Comparison of the Deep Drawability of Aluminum and Steel using Numerical Simulation Experiments

Çağlar Sönmez*, A.Erman Tekkaya†, C.Hakan Gür*

*Department of Metallurgical and Materials Engineering, Middle East Technical University, Ankara/Turkey
†Department of Manufacturing Engineering, ATILIM University, Ankara/Turkey

Abstract. Sheet metal forming processes, especially deep drawing processes give diverse results by various materials. Extreme differences occur between steel sheets and aluminum sheets. The main causes of these differences are variances in micro- and macroscopic material properties, such as anisotropy. In this study, the behavior of two distinct materials, steel and aluminum alloy, during an axisymmetrical cup drawing operation has been studied numerically. For this purpose, finite element (FE) simulations of a simple cup drawing process, which was studied in the benchmarks of the NUMISHEET 2002 have been conducted using a commercial dynamic-explicit FE-analysis package. The materials analyzed have been 6111-T4 aluminum alloy and mild steel graded as deep drawing quality. Basic process parameters, which are the blank holding force and the lubrication condition, have been varied to obtain a “successful” product and the process windows for these two materials have been compared and investigated. Thickness distributions in the blank, force requirements for the process and product quality have been used for the basis of comparison. The results are also compared with an analytical model developed by Ramaekers.

INTRODUCTION

Environmental and safety concerns force the automotive industry to choose lighter-yet-safer materials and hence to reduce the weight of automobiles [1]. To achieve this, ‘alternative’ materials are being studied to replace conventional steel materials. For this purpose, several approaches are presented: the usage of high strength steels, aluminum alloys, magnesium-alloys and polymers [2]. Among these approaches, the utilization of aluminum-alloys is becoming more popular among automotive manufacturers. For instance, the heat treatable AA6111 aluminum alloy (which is investigated within the present study) is one of the most prominent materials employed in outer body panels of cars and light trucks due to its unique combination of formability, paint bake strengthening and superior corrosion resistance characteristics [3].

Sheet metal forming processes’, especially deep drawing processes’ outcome is strongly dependent on the materials used. Therefore, the process chains and the tool designs must be re-evaluated as swiftly as possible whenever another material is proposed to produce a certain part. The most radical design difference is required when aluminum sheets are substituted for steel sheets. This occurrence is due to the differences in micro- and macroscopic material properties of both materials.

The elastic modulus of aluminum is nearly one-third of that of steel, making the springback effects more dominant, and hence the elastic recovery poses a greater problem for aluminum sheets. Additionally, the residual stress distributions become completely different compared to steel, affecting part response to successive operations and product life. Moreover, aluminum and steel materials have different strain hardening coefficients, thus their strain hardening behaviors are different.

Furthermore, the normal anisotropy value ($r_n$-value) of steel is larger than unity, whereas aluminum has an $r_m$-value smaller than unity. This affects the final shape variations of steel and aluminum sheets upon a forming process. Therefore, the thickness variations of these materials for the same drawing operations may be different. In sheet metal working, anisotropy is subdivided into normal and planar
anisotropy. Normal anisotropy \((r_n)\) influences the maximum drawability of sheet, whereas planar anisotropy \((\Delta r)\) leads to earing [4]. For a successful sheet metal stamping, the normal anisotropy must be as large as possible whereas the planar anisotropy must be as small as possible. Although materials having greater \(r_n\)-values are more suitable for deep drawing, their deformation resistance is also increased with increasing \(r_n\)-values [5], and a high \(r_n\) value allows deeper parts to be drawn. In shallow, smoothly-contoured parts (like automobile panels) a high value may reduce the chance of wrinkling or ripples in the part [6]. If the magnitude of the planar anisotropy parameter is large, the orientation of the sheet with respect to the die or the part to be formed will be important. In such cases, asymmetric forming and earing will be observed [6]. When the \(r_n\)-value of a sheet metal is greater, the thinning should be smaller with increasing drawing, their deformation resistance is also increased [4]. For a successful forming process such as necking and bending, meaning that each forming process should have individual forming properties related to the anisotropy of the materials, and the different strain states would cause different forming failures [7].

