SPRINGBACK ANALYSIS OF SHEET METAL LAMINATES AFTER U-BENDING

Hamed ADIBI [a], Mohammad Hossein ASADIAN ARDAKANI [a], Bijan MOLLAEI DARIANI [a]

[a] *Amirkabir University of Technology, 424 Hafez Ave, 15875-4413, Tehran, Iran,*

E-mail address: h_adibi@aut.ac.ir

Abstract

In present study, the springback of two-ply sheet metal laminates is investigated theoretically and experimentally. The current model which is based on non-quadratic Hill yielding criterion and plane strain condition, takes into account effects of thickness thinning of each layer and deformation history on the sheet springback. Experimental tests were conducted to verify the analytical results. U-bending experiments for two-ply laminates consisting of pure aluminium (JIS Al1100) and stainless steel (JIS SUS304) were performed.

The results show that springback of sheet metal laminates is different from monolithic sheets. Strength difference between the components, the relative position of layers (layup), and the thickness ratio of each layer are remarkable factors that affect springback of sheet metal laminates, as well as the stretching force. When the stronger material is located outside of the bent laminate, the effect of stretching force on springback control is more than the reverse position of layers. It is demonstrated that the analytical results are in good agreement with experimental results.

Keywords: Laminated sheets, Springback, Side wall curl

1. INTRODUCTION

In recent years, two-layer sheets which consist of dissimilar metallic components have been widely used in various industries. Excellent mechanical and functional properties, corrosion resistance, and different electrical conductivity of each layer are the main advantages of two-layer sheets [1-3].

Springback is a common phenomenon in sheet metal forming processes that is the elastically-driven change of shape of a part after forming. Numerous studies have been conducted on this phenomenon in monolithic sheets when subjected to stretch-bending stretch-unbending to predict the final shape of parts [4-10]. However, few papers have been published on springback of multi-layer sheets so far. Complex deformation mechanisms of two-layer sheets compared with a monolithic sheet due to different mechanical properties and formability of each layer is the primary difficulty in any study of springback in the two-layer sheets.

For monolithic sheets, it is well known that the higher the stretching force, the smaller the springback. However, for sheet metal laminates consisting of dissimilar metal components, the springback behavior is much more complicated than for monolithic sheets [1]. Hino et al. [11] pointed out from the numerical simulations of uniform stretch-bending that higher stretching force does not always reduce the springback of sheet metal laminates.

In current paper, the springback behaviour of two-ply metallic laminates after U-bending process is investigated through theoretical and experimental analysis. A theoretical model based on stress analysis is developed to predict springback. The effects of deformation history and thickness thinning of layers on the springback of two-ply strips are taken into account in the present analysis. U-bending experiments under various stretching force were performed for two-ply laminated strips consisting of pure aluminum (A1100) and stainless steel (SUS304); after process the corner angles and residual curvatures of side wall due to springback were measured.

The effects of stretching force, strength difference between the components, relative position of stronger/weaker layers (layup), and thickness ratio of components on springback are discussed in this paper based on experimental and analytical results. With considering the above-mentioned factors the analytical model presented in this paper can be used to determine the optimum conditions for process parameters and to predict the springback.

2. THEORETICAL APPROACH

In U-bending, the sheet deformation in die and punch corner region can be considered as sheet stretch-bending. The following assumptions are applied:

1 The stretching force per unit width in each layer is considered to be uniform through thickness. However, it is different for each layer. It causes sheet thinning and neutral surface shifting.

2 Straight lines perpendicular to the neutral surface remain straight during process.

3 The strain in the width direction ε_z is zero.

4 The transverse stress, σ_r, in each layer is neglected.

5 The adherence of the two layers is perfect, so there is no strain discontinuity in two layers interface.

6 Volume conservation is kept during stretch–bending process, i.e. $\varepsilon_r + \varepsilon_\theta + \varepsilon_z = 0$.

Where ε_θ and ε_r are the tangential and transverse strain, respectively.

