Experimental and Numerical Investigations of Applying Tip-bottomed Tool for Bending Advanced Ultra-high Strength Steel Sheet

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Abstract. This research was carried out aiming to investigate the application of a tip-bottomed tool for bending an advanced ultra-high strength steel sheet. The V-die bending experiment of a dual phase steel (DP980) sheet which had a thickness of 1.6 mm was executed using a conventional bending and a tip-bottomed punches. Experimental results revealed that the springback of the bent worksheet in the case of the tip-bottomed punch was less than that of the conventional punch case. To further discuss bending characteristics, a finite element (FE) model was developed and used to simulate the bending of the worksheet. From the FE analysis, it was found that the application of the tip-bottomed punch contributed the plastic deformation to occur at the bending region. Consequently, the springback of the worksheet reduced. In addition, the width of the punch tip was found to affect the deformation at the bending region and determined the springback of the bent worksheet. Moreover, the use of the tip-bottomed punch resulted in the apparent increase of the surface hardness of the bent worksheet, compared to the bending with the conventional punch.

1. Introduction

Due to the requirement of light weight parts and/or structures, heavy sheet materials tend to be replaced by sheets which have higher strength-to-weight ratio. Among high strength materials, advanced ultra-high strength steels are developed and increasingly used. Koo and Luton invented a high strength steel sheet having a yield strength higher than 830 MPa. The high strength was obtained from the formation of the tempered martensite, bainite and the precipitated fine carbide [1]. Vandepputte et al. reported the production of an ultra-high strength steel sheet. By controlling the chemical compositions and the rolling processes, the multiple phase steel consisting of ferrite, martensite and bainite, was produced. Its guaranteed minimum tensile strength was approximately 1000 MPa [2]. Also, Zhong et al. developed a carbon-manganese steel sheet. Its compositions allowed the transformation of austenite into ferrite and martensite during the heat treatment following the rolling. The ultimate strength of this steel reached 1150 MPa [3]. Although the ultra-high strength steels possess the advantages in the permanent deformation resistance and the high failure strength,
their formability are typically limited, especially when compared with lower strength steels such as mild steel.

Springback, a shape error of formed parts, is one of the most severe problems in the bending and other sheet forming processes of ultra-high strength steel sheets. Our previous study showed that the dramatic springback of the ultra-high strength steel sheet mainly caused by its high yield strength and the presence of the large elastic deformation portion in the bending region of the worksheet. Based on this understanding, a key to successfully reduce the springback of the high strength steel sheet seems to be the reduction of the elastic deformation and/or increase the plastic deformation portions at the bending region. There are few techniques used for reducing the springback of high strength steel sheets during bending. Mori et al. employed an electrical resistance heater to heat up a SPFC980Y high-strength steel sheet before subjecting them to an U-die bending tool. They found that the springback of the bent worksheet decreased when the worksheet temperature increased from room temperature to 800 °C [4]. Lee et al. studied the 90° V-die bending of a DP980 steel sheet heated by a near-infrared rays. The angle of the bent sheet reduced from 95° (bent at room temperature) to 90.5° when bending at 600 °C. In these research works, the springback reduction seemed to be contributed by the lower yield strength of the steel sheets under elevated temperature [5]. Yanagimoto and Oyamada also carried out the V-die bending of HSS-I high-strength steel sheet. To increase the plastic deformation portion during bending, they derived the benefit from high-temperature creep of the steel and detected this phenomenon when the worksheet temperature was higher than 477 °C [6]. Although, the bending under elevated temperature was effectively used for suppressing the springback of the high strength steel sheets. However, since steels are rapidly oxidized at elevated temperature and normal atmosphere, the surface quality of steel sheets after hot bending become problematic. In addition, another concern of the hot bending is that the strength of steels would be deteriorated.

