The effect of elevated die temperature on deformation of deep drawn round metal cup

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Abstract. One of the major considerations in the current deep drawing practice is the product quality. In this research, the effect of heating temperature on the drawability of the round metal cup has been investigated. Firstly, round metal cups of aluminium and mild steel were drawn from the blank diameters of 60 mm, 65 mm and 70 mm. The experiment conducted at room temperature first, then at 50°C and 100°C. The elongation of the major and minor strains along the cup profile after the process is measured and analysed. On the other hand, the defects from the experiment output and ABAQUS/CAE simulation are compared. The result from experiment shows that the highest major elongation is 11.64 mm and it is happened to a deep drawn aluminium round cup with LDR of 1.69 at temperature of 100°C. On the other hand, for deep drawn mild steel round cup, shows highest major elongation of 12.44 mm for a cup with LDR of 1.56 at 100°C. Both of these statements indicates that the higher temperature could improve the formability of the deep drawn parts besides reducing the probability of the defect to be happened.

1. Introduction

Deep drawing is a manufacturing process in which sheet metal is progressively formed into a three-dimensional shape through the mechanical action of a die forming the metal around a punch. The deep drawn metal stamping process work hardens the metal, resulting in a seamless finished part that is stronger than the base material. Deep drawing can produce precise and intricate parts, including both symmetrical and asymmetrical parts.

Deep drawing operation for complex part geometries can only be realised by expensive multi-step production processes. In order to overcome this problem, deep drawing can be conducted at elevated temperatures so that the formability of the drawn cup in term of limiting drawing ratio (LDR) and strain elongation can improved significantly. Referring to Lean et al. [1], the application of temperature increment towards punch and die can produce several outcomes such as increasing limiting drawing ratio, increment on depth of drawn cup and reduce the fracture effect. Therefore, to study the effect of heating temperature on round deep drawing by utilizing aluminium and mild steel blank specimen is important in order to prove the indictment that has been made. On top of that, an experimental-numerical method also introduced to provide a vivid comparison between experimental outcomes and simulation. Not only that, a numerical analysis also useful for determining the safe condition also can be obtained which can act as the reference for the experimental works as indicated in previous research [2].
Next, the limiting drawing ratio (LDR) is ratio of the maximum diameter of the workpiece that is drawn without tearing also can resembled the formability of the drawn cup [3]. Referring to Kim et al. [4], there were several factors that can influence the formability of a material such as characteristics of sheet metal die, blank holding force, thickness of blank, forming temperature and heating technique, the bending and unbending effect, frictional force and geometrical parameters of the setup. This is because, as known before, the deep drawing process will involve almost all the parts of the cup. According to Zeng et al. [5], there will be huge difference for stress and strain distribution in regions caused by the punch and die in deep drawing process that utilize round blank. For the blank that situated around punch region, it much easier to expose the risk of tearing as the biaxial tensile stress that exists around the punch region, especially the punch corner area. Not only that, over the die region, the will be radial tensile stress while compressive stress existed during the deep drawing process.

The warm forming procedure is planned to overcome this low formability problem by utilizing elevated temperature which is under the recrystallization temperature. According to the works of Jayahari et al. [6], which conduct a study on austenitic stainless steel (ASS)-304 of under warm deep drawing with a different blank diameter. Based on the findings, the limiting drawing ratio (LDR) at room temperature was 2.1 and increase to 2.5 as the process conducted at 150°C. In this experiment, different blank diameters were tested with different temperatures up until 300°C and it show positive results in term of limiting drawing ratio. Not only that, Moon et al. [7] finds that the variation of material flow stress with temperature is substantial even with slight difference of tools temperature change. Poor decision on working parameters could leads to several kinds of failure such as wrinkling.

Wrinkling effect was formed when the radial tensile stress and tangential compressive stress occur simultaneously. It was causes by worst case of BHP pressure and it is preventable if the die set geometrical dimension and the forming forces were planned and tested beforehand. Not only that, Padmanabhan et al. [8], has state that in order to confine wrinkling on the drawn cup, the least blank holding pressure (BHP) is needed for the deep drawing operation. As the BHP pressure is too high, it will causes fracture at the top edge of the cup while if BHP pressure is low, it will causes wrinkling effect on the drawn cup. Hence, proper working parameters have to be decided first so that the relevant outcomes for the analysis purpose can be obtained.

