Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](#), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

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

Ehsan Karajibani¹, Ali Fazli², Ramin Hashemi³

1 - School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran

2- Mechanical Engineering Department, Faculty of Engineering and Technology, Imam Khomeini International University, Qazvin, Iran

3- School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran

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

*Corresponding author:

R.Hashemi

e-mail: rhashemi@iust.ac.ir, Tel.: +98-21-77240540, Fax: +98-21-77240540

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

1 Introduction

In these years, two-layer metallic sheets forming are increasingly used in a variety of automobile, aerospace, and chemical industries 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 that one of them is formability. The limit deformation of sheets in deep drawing process can be described by the limit drawing ratio which determined from the following relation:

$$LDR = \frac{D}{d} \quad (1)$$

Where D is the maximum blank diameter that can be drawn successfully and d is the diameter of cup made in this process. The LDR is an accepted measure of sheet metal formability, so it's 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 draw-ability of deep drawing process using analytical methods and finite element methods.

The first analytical method was presented in the early 50s, 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

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

(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, 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 constructed with the help of statistical analysis, and the critical value of the formability index 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 radiuses of die and punch on the limit drawing ratio by using DIN EN 10130–91 sheet metal. Their research

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

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 draw-ability 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, 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

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

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., A1050 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. Dilmec 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.

2. Experimental procedure

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

A 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 1mm where included of a 0.5mm steel layer and 0.5mm aluminum layer. The mechanical properties of each layer are presented in table 1.

Table 1 Mechanical and Material properties of St12 and Al 1100 sheets from tensile tests

Material	Thickness (mm)	Strain hardening exponent, n	Strength coefficient, K (MPa)	Yield strength, σ_y (MPa)	Poison's ratio, (ν)
St 12	0.5	0.21	510	195.59	0.3
Al 1100	0.5	0.25	210	63.8	0.33

The yield strengths, strain hardening exponents, strength coefficient and also the poison'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., $0^\circ, 45^\circ, 90^\circ$ 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.

Table 2 Measured values of the plastic strain ratios

Material	Thickness (mm)	r_0	r_{45}	r_{90}	$\bar{r} = \frac{r_0 + 2r_{45} + r_{90}}{4}$
St 12	0.5	1.9	1.94	1.92	1.925
Al 1100	0.5	0.679	0.687	0.651	0.676

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.
<https://link.springer.com/article/10.1007/s00170-015-6978-5>
<https://doi.org/10.1007/s00170-015-6978-5>

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

Figure 1: The tensile test sample dimension

To draw of the specimens, a 30 tones 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 Figure 2. The experimental deep drawing setup is shown in Figure 3.

Figure 2: Typical Load–Displacement curve from the deep drawing test

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

Figure 3: Experimental deep drawing setup

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 6260N. The tooling components (punch, die and blank holder) were modeled as a rigid body (the geometric set-up was used in this FEM simulation is shown in Figure 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 Figure 5.

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://doi.org/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.
<https://link.springer.com/article/10.1007/s00170-015-6978-5>
<https://doi.org/10.1007/s00170-015-6978-5>

Figure 4: The schematic of punch, die and blank holder

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.

Figure 5: Typical view of the model including punch, blank holder, blank and die

3.1. The governing yield function and hardening law

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

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

$$f(\sigma) = \sqrt{F(\sigma_{22} - \sigma_{33})^2 + G(\sigma_{33} - \sigma_{11})^2 + H(\sigma_{11} - \sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{31}^2 + 2N\sigma_{12}^2} \quad (2)$$

$$F = \frac{1}{2} \left(\frac{1}{R_{22}^2} + \frac{1}{R_{33}^2} - \frac{1}{R_{11}^2} \right)$$

$$G = \frac{1}{2} \left(\frac{1}{R_{33}^2} + \frac{1}{R_{11}^2} - \frac{1}{R_{22}^2} \right)$$

$$H = \frac{1}{2} \left(\frac{1}{R_{11}^2} + \frac{1}{R_{22}^2} - \frac{1}{R_{33}^2} \right)$$

$$L = \frac{3}{2R_{23}^2}$$

$$M = \frac{3}{2R_{13}^2}$$

$$N = \frac{3}{2R_{12}^2}$$

(3)

According to general form of Hill’s quadratic yield criterion [16], the equivalent stress is given as follows:

$$\sigma_y = \sqrt{\frac{3}{2} \left[\frac{F(\sigma_2 - \sigma_3)^2 + G(\sigma_3 - \sigma_1)^2 + H(\sigma_1 - \sigma_2)^2}{F + G + H} \right]} \quad (4)$$

Where F, G, H, L, M and N are coefficients of Hill’s 1948 yield function that can be imported to the ABAQUS by six yield stress factors R_{11} , R_{22} , R_{33} , R_{12} , R_{13} and R_{23} . The equivalent strain and the ratio of incremental minor strain to the major strain are calculated using Hill’s yield criterion [16] as follows:

