Numerical and experimental study of formability in deep drawing of two-layer metallic sheets

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Received: 22 September 2014 / Accepted: 26 February 2015 / Published online: 21 March 2015
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Abstract In this paper, the formability of two-layer (aluminum-st12 steel) sheets in the deep drawing process was investigated through numerical simulations and experiments. The purpose of this research was to obtain more formability in deep drawing process. The limit drawing ratio (LDR) was obtained in deep drawing of two-layer metallic sheets, with aluminum inner layer which was in contact with the punch and steel outer layer which was in contact with the die. Finite element simulations were performed to study the effect of parameters such as the thickness of each layer, value of die arc radius, friction coefficient between blank and punch, friction coefficient between blank and die, and lay up on the LDR. Experiments were conducted to verify the finite element simulations. The results indicated that the LDR was dependent on the mentioned parameters, so the LDR and as a result the two-layer metallic sheet formability could be increased by improvement of these parameters in deep drawing process.

Keywords Deep drawing · Two-layer metallic sheet · Limit drawing ratio · FEM

1 Introduction

In these years, two-layer metallic sheets forming are increasingly used in a variety of automobile, aerospace, and chemical industry applications ranging due to their advantages such as increasing formability of the low formable component, improving the corrosion and wear resistance, different electrical conductivity of each layer, decreasing of wrinkling and spring back, and finally reducing weight and cost of manufactured products.

Successful forming of a sheet metal component depends on many factors, one of them is formability. The limit deformation of sheets in deep drawing process can be described by the limit drawing ratio which is determined from the following relation:

\[
\text{LDR} = \frac{D}{d}
\]  

(1)

Where \(D\) is the maximum blank diameter that can be drawn successfully and \(d\) is the diameter of cup made in this process. The limit drawing ratio (LDR) is an accepted measure of sheet metal formability, so it is a criterion to determine the formability of sheets in cup drawing process.

Various methods are used to determine the LDR value in deep drawing of one-layer sheets. Some researchers studied the effects of various parameters in drawability of deep drawing process using analytical methods and finite element methods.

The first analytical method was presented in the early 1950s when Hill [1] suggested an upper limit of the LDR under pure radial drawing of an isotropic non-hardening material. His study illustrated that the LDR value was less than Euler’s number (\(e = 2.718\)). Budiansky and Wang [2] made an analysis of the swift cup test on the basis of a theory of plasticity for finite deformation of an orthotropic sheet that was isotropic in its plane. They studied the influence on draw-ability of: (a) the degree of anisotropy between the thickness and in-plane directions and (b) the strain hardening characteristics through both
the finite element method and the experimental approach. Leu [3] presented a new and practically applicable relation for predicting the LDR in the cup drawing of a cylindrical cup with a flat-nosed punch using an integral technique based on the load maximum principle for localization of the plastic flow. This relation was a function of the process parameters of normal anisotropy value, strain hardening exponent, coefficient of friction, die arc radius, and half die opening and yield strength and could clearly explore the interaction between the process parameters and the LDR in a theoretical manner. Chen and Lin [4] studied the influence of process parameters on the formability of the deep drawing of rectangular cups made of SUS304 stainless steel both numerically and experimentally. They used a statistical analysis to construct an orthogonal chart which reflects the effects of the process parameters and their interactions on the formability of rectangular cup drawing. A formability index for the deep drawing of SUS304 stainless steel rectangular cups is constructed with the help of statistical analysis, and the critical value of the formability index is estimated from the finite element simulation results. They offered a formability index which provided a convenient design rule for the deep drawing of SUS304 stainless steel rectangular cups. Padmanabhan et al. [5] studied the significance of three important process parameters, namely die arc radius, blank holder force, and coefficient of friction, on the deep drawing characteristics of a stainless steel axisymmetric cup. They found that die arc radius has the greatest effect on the deep drawing of stainless steel blank sheet. In addition, they demonstrated that a blank holder force application and local lubrication scheme improved the quality of the formed part. Özek et al. [6] presented an attempt to predict the influence of various radiiuses of die and punch on the limit drawing ratio by using DIN EN 10130–91 sheet metal. Their research indicated that the limit drawing ratio increased with increasing punch radius and die/blank holder angle. Fazli and Arezoo [7] presented an improved analytical method for predicting the limiting drawing ratio for the first drawing stage. In this method, they considered the effects of parameters such as the geometry and the material properties of die arc region into account for a more accurate prediction of LDR. Mostafapur et al. [8] studied the influence of a new pulsating blank holder system on improving the formability of aluminum 1050 alloy both numerically and experimentally. Their study demonstrated that by using the pulsating blank holder system coupled with proper frequency and gap, the cup depth can be increased and thickness distribution can be improved.