2.1 Thinning of each layer

Considering assumptions (3) and (6), the cross-section area remains constant in each layer and length of neutral surface L_n is constant during two-ply sheet stretch–bending process, following equations are obtained for each layer:

$$L_{m,i} \cdot t_i = L_n \cdot t_{0,i} \tag{1}$$

Where $L_{m,i}$, $t_{0,i}$ and t_i are the arc length of middle surface, initial and final thicknesses of i'th layer, respectively. It is obvious from geometry of Fig. 2:

$$\frac{L_{m,i}}{R_{m,i}} = \frac{L_n}{R_n} \tag{2}$$

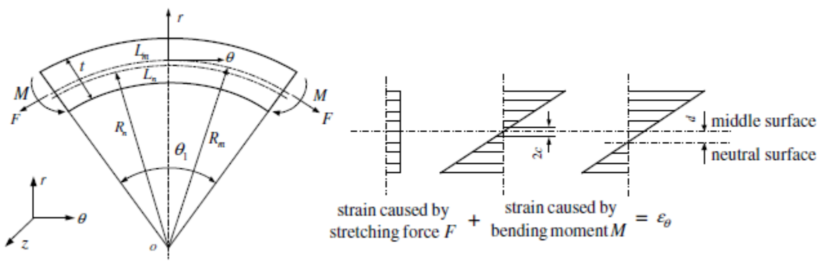


Fig. 1. The strain distribution and neutral surface displacement in sheet stretch bending

So, from (1) and (2):

$$t_i = \frac{R_n}{R_{m,i}} \cdot t_{0,i} \tag{3}$$

Where $R_{m,i}$ is bending radius of middle surface of i'th layer and R_n is the bending radius of neutral surface.

2.2 Calculation of stretching force

The tangential and transverse strain distributions through thickness for each layer are:

$$\varepsilon_\theta = \ln\frac{r}{R_n} \tag{4}$$

$$\varepsilon_r = \ln\frac{t_i}{t_{0,i}} \tag{5}$$

Where r is the bending radius of the concerned arc.
According to plastic flow principle, non-quadratic Hill yielding equation and the assumptions (3) and (4), the effective stress in term of tangential stress can be written as follows:

$$\sigma_e = \begin{cases} \frac{1}{f}.\sigma_\theta & \sigma_\theta \geq 0 \\ -\frac{1}{f}.\sigma_\theta & \sigma_\theta \leq 0 \end{cases} \tag{6}$$

Where σ_θ is the tangential stress, and f which is related to the transverse anisotropy in plane strain condition and combined hardening coefficient obtained as [4]:

$$f = \frac{1}{2}\left[2\left(1+\bar{r}\right)\right]^{\frac{1}{m}}\left[1+\left(1+2\bar{r}\right)^{\frac{-1}{m-1}}\right]^{\frac{m-1}{m}} \tag{7}$$

So, the distribution of tangential stress can be obtained as:

$$\sigma_\theta = \begin{cases} fk\left(\varepsilon_0 + \left|f\ln\frac{r}{R_n}\right|\right)^n & \text{Plastic zone} \\ \frac{E}{1-v^2}\ln\frac{r}{R_n} & \text{Elastic zone} \end{cases} \tag{8}$$

Generally, three possible stress states – elastic, compressive and tensile plastic – might develop through each layer thickness. According to Fig. 3, c_i and d_i are the r-coordinates of arcs at which the elastic/plastic transitions (compressive and tensile, respectively) occur.

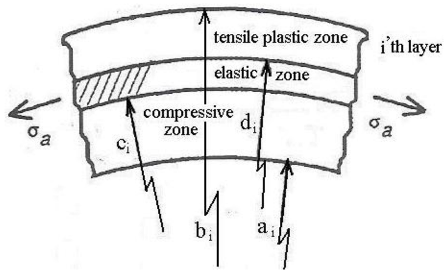


Fig. 2. Position of stress transition arces

So, the distribution of stress in the layer under study can be expressed as:

$$\sigma_{\theta,i} = \begin{cases} -fk\left(\varepsilon_0 - f\ln\dfrac{r}{R_n}\right)^n & a_i < r < c_i \\ \dfrac{E}{1\text{-}\nu^2}\ln\dfrac{r}{R_n} & c_i \le r \le d_i \\ fk\left(\varepsilon_0 + f\ln\dfrac{r}{R_n}\right)^n & d_i < r < b_i \end{cases} \tag{9}$$

In the above equation the material properties of related layer should be used. The net force across each layer is:

$$F_i = \int_{a_i}^{c_i} - fk\left(\varepsilon_0 - f\ln\frac{r}{R_n}\right)^n \cdot dr + \int_{c_i}^{d_i} \frac{E}{1\text{-}\nu^2} ln\frac{r}{R_n} \cdot dr + \int_{d_i}^{b_i} fk\left(\varepsilon_0 + f\ln\frac{r}{R_n}\right)^n \cdot dr \tag{10}$$