Owing to the limitation mentioned above, bending techniques that can reduce the springback of ultra-high strength steels and are performed at room temperature are still necessary. Semiatin explained an attractive bending method for reducing the springback of bent metal sheets, namely the bending with a punch having a bottom [7]. Using this type of punch, a high compressive stress occurred at the bending region facilitates the plastic deformation of bending metals. Then, the springback of bent sheets would be reduced. However, until now, the author has found no reports concerning the application of a tip-bottomed tool for bending high strength steel sheets. Therefore, in this research work, the bending of an ultra-high strength steel sheet with a tip-bottomed punch was investigated, experimentally at room temperature. The applicability of the tip-bottomed punch for suppressing the springback of the ultra-high strength steel was examined. In addition, the deformation of the worksheet during bending was simulated using FE analysis, compared with that of the bending using a conventional tool and discussed. Moreover, the micro Vicker hardness test was conducted for bent worksheets to look into the change of mechanical properties due to the tip-bottomed punch bending.

2. Experimental investigation of bending

2.1 Material and experimental procedures

The material used in this research work was an advanced ultra-high strength dual phase steel (DP980) sheet which had a thickness of 1.6 mm. Table 1 and 2 shows its chemical compositions and mechanical properties. Before bending test, raw DP980 sheet was cut into the bending worksheets,
which had a width of 20 mm and a length of 55 mm using a laser cutting machine. Then, the worksheets were cleaned ethanol and dried.

**Table 1 Chemical compositions of DP980 ultra-high strength steel sheet.**

| Chemical compositions / wt% | C   | Mn  | Si  | Cr  | S   | P   | Mo  | Ni  | Al  | Fe  |
|---------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|                           | 0.097 | 2.27 | 0.394 | 0.70 | 0.001 | 0.008 | 0.08 | 0.013 | 0.04 | Bal. |

Table 1 Chemical compositions of DP980 ultra-high strength steel sheet.

To bend the worksheets, the bending die-set shown in figure 1 was prepared and utilized. There were four springs installed at the guide pin of the die-set. Each spring had a stiffness of 2.96 N·mm⁻¹. During bending, the upper punch attached to the punch block was moved downward by the moving cross head of a universal testing machine (UTM, Model: Instron 5582), while the lower die attached to the die block was stationary. The velocity of the moving cross head (V) was fixed to be 2.5 mm·min⁻¹. In order to measure the bending load resistance of the worksheet, a load cell, which had a capacity of ±100 kN) was installed between the moving cross head of the UTM and the punch shoe.

**Table 2 Mechanical properties of DP980 ultra-high strength steel sheet**

(Test method: Uni-axial tension, Standard: Based on ASTM E8, Velocity of moving cross head: 5 mm·min⁻¹).

| Mechanical properties of steel sheet | Young's modulus $E$ / GPa | 0.2% offset yield strength $\sigma_{YS}$ / MPa | Tensile strength $\sigma_{TS}$ / MPa | Breaking strain $\varepsilon_{Break}$ |
|-------------------------------------|---------------------------|---------------------------------------------|-------------------------------------|----------------------------------|
|                                     | 179.7                     | 714.4                                       | 1058.2                              | 0.099                            |

Table 2 Mechanical properties of DP980 ultra-high strength steel sheet (Test method: Uni-axial tension, Standard: Based on ASTM E8, Velocity of moving cross head: 5 mm·min⁻¹).

To examine the applicability of the bottomed-tip punch for bending the ultra-high strength steel worksheet, two bending experiments were executed. First, the worksheets were bent using a conventional 90° punch and 90° die, as shown in figure 2 (a). Second, a 90° punch which had a tip at the bottom, as illustrated in figure 2 (b), was used. In this case, the die dimension was the same as that used in the first experiment. The punch and die were made of a JIS-SKD11 cold-work tool steel which had a hardness ranging from 60 to 63 HRC. For both experiments, the maximum bending depth $d_{B(Max)}$ was fixed as 13.275 mm. The $d_{B(Max)}$ was defined clearly in figure 2 (a). After reaching the maximum bending depth, the punch was lifted upward by the springs. Then, the bent worksheets were removed from the die-set to measure the springback. In this work, the bending experiment was carried out five times for each punch case. Finally, to investigate the mechanical property at the bending region of the bent worksheet, the micro Vickers hardness test was conducted.
2.2 Experimental results of bending

