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An Analysis of the Formability of Two-Layer Metallic Sheets by the Experiment and Finite Element Method

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Abstract
In this paper, the effects of various parameters on the limit drawing ratio (LDR) in deep drawing of two-layer (aluminum-st12) metallic sheets and changes on process conditions were investigated through a numerical simulations and experiments. The purpose of this research was to obtain more formability in deep drawing process. The LDR has been 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, and simulation results demonstrated a good agreement with experimental test results. The effects of parameters such as the thickness of each layer, value of die arc radius, friction coefficient between blank and punch and friction coefficient between blank and die on the LDR were investigated. The results indicated that the LDR is dependent on mentioned parameters, so the LDR and as a result the two-layer metallic sheet formability can be increased by improvement of these factors in deep drawing process.
Keywords: *"Deep drawing", "Two-layer metallic sheet", "Limit drawing ratio", "FEM".*

Introduction

In these years, two-layer metallic sheets forming are increasingly used in a variety of automobile, aerospace, and chemical industries applications ranging due 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 [1-5].

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:

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

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 [6] suggested an upper limit of the LDR under pure radial drawing of an isotropic non-hardening material. His study illustrated that the LDR value is less than Euler's number (e = 2.718). B. Budiansky and N. M. Wang [7] 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 analysis method and the experimental approach. Leu [8] 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. Fuh-Kuo Chen and Shih-Yu Lin [9] 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. [10] 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

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steel blank sheet. In addition, they demonstrated that a blank holder force application and local lubrication scheme improved the quality of the formed part. Cebeli Özek et al. [11] 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 indicated that the limit drawing ratio increased with increasing punch radius and die/blank holder angle. Fazli and Arezoo [12] 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. [13] 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 [14, 15] studied on the formability of multi-layer metallic sheets in 1979. Habibi Parsa et al. [16] 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. Hirohiko Takuda and Natsuo Hatta [17] used a criterion for ductile fracture to determine the formability of aluminum 2024 alloy sheet and its laminated composite sheets. Their studied 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. Huang-Chi Tseng et al. [18] 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.

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 both the finite element analysis method and the experimental approach.

Experimental procedure

Two-layer blanks (Al 1100- st12) were used in this study. The Al 1100 was combined with st12 layer to make two-layer sheets. Polyurethane adhesive was applied to join two layers with each other. The blanks were prepared with aluminum inner layer which was in contact with the punch and steel outer layer which was in contact with the die and different in diameter. The total blank thickness was considered to be 1mm where included of a 0.5mm steel layer and 0.5mm aluminum layer in thickness. The mechanical properties of each layer used in this research are presented in table 1. The yield strengths, strain hardening exponents, strength coefficient and also the poison’s ratio have been determined by standard testing using specimens made according to ASTM-E8 specification at a crosshead speed of 2 mm/min [19]. To draw of the specimens, a 30 tones constant speed hydraulic press was used. The experimental deep drawing setup is shown in Figure 1.

Table 1: Mechanical and Material properties of St and Al sheets from tensile tests

Material	*Strain hardening exponent, n*	*Strength coefficient, K (MPa)*	*Yield strength, σ_y(MPa)*	*Poison’s ratio, (υ)*
St 12	0.21	510	195.59	0.3
Al 1100	0.25	210	63.8	0.33

Fig. 1: Experimental deep drawing setup

FEM simulation

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 2). 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 3. Also the two-layer metallic blanks were modeled as deformable and they were meshed using S4R elements.

