Springback in The Bending of Advanced High Strength Steel Sheets

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Abstract - In this study, both the experimental approach and the finite element analysis were adopted to examine the springback phenomenon occurred in the bending of advanced high strength steel sheets. The V-bending, U-bending, and U-hat bending tests of 270 steel, 590R and 590Y high strength steels were performed to examine the effects of material strength, punch radius, sheet thickness on the occurrence of springback and side-wall curl. The deformation mechanics of springback phenomenon was also investigated with the use of the finite element analysis. The finite element simulation results reveal that the axial stress distribution in the bent sheet can be classified into three zones: the bending zone under the punch corner (zone I), unbending zone next to the bending zone (zone II), and the stress-free zone (zone III). The effects of the stress distributions in these three zones on the springback were examined in details, and it was found that the stress distribution in zone II plays an important role in reducing the springback.

Keywords - Springback, Side-wall curl, Bending, Advanced high strength steel, Deformation mechanics

I. INTRODUCTION

Due to the requirement of lightweight in the automotive body structure design, the application of advanced high strength steel (AHSS) has been widely adopted in the automotive industry. However, the technical difficulties are also experienced in the forming process of the advanced high strength steel. One of the major defects is springback. Springback is a common defect occurred in the sheet-metal forming processes. But it becomes more serious for the advanced high strength steels because of the high flow stress of material that introduces springback during the elastic recovery. Quite a few efforts have been made to obtain a deep understanding of the springback phenomenon occurred in the sheet metal forming process. Gan and Wagoner [1] proposed a new method for designing general sheet forming dies to produce a desired final part shape without the springback. Asnafi [2] investigated the springback of double curved autobody panels theoretically and experimentally. Both steel and aluminum sheets are included in his investigation. The springback occurring in the bending of high strength steels was also discussed by Davies [3], and Chu [4]. Mullan [5] examined the major difficulty with the bending of sheet steel products using a variety of forming methods. The results are used to derive an expression for predicting springback. Hill [6] also presented a general theory for the elastic-plastic pure bending under the plane strain condition. In addition to various theories on prediction of springback, efforts were also made to reduce the springback. Liu [7] demonstrated an efficient method which dramatically reduced the springback using the double-bend technique. A bending-restriking process was proposed by Nagai [8] to reduce springback.

In the present study, both the experimental approach and the finite element analysis were adopted to examine the springback phenomenon occurred in the bending process of advanced high strength steel sheets. The V-bending, U-bending, and U-hat bending of 270 steel and 590R, 590Y high strength steels were performed. The effects of the high flow stress of material and tooling profiles on the springback were examined by experiments. In addition, the deformation mechanics of the springback phenomenon was also investigated in detail by the finite element analysis in the present study.

II. EFFECTS OF HIGH STRENGTH AND PROCESS PARAMETERS ON SPRINGBACK

It is well known that the springback is affected by the elastic modulus and yield strength of the material. For steels, the elastic modulus is almost the same for all kinds of steel. But, the initial yield strength and the flow stress during the plastic deformation can be much different between different grades of steel. In the present study, 270 steel and 590R, 590Y high strength steels were examined. The numbers 270 and 590 represent the ultimate strength of the steel in MPa. Among them, 590Y is of dual phase steel. The stress-strain curves of these three steels obtained from tension tests are displayed in Fig. 1 and the yield strengths and ultimate strengths of these three steel are given in Table 1. It seen in both Fig. 1 and Table 1 that both yield strength and ultimate strength of 590R and 590Y are much higher than those of 270 steel, and 590R has the largest values of both yield strength and ultimate strength. It then can be inferred that 590R and 590Y steels exhibit much more springback than 270 steel in the bending process. In the present study, the V-bending, U-bending, and U-hat bending were conducted to examine the effects of high strength and process parameters on the occurrence of springback.