All of these mentioned researches have been studied in the one-layer sheets. However, some researchers tried to investigate the formability of multi-layer sheets, and they studied the effects of various parameters in drawability of two-layer sheets based on theoretical and experimental studies. Semiatin and Piehler [9, 10] studied on the formability of multi-layer metallic sheets in 1979. Parsa et al. [11] studied the behavior of two-layer aluminum–stainless steel (Al-SUS)-laminated sheets during deep drawing and direct and reverse redrawing processes (first and second drawing stages), through both the finite element analysis method and the experimental approach.

Their study indicated that while in direct redrawing, contact of stainless steel with the punch leads to the maximum drawing ratio; in reverse redrawing, aluminum should contact the punch in order to obtain the highest drawing ratio. Takuda and Hatta [12] used a criterion for ductile fracture to determine the formability of aluminum 2024 alloy sheet and its laminated composite sheets. Their research illustrated that the fracture initiation in the 2024 sheet with no appearance of necking is successfully predicted by the present numerical approach. Furthermore, they found that the formability of the 2024 sheet is improved by sandwiching it with the mild steel sheets. Tseng et al. [13] studied the possibility of applying forming limit diagrams to the formability and fracture determination of clad metal sheets. They investigated forming limits of clad metal sheets with different thickness combinations (e.g., Al1050 1.0, 1.5, 2.0 mm/C1100 1.0 mm) via forming limits test. They found significant differences in formability and analyzed comparisons of the fracture determination of clad metals with different initial thickness ratios both numerically and experimentally. Dilmez et al. [14] investigated the effects of sheet thickness and anisotropy of AA2024-T4 on forming limit diagram (FLD) experimentally based on ISO 12004-2 standard. They offered a new limit strain measurement method by using the grid analysis method so as to estimate limit strains conveniently and reliably. Results demonstrated that an increase in the sheet thickness increases the FLD level.

According to the literature review, it can be seen that many attempts have been made to predict the LDR in one-layer sheets and a few attempts have been made to study the behavior of two-layer sheets. However, according to the knowledge of the authors, the limit drawing ratio in two-layer metallic sheets has not yet been predicted. Moreover, in this work, the effects of various parameters on the LDR in deep drawing of two-layer metallic sheets were investigated through the finite element analysis. Also, experiments were conducted to verify the finite element simulations.

| Material | Thickness (mm) | Strain hardening exponent, $n$ | Strength coefficient, $K$ (MPa) | Yield strength, $\sigma_y$ (MPa) | Poisson’s ratio, $\nu$ |
|----------|----------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| St 12 | 0.5 | 0.21 | 510 | 195.59 | 0.3 |
| Al 1100 | 0.5 | 0.25 | 210 | 63.8 | 0.33 |
2 Experimental procedure

Two-layer Al 1100-St12 sheets were used in this study. The Al 1100 layer was combined with St12 layer to make the two-layer sheet. Polyurethane adhesive was applied to join the two layers with each other. The sheets were prepared with aluminum inner layer which was in contact with the punch and steel outer layer which was in contact with the die. The total sheet thickness was considered to be 1 mm, where a 0.5-mm steel layer and 0.5-mm aluminum layer were included. The mechanical properties of each layer are presented in Table 1.

The yield strengths, strain hardening exponents, strength coefficient, and also the Poisson’s ratio were determined by standard testing using specimens made according to ASTM-E8 specification at a crosshead speed of 2 mm/min [15].

For sheet metals, the plastic strain ratio values ($r$) were obtained for three various directions of loading in-plane (e.g., $0^\circ$, $45^\circ$, and $90^\circ$ to the rolling direction) that describe the anisotropy of the material in these directions. These values were obtained using specimens made according to ASTM-E517 specification [15]. Measured values of the plastic strain ratios are given in Table 2.

