Spring-back factor applied for V-bending die design

Sutasn THIPPRAKMAS*

* Dept. of Tool and Materials Engineering, King Mongkut's University of Technology Thonburi
126 Bangmod, Thungkru, Bangkok 10140, Thailand
E-mail: sutasn.thi@kmutt.ac.th

Received: 19 April 2019; Revised: 25 September 2019; Accepted: 23 October 2019

Abstract
To fabricate various parts with complex shapes in the sheet-metal bending industry, the V-die bending process is commonly applied. To achieve precisely bent sheet-metal parts, the design of a proper V-bending die which could prevent the spring-back characteristic and obtain the required bend angle as well as control and maintain the required bend radius is needed. The predicted spring-back and bent radius could be basically calculated by using the spring-back factor. In the present research, therefore, the accuracy of the spring-back factor for bend angle prediction and bend radius calculation in the V-die bending process was examined based on the finite element method (FEM) and laboratory experiments. The two existing spring-back factors, including the conventional and adjusted spring-back factors, were investigated. The results showed that, compared with experimental results, the accuracy of the bend angle prediction and the bend radius calculation obtained using the adjusted spring-back factor were better than those obtained using the conventional spring-back factor. These results were clarified based on the stress distribution analysis of the sheet-metal bent parts. Therefore, the adjusted spring-back factor was recommended over the conventional spring-back factor for V-bending die design applications to achieve a better accuracy bend angle prediction and bend radius calculation.

Keywords: Bending, Sheet metal, Spring-back, Bend angle, V-bending die, Finite element method

1. Introduction

A common and vital bending process to deform sheet metal into curved shapes, employed in many industrial fields such as the automotive, aerospace, electronics, and housing-utensil industries, is the V-die bending process. By using this process, various ranges of parts with complex shapes can be fabricated with an economical setup. In the past, therefore, most research on the V-die bending process has focused on the different ways of developing the process design as well as on achieving precision bent parts via the finite element method (FEM) and experimental analysis (Xie et al., 2015), (Thipprakmas, 2011), (Phanitwong and Thipprakmas, 2014), (Thipprakmas, 2013), (Wang et al., 2015), (Xiong et al., 2015), (Ahmadi et al., 2017), (Thipprakmas, 2010), (Li et al., 2015), (Wang et al., 2013), (Leu, 2013), (Abea et al., 2017), (Hakan and Mustafa, 2013). For example, (Xie et al., 2015) applied the direct-current pulses technique on the V-bending of AZ31B magnesium alloy sheet and investigated the influence of direct-current pulses on the spring-back characteristics during the bending phase. The mechanism of coined-bead application used in the V-die bending process was investigated. By using the FEM simulation technique, the mechanism of coined-bead application was elucidated (Thipprakmas, 2011) and the effects of coined-bead size on the spring-back characteristics were revealed as well (Phanitwong and Thipprakmas, 2014). The sided coined-bead technique was proposed to obtain a precision bend radius in the V-die bending process (Thipprakmas, 2013). (Wang et al., 2015) studied the effects of twinning and detwinning on the spring-back characteristics and the shift of the neutral layer in AZ31 magnesium alloy sheets in the V-die bending process. (Xiong et al., 2015) studied the geometric issues in the V-bending electromagnetic forming process of 2024-T3 aluminum alloy. (Ahmadi et al., 2017) investigated the deformation-induced martensitic transformation in V-bent anisotropic stainless steel 304L sheets using both experimental and numerical techniques.
However, in terms of bend angle, the spring-back characteristic is still the principal forming problem in this process, causing a pronounced decrease in the quality of the bent parts. In addition to the spring-back characteristics, the bent radius is also strictly controlled, especially in precision bent parts. To prevent the spring-back characteristic and achieve the required bend radius by achieving the proper V-bending die design for the fabrication of precision bent parts, the over-bending technique is commonly applied. This technique compensates for the spring-back characteristic by setting a smaller bend angle than that required. Therefore, the amount of spring-back should be neatly predicted for the proper V-bending die design. The tool radius should be properly designed to achieve the required bend radius after removing the tool and compensating for the spring-back characteristic. Basically, by using the spring-back factor, the spring-back can be predicted and the bend radius can be calculated. However, as the key factor for the spring-back prediction and bend radius calculation, the spring-back factor has not been thoroughly investigated, especially for the V-die bending process. Only a few research studies on this issue have been conducted (Ling et al., 2005), (Phanitwong and Thipprakmas, 2016), (Ling et al., 2005) confirmed the results, which corresponded well with the conventional spring-back factor (Lang, 1985) in that the decreases in the spring-back factor were obtained as the ratios of the die radius to the part thickness and the part radius to the part thickness increased. (Phanitwong and Thipprakmas, 2016) developed a new spring-back factor, named the adjusted spring-back factor, for a wiping die or L-die bending process. Their uses offered greater accuracy in the spring-back prediction than that achieved using the conventional spring-back factor.

