a CAD drawing of simulation prototype that will be using in ANSYS workbench software.

![Simulation prototype drawing]

**Figure 11: Simulation prototype drawing**

Figure 12 (a) shows the total deformation of deep drawing from ANSYS simulation. The difference of maximum total deformation (green line) and minimum deformation (red line) is shown in 2 lines in the graph. As displacement changed, the cup deformation changed. Figure 12 (b) shows the maximum shear stress from ANSYS workbench software. The lines show maximum (green line) and minimum shear stress (red line) of plate as it deforms when the die is punching downward.

![Graphs of total deformation and maximum shear stress]

**Figure 12: (a) Total Deformation, (b) Maximum Shear stress**
Table 2 shows a simulation result, the minimum total deformation at 25 °C is 1.3195mm. It is then decreases to 1.3156 mm at 50 °C, 1.3075mm at 75 °C and 1.3024mm at 100 °C. For maximum total deformation, an increment result is observed where it begins with 13.454mm at 25°C, increasing with varying temperature to 13.52mm at 50 °C, 13.562mm at 75 °C and 13.618mm at 100 °C. For minimum shear stress, the value started with 49.203MPa at 25°C, increased by 4.428MPa to 53.431MPa at 50 °C. When the temperature hits 75 °C, the minimum shear stress value is 61.577MPa, while at temperature 100 °C, the value is 62.604MPa. For the maximum value, a decrement result is seen where the value at 25 °C is 231.34MPa, decreases to 228.26MPa at 50 °C, 225.22MPa at 75 °C and lastly 221.73MPa at 100 °C.

Figure 13 shows simulation result of total deformation and maximum shear stress of aluminium deep drawing in elevated temperature. The difference between each set of simulation is explained by the color of total deformation and maximum shear stress. There are small differences between temperatures which can be observed, for an example, maximum shear stress of temperature 25 °C and temperature 50 °C, there is a small red area in the front view of temperature 25 °C but not 50 °C. The red color area in total deformation shows the area which experiences the most deformation when deep drawing the cup. The blue color area shows the least deformation. This is because the force is concentrated at the bottom of the cup when the punch is moving down. Aluminium plate will be pulled and extend to form a cup shape.
Figure 13 Simulation result of (a) total deformation and (b) maximum shear stress of aluminium
4. Conclusion

From the beginning of experimental method until the late simulation analysis will be ended up with the following conclusion.

1. Deep drawing with elevated temperature will result in a better material deformation for aluminium and steel sheet.
2. Heating both upper and lower dies is the best compared to heating only upper dies and heating only lower dies.
3. For aluminium, the major strain of deep drawn cup of heating both upper and lower dies increases by 2.83% when the temperature of die reach 75°C. The properties of aluminium will affect the result of major stain as temperature getting higher.
4. For steel, the major strain of deep drawn cup of heating both upper and lower dies increases by 6.80% when the temperature of die increases to 100°C.
5. There is a similarity between deep drawing of aluminium and steel sheet, where the sheet will deform more and result in increasing of major strain when temperature increases.
6. The total deformation of finite element analysis increases by 1.2% and the maximum shear stress of finite element analysis decreases by 4.15%.

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