2. Methodology

2.1 Set up of Experiment

The set up for the experimental procedures for warm deep drawing has been shown in figure 1. A single acting hydraulic cylinder is attached to a die set and it is controlled by hydraulic pump as shown in figure 2. On top of that, a temperature controller which shown in figure 3, is used to control the die set temperature while the die set is heated up by heater. A set of type K thermocouple is used to sense temperature and the reading is shown on the controller. The punching force generated from single acting hydraulic cylinder and being control by hydraulic pump. It has 101 kN capacity of force with 105 mm stroke which will press sheet metal downward into die cavity when the process takes place.
2.2 Procedure

The experimental works for the round deep drawing were conduct as follows:

1. Blank will be prepared into 3 different diameter sizes which are 60 mm, 65 mm and 70 mm. The blank also provided with circular grid with 10 mm diameter for analysis purposes as shown in figure 4.
2. After the preparation, the aluminium blank will be placed on the die set and being clamped using blank holder.
3. The die set will attached to the hydraulic cylinder with pump.
4. The experiment for room temperature condition is started as pump is activated and generates punching force onto the blank until it is fully deform.
5. The drawn cup being extracted from the die set. The changes in shape of engraved circular grid are being measured and tabulated. After that, the next blank diameter size undergoes the same process.
6. The experiment is repeated from step 1 to 6 but implementing the warm temperature and heating technique. The warm temperature decided to be at 50°C and 100°C. On top of that, the experiment will be conducted in 3 different heating technique:
a. Heating both upper and lower dies  
  b. Heating upper dies  
  c. Heating lower dies  

7. After that, all the procedure mention above is once again repeated but, by using mild steel blank. All the results data has been tabulated were discussed and analysed.

![Figure 4](image1.png)  
**Figure 4.** Circular Grid engraved on (a) aluminium and (b) mild steel blank specimen surface

### 3. Results and discussion

#### 3.1 Condition of deep drawn round cup

Before proceed with the described procedure, a series of test runs has been conducted in order to decide the best heating condition. From observation, most of the cup drawn from the experiment was in sound condition as the warm temperature was applied on lower side of the die set. These outcomes were the same as the indictment of Ghaffari Tari, Worswick, and Winkler [9] that the deep drawing process can be enhance by introducing the non-isothermal condition. This condition is achieved, as there is temperature difference between punch nose and flange regions. Therefore, based on the test runs outcomes, the lower die set been decided to be heated for this study. As per observation, it can be clearly seen that the earing effect exist at all sound cup that has been drawn from bot room and warm temperature condition. This can be referred in figure 5 shown below.

![Figure 5](image2.png)  
**Figure 5.** Example of the test runs outcomes of (a) aluminium and (b) mild steel round deep drawing

Next, the drawability condition of the drawn round aluminium cup is tabulated as shown in table 1 while for drawn round mild steel cup can be refer from table 2. Besides that, the limiting drawing ratio (LDR) of the successful drawn cup has been calculated and shown in the same table.

| No. | Blank size (mm) | LDR | Temperature (°C) | Heating Technique | Conditions |
|-----|----------------|-----|-----------------|-------------------|------------|
| 1   | 60             | 1.56| Room Temperature | -                 | Successful |
| 2   | 65             | 1.69| Room Temperature | -                 | Successful |
| 3   | 70             | 1.82| Room Temperature | -                 | Successful |
| 4   | 60             | 1.56| 50°C            | Lower             | Successful |
| 5   | 65             | 1.69| 50°C            | Lower             | Successful |
| 6   | 70             | 1.82| 50°C            | Lower             | Failed     |
| 7   | 60             | 1.56| 100°C           | Lower             | Successful |
| 8   | 65             | 1.69| 100°C           | Lower             | Successful |
| 9   | 70             | 1.82| 100°C           | Lower             | Failed     |