TABLE I. YIELD STRENGTH AND ULTIMATE STRENGTH OF THREE KINDS OF STEEL

Material	Y.S. (MPa)	U.S. (MPa)
270 steel	146	306
590R	498	720
590Y	417	645

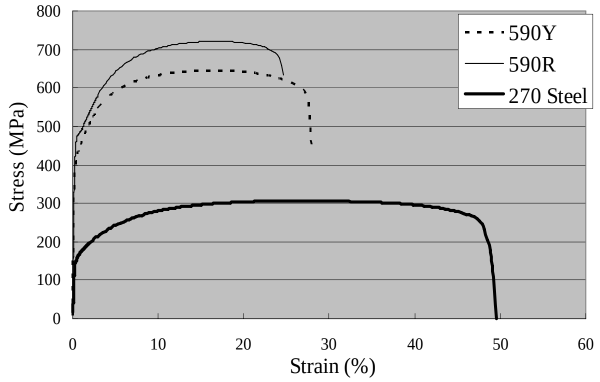

Fig. 1 Stress strain relations of three kinds of steel

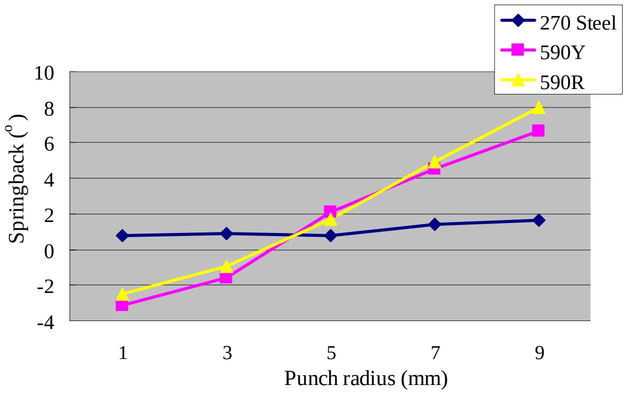

Fig. 3 Springback versus punch radius for three steels in V-bending

A. V-bending Tests

A set of bending tooling, including punch and die, was manufactured to perform 90° V-bending tests, as shown in Fig.2. In addition to the material strength, the effects of sheet thickness and punch radius on the springback were also examined. The selected sheet thicknesses were of 1.0 mm, 1.4 mm, and 2.0 mm for all three steels. Punches with different radii of 1 mm, 3 mm, 5 mm, 7 mm, and 9 mm were prepared for the tests and were denoted by R1, R3, R5, R7, and R9, respectively. The angles of deformed specimens were measured with a CMM and the springback is defined by the difference between the measured angle and the right angle (90o), i.e., the measured angle minus the right angle.

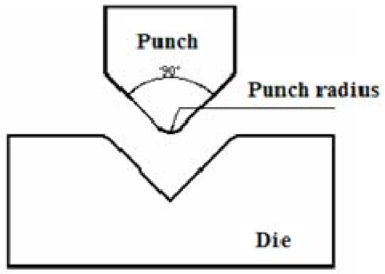

Fig. 2 Tooling used for V-bending

Fig. 3 shows the springback occurred in the V-bending with various punch radii for the three steels of thickness 1 mm. It is clearly seen in Fig. 3 that the 270 steel results in very insignificant springback and is insensitive to the punch radius. While both 590R and 590Y steels display significant springback phenomenon in the V-bending process. It is seen in Fig. 3 that the larger the punch corner radius, the more significant is the springback; thus, the effect of punch corner radius on the springback for the advanced high strength steel is obvious. It explains why in practice the springback is not a big issue in the bending of conventional sheets, but it becomes the most difficult problem in the tooling design for bending the advanced high strength steels. It is also to be noted that negative springback is observed in Fig.3 when the punch radius is less than 5 mm. The negative springback is always interesting to researchers. In the present study, the deformation mechanics of the occurrence of the negative springback is investigated and will be discussed later in the present paper.

