Finite Element Analysis of Asymmetrical Leg-length in Closed U-bending Process

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Abstract: In almost all industrial fields such as automobile and aerospace industries, in recent years, the precisely complicated shapes of channel and frame parts are increasingly applied. To fabricate these parts, the U-bending process being a common sheet-metal forming process is widely employed. However, the asymmetrical U-bending process lacks researches. Therefore, in this study, the effects of asymmetrical leg-length on spring-back characteristics in the U-bending process were investigated by using the finite element method (FEM) and laboratory experiments. Specifically, on the basis of stress distribution analysis, they were clearly clarified and also compared with those in the symmetrical leg-length case. These results revealed that, with asymmetrical leg-length in a U-shaped part, the changes in leg-length on one side did not result in any different spring-back characteristics and the obtained bend angle on the other side compared with the symmetrical U-shaped parts. Furthermore, the effects of leg-length on the spring-back characteristics were confirmed that the spring-back slightly increased as the leg-length increased. Laboratory experiments were performed to validate the accuracy of the FEM simulation results. Based on the bend angles and bend forces, the FEM simulation showed good agreement with the experiments in terms of both the bend angles and bending forces.

1 INTRODUCTION

In recent years, the precision requirements on sheet-metal parts shaped channels, beams, and frames of various sizes in almost all industrial fields such as automobile industry, aerospace industry, electronics industry, and housing-utensil industry are increased. To fabricate these shapes of channel, beam, and frame parts, the closed U-die bending process being a common sheet-metal forming process is employed (Lange, 1985, Schuler, 1998). With the merits of closed U-bending process, the thickness at the corner radius and required corner radius could be controlled (Lange, 1985, Schuler, 1998). The secondary operations could be cut off and result in the increases in productivity as well as the decreases in a time consuming and a material loss. In the past, many researches were carried out to focus on the improvement of quality of U-shaped parts by using the experiments and the FEM. Those researches, however, were carried out to investigate the symmetrical closed U-die bending process (Zhang, 2007, Bakhsi-Jooybari, 2009, Panthi, 2010, Thipprakmas, 2012, Phanitwong, 2013). Therefore, the asymmetrical closed U-die bending process has lacked research and then the basic database of its information was insufficient to design the suitable U-bending die (Thipprakmas, 2015). This resulted in the processing difficulty in the control of spring-back feature as well as this major problem also is the main barrier faced in product quality upgrading in the precision U-bending process. The means being absolutely need to provide for countering them is the understanding on process parameter effects on bending mechanism and spring-back characteristics in the asymmetrical closed U-die bending process. In the present research, the FEM simulation was used as a tool to investigate and clearly identify the asymmetrical leg-length effects on bending mechanism and spring-back characteristics, and laboratory experiments were also performed to validate the FEM simulation results. The FEM

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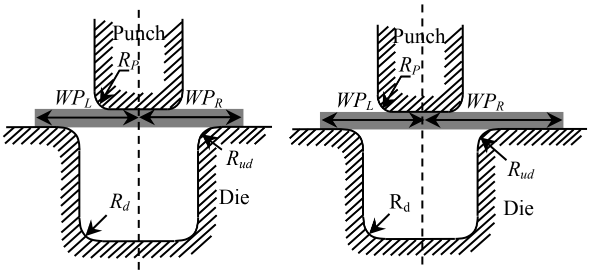
simulation results elucidated that the bending mechanism and spring-back characteristics were clearly elucidated via the changes of stress distribution on the bending allowance zone, the bottom of bent part, and the leg of the bent part. Based on these stress distribution analysis, the FEM simulation clearly revealed the effects of asymmetrical leg-length on bending mechanism and spring-back characteristics. The laboratory experiments confirmed the accuracy of the FEM simulation results. The FEM simulation results showed good agreement with the experimental results with reference to the bend angles and bending force.