Therefore, the stretching force of two-ply sheet is:

$$F = \sum_{i=1}^{2} F_i \tag{11}$$

2.3 The bending moment calculation

The bending moment for two-ply sheets is:

$$M = \sum_{i=1}^{2} M_i \tag{12}$$

$$M_i = M_{e,i} + M_{p,i} \tag{13}$$

Where $M_{e,i}$ is elastic moment and $M_{p,i}$ is plastic moment of the i´th layer that can be calculated as follows:

$$M_{e,i} = \int_{c_i}^{d_i} \left(E\ln\frac{r}{R_n} - \sigma_{nh\theta,i}\right) \cdot (r - R_{nh}) \cdot dr \tag{14}$$

$$\begin{aligned} M_{p,i} &= \int_{a_i}^{c_i} \left(- fK\left(\varepsilon_0 - f\ln\frac{r}{R_n}\right)^n - \sigma_{nh\theta,i}\right) \cdot (r - R_{nh}) \cdot dr \\ &+ \int_{d_i}^{b_i} \left(fK\left(\varepsilon_0 + f\ln\frac{r}{R_n}\right)^n - \sigma_{nh\theta,i}\right) \cdot (r - R_{nh}) \cdot dr \end{aligned} \tag{15}$$

R_{nh} is bending radius of the neutral surface without stretching force F that can be determined from equilibrium equation, and $\sigma_{nh\theta,i}$ can be obtained by replacing r with R_{nh} in Eq. (9).

2.4 Two-ply sheet reverse-bending

It is assumed that in sheet reverse stretch–bending, (a) in each layer, the stretching force is uniform and keeps constant, and (b) the sheet thickness remains unchanged. During punch movement, the sheet is initially stretched and bent around the die radius, then unbent due to leaving the contact surface. During reverse bending process, according to assumptions (a), the neutral surface position is unchanged. The change of tangential stress and bending moment are relative to material hardening rule due to the complicated deformation history. Considering isotropic hardening rule, the distribution of tangential stress change through thickness, $\left|\Delta\sigma_\theta\right|$, can be expressed as follows for the i´th layer:

$$\left|\Delta\sigma_\theta\right| = \begin{cases} fk\left(\varepsilon_0 + \left|f\ln\frac{r}{R_n}\right| - 2\frac{f\left|\sigma_e^r\right|}{E_1}\right)^n + 2f\left|\sigma_e^r\right| - f\sigma_Y & a_i \le r < c_i \quad \text{or} \quad d_i \le r < b_i \\ E_1\left|\ln\frac{r}{R_n}\right| & c_i \le r < d_i \end{cases} \tag{16}$$

$$\left|\sigma_e^r\right| = k\left(\varepsilon_0 + \left|f\ln\frac{r}{R_n}\right|\right)^n \tag{17}$$

$$\sigma'_{nh\theta,i} = \sigma_{nh\theta,i} - \left|\Delta\sigma_\theta\right|_{nh,i} \tag{18}$$

Here, $\left|\Delta\sigma_\theta\right|_{nh,i}$ can be calculated from Eq. (16). The change of bending moment for the i´th layer is:

$$\begin{aligned} \Delta M_i = & \int_{a_i}^{c_i}\left(fK\left(\varepsilon_0 - f\ln\frac{r}{R_n} - 2\frac{f\left|\sigma_e^r\right|}{E_1}\right)^n + 2f\left|\sigma_e^r\right| - f\sigma_Y - \sigma'_{nh\theta,i}\right)\times\left(r - R_{nh}\right)\cdot dr \\ & + \int_{c_i}^{d_i}\left(-E_1\ln\frac{r}{R_n} - \sigma'_{nh\theta,i}\right)^n\cdot\left(r - R_{nh}\right)\cdot dr \\ & + \int_{d_i}^{b_i}\left(fK\left(\varepsilon_0 + f\ln\frac{r}{R_n} - 2\frac{f\left|\sigma_e^r\right|}{E_1}\right)^n + 2f\left|\sigma_e^r\right| - f\sigma_Y - \sigma'_{nh\theta,i}\right)\times\left(r - R_{nh}\right)\cdot dr \end{aligned} \tag{19}$$

And for two-ply sheet, the total change of bending moment is:

$$\Delta M_{Total} = \sum_{i=1}^{2}\Delta M_i \tag{20}$$

Therefore, the distribution of tangential stress through sheet thickness σ_θ^* and the bending moment of cross-section M^* after sheet reverse stretch–bending can be expressed as follows:

$$\sigma_\theta^* = \begin{cases} \sigma_\theta - \left|\Delta\sigma_\theta\right| & R_n \le r < R_o \\ \sigma_\theta + \left|\Delta\sigma_\theta\right| & R_i \le r < R_n \end{cases} \tag{21}$$

$$M^* = M + \Delta M_{Total} \tag{22}$$

R_i and R_o are inner and outer surface radius of sheet respectively.