Table 1. Drawability condition for drawn round aluminium cup
Table 2. Drawability condition for drawn round mild steel cup

| No | Blank size (mm) | LDR  | Temperature (°C) | Heating Technique | Conditions |
|----|-----------------|------|------------------|-------------------|------------|
| 1  | 60              | 1.56 | Room Temperature | -                 | Successful |
| 2  | 65              | 1.69 | Room Temperature | -                 | Successful |
| 3  | 70              | 1.82 | Room Temperature | -                 | Successful |
| 4  | 60              | 1.56 | 50°C             | Lower             | Successful |
| 5  | 65              | 1.69 | 50°C             | Lower             | Successful |
| 6  | 70              | 1.82 | 50°C             | Lower             | Successful |
| 7  | 60              | 1.56 | 100°C            | Lower             | Successful |
| 8  | 65              | 1.69 | 100°C            | Lower             | Successful |
| 9  | 70              | 1.82 | 100°C            | Lower             | Successful |

3.2 Major and Minor elongation of drawn round cup (Aluminium)

The outcomes data after elongation of the circular grid is measured and recorded. For each drawn cups, there must be at least 10 clearly visible circles from the circular pattern, which, experience major and minor elongation. Then, it is calculated and compared to the original diameter of the circular grid pattern, which is 10 mm. The increment and decrement of the circle is recorded as shown in table 3 and 4.

Table 3. Elongation of drawn round aluminium cup with 60 mm blank diameter (LDR=1.56)

| Number of Element | Temperature (°C) | Major (mm) | Minor (mm) | Major (mm) | Minor (mm) | Major (mm) | Minor (mm) |
|-------------------|------------------|------------|------------|------------|------------|------------|------------|
|                   | Room Temperature | 50         | 100        |            |            |            |            |
|                   | Major (mm)       | Minor (mm) | Major (mm) | Minor (mm) | Major (mm) | Minor (mm) |
| 1                 | 10.49            | 9.42       | 10.75      | 8.92       | 10.24      | 9.67       |
| 2                 | 10.25            | 8.43       | 10.05      | 9.10       | 10.88      | 8.73       |
| 3                 | 10.49            | 9.90       | 10.49      | 9.20       | 11.98      | 9.35       |
| 4                 | 10.72            | 9.13       | 10.36      | 9.73       | 11.59      | 8.92       |
| 5                 | 10.41            | 8.93       | 11.16      | 9.26       | 11.19      | 8.45       |
| 6                 | 10.40            | 8.70       | 10.16      | 9.11       | 10.76      | 8.77       |
| 7                 | 10.71            | 9.48       | 11.02      | 8.27       | 10.44      | 9.21       |
| 8                 | 10.43            | 8.86       | 10.81      | 8.86       | 10.23      | 8.42       |
| 9                 | 10.53            | 8.93       | 11.19      | 8.87       | 11.09      | 8.36       |
| 10                | 10.49            | 9.11       | 10.89      | 8.95       | 11.97      | 9.41       |

Average 10.49 8.99 10.69 9.03 11.04 8.93
Table 3 indicates the average major elongation of deep drawn round aluminium cup with LDR 1.56 at room temperature was 10.49 mm and minor elongation was 8.99 mm. The major elongation was increase to 10.69 mm, as warm temperature of 50°C was applied to lower die set. This was also applicable to the minor elongation that increases to 9.13 mm. As the warm temperature increase up until 100°C, the major elongation increase to 11.04 mm while minor elongation decrease to 8.93 mm. This also can be observed from figure 6 shown above. It shows that, at warm temperature of 50°C, the major elongation experience 1.9% of increment compare to room temperature condition, while 5.2% for warm temperature of 100°C. On the other hand, the minor elongation for cup drawn at 50°C suffers 0.4% decrement and continues to decrease to 0.6% as the cup being drawn at 100°C.