Figure 3 shows the relationship between the bending load resistance of the worksheet and the indentation depth of punch for the bending with the conventional punch (C.P.) and the tip-bottomed punch (T.B.P.). In this representation, the indentation depth of zero is the position at which the tip of the punch touches the top surface of the worksheet. As shown in the figure, it was seen that the bending load resistance of the worksheet for both punch cases was similar for \( 0 < d_0 \leq 13.1 \text{ mm} \). Then, when the indentation depth increased to \( d_0 = 13.3 \text{ mm} \), the peak point of the bending load resistance \( f_\text{fit(peak)} \) for both tool cases was observed. Here, \( f_\text{fit(peak)} \) in the case of the T.B.P was found to be higher than that of the C.P. case. The occurrence of higher bending load resistance at the identical indentation depth of punch seemed to indicate that higher strain hardening and/or the larger plastic deformation portion of the worksheet occurred when using the T.B.P.

After bending, the springback of the worksheets was visually examined. Figure 4 shows the representative worksheets bent by the C.P. and the T.B.P. To investigate the springback of the worksheet more precisely, the springback angle of the bent worksheets was measured by an image analyzer. Then, the springback factor \( k_s \), as described in figure 5, was calculated and plotted with respect to the types of the punches used, as shown in figure 6. From figures 4 and 6, it was found that the springback of the worksheet bent by the T.B.P was apparently less than that of the C.P. case. The experimental results revealed that the application of the T.B.P seemed to contribute the increase of the plastic deformation portion at the bending region. Consequently, the springback of the bent worksheet decreased. To furthermore discuss the deformation and the springback of the bent worksheet, the FE analysis of the bending was carried out. Its results will be shown in the next sections.
3. Finite element (FE) analysis of bending

3.1 Development of FE model and its verification

For the FEM simulation, a commercial software, Simufact Forming version 12.0.3 was employed to simulate the bending of the DP980 worksheet. A two-dimensional FE model shown in figure 7 was developed and used. Here, the worksheet was assumed to be deformable body and was constructed with the 4-node plane strain quadrilateral element. The thickness of the worksheet was considered as 1.6 mm. The bending zone of the worksheet was modeled using fine elements, which had a side length of 42 \( \mu \)m. For far zone, larger elements having a side length of 120 \( \mu \)m were used. The deformable worksheet was assumed to be isotropic elasto-plastic with work hardening. Its constitutive equation determined by the uni-axial tensile test, as shown in figure 8, was assumed to the analysis. The punch and die were assumed to be rigid body.

Due to the crushing of many elements at the bending region, the calculation tended to be fault. To overcome this problem, an automatic re-meshing function was utilized to re-generate new faultless elements. The re-meshing was executed when the strain change of elements reached 0.4. For the new re-meshing elements, their side length was controlled to be approximately 50 \( \mu \)m. The coulomb friction model was assumed to all contact interfaces. The friction coefficient for all interfaces was fixed to be 0.1. Since there are no separation or crack of the worksheet during bending, no damage model was applied to the bending simulation. After simulating, the simulated bending load resistance, the springback of the worksheet and the distribution of the equivalent stress were investigated under the variation of the punch types.
3.2 Verification of developed FE model

To ensure the applicability of the developed FE model for simulating the bending of the DP980 worksheet, the verification of the FE model was carried out. In order to do this, the bending load resistance measured in the bending experiments was plotted and compared with the bending load resistance simulated by FE analysis.

Figure 9 shows the experimental and simulated bending load resistance for the C.P. and T.B.P cases. Apart from the bending load resistance, the applicability of the developed FE model for the simulation was further checked by comparing the experimental springback factor with that simulated by FE analysis, as shown in figure 10.