2.5 Analysis of sheet U-bending

The deformation area of sheet U-bending can be divided into five regions along the length direction as shown in Fig. 4, and the stretching force and bending moment acting on each region are shown in Fig. 4(a)–(e), respectively.

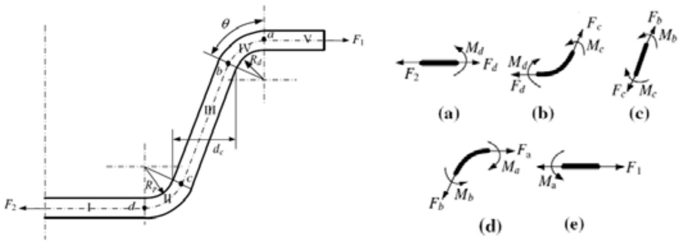


Fig. 1. Deformation regions in U-bending

Region I and V are the flat parts contacting with the straight edges of punch and die, respectively. For simplicity, the bending moment acting on these two regions is neglected, although they should have a curvature. Region II and IV undergoes stretch–bending around the punch and die corner, respectively, in which the sheet thickness, stress and strain distribution and bending moment of cross-section are calculated by stretch–bending formulation.

Region III is the unsupported part and has undergone complex deformation history. It is initially stretched and bent around die corner and then unbent to become sidewall of U-part. The stress and strain distribution and bending moment are calculated using isotropic hardening rule. Because of the bending moment acting on sheet cross-section, the sheet in this region should also have a curvature during forming process. But since the clearance between the die and punch is far smaller than the punch stroke distance, this region can be considered as straight during forming process. However, after the loading is removed, the sheet in this region has a relatively large curvature because of springback.

2.6 Springback of sheet U-bending

The non-uniform distribution of stress in cross-section during forming process will change the part profile and cause springback when the loading is removed. For U-bending, springback happens only in the regions II, III and IV, while the regions I and V remain to be flat before and after the loading are removed. Assuming that the unloading does not cause reverse yielding, the deformation in springback is equivalent to the deformation by adding a reverse bending moment -M in corresponding region.

3. OVERVIEW OF EXPERIMENTS

Fig. 5 shows schematic illustration of U draw-bending process. In order to experimental analysis, three types of two-ply laminates consisting of pure aluminium (JIS A1100) and stainless steel (JIS SUS304) in different thickness ratios were prepared. The total thickness of the two-ply sheet was constant and about 1.2 mm. The material thickness ratios in each studied cases are listed in Table 1.

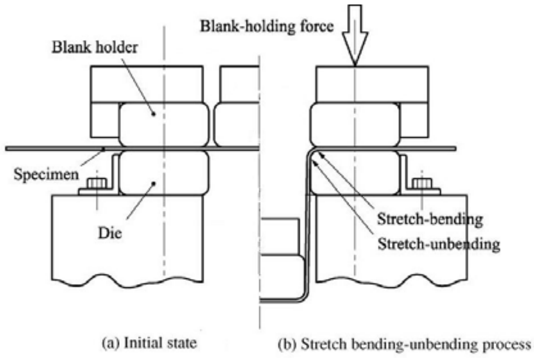


Fig. 5. Schematic illustrations of the draw-bending test

Table 1. Thickness ratio of each material composing a laminated sheet in this study

Material	Case (I)		Case (II)		Case (III)	
	t (mm)	Thickness ratio %	t (mm)	Thickness ratio %	t (mm)	Thickness ratio %
A1100	0.4	33.3	0.6	50	0.8	66.7
SUS304	0.8	66.7	0.6	50	0.4	33.3

In order to obtain mechanical properties, uniaxial tensile tests in 0°, 45°, and 90° directions were performed on each component and results are listed in Table 2.

Table 1**.** The material properties of components.