Table 4. Elongation of drawn round aluminium cup with 65 mm blank diameter (LDR=1.69)

| Number of Element | Room Temperature | Temperature (°C) | 50 | 100 |
|------------------|------------------|-----------------|----|-----|
|                  | Major (mm)       | Minor (mm)      | Major (mm) | Minor (mm) | Major (mm) | Minor (mm) |
| 1                | 11.71            | 8.58            | 11.98    | 8.32    | 12.24    | 8.02    |
| 2                | 10.06            | 9.57            | 10.45    | 9.05    | 10.84    | 8.53    |
| 3                | 10.77            | 8.27            | 11.48    | 8.94    | 12.18    | 8.24    |
| 4                | 10.69            | 8.23            | 11.57    | 8.58    | 12.45    | 9.1     |
| 5                | 10.39            | 9.29            | 10.56    | 9.17    | 10.72    | 8.57    |
| 6                | 10.64            | 9.37            | 11.22    | 8.18    | 11.79    | 8.82    |
| 7                | 10.52            | 9.13            | 11.41    | 9.3     | 12.29    | 8.34    |
| 8                | 10.68            | 8.41            | 10.88    | 8.22    | 11.08    | 9.27    |
| 9                | 10.53            | 8.7             | 11.07    | 8.17    | 11.6     | 8.73    |
| 10               | 10.49            | 8.91            | 10.83    | 9.33    | 11.17    | 9.32    |
| Average          | 10.65            | 8.85            | 11.09    | 8.73    | 11.64    | 8.69    |

![Figure 6. Elongation for deep drawn round aluminium cup with LDR of 1.56](image)
Table 4 show the average major elongation of deep drawn round aluminium cup with LDR 1.69 at room temperature was 10.65 mm and minor elongation was 8.85 mm. The major elongation is increase to 11.09 mm as warm temperature of 50°C was applied to lower die set. On the other hand, the minor elongation showed increase to 8.73 mm. As the warm temperature increase up until 100°C, the major elongation increase to 11.64 mm while minor elongation decreasing to 8.69 mm. This also can be observed from figure 7 shown above. It shows that, at warm temperature of 50°C, the major elongation experience 4.1% of increment compares to room temperature condition, while 5.0% for warm temperature of 100°C. On the other hand, the minor elongation for cup drawn at 50°C suffers 0.4% decrement and continues to decrease to 0.5% as the cup being drawn at 100°C.

3.3 Major and Minor elongation of drawn round cup (Mild Steel)

After all of the aluminium blank has been successfully being drawn, the experiment move on by proceed to warm deep drawing process of mild steel blanks. The outcomes data after elongation of the circular grid is measured and recorded. For each drawn cups, there must be at least 10 clearly visible circles from the circular pattern, which, experience major and minor elongation, which then will be calculated and compared to the original diameter of the circular grid pattern, which is 10 mm. The increment and decrement of the circle is recorded as shown in table 5, 6, and 7.

Table 5. Elongation of drawn round mild steel cup with 60 mm blank diameter (LDR=1.56)

| Number of Element | Major (mm) | Minor (mm) | Major (mm) | Minor (mm) | Major (mm) | Minor (mm) |
|------------------|-----------|------------|-----------|------------|-----------|------------|
|                  | Room Temp | 50°C | 100°C | Room Temp | 50°C | 100°C |
| 1                | 9.51      | 8.48      | 10.98    | 8.89       | 12.44     | 8.29       |
| 2                | 9.67      | 6.87      | 10.45    | 8.42       | 11.43     | 9.33       |
| 3                | 10.13     | 9.31      | 11.43    | 8.60       | 12.67     | 7.88       |
| 4                | 11.43     | 8.34      | 11.25    | 8.73       | 11.07     | 8.13       |
| 5                | 10.58     | 9.59      | 10.47    | 9.06       | 10.36     | 8.52       |
| 6                | 10.71     | 8.15      | 10.71    | 8.33       | 10.71     | 8.39       |
| 7                | 10.08     | 9.03      | 10.32    | 8.43       | 10.45     | 8.07       |
| 8                | 10.23     | 9.54      | 10.53    | 7.65       | 10.82     | 8.45       |
| 9                | 11.02     | 8.12      | 10.83    | 8.71       | 10.64     | 8.30       |
| 10               | 10.32     | 8.93      | 11.54    | 9.15       | 11.56     | 9.12       |