3.2.1 Bending load resistance

Seeing figure 9, the simulated bending load resistance of the worksheet was similar to that of the experiment. In addition, the similarity of the load resistance was observed for all punch cases. For the springback of the worksheet, as seen in figure 10, although the magnitude of the springback factor simulated by FEM was slightly different from that of the bending experiments, the tendency of the simulated springback factor had a good agreement with the experimental results. This comparison indicated that the developed FE model was applicable for simulating the bending of the DP980 worksheet.
3.3 Effect of punch type on deformation of bending worksheet

After getting the FE model, the bending with the C.P. and the T.B.P. was analyzed. For discussing the deformation of the bent worksheet, the contour band diagrams of the equivalent stress ($\sigma_{\text{Equi}}$) were plotted for the punch types used. In the diagrams, the red bands represent the area where the equivalent stress in the worksheet was higher than the yield strength of the worksheet evaluated by the uni-axial tension test. In other words, the red bands indicate the zones where the worksheet plastically deforms, while other colours indicate the zones that the worksheet elastically deforms.

Figure 11 shows the representative overviews of the bent worksheets and the distribution of the equivalent stress for the C.P. and the T.B.P. cases. From this figure, the different deformation at the bending region of the worksheets was observed. Namely, in the T.B.P. case, the elastic deformation portion at the centre of the bending region seemed to be smaller than that of the C.P. case. For other zone, the stress distribution were fairly similar to each other.

To see the deformation at the bending region more clearly, the zoom figures showing the distribution of the equivalent stress at the centre of the bending were made. However, since the distribution of the equivalent stress slightly varied during the indentation of punch, the authors plotted the contour band diagrams of the equivalent stress at the indentation where an expected high equivalent stress occurred, namely at the indentation just before the $d_{B(\text{max})}$ and at the $d_{B(\text{min})}$. This plot is shown in figure 12. From the figure, it was found that the elastic deformation at the centre of the bending region in the case of the T.B.P. was limited, compared to the case of the C.P. This deformation characteristic was observed for all the indentation depths, Figures 11 and 12 indicated that the application of the T.B.P. contributed the plastic deformation to occur at the central region of bending. This seemed to result in the suppression of the springback when considering the T.B.P.
**Figure 12** Contour band diagram of equivalent stress at bending zone of worksheet at various indentation depths of punch.

**Figure 13** Simulated bending load resistance for width of punch tip.
3.4 Effect of geometry of tip-bottomed punch on deformation of bending worksheet

For the T.B.P. bending, the tip of the punch tends to indent to the worksheet during bending. Thus, the geometry of the punch tip would be an important factor affecting the deformation of the worksheet at the bending region and the springback of the bent worksheet. In this work, to investigate the effects of the punch tip geometry, i.e. the width of the punch tip, the width of the punch tip \( w_T \) was varied in the FE as 200, 500 and 800 \( \mu \)m and simulated. The angles of the punch and the die were still fixed to be 90°. Other simulation conditions which were not mentioned here were the same as those explained in section 3.1.

Figure 13 shows the plot of the bending load resistance when varying the width of the punch tip. As seen in this figure, the \( f_{B(peak)} \) in the cases of \( w_T = 500 \) and 800 \( \mu \)m appeared to be higher than that of the case of \( w_T = 200 \) \( \mu \)m, while the characteristic of the bending load resistance for \( 0 < d_B < d_{B(max)} \) was similar for all punch cases.

Figure 14 represents the contour band diagrams of equivalent stress at the bending region for \( w_T = 200, 500 \) and 800 \( \mu \)m. Seeing figure 14 (a), in the case of \( w_T = 200 \) \( \mu \)m, at all the indentation depths, the shallow-deep indentation occurred on top surface of the worksheet. In this case, a quite large elastic deformation portion was observed at the centre of the bending region. For the cases of \( w_T = 500 \) and 800 \( \mu \)m, at \( d_B = 12.63, 12.95 \) and 13.27 mm, on the contrary, the wider indentations occurred on the top surface of the worksheets. Seeing the elastic deformation portion in the cases of \( w_T = 500 \) and 800 \( \mu \)m, it appeared to be limited, compared to that of the \( w_T = 200 \) \( \mu \)m case.