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](#), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

$$\bar{\varepsilon} = \frac{1+\bar{r}}{\sqrt{1+2\bar{r}}} \left[(\varepsilon_1)^2 + (\varepsilon_2)^2 + \frac{2\bar{r}}{1+\bar{r}} (\varepsilon_1)(\varepsilon_2) \right]^{\frac{1}{2}} \quad (5)$$

$$\beta = \frac{d\varepsilon_2}{d\varepsilon_1} \quad (6)$$

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

$$\bar{r} = \frac{r_0 + 2r_{45} + r_{90}}{4} \quad (7)$$

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

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

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

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

$$R_{12} = \sqrt{\frac{3(r_x + 1)r_y}{(2r_{45} + 1)(r_x + r_y)}} \quad (8)$$

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

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

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

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

$$\bar{\sigma}_Y = K \left(\bar{\varepsilon} \right)^n \quad (9)$$

Where $\bar{\sigma}_Y$ denotes the effective stress, $\bar{\varepsilon}$ 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 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):

$$e_1 = FLD_0 + e_2(0.784854 - 0.008565 e_2) \quad (10)$$

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

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):

$$e_1 = FLD_0 + e_2(0.027254 e_2 - 1.1965) \quad (11)$$

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):

$$FLD_0 = \frac{n}{0.2116}(23.25 + 356.1C_1) \quad (12)$$

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 (ε_1 and ε_2) are obtained using Eq. (13):

$$\begin{aligned} \varepsilon_1 &= \ln\left(1 + \frac{e_1}{100}\right) \\ \varepsilon_2 &= \ln\left(1 + \frac{e_2}{100}\right) \end{aligned} \quad (13)$$

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

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](#), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

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, and 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 63.38mm diameter determined by experiment and FE simulations. The two-layer Al 1100-St12 sheet with a 1mm thickness (e.g., the aluminum layer with a thickness of 0.5 mm and the steel layer with a thickness of 0.5mm) was used. The aluminum inner layer was in contact with the punch and steel outer layer was in contact with the die.

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.
<https://link.springer.com/article/10.1007/s00170-015-6978-5>
<https://doi.org/10.1007/s00170-015-6978-5>

Figure 6: Comparison of necking positions from simulation and experiment for Al 1100-St 12 with aluminum inner layer and steel outer layer for a 63.38 mm blank diameter: (a) experimental result and (b) FE simulation result

And its extended strain-based forming limit diagram is shown in Figure 7. It's clear from Figure 7 that the equivalent strain value of some elements was more than the calculated failure strain, so during the process fracture would be occurred on the blank.

Figure 7: The extended FLD for a 63.38 mm blank diameter

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.
<https://link.springer.com/article/10.1007/s00170-015-6978-5>
<https://doi.org/10.1007/s00170-015-6978-5>

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

Figure 8: Final shapes for Al 1100-St 12 with aluminum inner layer and steel outer layer for a 62.42 mm blank diameter: (a) experimental result and (b) FE simulation result

And also its extended strain-based FLD is shown in Figure 9. As the Figure 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.

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

Figure 9: The extended FLD for a 62.42 mm blank diameter

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.

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.
<https://link.springer.com/article/10.1007/s00170-015-6978-5>
<https://doi.org/10.1007/s00170-015-6978-5>

Figure 10: Effect of steel thickness percentage on the LDR

Figure11 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.

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](#), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

Figure 11: Effect of die arc radius on the LDR

The effect of the friction coefficient between blank and punch on the LDR is shown in Figure12. It is clear from the graph that, the LDR increases as the friction coefficient increases. It has been seen that there is a positive co-relation between LDR and friction coefficient between blank and punch.

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.
<https://link.springer.com/article/10.1007/s00170-015-6978-5>
<https://doi.org/10.1007/s00170-015-6978-5>

Figure 12: Effect of friction coefficient between blank and punch on the LDR

The effect of the friction coefficient between blank and die on the LDR is shown in Figure13. As the Figure13 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 13: Effect of friction coefficient between blank and die on the LDR

The Figure 14 illustrates the effect of lay-up on the value of the LDR. As the Figure14 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.

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

Figure 14: Effect of lay-up on the LDR

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. 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 that it means the formability of the two-layer metallic sheets will be improved.

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](#), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

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's 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.

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

Acknowledgement

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

References

- [1] R. Hill, 1950, “The Mathematical Theory of Plasticity”, Clarendon Press, Oxford, UK.
- [2] B. Budiansky, N.M. Wang, 1966 “On the Swift Cup Test”, J. Mech. Phys. Solids, Vol. 14, pp. 357—374. [3] Leu, D.K., 1999, “The limiting drawing ratio for plastic instability of the cup drawing process”, J. Mater. Process. Technol. 86, 168–176.
- [4] Fuh-Kuo Chen, Shih-Yu Lin, 2007, “A formability index for the deep drawing of stainless steel rectangular cups”, Int. J. Adv. Manuf. Technol. 34:878–888.
- [5] R. Padmanabhan, M.C. Oliveira, J.L. Alves, L.F. Menezes, 2007, “Influence of process parameters on the deep drawing of stainless steel”, Finite Elem. Anal. Des. 43, 1062–1067.