In terms of the V-die bending process, the accuracy of the conventional spring-back factor application in V-bending die designs has not yet been examined—nor has the adjusted spring-back factor. In the present research on the conventional and adjusted spring-back factors, their uses were investigated for the examination of accuracy of spring-back prediction and bend radius calculation in the V-die bending process using the FEM and laboratory experiments. The results showed the better accuracy of spring-back prediction and bend radius calculation using the adjusted spring-back factor as compared to those achieved using the conventional spring-back factor. On the basis of the stress distribution analysis, the causes of these results were elucidated by the FEM simulation results. It was found that not only the bending stress was generated on a bending allowance zone, but the reversed bending stress was also generated on a bending allowance zone. In addition, the bending and reversed bending stresses were also generated on legs of the workpiece. Therefore, to design proper V-bending dies for precision bent parts, the spring-back factor should be strictly considered for spring-back prediction and bend radius calculation. It was thus concluded in the present research that the adjusted spring-back factor is more suitable than the conventional spring-back factor for V-bending die design applications, to achieve good accuracy spring-back prediction and bend radius calculation.

2. Spring-back and spring-back factor

On the basis of plastic deformation theory, in terms of bending process, the material is generally divided into two zones of elastic and the plastic during bending phase. After removing bending load, the elastic property tries to maintain the material in the initial shape, whereas the plastic property tries to retain the material in the deformed shape. This results in a partial recovery toward its initial shape and is called “spring-back”. Therefore, after the bending operation, the bent part tries to slightly open out and causes the final bend angle is greater than initial bend angle formed. The radius of the bend will try and return in the same way the angle does as well. It means that the final radius is also greater than the initial radius formed. These cause the main barrier to control the dimensions of bent parts to meet their requirements. In general, the spring-back factor has come a long way to apply for spring-back prediction and bend radius calculation (Lang, 1985), (Sculer, 1998), (Ling et al., 2005), (Phanitwong and Thipprakmas, 2016). In terms of V-die bending process, the spring-back factor is commonly defined as the ratio of the bend angle of the tool to the bend angle of workpiece after unloading as shown in Equation (1). Next, during V-die bending phase, the workpiece is bent and the arc is generally formed on bending allowance zone (Lang, 1985), (Sculer, 1998). Absolutely, the length of the arc directly depends on the radius of the arc and the central angle of the arc and its relationship is shown as Equation (2). Namely, in terms of V-die bending process, it depends on the bend angle and bend radius. On the basis of these relationships of spring-back factor and arc length, the spring-back factor could be derived for bend radius calculation as shown in Equation (3).

\[
\text{Spring-back factor} = \left( \frac{\theta_t}{\theta_w} \right)
\]

Where \(\theta_t\) is the bend angle of the tool and \(\theta_w\) is the bend angle of workpiece after unloading.
Arc length = $2\pi R \left( \frac{C}{360} \right)$

Where $C$ is the central angle of the arc in degrees and $R$ is the radius of the arc.

Spring-back factor = $(R_t + 0.5t) / (R_w + 0.5t)$

Where $R_t$ is the tool radius, $R_w$ is the bend radius of workpiece after unloading, and $t$ is the material thickness.

However, in the recent years, the spring-back factor has been investigated and developed to achieve more accuracy of spring-back prediction and bend radius calculation (Ling et al., 2005), (Phanitwong and Thipprakmas, 2016). The new finding revealed in (Phanitwong and Thipprakmas, 2016) is that, in L-die bending process, not only the pure bending characteristics are generated in the bending allowance zone and reversed bending characteristics are also generated in the unclamped leg. These generated stress characteristics are considered for an adjusted spring-back factor. In addition, it also revealed that the spring-back factors depended on the bend angle. Specifically, the spring-back factors increased as the bend angles increased. (Phanitwong and Thipprakmas, 2016) confirmed that, to achieve the required precise bend angle, the use of the adjusted spring-back factor, which considers the effects of the bend angle on the bending characteristics in the bending allowance zone and the reversed bending characteristics in the unclamped leg of the workpiece, is vital and is strongly recommended.