Finally, due to different grain structures, the final surface qualities of aluminum and steel sheets are different; therefore the surface properties of steel and aluminum sheets are different. Especially, the formation of large grains in aluminum due to large deformations makes aluminum sheets esthetically unusable.

Within this study, the performances of two different materials (6111-T4 aluminum alloy and DDQ mild steel) upon an axisymmetric cup drawing operation were investigated. For this purpose, the dynamic-explicit finite element analysis code PAM-STAMP 2G (version 2003) was utilized. Simulations were conducted using the tool setup specified in NUMISHEET 2002 Benchmark A [8], and the process windows for the successful simulation results in terms of blank holding forces and lubrication conditions were determined. The simulation findings were also compared to an analytical model developed by Ramaekers [9].

| TABLE 1. Material properties of aluminum and steel. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Material        | \(E\) [GPa]     | \(\nu\)         | \(\rho\) [g/mm\(^3\)] | \(R_0\)         | \(R_{45}\)      | \(R_{90}\)      |
| 6111-T4 aluminum| 70.725           | 0.3395          | 2.6                 | 0.894           | 0.611           | 0.66            |
|                  |                  |                 |                     |                 |                 |                 |
| DDQ mild steel  | 221.368          | 0.3             | 7.8                 | 2.16            | 1.611           | 2.665           |
|                  |                  |                 |                     |                 |                 |                 |

**PROCESS, MATERIALS AND MODEL**

The tool setup, as defined in NUMISHEET 2002 benchmark A, is given in Figure 1 [8]:

![Tool setup](image)

**FIGURE 1. Tool setup**

The initial blank thickness is 1 mm, and blank radii are set as 90 mm. It should be noted that the die clearance of 1.25 mm removes the possibility of ironing. The punch speed is set as 500 mm/s at maximum. The speed of the punch is defined stroke dependent to reduce dynamic effects. The punch accelerates from stationary position up to the specified maximum speed, and decelerates to a halt at the end of the stroke. Punch stroke is 40 mm as defined in NUMISHEET 2002 Benchmark A. The blank holding forces are varied between 0 to 70 MPa and the lubrication conditions (in terms of Coulomb friction coefficient) are varied from 0.05 to 0.20 for the determination of process windows.

Table 1 summarizes the material properties of the steel and aluminum alloys investigated within this study. \(E\) is the elastic modulus, \(\nu\) is the Poisson’s ratio, \(\rho\) is the density and \(R_0\), \(R_{45}\), and \(R_{90}\) denote the anisotropy coefficients obtained from uniaxial tensile tests at 0, 45 and 90 degrees to rolling direction respectively. These two materials have nearly identical flow curves; however their different anisotropic behaviors make them suitable for the comparison study. It should be noted that the normal anisotropy value \((r_n)\) of aluminum is 0.694, whereas steel has an \(r_n\) value of 2.012. On the other hand the planar anisotropy \((\Delta r)\) value of aluminum and steel are 0.083 and 0.401 respectively.

<table>
<thead>
<tr>
<th>Material</th>
<th>(E) [GPa]</th>
<th>(\nu)</th>
<th>(\rho) [g/mm(^3)]</th>
<th>(R_0)</th>
<th>(R_{45})</th>
<th>(R_{90})</th>
</tr>
</thead>
<tbody>
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</tr>
</tbody>
</table>

**Hollomon Law \(\sigma = K\varepsilon^n\)**

<table>
<thead>
<tr>
<th>(K) [MPa]</th>
<th>(n)</th>
<th>(\sigma) [MPa]</th>
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<tbody>
<tr>
<td>538.225</td>
<td>0.2255</td>
<td>180.825</td>
</tr>
</tbody>
</table>

**Swift Law \(\sigma = K(\varepsilon + \varepsilon_0)\)**

<table>
<thead>
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<th>(K) [MPa]</th>
<th>(n)</th>
<th>(\varepsilon_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>547.763</td>
<td>0.2692</td>
<td>0.00876</td>
</tr>
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</table>
The Hill 48 isotropic hardening material law is utilized within the simulations. 5808 4-node Belytschko-Tsay shell elements with 5 integration points through thickness are utilized for the deformable blank. The average element size is 2 mm. Additionally, the non-linear contact algorithm is applied. [10]