The effect of sheet thickness on the occurrence of springback is also not significant in the V-bending of 270 steel. The springback measured from 270 steel sheets with three different thicknesses of 1 mm, 1.4 mm , and 2.0 mm are almost the same for various punch radii. However, the effect of sheet thickness becomes significant for both 590R and 590Y steels. Fig. 4 shows the springback produced in the V-bending of 590Y steel with different punch radii for different sheet thicknesses. It is noted that the springback increases as the sheet becomes thinner and the larger punch radius makes the difference more obvious. Hence, it can be inferred that the bending of thinner advanced high strength steel is more difficult.

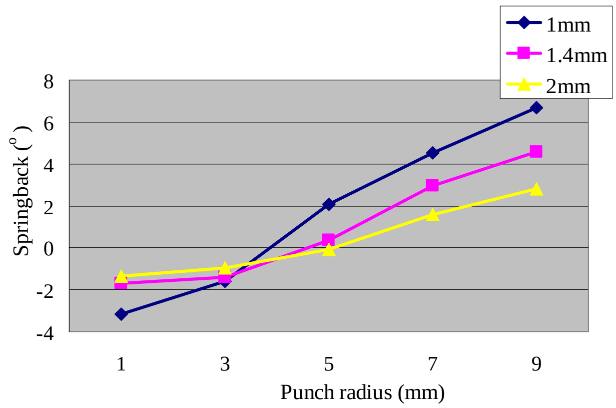

Fig. 4 Springback versus punch radius for 590Y with various thicknesses in V-bending

B. U-bending Tests

A set of tooling with various punch radii of 1 mm, 3 mm, 5 mm, 7 mm, and 9 mm was prepared for the U-bending tests. Since the blank-holder is not required in the U-bending process, the effect of die radius is not crucial and is not considered in the tests. The three kinds of steel with three different thicknesses used in the V-bending tests were adopted in the U-bending tests as well to examine the effects of steel strength, punch radius, and sheet thickness on the occurrence of springback. Fig. 5 displays the deformed shapes of 590R steel after U-bending. It is seen in Fig. 5 that the springback phenomenon is very significant for 590R steel and the negative springback is clearly observed for punch of 1 mm radius. The effect of punch radius is shown in Fig. 6. As seen in Fig. 6, both 590R and

590Y steels exhibit much more significant springback than 270 steel does. The trend is similar to that in the V-bending. However, the 270 steel displays negative springback as the punch radius is smaller than 7 mm in the U-bending that is different from V-bending in which the 270 steel exhibits positive springback for all punch radii. For 590R and 590Y steels, the negative springback occurs when the punch radius is smaller than 5 mm.

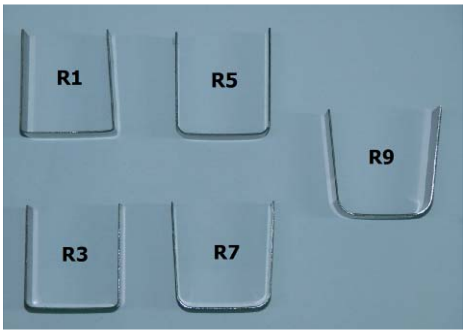

Fig. 5 Deformed shapes for 590R steel after U-bending

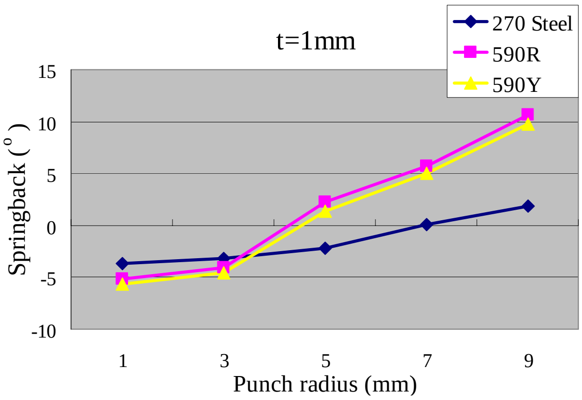

Fig. 6 Springback versus punch radius for three steels in U-bending

The U-bending tests results also indicate that the advanced high strength steel experiences more serious springback problem than the conventional steel does.