Figure 15 illustrates the relationship between the springback factor and the width of the punch tip. As shown in this figure, the springback in the case of \( w_T = 200 \) \( \mu \)m tended to be larger than that of the cases of \( w_T = 500 \) and 800 \( \mu \)m,
Considering the results shown in figures 13–15, it was revealed that the application of the punch, which had a narrow tip, resulted in the limited plastic deformation on the top surface of the worksheet. However, it could not contribute the plastic deformation to occur at the centre of the bending region. When wider punch tip was considered, the plastic deformation seemed to be promoted not only a limited area near the top surface of the worksheet, but also the centre of the bending region. Consequently, the springback of the bent worksheet tended to be reduced.

4. Mechanical property of worksheet at bending zone
As depicted in the previous sections, the application of the T.B.P could suppress the springback of the ultra-high strength steel bent worksheet. However, the mechanical property after bending of the worksheet is an important factor determining the durability of formed ultra-high strength steel parts. Thus, in this work, the mechanical property at the bending region of the worksheets bent by the T.B.P was evaluated by micro Vickers hardness test and compared with the hardness of the worksheet bent by the C.P.

![Figure 15](image-url)  
**Figure 15** Relationship between springback factor and width of punch tip.

![Figure 16](image-url)  
**Figure 16** Hardness of the bent worksheets at the bending region and the measurement positions.
For the hardness test, the indentation load and the dwell time were set as 50 gf and 10 seconds, respectively. The measurement was performed along the three paths, i.e., near the top surface, at the centre and near the bottom surface of the worksheet, as shown in figure 16 (a). From the measurement results shown in figures 16 (b) - (d), it was revealed as follows: (i) near the top surface of the bent worksheet, for all measurement positions \( (p_m) \) from −600 to 600 \( \mu m \), the hardness remarkably increased from the base hardness of the DP980 (368.7 HV). This was observed in both C,P, and T,B,P, cases. (ii) the application of the T,B,P, provided significantly higher hardness near the top surface of the bent worksheets, compared to the case of C,P. Namely, the hardness in the cases of the T,B,P was higher than the base hardness of the DP980 approximately 13.9\%, while the increase was only 4.6\% for the C,P, case. This higher hardness seemed to be caused by higher strain hardening at the top surface of the bent worksheet when applying the T,B,P, (iii) At the centre of the bent sheet, the hardness for both punch cases tended to be higher at the position near the centre of bending \( (p_m) \) between −200 to 200\( \mu m \), while it appeared to be identical to the base hardness of the DP980 for the far zones \( (−600 \leq p_m < −200 \mu m) \) and between \( (200 < p_m \leq 600 \mu m) \). (iv) near the bottom surface of the bent worksheet, the hardness measured in both punch cases was apparently increased from the base hardness. However, the magnitude of the hardness for both punch cases were similar to each other.

Here, it was confirmed the application of the T,B,P, was not only reduced the springback of the ultra-high strength steel worksheet but also increased the hardness, especially near the top surface of the bent worksheet.

5. Conclusions
In this research work, the application of tip-bottomed punch was applied for bending an advanced ultra-high strength steel (DP980) sheet. The bending characteristics of the worksheet such as the bending load resistance, the springback and the deformation of the worksheet, were investigated. Based on the experimental and simulation results, the following conclusions were obtained:

(i) the application of the tip-bottomed punch could reduce the springback of the DP980 bent worksheet.

(ii) The distribution of the equivalent stress appeared to be useful for explaining the deformation of the worksheet at the bending region. As found in this work, the springback of the worksheet was found to correspond to the elastic deformation portion at the bending region, especially at the centre of the bending region.

(iii) The use of the tip-bottom punch contributed the plastic deformation to occur at the centre of the bending region. Thus, it contributed to suppress the springback of the bent worksheet. However, a certain wide tip of punch was necessary.

(iv) The application of the tip-bottom punch caused the increase of the hardness, especially near the top surface of the bent worksheet. The top surface hardness was found to increase approximately 13.9\% from the base hardness of the DP980 worksheet.

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