3. The FEM simulation and experimental procedures
3.1 The FEM simulation procedures

In the present research, to compare the stress distribution analysis between L- and V-die bending processes, the models of L- and V-die bending processes were investigated, as respectively shown in Figures 1(a) and (b). The bend angles of $90^\circ$ and $120^\circ$ were investigated in the present research. An L-bending die model with die radii ($R_d$) of 2 mm and 8 mm and a V-bending die model with punch radii ($R_p$) of 2 mm, 6 mm, and 8 mm were used. The two-dimensional, implicit quasi-static finite element method of a commercial analytical code, DEFORM-2D, was used for the FEM simulation. The applied solution algorithm in these FEM models was based on the Newton-Raphson iteration. In addition, an adaptive remeshing technique was also applied to prevent divergence of the calculation due to excessive deformation of the elements during the bending phase. It was set in every three steps. Two-dimensional plane strain, with a workpiece length of 80 mm, was applied. As listed in Table 1, the punch and die were set as rigid types. The workpiece material was set as an elasto-plastic type and the plastic properties of this workpiece material were assumed to be isotropic and described by the von Mises yield function. The rectangular elements of approximately 3500 elements were generated. The aluminum A1050-H14 (JIS) was used as the workpiece material and it was described as an elasto-plastic, power-exponent, isotropic hardening model. As per the past researches (Thipprakmas and Phanitwong, 2012), (Thipprakmas and Boochakul, 2015), (Phanitwong and Thipprakmas, 2016), its mechanical properties were taken from the tensile testing data and its constitutive equation was determined from the stress–strain curve. The strength coefficient and the strain hardening exponent values were 114.18 MPa and 0.095, respectively. The other material properties are given in Table 1, where $E$, $\nu$, and $\sigma_u$ denote the Young modulus, the Poisson's ratio, and the ultimate tensile stress, respectively. The other process parameter conditions were also designed, as shown in Table 1. On the basis of the contact surface model defined by a Coulomb friction law, as per past researches (Thipprakmas and Boochakul, 2015), (Phanitwong and Thipprakmas, 2016), a friction coefficient ($\mu$) of 0.10 was applied. In usual, deformations in V-bending are divided into 3 stages, i.e., 1) air bending stage, 2) bottoming stage and 3) coining stage. Spring-back phenomenon in V-bending depends on the stage just before the unloading started. In the present research, by observing the bending load and generated compressive stress distribution on the bent parts, the unloading stage immediately started after the steeply increasing in bending load formed as well as in generated compressive stress distribution formed on the bent parts.
Simulation model

Object types
Workpiece: Elasto-plastic
Punch/Die/Blank holder: Rigid

Workpiece material
A1050-H14
Ultimate tensile stress ($\sigma_u$): 105 MPa
Elongation ($\delta$): 10%
Plastic anisotropy ($r_0$): 0.345
Young’s modulus ($E$): 69000 MPa
Poisson’s ratio ($\nu$): 0.33

Friction coefficient ($\mu$)
0.1

Flow curve equation
$\tau = 144.18\varepsilon^{0.095} + 89.38$

Workpiece geometries
Thickness ($t$): 1 and 3 mm
Length ($WP_L$): 80 mm

L-bending die geometries
Punch radius ($R_p$): 5 mm
Die radius ($R_d$): 2 and 8 mm
Bend angle ($\theta$): 90° and 120°

V-bending die geometries
Punch radius ($R_p$): 2, 5, and 8 mm
Bend angle ($\theta$): 90° and 120°
Upper die radius ($R_{ud}$): 5 mm

| Simulation model | Plane strain model |
|------------------|--------------------|
| Object types     | Workpiece: Elasto-plastic |
|                  | Punch/Die/Blank holder: Rigid |
| Workpiece material| A1050-H14 |
|                  | Ultimate tensile stress ($\sigma_u$): 105 MPa |
|                  | Elongation ($\delta$): 10% |
|                  | Plastic anisotropy ($r_0$): 0.345 |
|                  | Young’s modulus ($E$): 69000 MPa |
|                  | Poisson’s ratio ($\nu$): 0.33 |
| Friction coefficient ($\mu$) | 0.1 |
| Flow curve equation | $\tau = 144.18\varepsilon^{0.095} + 89.38$ |
| Workpiece geometries | Thickness ($t$): 1 and 3 mm |
|                  | Length ($WP_L$): 80 mm |
| L-bending die geometries | Punch radius ($R_p$): 5 mm |
|                  | Die radius ($R_d$): 2 and 8 mm |
|                  | Bend angle ($\theta$): 90° and 120° |
| V-bending die geometries | Punch radius ($R_p$): 2, 5, and 8 mm |
|                  | Bend angle ($\theta$): 90° and 120° |
|                  | Upper die radius ($R_{ud}$): 5 mm |