Dimensions of specimens used in tensile tests are shown in Fig. 1.

To draw the specimens, a 30-ton constant speed hydraulic press was used. A sudden drop in the load displacement graph was used as a stopping criterion for the test. This curve is presented in Fig. 2. The experimental deep drawing setup is shown in Fig. 3.

3 FEM simulation to predict LDR

The deep drawing process was simulated in three-dimensional (3D) using ABAQUS/Explicit 6.9 to determine the formability of two-layer sheets. The force on blank holder was considered to be 6260 N. The tooling components (punch, die, and blank holder) were modeled as a rigid body (the geometric setup that was used in this FEM simulation is shown in Fig. 4). The die was fixed, and the punch and blank holder were considered to move in the Z-direction and through the punch’s axis. In addition, the punch, die, and blank holder were meshed using R3D4 elements. The typical view of the model including the tooling components is shown in Fig. 5.

Moreover, the two-layer metallic sheets were modeled as deformable part with composite shell section, and they were meshed using S4R elements. Because the middle layer, polyurethane, was extremely thin, it was assumed that the alignment of the middle layer would not affect the forming process.

3.1 The governing yield function and hardening law

Hill’s 1948 yield function was considered to model the behavior of the sheet metals. This model is explained as follows [16]:

$$f(\sigma) = \sqrt{F(\sigma_{22} - \sigma_{33})^2 + G(\sigma_{33} - \sigma_{11})^2 + H(\sigma_{11} - \sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{31}^2 + 2N\sigma_{12}^2}$$  (2)
According to the general form of Hill’s quadratic yield criterion [16], the equivalent stress is given as follows:

$$\sigma = \sqrt{1 + 2\bar{\tau} \left[ (\varepsilon_1)^2 + (\varepsilon_2)^2 + \frac{2\bar{\tau}}{1 + \bar{\tau}}(\varepsilon_1)(\varepsilon_2) \right]}$$

(5)

$$\beta = \frac{d\varepsilon_2}{d\varepsilon_1}$$

(6)

where the average value of the plastic strain ratio can be calculated by following relation:

$$\bar{\tau} = \frac{r_0 + 2r_{45} + r_90}{4}$$

(7)

In plane stress condition, the six yield stress factors $R_{11}, R_{22}, R_{33}, R_{12}, R_{13}, \text{and } R_{23}$ can be calculated using anisotropic parameters $r_0, r_{45}, \text{and } r_{90}$ by the following relations [17]:

$$R_{11} = R_{13} = R_{23} = 1$$

$$R_{22} = \sqrt{\frac{r_x(r_x + 1)}{r_y(r_y + 1)}}$$

$$R_{33} = \sqrt{\frac{r_x(r_x + 1)}{(r_x + r_y)}}$$

$$R_{12} = \sqrt{\frac{3(r_x + 1)r_y}{(2r_{45} + 1)(r_x + r_y)}}$$

(8)

These anisotropic parameters were computed for St12 and Al 1100 sheets. The results are shown in Table 3.

Each layer was used in the Holloman’s hardening law that explains work hardening. The Holloman’s hardening law is given as follows:

$$\sigma_y = K(\varepsilon)^n$$

(9)

| Table 3 | The anisotropic parameters of Hill’s quadratic yield criterion |
|---------|---------------------------------------------------------------|
|         | $R_{11}$ | $R_{22}$ | $R_{33}$ | $R_{12}$ | $R_{13}$ | $R_{23}$ |
| St 12   | 1        | 1.00357  | 1.21     | 0.949    | 1        | 1        |
| Al 1100 | 1        | 1.00348  | 0.918    | 1.0329   | 1        | 1        |
where $\sigma_Y$ denotes the effective stress, $\varepsilon$ is the effective strain, $K$ is the strength coefficient, and $n$ is strain hardening exponent.