III. U-HAT BENDING TESTS

In the U-hat bending process, blank-holders are added to the tooling to hold the sheet during the bending process, as shown in Fig. 7. Therefore, the U-hat bending process is actually a drawing process. Unlike the V-bending and U-bending, the sheet metal is deformed along the side-wall in addition to the bending at the punch corner in the U-hat bending process. If the stress along the side-wall is unevenly distributed, the side-wall will be curled in addition to springback, which is called side-wall curl. The outward curl is defined as positive side-wall curl and the inward curl is negative. The tooling used in the U-bending tests was adopted along with the blank-holders added to conduct the U-hat bending tests. Since the stress distribution along the side-wall is affected by the die corner radius, dies with corner radii of 1 mm, 3 mm, 5 mm, 7 mm, and 9 mm was also prepared for the U-hat bending tests. The three kinds of steel with three different thicknesses used in the V-bending and U-bending tests were adopted in the U-hat bending tests to examine the effects of steel strength, punch radius, die radius, and sheet thickness on the occurrence of springback and side-wall curl.

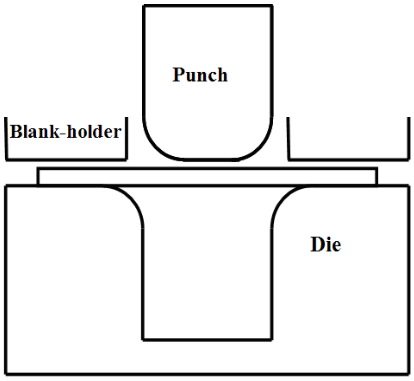

Fig. 7 Tooling used for U-hat bending

The side-wall curls occurred in the U-hat bending for the three steels with sheet thickness of 1.4 mm are shown in Fig. 8. It is seen in Fig. 8 that both springback and side-wall curl are not obvious for the 270 steel. However, the side-wall curl is clearly noticed for both 590R and 590Y steels in addition to springback. The trend of the occurrence of springback in the U-hat bending tests for the three steels is similar to that occurred in the U-bending. The amount of side-wall curls resulted from different die corner radii for the three steels with sheet thickness of 1 mm is plotted in Fig. 9. The mean radius of the curvature of the side-wall curl is adopted to describe to amount of side-wall curl quantitatively. The smaller radius represents more serious side-wall curl. It is noted in Fig. 9 that both 590R and 590Y steels display more serious side-wall curl phenomenon than 270 steel does. All three steel have negative side-wall curl when the die corner radius is smaller than 3 mm. However, all three steels are not sensitive to the die corner radius in the occurrence of side-wall curl when the die corner radius is larger than 3 mm. The test results also indicate that the effect of blank-holder force on the occurrence of side-wall curve is not significant and the side-wall curl becomes more serious when the sheet thickness decreases.

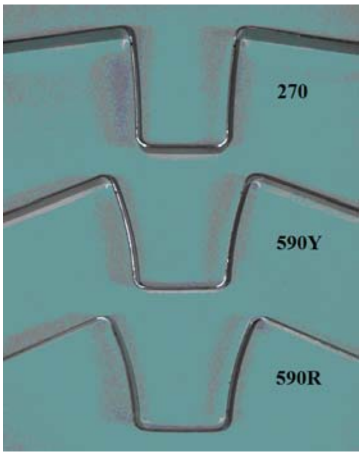

Fig. 8 Side-wall curls occurred in the U-hat bending for three steels

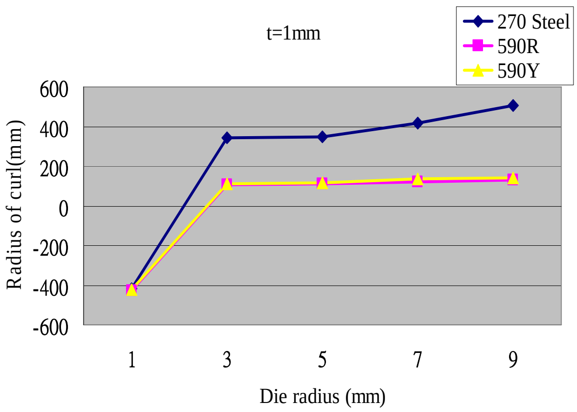

Fig. 9 Side-wall curls occurred in the U-hat bending for three steels

The U-hat bending tests reveal that the bending of advanced high strength steel not only have difficulty in springback but also in side-wall curve. Therefore, in practice, the drawing of advanced high strength steel that results in more complicate stress distribution along the sheet thickness will experience more problems.