3.2 The experimental procedures

The laboratory experiments were performed to validate the FEM simulation results. As per the experiments of past research studies (Thipprakmas, 2015), (Phanitwong and Thipprakmas, 2014), (Phanitwong and Thipprakmas, 2016), the press machine, which includes a 5-ton universal testing machine (Lloyd Instruments Ltd) and L- and V-bending dies were shown in Figure 2. In the present research, a workpiece width of 30 mm was applied. With this width, a ratio of workpiece width to thickness of 30 was obtained. Therefore, it was ensured that the bending deformation was primarily under plane strain conditions in the experiments. Again, to clearly determine the unloading stage, the bending load was carefully observed during bending phase and the unloading stage immediately started after the steeply increasing in bending load formed. To calculate the amount of spring-back and the bend radius, the bend angle and bend radius after unloading were measured. In the present research, five samples from each bending condition were used to inspect the obtained bend angles and bend radii and they were measured using a profile projector (Mitutoyo Model PJ-A3000). Based on these obtained bend angles, the average bend angle and the average bend radius with their standard deviations (SD) were reported. These experimentally determined average values of bend angle and bend radius were compared with those determined by the FEM simulations.
4. Results and discussion

4.1 The use of FEM simulation and its validation

In the present research, the basis of L- and V-die bending process, the characterizations of the stress distribution analysis, and the prediction of the obtained bend angle and bend radius were investigated and clarified by FEM simulation. Therefore, a validation of the FEM simulation results was performed. By comparing with the laboratory experiments, as respectively shown in Figures 3 and 4 for L- and V-die bending processes, the obtained bent parts were compared with the FEM simulation results, and a good agreement was found. Based on the five bent parts, the average measured bend angle and bend radius with their standard deviations were reported. The FEM simulation results showed that the predicted bend angle corresponded well with the experiments. Specifically, in the case of the L-die bending process, the FEM simulation results showed predicted bend angles of approximate 92.31° and 123.56° in the cases of 90° and 120° bend angles, respectively. The results also showed the same manner as the experimental results. The experimental results showed that the average bend angles of approximate 91.89° and 123.20° in the cases of 90° and 120° bend angles, respectively, were obtained. These FEM simulation and experimental results, in terms of spring-back characteristics, generally agreed with those reported in the literature (Phanitwong and Thipprakmas, 2016) in that the spring-back increased as the bend angle increased. The errors in the analyzed bend angle, by comparing with the experimental results, were approximately less than 1%. Next, in terms of bend radius, the FEM simulation results showed that the predicted bend radii were larger than the tool radius, which agrees with the bending theory (Lang, 1985), (Sculer, 1998). They were approximately 2.103 mm and 8.304 mm in the cases of 90° and 120° bend angles, respectively. These FEM simulation results again showed good agreement with the experimental results. The experimental results showed the average obtained bend radii of approximately 2.098 mm and 8.290 mm in the cases of 90° and 120° bend angles, respectively. The errors in the predicted bend radius were approximately less than 1%, as compared to those obtained by the experimental results.

Next, in the case of the V-die bending process, the FEM simulation results also showed good agreement with those obtained by the experiments, as shown in Figure 4. The FEM simulation results showed that the spring-back characteristic was generated in the case of a 90° bend angle and the spring-go (negative spring-back) characteristic was generated in the case of a 120° bend angle. This spring-go characteristic was also occurred in the experimental results. Specifically, for the 90° bend angle, the predicted bend angle of approximate 90.09° was analyzed by FEM simulation and the average bend angle of approximate 90.21° was obtained by the experiments. Next, in the case of the 120° bend angle, the predicted bend angle of approximate 119.46° was analyzed by FEM simulation and the average bend angle of approximate 118.98° was obtained by the experiments. The errors in the analyzed bend angles were approximately less than 1%, according to a
comparison with those obtained by the experiments. In terms of the bend radius, the FEM simulation results again showed good agreement with the bending theory (Lang, 1985), (Sculer, 1998). Specifically, the predicted bend radii were larger than the tool radius in the case of 90° bend angles where the spring-back characteristic was generated, but the predicted bend radii were smaller than the tool radius in the case of 120° bend angles where the spring-go characteristic was generated. They were approximately 2.035 mm and 7.895 mm in the cases of 90° and 120° bend angles, respectively. By comparison with the experiments, these FEM simulation results again showed good agreement.