**NUMERICAL RESULTS**

Figure 2 gives the force requirements for aluminum and steel in two different blank holding states. In the first state, the blank holding pressure ($P_{BH}$) is 1 MPa and the friction coefficient ($\mu$) is 0.05, whereas the second state has $P_{BH} = 6$ MPa and $\mu = 0.15$. In both cases, steel shows a greater deformation resistance due to its larger normal anisotropy value, as expected.

![FIGURE 2. Force requirements for aluminum and steel simulation](image1)

Due to the difference in the anisotropic behavior of the two materials, the final flange outlines are also different. Figures 3 & 4 show the flange profiles of aluminum and steel for the blank holding conditions of $P_{BH} = 1$ MPa with $\mu = 0.05$ and $P_{BH} = 6$ MPa with $\mu = 0.15$ respectively. For both cases, steel flanges exhibit square-like forms, whereas the forms of the aluminum flanges are more circular.

![FIGURE 3. Final flange profiles for steel and aluminum (1)](image2)

The variation of maximum and minimum thickness values with loading and lubrication conditions are inspected on the simulation results of aluminum and steel. The following figures give the maximum and minimum thickness variations of aluminum and steel respectively (Figure 5 & 6). Maximum thickness values are observed at the outer rim of the flange and minimum thickness values are normally at the tip of the cup.

![FIGURE 5. Variation of maximum and minimum blank thickness values during drawing of aluminum](image3)

Comparison of Figures 5 and 6 reveal that aluminum has a stronger tendency to thicken; the maximum thickness values for all simulations lie near 1.2 mm, whereas steel material thickens up to 1.1 mm at maximum. On the other hand, with the greater thinning tendency of aluminum, it is concluded that...
obtaining the product tolerances poses a greater problem for aluminum compared to steel. For all loading and lubrication conditions, the difference between the final maximum and minimum thickness values for aluminum blanks is larger than that of steel.

FIGURE 6. Variation of maximum and minimum blank thickness values during drawing of steel

There exists an artificial occurrence due to the contact of rigid tools with anisotropic deformable bodies: During drawing, the blank thickness is not constant at the flange region due to the presence of anisotropy. At the regions where the flange is thicker, there is satisfactory contact of the blank with the blank holder. However, since the blank holder object is rigid, there is insufficient contact at the regions where the flange has experienced less thickening. Therefore at these regions, the loading cannot be applied fully, causing some partial wrinkling. These kinds of wrinkles are called as secondary wrinkles throughout this study, and this wrinkling phenomenon is called as secondary wrinkling. This occurrence makes the detection and investigation of wrinkling difficult for anisotropic materials. As seen in Figure 7, amplitudes of secondary wrinkles decrease as the blank holding pressure and/or the friction coefficient increases, and the region, where the secondary wrinkling occurrence is observed, spreads to the whole flange when the blank shows true wrinkling. On the other hand, this phenomenon is not present for isotropic materials.

FIGURE 7. Secondary wrinkling

Within the comparisons, a series of simulations are conducted for both materials with varying blank holding forces and friction coefficients. The results are classified in three categories: wrinkled (when the wrinkling waves are present in the whole flange region), safe (when the thinning of the blank is below the total elongation limit), failed (when excessive thinning of the blank is observed). Figure 8 compares the process windows for aluminum and steel materials in the axisymmetric cup drawing operation according to the numerical simulations.

FIGURE 8. Comparison of the process windows of aluminum and steel according to numerical simulations
Inspecting Figure 8, it is concluded that the formability of 6111-T4 aluminum in the axisymmetrical cup drawing operation is nearly three times less than that of steel. For all loading and lubrication conditions, excessive thinning failures of aluminum are observed always prior to steel. Detailed information is given in [11].