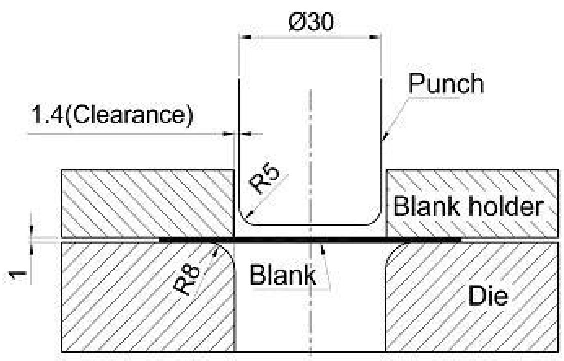

Fig. 2: The schematic of punch, die and blank holder

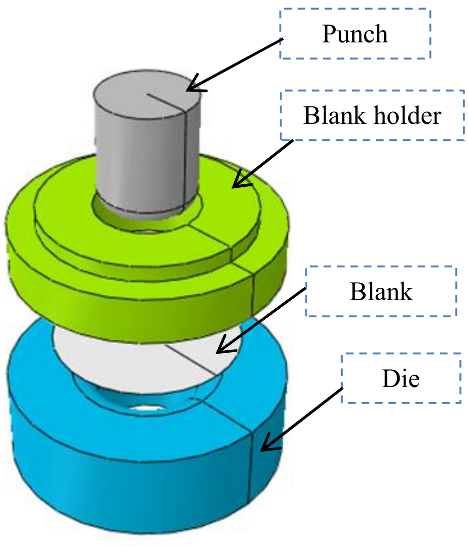

Fig. 3: Typical view of the model including punch, blank holder, blank and die

Predicted LDR based on statistical forming limit diagram model

The FLD (forming limit diagram) is often used to determine the formability of sheet metals. There is a statistical model to plot FLD which have developed by Stuart Keeler and William Brazier [20], based on data collected for deep drawing quality steels. The points of the FLD determine 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. (2):

$$e_1 = FLD_0 + e_2(0.784854 - 0.008565e_2) \qquad (2)$$

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. (3):

$$e_1 = FLD_0 + e_2(0.027254e_2 - 1.1965) \qquad (3)$$

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. (4):

$$FLD_0 = \frac{n}{0.2116}(23.25 + 356.1C_1) \qquad (4)$$

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. (5):

$$\varepsilon_1 = \ln(1 + \frac{e_1}{100}) \qquad \varepsilon_2 = \ln(1 + \frac{e_2}{100}) \qquad (5)$$

Using the statistical FLD as the ductile fracture criterion, for each element of the blank in FE simulation, the minor strain of this element is used and the major failure strain is computed using the present method. If the true strain value of this element is less than the computed failure strain, the element is considered to be formed without any fracture and vice versa. However, it is well known that the strain-based forming limit diagram, introduced by Keeler and Backofen [21] and Goodwin [22], 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. 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, 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]).

Results and discussion

This study presents the effects of various parameters on the limit drawing ratio in deep drawing of two-layer (aluminum-st12) metallic sheets. The LDR has been 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, and simulation results demonstrated a good agreement with experimental test results.

Comparison of Necking Positions

Figure 4 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 metallic blank was included of a 0.5mm steel layer and 0.5 mm aluminum layer in thickness with aluminum inner layer which was in contact with the punch and steel outer layer which was in contact with the die. And its extended strain-based forming limit diagram is shown in Figure 5. It's clear from Figure 5 that the strain value of some elements are more than the calculated failure strain, so during the process fracture will be occurred on the blank.

Figure 6 shows a successful forming of a two-layer metallic sheet for a 62.42mm blank diameter. The two-layer metallic blank was included of a 0.5mm steel layer and 0.5 mm aluminum layer in thickness with aluminum inner layer which was in contact with the punch and steel outer layer which was in contact with the die. And also its extended strain-based FLD is shown in Figure 7. As the Figure 7 shows the strain values of the elements are less than the calculated failure strain, so during the process the blank will be formed without any fracture.

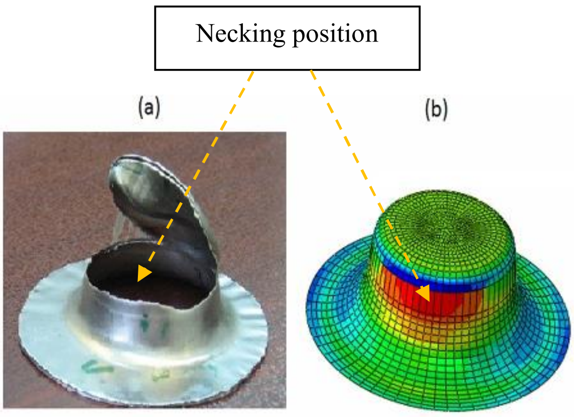

Fig. 4: Comparison of necking positions from simulation and experiment for Al 1100-St 12 with aluminum inner layer and steel outer layer for a 63.38 mm blank diameter: (a) experimental result and (b) FE simulation result