Average 9.51  8.48  10.98  8.89  12.44  8.29
Table 5 shows the average major elongation of deep drawn round mild steel cup with LDR 1.56 at room temperature was 9.51 mm and minor elongation was 8.48 mm. The major elongation is increase to 10.98 mm as warm temperature of 50°C was applied to lower die set. On the other hand, the minor elongation showed increase to 8.89 mm. As the warm temperature increase up until 100°C, the major elongation increase to 12.44 mm while minor elongation decreasing to 8.29 mm. This also can be observed from figure 8 shown above. It shows that, at warm temperature of 50°C, the major elongation experience 15.46% of increment compares to room temperature condition, while 13.3% for warm temperature of 100°C. On the other hand, the minor elongation for cup drawn at 50°C increase 4.8% compare to room temperature condition. After that, the minor elongation continues to suffer decrement about 6.75% as the cup being drawn at 100°C.

Table 6. Elongation of drawn round mild steel cup with 65 mm blank diameter (LDR=1.69)

| Number of Element | Room Temperature | Temperature (°C) | 50 | 100 |
|-------------------|------------------|-----------------|----|-----|
|                   | Major (mm)       | Minor (mm)      | Major (mm) | Minor (mm) | Major (mm) | Minor (mm) |
| 1                 | 10.91            | 9.13            | 11.21 | 9.10 | 11.49 | 8.84 |
| 2                 | 11.1             | 8.39            | 11.23 | 8.49 | 11.31 | 8.51 |
| 3                 | 11.07            | 9.17            | 12.82 | 8.75 | 10.57 | 8.32 |
| 4                 | 11.38            | 8.75            | 10.42 | 8.81 | 11.33 | 8.87 |
| 5                 | 11.09            | 9.06            | 11.29 | 8.70 | 11.48 | 8.53 |
| 6                 | 10.7             | 9.45            | 10.92 | 9.23 | 11.13 | 8.75 |
| 7                 | 10.47            | 9.35            | 10.71 | 8.80 | 10.91 | 8.25 |
| 8                 | 10.84            | 8.39            | 11.58 | 8.47 | 11.32 | 8.54 |
| 9                 | 11.27            | 9.51            | 11.18 | 9.09 | 12.09 | 8.67 |
| 10                | 11.44            | 8.85            | 11.39 | 8.88 | 11.45 | 8.91 |
| **Average**       | **11.03**        | **9.01**        | **11.27** | **8.83** | **11.31** | **8.62** |
Figure 9. Elongation for deep drawn round mild steel cup with LDR of 1.69

Table 6 shows the average major elongation of deep drawn round mild steel cup with LDR 1.69 at room temperature was 11.03 mm and minor elongation was 9.01 mm. The major elongation is increase to 11.27 mm as warm temperature of 50°C was applied to lower die set. On the other hand, the minor elongation showed decrease to 8.83 mm. As the warm temperature increase up until 100°C, the major elongation increase to 11.31 mm while minor elongation decreasing to 8.62 mm. This also can be observed from figure 9 shown above. It shows that, at warm temperature of 50°C, the major elongation experience 2.18% of increment compares to room temperature condition, while 0.35% decrement for warm temperature of 100°C. On the other hand, the minor elongation for cup drawn at 50°C decrease 1.99% compare to room temperature condition. After that, the minor elongation continues to suffer decrement about 2.38% as the cup being drawn at 100°C.

