Effect of various shearing shape conditions for the scrap-used coining method on tensile residual stress on sheared edge

Y Honda¹, T Yasutomi¹ and M Yamagata¹
¹ Nippon Steel Corporation., 20-1 Shintomi, Futtsu 293-8511, Japan

E-mail: honda.x66.yoshiaki@jp.nipponsteel.com

Abstract. Application of high strength steel for automobiles is required to achieve fulfilment of the CO₂ emission regulation and improvement of collision safety. Nevertheless, high strength steel has the problem that hydrogen embrittlement and fatigue cracks are likely to occur especially on sheared edge. The previously proposed scrap-used coining method could reduce tensile residual stress on sheared edge using the scrap generated by shearing as the coining tool with a counter punch. However, the conditions this method could reduce tensile residual stress effectively were not clarified. In this report, the effects of the following shearing shape factors on residual stress on sheared edge were investigated, the size of shearing line curvature using punches with a diameter of 10 and 20 mm, positive and negative sign of curvature by testing both of the product and scrap part, and the flat and dome shape of counter punch head. Residual stress on sheared edge could be reduced in the 10 and 20 mm of punch diameter regardless of the product or scrap part. FEM analyses showed that the change of stress distribution in processing area during the scrap-used coining is caused by the shearing hole expansion and reduction and the sheared edge compression by contact of the product and scrap and these mechanisms are common to both of the parts. The dome shaped counter punch is able to reduce the coining load in addition to almost the same amount of residual stress as the flat shaped one. Thus, the tool cost decreases because the cushion pin required to get the reaction force for coining could be reduced.

1. Introduction
In recent years, application of high strength steel for automobiles has been oriented to achieve the weight saving to fulfill CO₂ emission regulation and improvement of collision safety to protect passengers. However, high strength steel has difficulties because hydrogen embrittlement and fatigue cracks prone to occur especially on sheared edge. Tensile residual stress on sheared edge is known to affect both of hydrogen embrittlement and fatigue property. Therefore, development of the shearing method which can reduce tensile residual stress on sheared edge is required. Shirasawa et al. reported that the coining method can improve fatigue property and reduce residual stress on sheared edge[1]. However, conventional coining method has the difficulties in coining the entire fracture surface uniformly because the prediction of the shape of sheared edge and alignment of sheared edge and coining punch for every blank are difficult to perform in manufacturing process.

In the previous study, the scrap-used coining method was proposed[2]. This method could reduce tensile residual stress on sheared edge of high strength steel by coining using scrap part generated by shearing. As to the effect of shearing conditions on reduction of residual stress, the effect of clearance and coining stroke were investigated. However, the various shearing shape factors exist in actual
manufacturing process, e.g. the shearing hole diameter and shearing line shape, and the range of conditions the method could reduce tensile residual stress effectively are not clear.

In the present study, using the scrap-used coining method, the effects of the following shearing shape factors on residual stress on sheared edge were investigated, the size of shearing line curvature using punches with a diameter of 10 and 20 mm, the positive and negative sign of curvature by testing both of the product and scrap part, and the flat and dome shape of counter punch head.

It is noted that the X-ray measurement can evaluate the residual stress at only certain spot of sheared edge. On the other hand, the hole expansion test can evaluate the entire shearing edge. However, the various factors affect the hole expansion ratio, e.g. work hardening. Thus, X-ray measurement of residual stress is adopted in this study to evaluate the effectiveness of proposed method. Instead, the residual stress at the both sides of diameter position in the shearing hole, the farthest position of the sheared edge, are measured to evaluate the circumferential uniformity of the proposed method.

2. Overview of the scrap-used coining method
The conventional shearing method and the proposed scrap-used coining method are shown in Figure 1. In the conventional shearing method, the blank is sheared with punch, die and holder into the product and scrap part. In the proposed method, the scrap part generated by shearing is used as a coining tool with the counter punch placed directly below the scrap. After shearing, the coining process is performed successively pushing the counter punch with the reaction force of shearing earned by cushion pin. In the coining, the scrap part can contact the product part because the scrap diameter is generally larger than the shearing hole diameter of the product part. And the shape of sheared edge of the product and scrap part is matched regardless of the shearing conditions. Therefore, the scrap-used coining could be processed without prediction of the shape of sheared edge and alignment of the positions of the tools and blank.