The experimental results showed the average obtained bend radii of approximately 2.063 mm and 7.845 mm in the cases of 90° and 120° bend angles, respectively. The errors in the predicted bend radius were approximately less than 1%, as compared to those obtained by the experimental results.

4.2 Bend angle and bend radius predictions using spring-back factor application

In the present research, the spring-back factor was applied to predict the bend angle. Based on the bending theory (Sculer, 1998), the spring-back factor is the ratio of the bend angle of the tool to the bend angle of the workpiece after unloading, as shown Equation (1). In the present research, based on the conventional and adjusted spring-back factors, the predicted bend angles could be calculated; they are listed in Table 2. To clearly explain the expendability of current results when changing the material thickness of workpiece and bend radius, the material thickness of 3 mm was also investigated and the results were also reported in Table 2. In the case of 90° bend angle, 6-mm bend radius, and 3-mm material thickness, the spring-back factor was 0.975 in the case of conventional spring-back factor application (Lang, 1985), and the calculated bend angle was 92.30°. On the other hand, in the case of adjusted spring-back factor application (Phanitwong and Thipprakmas, 2016), the spring-back factors were 0.976 for 90° bend angle. Therefore, its calculated bend angle was 92.21°. By comparing with the bend angles obtained from the experiments, as listed in Table 2, the errors of the uses of the conventional and adjusted spring-back factors in the case of the 90° bend angle were respectively 4.38% and 4.28%. Next, in the case of the 120° bend angle, 8-mm bend radius, and 1-mm material thickness, the spring-back factor was 0.942 in the case of conventional spring-back factor application (Lang, 1985), and the calculated bend angle was 127.39°. On the other hand, in the case of adjusted spring-back factor application (Phanitwong and Thipprakmas, 2016), the spring-back factor was 0.971 for 120° bend angle. Therefore, its calculated bend angle was 123.57°. By comparing with the bend angles obtained from the experiments, as listed in Table 2, the errors of the uses
Fig. 4 Comparison of FEM simulation and experimental results in the case of the V-die bending process.

Table 2  Bend angle calculation using the spring-back factor.

| V-die bending model | Bend angle / Bend radius / Material thickness |
|---------------------|---------------------------------------------|
|                     | 90° / 6 mm / 3 mm | 120° / 8 mm / 1 mm |
|                     | Experimental results: Average bend angle     | 88.26° | 118.98° |
| Bend angle          | Conventional spring-back factor (K)          | K: 0.975 | 92.30° | K: 0.942 | 127.39° |
| calculation         | Adjusted spring-back factor (K_a)            | K_a: 0.976 | 92.21° | K_a: 0.971 | 123.57° |
| % Errors            | Comp. Conventional spring-back factor (K)    | 4.38     | 6.60   |
|                     | Exp Adjusted spring-back factor (K_a)        | 4.28     | 3.71   |

of the conventional and adjusted spring-back factors in the case of the 120° bend angle were respectively 6.60% and 3.71%. These results again confirmed that the spring-back prediction could be more accuracy by using the adjusted spring-back factor. In addition, these results also confirmed the expendability of current results when the various material thicknesses of workpieces were applied. As these results clearly illustrate, the adjusted spring-back factor offered greater accuracy in the bend angle prediction than the conventional spring-back factor. It was also observed that the error decreased as the bend angle decreased. These results confirmed that the adjusted spring-back factor could be more suitable than the conventional spring-back factor in applications for bend angle prediction in the V-die bending process.