2 THE FEM SIMULATION AND EXPERIMENTAL PROCEDURES

In this research, the FEM simulation was used as a tool to investigate and clearly identify the asymmetrical leg-length effects on bending mechanism and spring-back characteristics, and laboratory experiments were also performed to validate the FEM simulation results. Therefore, the FEM simulation and experimental procedures were consequently explained as the followings.

2.1 FEM Simulation Procedure

In this research, to clearly identify the asymmetrical leg-length effects in the closed U-bending process, the models of symmetrical and asymmetrical leg-length were investigated and shown in Fig. 1. Fig. 1(a) and (b) depicted the symmetrical and asymmetrical leg-lengths in the closed U-pending process, respectively. The details of these models and the process parameter conditions investigated in the present research were listed in Table 1. Specifically, the U-die bending model with the die radius (R_d) of 8 mm, punch radius (R_p) of 5 mm, and U-channel width (W) of 40 mm was investigated. The three asymmetrical leg-length levels, as listed in Table 1, were investigated. The 90° bend angle was used as the U-bending angle model to investigate the leg-length effects. The FEM simulation model was a two-dimensional plane strain 3 mm in thickness. The commercial analytical code for the two-dimensional implicit quasi-static finite element method (DEFORM-2D) with the automatic remeshing generation was used as the FEM simulation tool. The work piece material was set as an elasto-plastic type with the rectangular element of approximately 3,500 elements. The punch and die were set as a rigid type. As per the past researches (Thipprakmas, 2012, Phanitwong, 2013), the material used, in the present study, was aluminum A1100-O (JIS). The power-law isotropic hardening model was used and the constitutive equation was determined from the SS-curve obtained by the tensile testing experiment. Specifically, the strength coefficient and strain hardening exponent values were 153.5 MPa and 0.20, respectively.



(a) Symmetrical leg-length (b) Asymmetrical leg-length

Figure 1: FEM simulation models.

Table 1: FEM simulation and experimental conditions.

Simulation model	Plane strain model
Object types	Workpiece : Elasto-plastic Punch/Die : Rigid
Workpiece material	A1100-O, Thickness (t): 3 mm
Friction coefficient (μ)	0.1
Flow curve equation	$\bar{\sigma} = 153.5\bar{\varepsilon}^{0.20} + 88$
Leg-length (WP_L-WP_R) (mm-mm)	40-50, 50-50, 70-50
U-die geometries	U-channel width (W): 40 mm
	Punch radius (R_p): 5 mm
	Die radius (R_d): 8 mm
	Bend angle (θ): 90
	Upper die radius (R_{ud}): 5 mm

2.2 Experimental Procedure

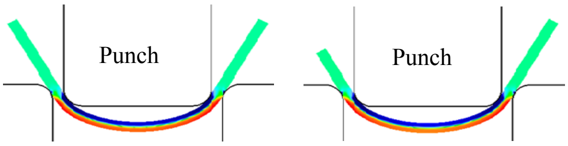
The laboratory experiments were performed to validate the FEM simulation results. As per the experiments of past researches (Thipprakmas, 2012, Phanitwong, 2013), Fig. 2 shows punch and die sets used for the closed U-bending experiments. The 5-ton universal testing machine (Lloyd instruments Ltd) were used for the laboratory U-die bending experiments. After unloading a profile projector (Mitutoyo model PJ-A3000) was used for the bend angle measurement.The bend angle was observed, and the bending force was recorded and compared with the bending force analysed by the FEM simulation.

Figure 2: The punch and die components for experiments.