3.2 A statistical forming limit diagram

Forming limit diagram (FLD) is often used to determine the formability of sheet metals. There is a statistical model to plot a FLD which was developed by Stuart Keeler and William Brazier [18] based on experimental data collected for deep drawing quality steels. The points of the FLD determined by $e_1$ and $e_2$ as the major and minor engineering strain values are expressed in percent. In this model, in the right-hand side of FLD where $e_2>0$, the values of $e_1$ and $e_2$ are related to each other using Eq. (10):

$$e_1 = FLD_0 + e_2(0.784854 - 0.008565 e_2)$$

and in the left-hand side of the FLD where $e_2<0$, the values of $e_1$ and $e_2$ are related to each other by Eq. (11):

$$e_1 = FLD_0 + e_2(0.027254 - e_2 - 1.1965)$$

The $FLD_0$ is the engineering failure strain in plain strain condition where $e_2=0$. The statistical value of $FLD_0$ can be computed by Eq. (12):

$$FLD_0 = \frac{n}{0.2116}(23.25 + 356.1C_1)$$

The value of $C_1$ for thicknesses ($t_0$) less than 0.29972 mm is equal to $t_0/25.4$. However, for larger thickness values, $C_1$ is considered to be equal to 0.0118.

Computing the values of $e_1$ and $e_2$, the true major and minor strains of the FLD ($\varepsilon_1$ and $\varepsilon_2$) are obtained using Eq. (13):

$$\varepsilon_1 = \ln\left(1 + \frac{e_1}{100}\right)$$

$$\varepsilon_2 = \ln\left(1 + \frac{e_2}{100}\right)$$

However, it is well known that the strain-based forming limit diagram, introduced by Keeler and Backofen [19] and Goodwin [20], does not estimate the formability limit (the onset of necking) when the sheet metal is subjected to non-
linear strain paths. Therefore, an extended strain-based FLD has been represented, and this curve is much less sensitive to strain path changes than the conventional forming limit diagram [21, 22]. The extended strain-based FLD is constructed based on effective strains (equivalent strains) at the onset of localized necking and material flow direction at the end of sheet metal forming. This curve can determine the limit of formability under non-linear strain paths. Moreover, the extended strain-based FLC can be implemented into finite element numerical simulations to analyze and design the sheet metal forming operation. Since finite element software such as ABAQUS can calculate the strains incrementally in each element, therefore, the strain ratio and the equivalent strain in each element can be derived at every increment of deformation. Ultimately, the equivalent strains and corresponding strain ratios for the entire strain path of each element can be extracted from the output file of the FE software, and the deformation process can be analyzed by comparing the equivalent strains vs. strain ratios for the final strain increment with the extended FLD. The forming process will be safe if all the measured effective strains are located under the extended strain-based FLD (e.g., see [23, 24]).

4 Results and discussion

4.1 Comparison of necking positions

Figure 6 compares necking positions or failure locations for a two-layer metallic blank with 63.38 mm diameter determined by experiment and FE simulations. The two-layer Al 1100-St12 sheet with a 1-mm thickness (e.g., the aluminum layer with a thickness of 0.5 mm and the steel layer with a thickness of 0.5 mm) was used. The aluminum inner layer was in contact with the punch, and steel outer layer was in contact with the die.
Its extended strain-based forming limit diagram is shown in Fig. 7. It is clear from Fig. 7 that the equivalent strain value of some elements was more than the calculated failure strain, so during the process, fracture would occur on the blank.

Figure 8 shows a successful forming of a two-layer metallic sheet for a 62.42-mm blank diameter. The two-layer Al 1100-St12 sheet with a 1-mm thickness (e.g., the aluminum layer with a thickness of 0.5 mm and the steel layer with a thickness of 0.5 mm) was used. The aluminum inner layer was in contact with the punch, and steel outer layer was in contact with the die.

Also, its extended strain-based FLD is shown in Fig. 9. As Fig. 9 shows, the equivalent strain values of the elements were less than the calculated failure strain, so during the process, the blank would be formed without any fracture.

4.2 Parametric study

The parametric analysis has been carried out to study the effect of parameters such as the thickness of each layer, value of die arc radius, friction coefficient between blank and punch, friction coefficient between blank and die, and lay up on the LDR. Figure 10 demonstrates the effect of blank thickness on the LDR in deep drawing of two-layer metallic sheets.

It has been shown that the LDR is increasing with increasing of the steel thickness percentage (i.e., assuming that the total blank thickness is constant). On the other hand, it can be concluded that the formability of the steel layer is greater than the aluminum layer.