Next, in terms of the bend radius, the spring-back factor could be applied to calculate the bend radius as well. Based on the bending theory (Sculer, 1998), the equation of bend radius calculation is shown in Equation (3). Again, based on the conventional and adjusted spring-back factors, the bend radii were calculated as listed in Table 3. To clearly explain the expendability of current results when changing the material thickness of workpiece and bend radius, the material thickness of 3 mm was also investigated and the results were also reported in Table 3. In the case of 90° bend angle, 6-
mm bend radius, and 3-mm material thickness, the spring-back factor was 0.975 in the case of conventional spring-back factor application (Lang, 1985), and the calculated bend radius was 6.192 mm. On the other hand, in the case of adjusted spring-back factor application (Phanitwong and Thipprakmas, 2016), the spring-back factors were 0.976 for 90° bend angle. Therefore, its calculated bend radius was 6.184 mm. By comparing with the bend radii obtained from the experiments, as listed in Table 3, the errors of the uses of the conventional and adjusted spring-back factors in the case of the 90° bend angle were respectively 7.87% and 7.73%. Next, in the case of the 120° bend angle, 8-mm bend radius, and 1-mm material thickness, the spring-back factor was 0.942 in the case of conventional spring-back factor application (Lang, 1985), and the calculated bend radius was 8.523 mm. On the other hand, in the case of adjusted spring-back factor application (Phanitwong and Thipprakmas, 2016), the spring-back factor was 0.971 for 120° bend angle. Therefore, its calculated bend radius was 8.254 mm. By comparing with the bend radii obtained from the experiments, as listed in Table 3, the errors of the uses of the conventional and adjusted spring-back factors in the case of the 90° bend angle were respectively 7.96% and 5.00%. These results again confirmed that the bend radius calculation could be more accuracy by using the adjusted spring-back factor. In addition, these results also confirmed the expendability of current results when the various material thicknesses of workpieces were applied. As these results, in addition to bend angle, they again illustrated and confirmed that the adjusted spring-back factor offered greater accuracy in the bend radius calculation than the conventional spring-back factor. These results confirmed that the adjusted spring-back factor could be more suitable than the conventional spring-back factor in applications for bend radius calculation in the V-die bending process.

4.3 Stress distribution analysis of the bent parts with respect to the L- and V-die bending process

Figure 5 shows the stress distribution analysis of the bent parts before unloading to clarify the differences of spring-back characteristics on L- and V-die bending processes. The cases of L- and V-die bending processes with a 90° bend angle are respectively shown in Figures 5(a), 5(b) and the cases of L- and V-die bending processes with a 120° bend angle are respectively shown in Figures 5(c), 5(d). The FEM simulation results illustrated that the analyzed stress distribution corresponded well with the bending theory and the literature in the case of L- and V-die bending processes. Namely, the bending stress distribution was commonly generated on the bending allowance zone in the case of the L-die bending process (Phanitwong and Thipprakmas, 2016). In contrast, because the bottom of workpiece was again bent in a reversed direction by the die, as shown in Figure 6(a), the workpiece was then moved upward to make more contact with the punch tip, as shown in Figure 6(b). This process resulted in an increase in the formation of reversed bending stress distribution, as shown in Figure 6(b). Therefore, as the workpiece was completely clamped by the punch and die, the reversed bending stress distribution was generated on the bending allowance zone instead of bending stress distribution. This resulted in decreases in the bending stress distribution on this zone, as shown in Figures 5(b), 5(d). Next, the reversed bending stress distribution was generated in the unclamped leg in the L-die bending process (Phanitwong and Thipprakmas, 2016). According to past research studies (Thipprakmas, 2011), (Phanitwong and Thipprakmas, 2014), (Thipprakmas, 2013), (Phanitwong and Thipprakmas, 2016), the reversed bending stress distribution is usually generated in both leg sides in the V-die bending process. However, with a small bend angle and bend radius, the legs were reversely bent twice and then the bending and reversed bending stress distributions were generated, as shown in Figure 5(d). As per past research studies (Thipprakmas, 2011), (Phanitwong and Thipprakmas, 2014), (Thipprakmas, 2013), (Phanitwong and Thipprakmas, 2016), the bending stress caused the spring-back characteristic and the bent part slightly opened; in contrast, the reversed bending stress caused the spring-go characteristic and the bent part slightly closed. The spring-back and spring-go characteristics could

Table 3 Bend radius calculation using the spring-back factor.