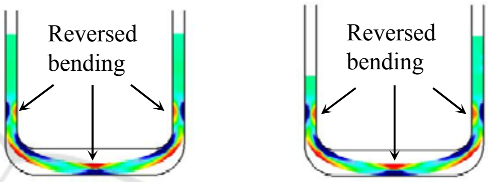
3 RESULTS AND DISCUSSIONS

3.1 Comparison of Bending Mechanism between Symmetrical and Asymmetrical Leg-lengths in Closed U-bending Process

Fig. 3 shows the comparison of stress distribution analysis during bending phase between symmetrical and asymmetrical leg-length cases in closed U-bending process. Fig. 3(a) and (b) show the symmetrical and asymmetrical leg-length cases, respectively. With the bending stroke of approximate 9.5 mm, based on the bending theory, the workpiece was bent underneath the punch and the bending moment was generated. This characteristic resulted in the compressive and tensile stresses respectively generated on the punch and die sides, as illustrated in Fig. 3(a-1) and (b-1). These manners of the stress distribution analysis corresponded well with the bending theory and the literature (Lange, 1985, Schuler, 1998, Thipprakmas, 2012). As the bending stroke proceeded further, as illustrated in Fig. 3(a-2) and (b-2), the workpiece was moved downward and made a contact with die. After that, the reversed bending stress was initially generated in which the tensile and compressive stresses generated on the punch and die sides, respectively. It was observed that the reversed bending stresses were initially generated in the legs as well. These manners of the reversed bending stress distribution analysis again corresponded well with the bending theory and the literature (Phanitwong, 2013). Next, as the bending stroke increased to be 50.0 mm, the workpiece was again bent and it also made a contact with the punch again. These manners resulted in the generated bending and reversed bending stresses as depicted in Fig. 3(a-3), and (b-3). It was also noted that the reversed bending stresses were completely generated in the legs. These manners of the stress distribution analysis corresponded well with the bending theory and the literature (Phanitwong, 2013).



(1) Bending stroke 9.5 mm



(2) Bending stroke 46.0 mm

(3) Bending stroke 50.0 mm

(a) Symmetrical case (b) Asymmetrical case

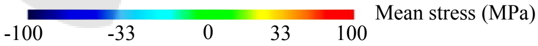
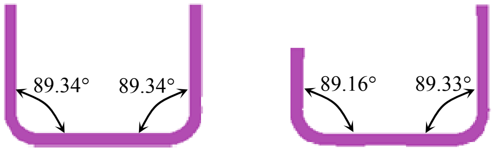


Figure 3: Comparison of stress distribution analysis between symmetrical and asymmetrical leg-length cases.

As per the past researches (Thipprakmas, 2012, Phanitwong, 2013), with compensating these bending and reversed bending stresses, the obtained bend angle could be predicted. After removing punch, as shown in Fig. 4(a) and (b), the predicted bend angles were of 89.24° and 89.24°, and 89.16° and 89.23° in the cases of symmetrical and asymmetrical leg-lengths, respectively. As these results, they corresponded well with the bending theory and the literature (Phanitwong, 2013). Specifically, the spring-back slightly increased as the leg-length increased. These results also confirmed the effects of leg-length on the spring-back characteristic.



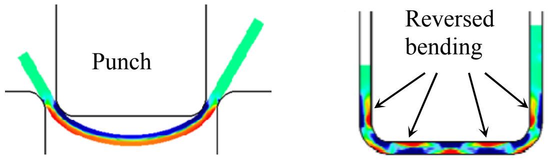
(a) Symmetrical case (50-50 mm)

(b) Asymmetrical case (40-50 mm)

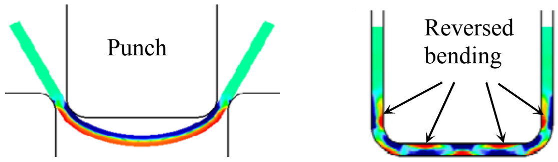
Figure 4: Comparison of the predicted bend angles between symmetrical and asymmetrical leg-length cases.