IV. DEFORMATION MECHANICS OF SPRINGBACK

Most previous theories for pure bending have only analyzed the deformation at bend area right under the punch corner. The major difference among the various theories lies essentially in the choice of material models. However, a close investigation of V-bending and U-bending reveals that the springback results from the deformation not only at the punch corner but also at the neighboring area next to the punch corner, i.e. the side wall adjacent to the punch corner area.

In order to examine the deformation mechanics along the whole sheet after bending, the 2-D finite element simulations were performed in the present study. The tooling used in the bending process was modeled as rigid bodies, including punch and die. As for the sheet-metal, the 4-node plane-strain element was adopted to construct the mesh. Since the number of elements in the thickness direction has significant effect on the accuracy of the simulation, the convergence tests were performed to determine a suitable number of elements to be used in the thickness direction. After the sheet-metal being bent into tooling shape, the punch was removed and the springback was measured by comparing the difference of the bent angle before and after the tooling was removed. In each simulation, the Coulomb friction coefficient was used to describe the interface friction condition between the tooling and sheet-blank. The finite element code ABAQUS/standard was adopted to conduct all the simulations, and the material properties of the three steels obtained from the tension tests conducted in the present study, as shown in Fig. 1, were used for the finite element simulations.

Since the deformation mechanics of the springback occurred in the V-bending and the U-bending is similar, to limit the length of the present paper, only the deformation mechanics of the V-bending process is discussed. Fig. 10 illustrates the deformation of sheet in the V-bending process. In the beginning of the process, the sheet is bent between the punch corner and the die wall, as shown by the area between the punch corner and the point marked by A. However, in the subsequent bending, the sheet will contact the punch side-wall, as marked by B in Fig. 10, forming a second bending area and results in a complex deformation mechanics along the side wall of the punch in addition to the deformation at the punch corner. It has been shown by the previous theories that the elastic recovery of sheet at the punch corner leads to a positive springback. However, as shown in Fig. 3, negative springback may occur if the punch corner radius is smaller than a certain value. It implies that the deformation of sheet other than the punch corner area also contributes to the springback.

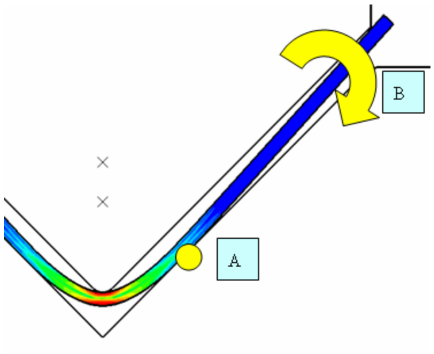

Fig. 10 Deformation of sheet metal in V-bending

Since springback is mainly due to the elastic recovery of the stress distribution along the axial direction, the stress distributions in the bent sheet obtained from the finite element simulations were transformed into the axial direction accordingly, and the stress distribution mentioned hereafter is associated with axial direction. Fig. 11 shows the stress distribution in the bent sheet along the axial direction at the end of bending process before the punch being removed. Based on the stress distribution patterns, the bent sheet is classified into three zones: bending zone at the punch corner, unbending zone at side wall, and stress-free zone, which are marked by I, II, and III, respectively, in Fig. 11. It is noted in Fig. 11 that the sheet metal in zone III is stress free since no deformation is occurred during the bending process. It is then obvious that the springback is independent of zone III, and is mainly attributed to the stress distributions in zone I and zone II.