| V-die bending model | Bend angle / Bend radius / Material thickness |
|---------------------|-------------------------------------------|
|                     | 90° / 6 mm / 3 mm                         |
|                     | 120° / 8 mm / 1 mm                        |
| Conventional spring-back factor (K) | 0.975 | 6.192 mm |
| Conventional spring-back factor (Kc) | 0.976 | 6.184 mm |
| Adjusted spring-back factor (K)      | 0.942 | 8.523 mm |
| Adjusted spring-back factor (Kc)     | 0.971 | 8.254 mm |
| % Errors                          | Comp. | 7.87   |
|                                  | Exp.  | 7.73   |
be predicted by compensating these bending and reversed bending stress distributions and then the calculated bend angle could be obtained. In the case of the 90° bend angle, excluding the bending stress distribution generated on the bending allowance zone, the FEM simulation results showed that the small reversed bending stress distribution was generated on the unclamped leg in the L-die bending process, as shown in Figure 5(a). After compensating for these stress distributions, the predicted spring-back was 2.31° and the obtained bend angle was 92.31° in the case of the L-die bending process. In contrast, the bending and reversed bending stresses distribution was generated on the bending allowance and both leg sides in the V-die bending process, as shown in Figure 5(b). This manner of stress distribution analysis generally agrees with that reported in the literature (Phanitwong and Thipprakmas, 2014). The predicted spring-back was 0.09° and the obtained bend angle was 90.09° in the case of the V-die bending process. In the case of the 120° bend angle, the L-die bending process (as shown in Figure 5(c)) led to reversed bending stress distribution generated on the unclamped leg, and it was larger than that in the case of the 90° bend angle. This manner of stress distribution analysis generally agrees with that reported in the literature (Phanitwong and Thipprakmas, 2016). However, owing to the reversed bending stress generated on only the unclamped leg in the L-die bending process whereas the reversed bending stress was generated on both leg sides in the V-die bending process, as shown in Figure 5(d), the predicted spring-back value in the L-die bending process was larger than that in the V-die bending process. After compensating for these stress distributions, the predicted spring-back was 3.56° in the case of the L-die bending process. In contrast, the predicted spring-go was 0.54° in the case of the V-die bending process. Therefore, the calculated bend angles were 123.56° and 119.46° in the L- and V-die bending processes, respectively. Based on these stress distribution analyses, the results revealed different stress distributions and spring-back characteristics between the L- and V-die bending processes. As per past research (Phanitwong and Thipprakmas, 2016), the conventional spring-back factor, for which only the stress distribution generated on the bending allowance zone is considered, was modified and named the adjusted spring-back factor for the L-die bending process by including the reversed stress distribution generated on the leg of the workpiece.

Fig. 5 Stress distribution analysis. (a) 90° L-die bending model, (b) 90° V-die bending model, (c) 120° L-die bending model, (d) 120° V-die bending model.
The results in the past research (Phanitwong and Thipprakmas, 2016) also illustrated that the application of the adjusted spring-back factor could provide greater accuracy in the spring-back prediction than that of the conventional spring-back factor. In the present research, as mentioned above, the reversed stress distribution was also generated on the bending allowance zone and the legs of the workpiece in the V-die bending process, which corresponded well with the literature (Thipprakmas, 2011), (Phanitwong and Thipprakmas, 2014), (Thipprakmas, 2013). Therefore, in comparison to the conventional spring-back factor, the use of the adjusted spring-back factor could be more suitable for V-die bending process applications to achieve better accuracy in spring-back prediction, bend angle prediction, and bend radius calculation.

5. Conclusions

To design a proper V-die, taking into account the bend angle and bend radius requirements, the determination of the predicted spring-back characteristic and calculated bend radius should adequately accurate. In general, the spring-back characteristic and bend radius could be predicted and calculated using the spring-back factor. In the present research, therefore, the accuracy of spring-back factor application for spring-back prediction, bend angle prediction, and bend radius calculation in the V-die bending process was investigated based on FEM simulation and experiments. The two existing spring-back factors—namely, conventional and adjusted spring-back factors—were examined. First, to use the FEM simulation as a tool for the clarification of spring-back characteristics, the FEM simulation results were validated by the experiments. The FEM simulation results showed that the bend angle prediction and bend radius calculation corresponded well with the experiments. Next, by using the spring-back factor, the results illustrated that the adjusted spring-back factor offered greater accuracy than the conventional spring-back factor in the spring-back prediction, bend angle prediction, and bend radius calculation. These results were verified based on the stress distribution analysis, which indicated that not only the bending stress distribution was generated on the bending allowance zone, but the reversed bending stress distribution was also generated on the leg of the workpiece in the case of the L-die bending process. These results were also found in the case of the V-die bending process. Moreover, the reversed bending stress distribution was also generated on the bending allowance zone, while the bending and reversed bending stress distributions were also generated on the legs. Therefore, the application of the adjusted spring-back factor, which was based on the bending stress distribution generated on the bending allowance zone and the reversed bending stress distribution generated on the leg of the workpiece, could provide higher accuracy in the determination of the bend angle prediction and bend radius calculation than did the application of the conventional spring-back factor, which was based on only the bending stress distribution generated on the bending allowance zone. However, although the adjusted spring-back factor was found to give higher accuracy in the spring-back prediction, bend angle prediction, and bend radius calculation than did the
conventional spring-back factor, as a future work, the spring-back factor for the V-die bending process still needs to be developed because the stress distribution generated in the bent parts is totally different from that generated in the bent parts obtained through the L-die bending process.