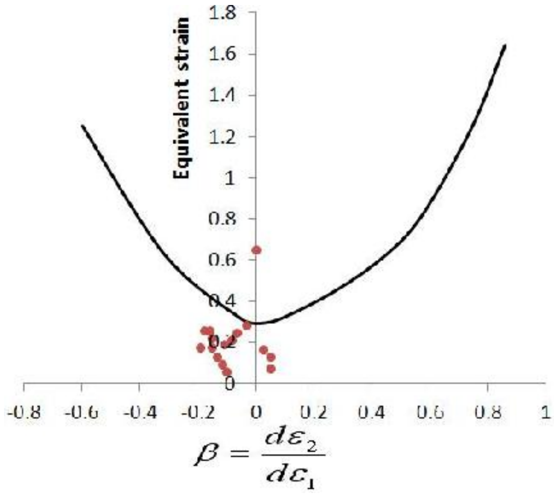

Fig. 5: The extended strain-based FLD for a 63.38mm blank diameter

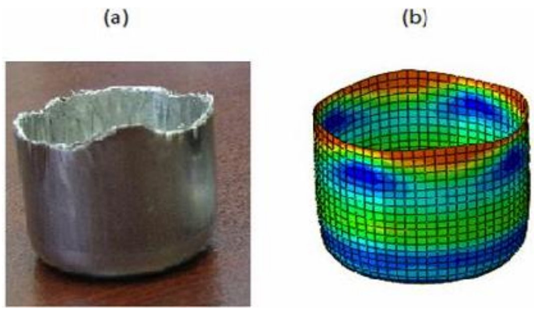

Fig. 6: Final shapes for Al 1100-St 12 with aluminum inner layer and steel outer layer for a 62.42 mm blank diameter: (a) experimental result and (b) FE simulation result

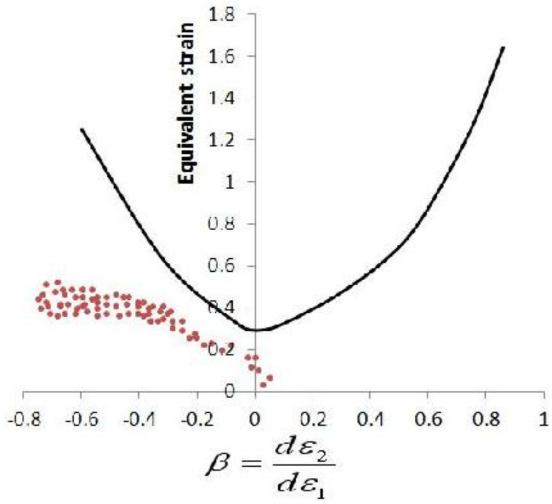

Fig. 7: The extended strain-based FLD for a 62.42mm blank diameter

Parametric study

A parametric study has been carried out for obtaining the effect of various process parameters on the LDR. Figure 8 demonstrate the effect of blank thickness on the LDR. As the Figure 8 shows, with increase in steel thickness percentage in a constant total blank thickness, the LDR will be increased that it means the formability of two-layer sheet will be improved. In

other hand, it can be concluded that the formability of the steel layer is greater than the aluminum layer.
Figure 9 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 changes their slope at some value of die arc radius. The reason may be, with increasing the die arc radius, the rate of decrease of the restraining force 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 is because of the fact that the radial drawing stress decreases and 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 is shown in Figure 10. It is clear from the graph that, the LDR increases as the friction coefficient increases. It is seen that there is a positive co-relation between LDR and friction coefficient between blank and punch.

The effect of the friction coefficient between blank and die is shown in Figure 11. As the Figure 11 shows, with increase in friction coefficient between blank and die, the value of the LDR will be decreased that it means the formability of two-layer sheet will be reduced.