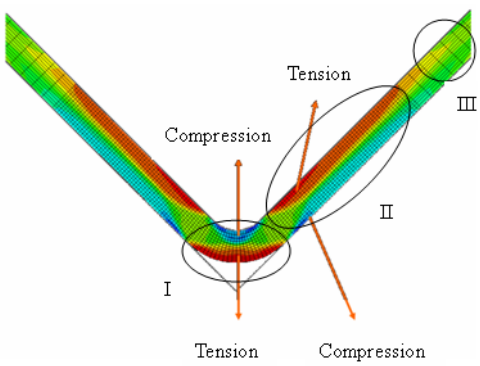

Fig. 11 Stress distribution along the sheet metal in V-bending

The stress distribution in zone I, as shown in Fig. 11, follows the bending theory that the sheet is compressed inside and stretched outside. The elastic recovery of the sheet in this zone, equivalent to an application of an opposite moment, makes the sheet to bend outward, resulting in a positive springback. While the stress in zone II, as shown in Fig. 11, has an opposite distribution pattern to that in zone I, i.e., tension inside and compression outside. The elastic recovery of the sheet in this zone therefore creates a negative springback. Consequently, the total springback is determined by the combined effects contributed by zone I and zone II. The bent sheet will have a positive springback after the punch is removed, if the springback phenomenon is dominated by the stress distribution in zone I. On the other hand, the V-bending process results in a negative springback, if the stress distribution in zone II is pronounced.

To further illustrate the effects of the stress distributions in zone I and zone II on springback, the finite element analysis was performed to examine the stress distributions along the sheet in the V-bending with different punch radii. The finite element simulation results indicate that the area of zone I with a bigger punch corner radius is much larger than that with a smaller punch corner radius, whereas the area of zone II is smaller in the V-bending of a sheet with a larger punch corner radius. It is evident that the larger the punch corner radius, the more significant is the positive springback in zone I. On the other hand, the smaller punch corner radius obviously produces more springback in the opposite direction.

The above stress analysis clearly explains the deformation mechanics of the springback phenomenon that occurs in the V-bending process, especially the formation of negative springback. Since the springback is inevitable in the V-bending process, in order to reduce the total springback, an optimum process design is required to make the stress distribution in zone II more significant to balance the springback caused by the elastic recovery of the stress distribution in zone I. However, over-adjustment will result in a negative springback and should be avoided. The finite element analysis performed for the U-bending process also reveals the same deformation mechanics for the occurrence of springback.

V. SUMMARY

The V-bending, U-bending, and U-hat bending tests have demonstrated that the springback phenomenon becomes more pronounced as the strength of the steel increases. The 590R and 590Y steels not only experience more springback but also more significant side-wall curl than the conventional steel does. The U-hat bending tests also indicate that the drawing process with the use of blank-holders introduces more complicate stress distribution along the sheet and causes side-wall curl in addition to springback. Therefore, in practice, the drawing of advanced high strength steel will encounter more problems. One way to cope with this problem is to use multi-forming process instead of drawing process to form the part. The test results also reveal that the springback and side-wall curl becomes more serious as the decrease of punch radius and sheet thickness. A smaller punch radius also causes a negative springback.

The deformation mechanics of springback phenomenon in the bending of sheet-metals was also investigated with the use of the finite element analysis in the present study. The axial stress distribution in the bent sheet was classified into three zones: the bending zone under the punch corner (zone I), unbending zone next to the bending zone (zone II), and the stress-free zone (zone III). The springback mainly depends on the stress distributions in zone I and zone II. The stress distribution in zone I results in a positive springback, whereas the stress distribution in zone II produces a negative springback. In order to reduce the springback in the bending process, the effect of zone II needs to be more significant to balance the positive springback produced in zone I. However, over-adjustment may result in a negative total springback. The analysis of the deformation mechanics of springback not only explains the cause of positive springback but also the phenomenon of negative springback. It also provides a useful guideline for improving the springback defect in the bending of advanced high strength steels.

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