Acknowledgements

This research was supported by a grant from The Thailand Research Fund (TRF) under Grant No. RSA6180047. The author would especially like to thank Miss Wiriyakorn Phanitwong, Ph.D., and graduate student Mr. Arkarapon Sontamino for their help in this research.

References

Abea, Y., Ijichia, W., Moria, K. and Miyazawaa, S., Uniform angle distribution in V-shaped bending of ultra-high strength steel sheets having wall thickness distribution, Procedia Engineering, Vol. 207, (2017), pp. 1629–1634.
Ahmadi, M., Sadeghi, B. M. and Arabi, H., Experimental and numerical investigation of V-bent anisotropic 304L SS sheet with spring-forward considering deformation-induced martensitic transformation, Materials & Design, Vol. 123, (2017), pp. 211–222.
Hakan, D. andMustafa, O., Effect of material properties and punch tip radius on spring-forward in 90° V bending process, Journal of Iron and Steel Research International, Vol. 20, (2013), pp. 64–69.
Leu, D.K., Position deviation in V-die bending process with asymmetric bend length, International Journal of Advanced Manufacturing Technology, Vol. 64, (2013), pp. 93–103.
Li, B., McClelland, Z., Horstemeyer, S.J., Aslam, I., Wang, P.T. and Horstemeyer, M.F., Time dependent spring-back of a magnesium alloy, Materials & Design, Vol. 66, (2015), pp. 575–580.
Ling, Y.E., Lee, H.P. and Cheok, B.T., Finite element analysis of springback in L-bending of sheet metal, Journal of Materials Processing Technology, Vol. 168, (2005), pp. 296–302.
Phanitwong, W. and Thipprakmas, S., Determination of coined-bead geometry in the V-bending process, Advances in Mechanical Engineering, (2014), 345152.
Phanitwong, W. and Thipprakmas, S., Development of anew spring-back factor for a wiping die bending process, Materials & Design, Vol. 89, (2016), pp. 749–758.
Schuler, G., Metal Forming Handbook (1998), New York, Springer-Verlag Berlin Heidelberg.
Thipprakmas, S., Finite element analysis on the coined-bead mechanism during the V-bending process, Materials & Design, Vol. 32, (2011), pp. 4909–4917.
Thipprakmas, S., Finite element analysis of sided coined-bead technique in precision V-bending process, International Journal of Advanced Manufacturing Technology, Vol. 65, (2013), pp. 679–688.
Thipprakmas, S., Effect of ratio of punch height to workpiece length in partial V-bending process, Steel Research International, Vol. 81(9), (2010), pp. 769-772.
Thipprakmas, S. and Phanitwong W., Finite element analysis of flange-forming direction in the hole flanging process, International Journal of Advanced Manufacturing Technology, Vol. 61(5), (2012), pp. 609–620.
Thipprakmas, S. and Boochakul U., Comparison of spring-back characteristics in symmetrical and asymmetrical U-bending processes, International Journal of Precision Engineering and Manufacturing, Vol. 16(7), (2015), pp. 1441-1446.
Wang, L., Huang, G., Han, T., Mostaed, E., Pan, F. and Vedani, M., Effect of twinning and detwinnning on the spring-back and shift of neutral layer in AZ31 magnesium alloy sheets during V-bend, Materials & Design, Vol. 68, (2015), pp. 80–87.
Wang, L., Huang, G., Zhang, H., Wang, Y. and Yin, L., Evolution of spring-back and neutral layer of AZ31B magnesium alloy V-bending under warm forming conditions, Journal of Materials Processing Technology, Vol. 213, (2013), pp. 844–850.
Xie, H., Wang, Q., Liu, K., Peng, F., Dong, X. and Wang, J., Investigation of influence of direct-current pulses on springback during V-bending of AZ31B magnesium alloy sheet, Journal of Materials Processing Technology, Vol. 219, (2015), pp. 321–327.
Xiong, W., Wang, W., Wan, M. and Li, X., Geometric issues in V-bending electromagnetic forming process of 2024-T3 aluminum alloy, Journal of Manufacturing Processes, Vol. 19, (2015), pp. 171–182.