Material	Poisson ratio (υ)	n (Hardening coefficient)	K (Strength coefficient) (MPa)	Yield Stress (MPa)	Elastic Modulus (GPa)	r (anisotropic coefficient)
SUS304	0.29	0.341	879	205	193	1.04
A1100	0.33	0.06	181	34.5	68.9	0.64

The U-channel bending carried out with the experimental set-up which is shown in Fig. 6. In order to study the effect of parameters, five different set of thickness of strips composed of aluminium alloy and stainless steel sheets tested according to Table 1. Moreover, the effect of blank holder force and relative position of layers (layup) were investigated in these experiments. The loads were applied by a hydraulic system and no lubricant was used for punch/sheet and die/sheet contact surfaces. Fig. 7 shows the geometrical parameters of the die assembly.

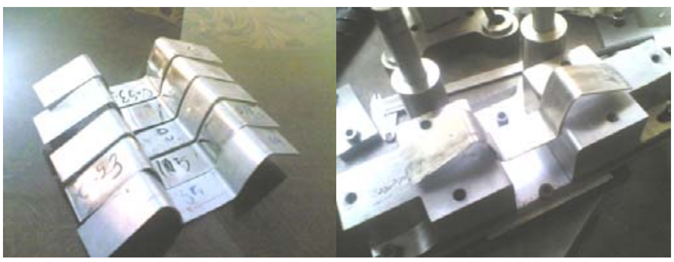


Fig. 6. Experimental set-up and drawn parts.

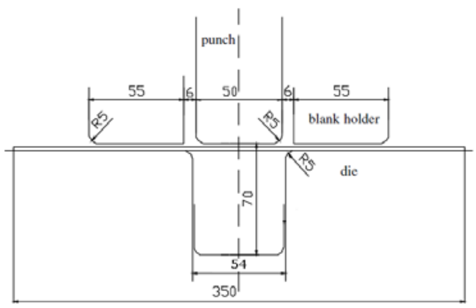


Fig. 7. 2-D schematic of tooling geometry

4. RESULTS AND DISCUSSION

The proposed theoretical model is applied to analyze the 2-D draw bending problem studied in NUMISHEET'93 [16] as shown in Fig. 7 and the springback parameters of θ_1, θ_2 and ρ studied by this benchmark are shown in Fig.8. If the springback angles in the region II, III and IV are Δθ1, Δθsw and Δθ2, respectively, then θ_1 and θ_2 in Fig. 8. can be expressed as:

$$\theta_1 = 90 + \Delta\theta_1 + \frac{\Delta\theta_{sw}}{2} \quad (23)$$

$$\theta_2 = 90 + \Delta\theta_2 - \frac{\Delta\theta_{sw}}{2} \quad (24)$$

For convenience layup of laminates are denoted by their abbreviations, conditions AS and SA denote the relative position of the component layers of the specimen. AS means the condition where the stainless steel layer is located inside of the bent specimen and contacts a die corner. On the other hand, under the condition SA, the aluminum layer is located inside of the bent specimen. ts/t stands for the layer-thickness ratio .