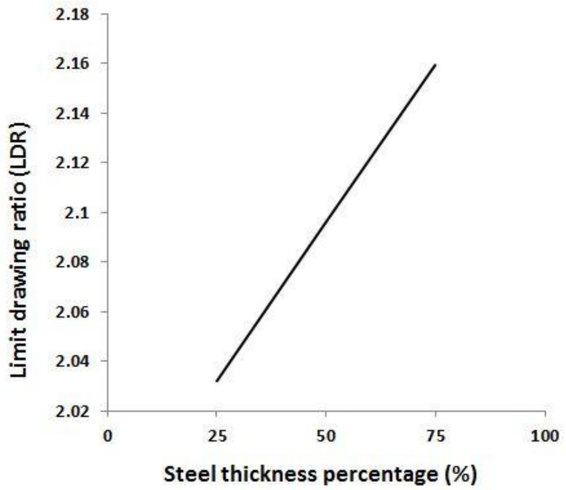

Fig. 8: Effect of steel thickness percentage on the LDR

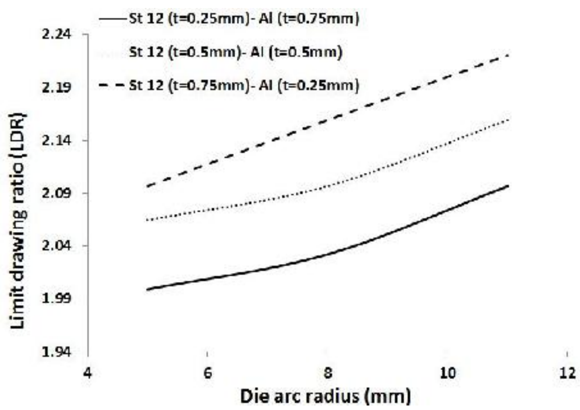

Fig. 9: Effect of die arc radius on the LDR

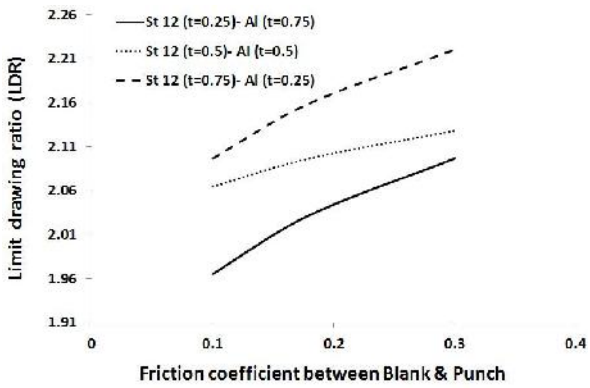

Fig. 10: Effect of friction coefficient between blank and punch on the LDR

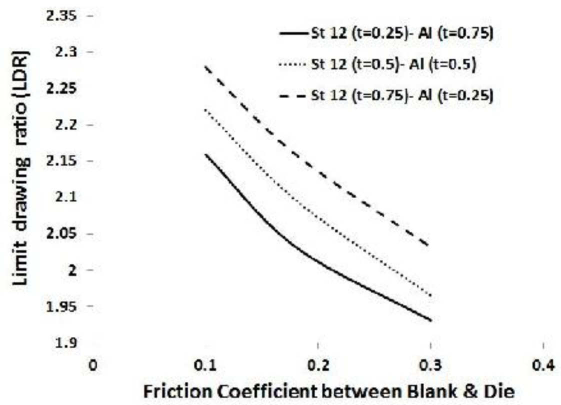

Fig. 11: Effect of friction coefficient between blank and die on the LDR

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 various parameters on the formability of two-layer sheets were studied by a finite element simulation. Finite element model has been verified with experimental results. The following are the conclusions obtained:

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.
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.

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

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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
υ	Poison's ratio
σ_y (MPa)	Yield stress value
β	In-plane principal strain ratio
e_1	Major engineering strain value
e_2	Minor engineering strain value
ε_1	Major strain
ε_2	Minor strain