3.2 Effects of Leg-length on Spring-back Characteristics

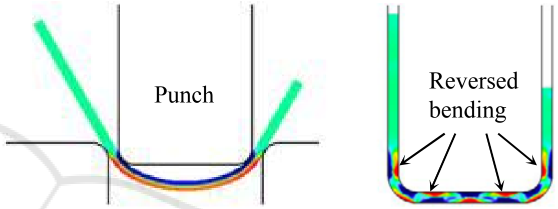
To clearly understand the effects of leg-length on the spring-back characteristics, the symmetrical 90° bend angle was set as the U-bending angle models. Fig. 5 illustrates the stress distribution analyses in the leg-length cases of 40-50 mm, 50-50 mm, and 70-50 mm. With the bending stroke of approximate 9.5 mm, the results showed the same manners of stress distribution analysis in all leg-length cases, as illustrated in Fig. 5(a-1), (a-2), and (a-3). These manners corresponded well with the bending theory and the literature (Thipprakmas, 2012, Phanitwong, 2013). Specifically, the compressive and tensile stresses respectively generated on the punch and die sides. Before unloading phase, as shown in Fig. 5(b-1), (b-2), and (b-3), as aforementioned, the bending and reversed bending stresses were generated in the bottom surface as well as the reversed bending stress was also generated in the leg. The results again showed the same manners of stress distribution analysis in all leg-length cases with a little different scale. These results corresponded well with the bending theory and the literature (Phanitwong, 2013). Specifically, for the symmetrical leg-length, the generated stresses on the left and right sides were equally balanced. In contrast, in the asymmetrical leg-length, the generated stresses were not balanced. Specifically, due to the effects of the leg-length during the bending phase, the generated bending stress depended upon the leg-length as previously mentioned. Therefore, after removing punch, these bending and reversed bending stresses generated in bottom surface and leg were compensated. As depicted in Fig. 6, the results revealed the slightly difference levels of the predicted bend angle being 89.16° and 89.23°, 89.24° and 89.24°, and 89.42° and 89.26° in the leg-length cases of 40-50 mm, 50-50 mm, and 70-50 mm, respectively. However, in the case of too small leg-length as depicted in Fig. 7, it was observed that the reversed bending stress generated in the leg was very small.



(1) Leg-length 40-50 mm



(2) Leg-length 50-50 mm



(3) Leg-length 70-50 mm

(a) Bending str. 9.5 mm (b) Before unloading

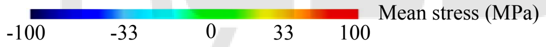
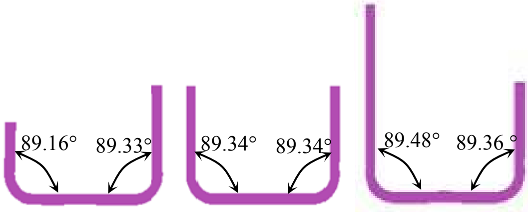


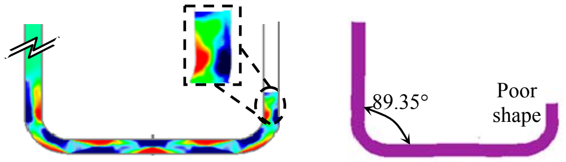
Figure 5: Illustration of stress distribution analysis with respect to the various leg-lengths.

In addition, it was also observed that the poor U-shape was formed. Therefore, these results revealed that, with asymmetrical leg-length in a U-shaped part, the changes in leg-length on one side did not result in any different spring-back characteristics and the obtained bend angle on the other side compared with the symmetrical U-shaped parts. As these results, on practical use, the effect of asymmetrical leg-length in a U-shaped part on spring-back characteristics could be ignored for the design of U-bending die.



(a) 40-50 mm (b) 50-50 mm (c) 70-50 mm

Figure 6: Comparison of the predicted bend angles with respect to the various leg-lengths.

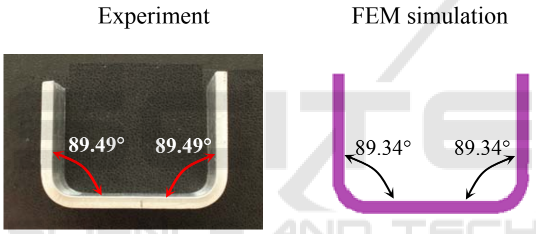


(a) Stress distribution analysis. (b) Predicted bend angle

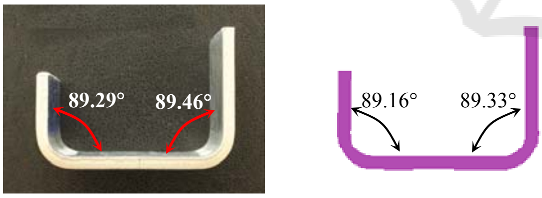
Figure 7: Illustration of stress distribution analysis and predicted bend angle in too small leg-length case.