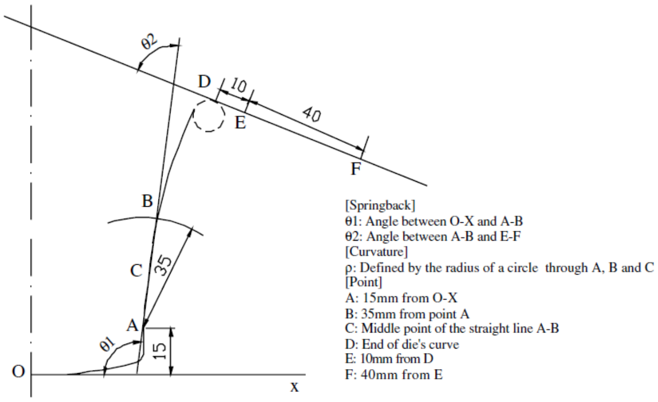
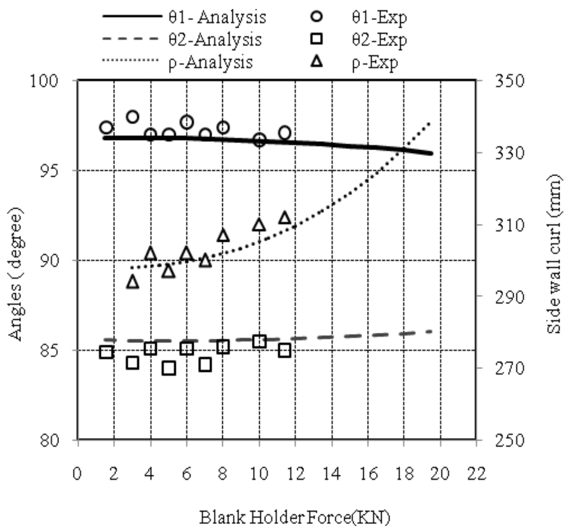
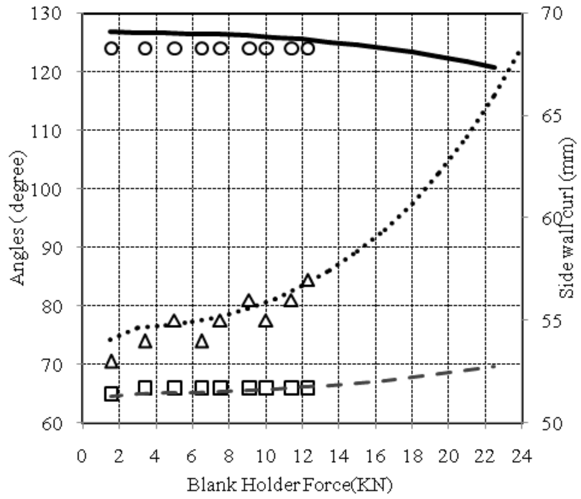


Fig. 8. Measure method of springback

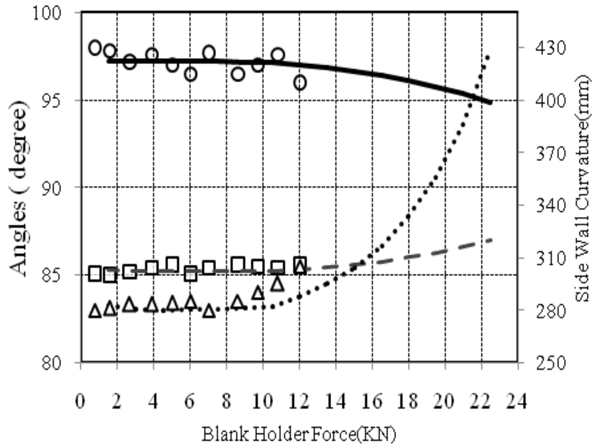
The effect of BHF on the residual curl (ρ) of side-wall and corner angles (θ_1, θ_2) after springback in all studied cases is provided in figures 9 and 10. Figure 9(a)-(c) shows the effect of thickness ratio on springback parameters, as it is depicted in Table 2, the ratio of weaker component thickness to total thickness of laminate increases from Case (I) to Case (III). So, by decrease in thickness ratio of stronger material in same layup the effect of BHF is more observable, i.e. the more BHF, the more control of corner angles and side-wall curvature. The similar tendency is observable in AS layup as is illustrated in figure 10 (a)-(c). Also, figures 9 (a) and 10 (a) demonstrate that in same thickness ratio, the springback of AS layup is more than SA layup. The similar behavior is observed for other studied cases.