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](#), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

[6] C. Özek, M. Bal, 2009, “The effect of die/blank holder and punch radiuses on limit drawing ratio in angular deep-drawing dies”, *Int. J. Adv. Manuf. Technol.* 40:1077–1083.

[7] A. Fazli, , B. Arezoo, 2012, “Prediction of Limiting Drawing Ratio Considering the Effective Parameters of Die Arc Region”, *J. Mater. Process. Technol.* 212(4), pp. 745–751.

[8] A. Mostafapur, S. Ahangar, R. Dadkhah, 2013, “Numerical and experimental investigation of pulsating Blank holder effect on drawing of cylindrical part of aluminum alloy in deep drawing process”, *Int. J. Adv. Manuf. Technol.* 69:1113–1121.

[9] S.L. Semiatin, H.R. Piehler 1979, “Deformation of sandwich sheet materials in uniaxial tension”, *Metallurgical Trans* 10A:85-96.

[10] S.L. Semiatin, H.R. Piehler, 1979, “Formability of sandwich sheet materials in plane strain compression and rolling”, *Metallurgical Trans* 10A:97-107.

[11] .H. Habibi Parsa, K. Yamaguchi, N. Takakura, 2001, “Redrawing analysis of aluminum-stainless steel laminated sheet using FEM simulations and experiments”, *Int. J. Mech. Sci.* 43, pp.2231-2347.

[12] H. Takuda, N. Hatta, 1998, "Numerical Analysis of the Formability of an Aluminum 2024 Alloy Sheets and Its Laminates with Steel Sheets", *Metallurgical And Materials Transactions A*, 29(11), pp.2829-2834.

[13] H.C. Tseng, C. Hung, C.C. Huang, 2010, “An analysis of the formability of aluminium/copper clad metals with different thicknesses by the finite element method and experiment”, *Int. J. Adv. Manuf. Technol.* 49:1029–1036.

[14] M. Dilmeç, H. Selçuk Halkacı, F. Öztürk, H. Livatyali, O. Yigit., 2013, “Effects of sheet thickness and anisotropy on forming limit curves of AA2024-T4”, *Int. J. Adv. Manuf. Technol.* 67:2689–2700.

[15] Metals Test Methods and Analytical Procedures, Annual Book of ASTM Standards, ASTM-E8 and ASTM-E517, West Conshohocken, PA Vol 03.01, 2000.

[16] R. Hill, “A Theory of Yielding and Plastic Flow of Anisotropic Metals,” *Proc. Roy. Soc. Lond.*, 1948, 193A, pp 197–281.

[17] ABAQUS User Guide, ABAQUS Analysis User’s Manual.

[18] FMTI Systems, Inc., “Technical Application Note 12: Analytical Method for FLC,”
<http://www.fmtisystems.com/technotes.htm>

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](#), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

[19] S. P. Keeler, 1965, “Determination of forming limits in automotive stampings,” Sheet Metal Industry, 42, 683–691.

[20] G. M. Goodwin, 1968, “Application of strain analysis to sheet metal forming problems in the press shop,” SAE paper 680093.

[21] A. Assempour, R. Hashemi, K. Abrinia, M. Ganjani, E. Masoumi, 2009, “A methodology for prediction of forming limit stress diagrams considering the strain path effect”, Computational Materials Science, 45(2), 195-204.

[22] R. Hashemi, K. Abrinia, 2014, "Analysis of the extended stress-based forming limit curve considering the effects of strain path and through-thickness normal stress", Materials and Design, 54, 670-677.

[23] D. Zeng, L. Chappuis, Z.C. Xia, et al, 2008, “A path independent forming limit criterion for sheet metal forming simulations”, SAE. Int. J. Mater. Manuf. 1: 809–817.

[24] M. Nurcheshmeh, D.E. Green, 2014, “On the use of effective limit strains to evaluate the forming severity of sheet metal parts after nonlinear loading”, Int. J. Mater. Form. 7:1–18.

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.
<https://link.springer.com/article/10.1007/s00170-015-6978-5>
<https://doi.org/10.1007/s00170-015-6978-5>

Appendix I: Notation

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
n	Strain hardening exponent
ν	Poisson's ratio
r	Anisotropic parameter
$\bar{r}$	Average anisotropic parameter
σ_y (MPa)	Yield stress value
β	In-plane principal strain ratio
e	Engineering strain
e_1	Major engineering strain value
e_2	Minor engineering strain value
ε	True strain
$\bar{\varepsilon}$	Effective plastic strain
ε_1	Major strain
ε_2	Minor strain

Post-print of “Ehsan Karajibani, Ali Fazli, [Ramin Hashemi](https://link.springer.com/article/10.1007/s00170-015-6978-5), Numerical and experimental study of formability in deep drawing of two-layer metallic sheets, The International Journal of Advanced Manufacturing Technology, 2015, Volume 80, Issue 1–4, pp 113–121”.

<https://link.springer.com/article/10.1007/s00170-015-6978-5>

<https://doi.org/10.1007/s00170-015-6978-5>

ε_3	Thickness strain
S	Engineering stress
σ	True stress
$\bar{\sigma}_Y$ (MPa)	Effective stress obtained from hardening law