3.3 Validation of FEM Simulation Results

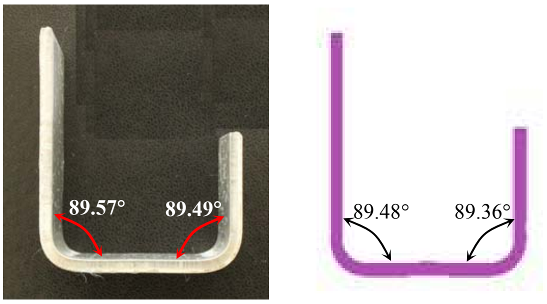
In this research, the laboratory experiments were carried out to validate the accuracy of the FEM simulation results. Fig. 8 shows the comparison of the bent parts in the case of symmetrical and asymmetrical leg-length with 90° bend angle and 5 mm in tool radius obtained by the FEM simulation analyses and the experiments. The FEM simulation result showed good agreement with the experimental result, in which the errors in the bend angles as compared to the experimental results were approximately 1 %. The analysed bending force was also compared with that obtained by experiment, as shown in Fig. 9. The FEM simulation result illustrated a good agreement with the experimental result, in which the error was approximately 1 %.



(a) Leg-length 50-50 mm



(b) Leg-length 40-50 mm



(c) Leg-length 70-50 mm

Figure 8: Comparison of the bend angles between the experimental and simulation results.

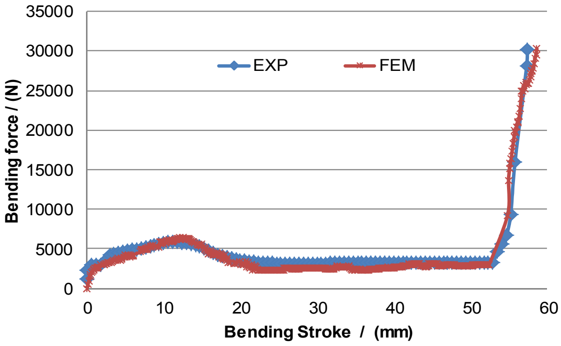


Figure 9: Comparison of the bend forces between the simulation and the experimental results. (Leg-length 40-50 mm).

4 CONCLUSIONS

In the present research, the bending mechanism in the case of asymmetrical leg-length was investigated by using the FEM simulation to clearly understand the spring-back characteristics in the closed U-bending process. Based on the stress distribution analysis, the bending mechanism was investigated and clearly identified via the changes of stress distribution analysis. This bending mechanism was also compared with that in the symmetrical leg-length case. The FEM simulation results revealed that the bending and reversed bending stresses generated in the corner radius, bottom surface, and legs. With the different asymmetrical leg-length cases, the results illustrated that, with asymmetrical leg-length in a U-shaped part, the changes in leg-length on one side did not result in any different spring-back characteristics and the obtained bend angle on the other side compared with the symmetrical U-shaped parts. However, the effects of leg-length on the spring-back characteristic which corresponded well with the past research were again confirmed that the spring-back slightly increased as the leg-length increased. It was also noted that the application of too small leg-length caused the poor U-shape part. The FEM simulation results, as validated by laboratory experiments, showed good agreement with the experimental results, in which the errors in both the bend angles and bending forces compared with the laboratory experimental results were approximately 1% and 1%, respectively.

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APPENDIX

NOMENCLATURES

R_d = Die radius
R_p = Punch radius
R_{ud} = Upper die radius
t = Workpiece thickness
W = U-channel width
WP_L = Workpiece length left side
WP_R = Workpiece length right side
θ = Bend angle
μ = Friction coefficient.