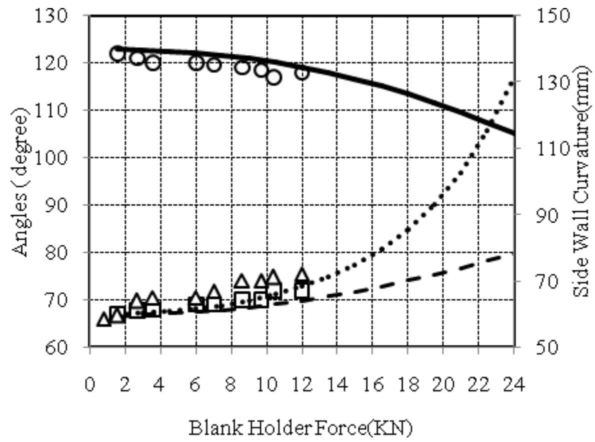
(a) CASE I , SA



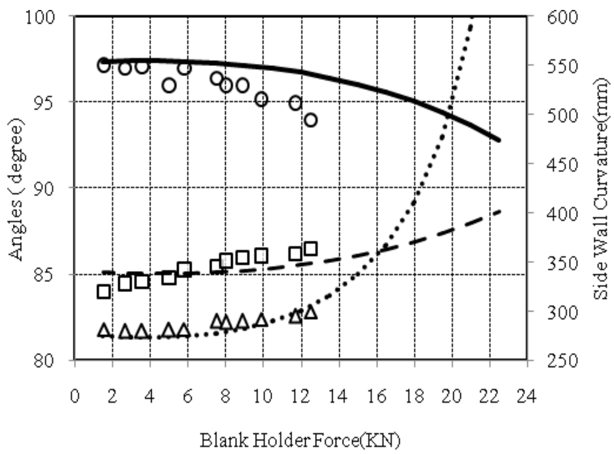
(a) CASE I, AS



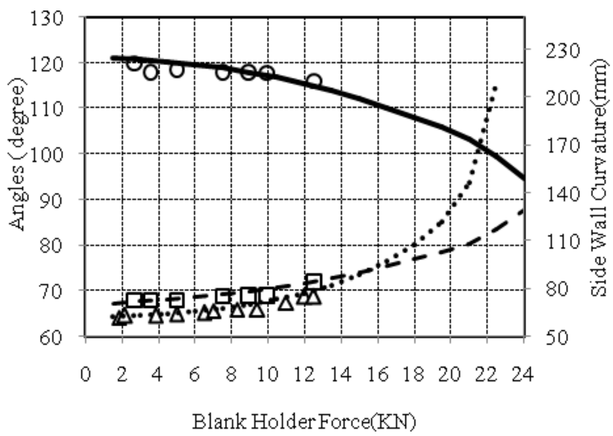
(b) CASE II , SA



(b) CASE II , AS

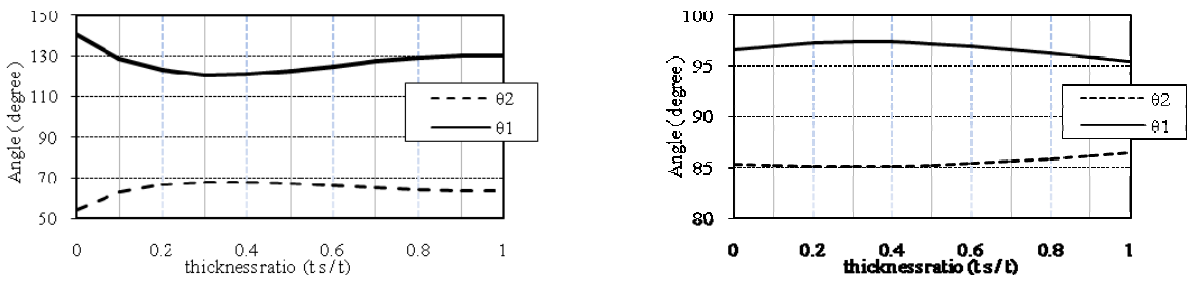


(c) CASE III , SA



(c) CASE III , AS

Fig. 11 shows the effect of thickness ratio of layers on resulted corner angles θ_1, θ_2. As a result, for (ts/t< 0.3) the increasing the stronger material (stainless steel) decrease the springback, but for more than this ratio it effect reversely, there is an optimum condition (ts/t=0.3) that the springback is the least for both relative positions.



(a) AS layup , BH=5KN **(b) SA layup , BH=5 KN**

Fig. 11. Predicted θ1 , θ2 of laminated sheet.

In summary, the analytical results show the same tendency with the experimental ones, but there are found some discrepancy between them. The prediction could be improved by refining the constitutive model, especially for the description of the Bauschinger effect of component materials, and also by considering the stress distribution in the width direction of a laminate strip.

5. CONCLUSION

A new analytical model is developed for prediction of corner angles and side wall curl of laminated sheets in u-bending process related to springback phenomenon. The predicted results are in good agreement with experimental ones. Based on both theoretical and experimental investigations, the springback behavior of sheet metal laminates is strongly affected by the strength difference between the component layers of the laminates, the relative position of the layers, and the layer-thickness ratio, as well as by the stretching force acting on the laminates.

Under the condition SA, where the punch contact metal is the stronger material (stainless steel), the stretching force has more influence on decreasing the springback. It is concluded that in a same blank holder force the condition AS has more springback.

In sum, for determining the optimum condition for springback of laminated strips, one should pay attention to above mentioned factors. The analytical approach presented in this paper would make a great contribution toward springback prediction.

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