Table 7. Elongation of drawn round mild steel cup with 70 mm blank diameter (LDR=1.82)

| Number of Element | Room Temperature | Temperature (°C) | Major (mm) | Minor (mm) | Major (mm) | Minor (mm) | Major (mm) | Minor (mm) |
|-------------------|------------------|------------------|------------|------------|------------|------------|------------|------------|
|                   |                  | 50               | 100        | 50         | 100        | 50         | 100        |
| 1                 | 13.25            | 7.84             | 12.77      | 7.91       | 11.89      | 7.98       |            |            |
| 2                 | 11.93            | 9.06             | 12.25      | 8.98       | 12.56      | 8.89       |            |            |
| 3                 | 10.58            | 9.1              | 11.42      | 9.21       | 12.07      | 9.21       |            |            |
| 4                 | 10.86            | 9.24             | 11.21      | 8.67       | 11.53      | 8.1        |            |            |
| 5                 | 12.61            | 7.89             | 12.16      | 7.57       | 12.51      | 7.25       |            |            |
| 6                 | 11.01            | 9.15             | 11.28      | 8.38       | 11.55      | 7.61       |            |            |
| 7                 | 10.82            | 8.23             | 10.96      | 8.42       | 12.1       | 8.61       |            |            |
| 8                 | 12.23            | 8.88             | 11.82      | 8.65       | 11.41      | 8.46       |            |            |
| 9                 | 11.98            | 7.98             | 11.73      | 8.40       | 11.79      | 8.82       |            |            |
| 10                | 12.43            | 9.12             | 12.64      | 9.10       | 12.84      | 8.47       |            |            |
| Average           | 11.77            | 8.65             | 11.82      | 8.53       | 12.03      | 8.34       |            |            |
Table 11 shows the average major elongation of deep drawn round mild steel cup with LDR 1.82 at room temperature was 11.77 mm and minor elongation was 8.65 mm. The major elongation is increase to 11.82 mm as warm temperature of 50°C was applied to lower die set. On the other hand, the minor elongation showed decrease to 8.53 mm. As the warm temperature increase up until 100°C, the major elongation increase to 12.03 mm while minor elongation decreasing to 8.34 mm. This also can be observed from figure 10 shown above. It shows that, at warm temperature of 50°C, the major elongation experience 0.42% of increment compares to room temperature condition and 1.78% increment for warm temperature of 100°C. On the other hand, the minor elongation for cup drawn at 50°C decrease 1.39% compare to room temperature condition. After that, the minor elongation continues to suffer decrement about 2.23% as the cup being drawn at 100°C.

3.4 Discussion on major and minor elongation of drawn round cup (Aluminium)

Based on observation, the drawn cup using blank with 60 mm diameter where the major elongation is increase with temperature while the minor elongation is decrease with temperature and the same condition happen as blank with 65 mm diameter.

However, we can notice that bigger increment happen for drawn cup with LDR of 1.69 at warm temperature. Not only have that, from the results also we notice that the major elongation shows more percentage increment compared to minor elongation. Therefore, figure 11 shown below will shows a comparison between major elongation and limiting drawing ratio for all temperature condition has been made. This is due to achieve a better understanding regarding the phenomena as correlation between the parameters can be analysed in details.
In figure 11, the major elongation against LDR in different temperature condition was shown. From this graph, we could notice that major elongation for drawn cup is increasing as the temperature increase. On top of that, as the LDR increase, the difference between major elongations among different temperature condition is higher. This is most likely to happen due to the warm temperature that applied during the process was almost similar the recrystallization temperature of the aluminium. Thus, it helps to improve the material flowability during the process. Moreover, the material does not repel to deformation, as much as it in room temperature condition.

In addition to that, compare to these three temperature condition, the warm temperature of 100°C show the highest increment percentage in term of major elongation. This indicates that the temperature difference can improve the drawability in term of elongation. In addition to that, the possibility to produce sound cup with higher LDR is increased with this approach which is proves the outcomes from Palumbo et al. works [10].

3.5 Discussion on major and minor elongation of drawn round cup (Mild Steel)

As we can see from the outcomes, the drawn mild steel cup manages to be drawn at higher LDR compare to aluminium. From the graph, the drawn cup with LDR of 1.56 and 1.69 shows the major elongation is spiking up with a steep line gradient as the temperature increase. Different from the others, the drawn cup with LDR of 1.89 shows a low major elongation increment, which appear as a mild slope on figure 10.