**COMPARISON WITH AN ANALYTICAL MODEL**

The simulation results are also compared with an analytical model developed by Ramaekers [9]. Within this model, wrinkling and failure predictions are done by inspecting the blank holding load and the punch force respectively. The minimum blank holding load is estimated for a given process to overcome wrinkling according to Siebel. The total drawing force \( F_D \) is calculated as the sum of the deformation force at the flange region \( F_{D\beta} \), the friction force between flange and tool \( F_{F\beta} \), the bending and rebending forces at the die-radius \( F_D\rho \) and the friction force at the die radius \( F_{F\rho} \) (Eq. 1):

\[
F_D = F_{D\beta} + F_{F\beta} + F_D\rho + F_{F\rho}
\]

Detailed information about the derivation of each term is given in [9].

Failure is predicted by considering the excessive thinning of the cup at the punch tip. A critical force is determined from:

\[
F_C = \left( \frac{R+1}{\sqrt{2R+1}} \right)^{n+1} \cdot n^a \left( \frac{s_0 + s_0 + \frac{e - s_0}{r_p}}{\rho_p} \right)
\]

where \( F_C \) is the critical force, \( R \) is the mean anisotropy factor, \( n \) is the strain hardening factor in Swift law, \( s_0 \) is initial sheet thickness, \( r_p \) is the punch radius, \( \rho_p \) is the punch fillet radius and \( e_0 \) is the strain history of the material. It should be noted that the estimated critical force is not dependent on the lubrication conditions of the system. If the punch force exceeds the predicted limiting force at any time, it is assumed that the drawing will result in a bottom tearing failure.

Figure 9 compares the force requirements of the drawings of steel and aluminum according to numerical simulations and analytical findings. The punch forces (according to simulations and analytical findings) are plotted versus the drawing ratio \( \beta \) which is given as (Eq. 3):

\[
\beta = \frac{r_i}{r_p}
\]

where \( r_i \) is the instantaneous flange radius and \( r_p \) is the punch radius.

**FIGURE 9.** Comparison of the force requirements according to numerical simulations and analytical findings (2)

From Figure 9, it is observed that for aluminum the punch forces according to numerical simulations are below the analytical findings. This is because of the material model utilized in the simulations. It is known that the Hill 48 model is less accurate for modeling aluminum. On the other hand, the maximum punch forces according to simulation and analytical findings are more or less in agreement for steel. It should be noted that the analytical model predicts failure for aluminum since the punch force exceeds the critical force, whereas according to the simulations there is no excessive thinning of the blank at the given blank holding condition.

The process windows of both materials for the cup drawing operation according to the Ramaekers’ analytical formulation are given in Figure 10. Both for aluminum and steel, the formabilities are much lower than the simulation findings, although the formability of aluminum is again found to be lower than that of steel. This difference may be due to the overestimation of the numerical analyses owing to the material model utilized, or due to the underestimation of the analytical model, which does not consider the effect of friction forces in the estimation of the minimum blank holding load to overcome wrinkling and in critical force calculations.
CONCLUSIONS

Within this study, the formabilities of a 6111-T4 aluminum alloy and DDQ mild steel is investigated. The formability of aluminum is significantly lower than steel, and product properties in terms of thickness tolerances are significantly inferior to steel.

In the deep drawability comparison study, it is found that (in terms of failure by tearing, excessive thickness change and wrinkling) aluminum material is nearly three times less formable than steel due to its anisotropic properties. Additionally, the process windows for both materials are determined for the cup drawing simulation in terms of lubrication and blank holding forces. The comparison of the formabilities of these aluminum and steel alloys may be useful for the industry, since it can give a general idea about the performances of aluminum and steel in similar operations.

On the other hand, the utilization of Hill 48 material model leads to inaccurate results, especially for aluminum alloys, since the anisotropic properties of aluminum alloys are not fully compatible with the model. Therefore, the formability of aluminum is overestimated with this model. However, the utilization of this model is very practical since it requires a small number of basic material parameters, which can be determined experimentally, or obtained from the literature easily. More accurate models, having more complex definitions and larger numbers of material parameters (like the Barlat 91 or Hill 90 models) must be utilized for the inspection of the formability of both materials.

REFERENCES