Figure 11 shows the effect of die arc radius on the LDR. As can be seen, the LDR is a strong function of the die arc radius. It can be seen that the curves change their slope at some value of die arc radius. The reason may be, with increasing the die arc radius, the rate of restraining force decrease in the flange region is matched with the increase in the bending/unbending
force, so the LDR increases with increasing the value of die arc radius. This phenomenon happens because of the fact that the radial drawing stress decreases. It is quite possible that with higher die arc radius, other defects like wall wrinkling may happen.

The effect of the friction coefficient between blank and punch on the LDR is shown in Fig. 12. It is clear from the graph that the LDR increases as the friction coefficient increases. It has been seen that there is a positive correlation between LDR and friction coefficient between blank and punch.

The effect of the friction coefficient between blank and die on the LDR is shown in Fig. 13. As Fig. 13 shows, with increase in friction coefficient between blank and die, the value of the LDR will be decreased. It means that the formability of two-layer sheet will be reduced.

Figure 14 illustrates the effect of lay up on the value of the LDR. As Fig. 14 shows, for a given steel thickness percentage, there is an increase in the LDR value when the steel layer is the inner layer. This is because of the fact that when the layer with more formability (e.g., the steel layer) is in contact with the punch, the radius of bending for the steel layer on the die corner is higher than that for the case which the steel layer is in contact with the die. That is, to say, when the steel layer is in contact with the punch, the formability of the blank will be improved.

## 5 Conclusions

The main goal in this paper was to obtain more formability in deep drawing process of two-layer metallic sheets. Moreover, the effects of parameters such as the thickness of each layer, value of die arc radius, friction coefficient between blank and punch, friction coefficient between blank and die, and lay up on the formability of two-layer sheets were studied by finite element simulations. Finite element model has been verified with experimental results. The conclusions obtained can be summarized as follows:

1. The LDR of the two-layer metallic sheet is located between the LDR of its components, and its precise position depends on thickness of the components.
2. An increase in the thickness percentage of a layer with more formability by assuming that the total blank thickness is constant increases the LDR value of two-layer metallic sheet.
3. Increase in value of die arc radius tends to increase the LDR value, which means the formability of the two-layer metallic sheets will be improved.
4. The LDR of two-layer metallic sheets increases with increase in the friction coefficient between blank and punch but decreases with increase in friction coefficient between blank and die.
5. It is clear from the studies that the lay up has a marked effect on the LDR of two-layer metallic sheets. There is an increase in the LDR value when the layer with more formability is in contact with the punch.

The LDR of the two-layer metallic sheets can be increased by improvement of these factors in deep drawing process.

### Acknowledgments

The author would like to acknowledge the financial support of Iran National Science Foundation (INSF).

### Appendix

#### Notation

| Symbol | Description |
|--------|-------------|
| LDR    | Limit drawing ratio |
| FLD    | Forming limit diagram |
| $fld_0$| Major strain in plane strain state |
| D      | Initial blank diameter |
| d      | Punch diameter |
| $K$ (MPa) | Strength coefficient |
\begin{align*}
 n & \quad \text{Strain hardening exponent} \\
 \nu & \quad \text{Poisson’s ratio} \\
 r & \quad \text{Anisotropic parameter} \\
 \rho & \quad \text{Average anisotropic parameter} \\
 \sigma_y (\text{MPa}) & \quad \text{Yield stress value} \\
 \beta & \quad \text{In-plane principal strain ratio} \\
 e & \quad \text{Engineering strain} \\
 e_1 & \quad \text{Major engineering strain value} \\
 e_2 & \quad \text{Minor engineering strain value} \\
 \varepsilon & \quad \text{True strain} \\
 \varepsilon & \quad \text{Effective plastic strain} \\
 \varepsilon & \quad \text{Major strain} \\
 \varepsilon & \quad \text{Minor strain} \\
 \varepsilon_3 & \quad \text{Thickness strain} \\
 S & \quad \text{Engineering stress} \\
 \sigma & \quad \text{True stress} \\
 \sigma_y (\text{MPa}) & \quad \text{Effective stress obtained from hardening law}
\end{align*}

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