Therefore, as the major elongation appears to have more percentage increment compared to minor elongation, a comparison between major elongation and limiting drawing ratio for all temperature condition has been made. This is because; the correlation between the parameters is much clearer and can be seen in figure 12.
Figure 12. Major elongation of drawn mild steel cup against LDR in different temperature condition

Figure 12 shows the major elongation against LDR in different temperature condition for deep drawing process of mild steel cup. From this graph, we could notice that major elongation for drawn cup with LDR of 1.56 in increasing as the temperature increase except for round mild steel cup that drawn at 100°C. On the other hand, for drawn cup with LDR of 1.69, all of them were increase as the temperature being increase. However, when we compare the major elongation for the cup drawn at 100°C, we can notice that the major elongation at LDR 1.82 is much lower compare to LDR 1.56.

According to Lean et al. [1], the deep drawing process exhibit the principal plane of a plate sheet is positive while the other side is negative. Furthermore, the elevated temperature will affect the sign of principal plane. Changing sign of plate without changing the punching direction will shows a difference in collecting major strain data. Thus, this explains why the major elongation for drawn cup with LDR of 1.69 is lower when compares to the other cup with different LDR. Not only that, another reason that can contribute to this phenomena is the warm temperature applied to the process is not near enough to the recrystallization temperature of the material. Hence, the reduction of strength of the material were still not achieved and the materials still hard to flow during the process.

For deep drawing process that conducted at 100°C, we also can notice that the major elongation at lower LDR that is 1.56 is higher when compare to the others and shows a contradiction with the previous discussion. This is most likely to happen due to long heating time that being experience by each cup with different LDR. During the test run, the average time for the heating process was around 30 minutes. Based on this, 30 minutes has been set up as heating time throughout the experiment. The smaller the LDR with smaller blank diameter tends to absorb heat much more faster compare to the bigger one. Hence, the cup with smaller blank can achieve recrystallization stage while the other cannot and results better material flow and elongation.
3.6 Comparison between experimental and ABAQUS/CAE outcomes

ABAQUS/CAE Finite Element Analysis is a software for finite element analysis which already being utilized to analyse the part of the car, aviation, and mechanical items. In this research, the simulation of ABAQUS/CAE only conducted in 2D form. In this simulation, the comparison among different blank size is conducted. The comparison between simulation and experimental result also being carried out and shown in table 8.

**Table 8. Comparison between experimental outcomes and ABAQUS/CAE simulation**

| Blank Diameter (mm) | Experimental | ABAQUS Simulation |
|---------------------|--------------|-------------------|
| 60                  | ![Image](image1) | ![Image](image2)  |
| 65                  | ![Image](image3) | ![Image](image4)  |
| 70                  | ![Image](image5) | ![Image](image6)  |

The comparison between experimental and ABAQUS/CAE simulation were carried out in order to predict and verify the process outcomes that has been yield. Based on observation from experimental conduct, there was no wrinkling effect present onto the cup flange. This indicates that a sound cup has been produced through the process and this also has been verified by the simulation outcomes from ABAQUS/CAE as there were also no wrinkling occurs. As the LDR being increase, we can observe that there is a mild wrinkling effect present at top of the cups. This trait also noticed on the outcomes from the simulation of ABAQUS/CAE as the drawn cup also being slightly wrinkled. The reason behind this was the insufficient die height that causes the cup not being fully deformed. On top of that, the blank holding force that exerted onto the blank could be insufficient and cause the radial tensile stress and tangential compressive stress occur simultaneously.
4. Conclusion
From the experimental work conduct and finite element analysis simulation, we can deduce that:

1. The deep drawing process in elevated temperature will give a good formability for aluminium and mild steel. The increment in temperature will increase the major elongation and the LDR.
2. The physical, mechanical and thermal properties of material can affect warm deep drawing as the parameter need to be set-up properly according to the specification.
3. The working temperature increment could decrease the probability of defect such as fracture and wrinkling effect to be happen. Therefore, a sound cup with better aesthetic value could be produce with high temperature value.
4. There is result from experimental works could be predicted and compared through finite element analysis simulation method by using ABAQUS/CAE software.

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