![Diagram](image)

**Figure 1.** Schematic of experimental procedure. (a) Conventional shearing method. (b) Proposed method.
3. Experimental methods
As mentioned in Section 2, the coining process is performed successively after shearing by pushing the scrap from below the shearing hole in actual manufacturing process. On the other hand, in this study, to process the scrap-used coining method simply, the shearing and coining test were performed separately.

3.1. Shearing test
The mechanical properties of the material used in this study measured by tensile test is shown in Table 1. The thickness of the material is 1.6 mm and the width is 50mm square. The shearing conditions are shown in Table 2. In this study, three punch diameter were used, 10 and 20 mm for the effect of the size of shearing line curvature, and positive and negative sign of curvature, 30 mm for the effect of shape of counter punch head, respectively. The ratio of clearance to thickness is constant at 10% in all the experiments. Shearing is processed by servo press and punching speed is set at 100 mm/s.

| Table 1. Mechanical properties of the material. |
|-----------------------------------------------|
| Yield stress [MPa] | Tensile strength [MPa] | Elongation [%] |
| 675 | 1021 | 17.9 |

| Table 2. Shearing conditions. |
|-------------------------------|
| Punch diameter [mm] | Clearance [mm] | Punching speed [mm/s] |
| 10, 20, 30 | 0.32 | 100 |

3.2. Coining test
After shearing test, the product and scrap part are arranged as shown in Figure 2. The product and scrap part are turned over manually after shearing and the scrap is pushed into the shearing hole from above. The alignment of the positions of the shearing hole and scrap part is set successfully because of the piercing, the axial symmetry condition. In coining test, in addition to the same tools as shearing test, the flat and dome shaped counter punch are used to investigate the effect of shape of counter punch head. To process the coining test, load is applied to the scrap part by counter punch and press it into the hole of the product part. The punching speed of the coining test is set at 1mm/s. In the experiments on the effects of the size and sign, positive and negative, of curvature, two coining stroke (s) conditions, s = 1.6 and 3.2 mm, are processed. At s = 1.6 mm, the surface of the roll over side of the product part and the burr side of the scrap part will be the same height. At s = 3.2 mm, the scrap penetrated the shearing hole into the burr side completely. The height of the counter punch head (h) is set at 0, 0.8, 1.6, 2.4 mm. In the experiments on the effect of the shape of counter punch head, only s = 2.6 mm is processed where the scrap penetrated the shearing hole completely. The number of tests for the effects of the size and sign, positive and negative, of curvature are once, and for the effect of shape of counter punch head are three times.

**Figure 2.** Schematic of the coining test. (a) After shearing. (b) Coining by the flat shaped counter punch. (c) Coining by the dome shaped counter punch.
3.3. Measurement of residual stress
After coining test, the measurement of residual stress are performed as shown in Figure 3. The sheared product part is divided into two pieces at the hole diameter part before the measurement. To investigate the effect of positive and negative sign of curvature, residual stress of both the product and scrap part are measured at the same circumferential position on shearing hole edge. And to evaluate the circumferential uniformity of coining process, the measurement of residual stress are performed at the both sides of diameter part of shearing hole. The circumferential residual stress on sheared edge at through-thickness center is measured by X-ray sin²ψ method. The X-ray beam diameter is set at 500 μm.

![Cross-sectional view of sheared edge](image)

**Figure 3.** Measurement position of residual stress.

3.4. Numerical analyses
The change of the stress distribution in processing area during the scrap-used coining is assumed to be caused by two mechanisms, the shearing hole expansion and reduction and the sheared edge compression by contact of the product and scrap part. Therefore, two numerical analyses are performed to investigate these mechanisms separately using commercial finite element method code ABAQUS/implicit. To perform numerical analyses quantitatively, the initial setting of residual stress on sheared edge and the modeling of the proposed method are required to perform accurately. However, the residual stress of sheared edge is distributed in the circumferential, thickness and depth of sheared edge direction, and the distribution is difficult to measure especially in the depth direction. And, the modeling of the experimental conditions of coining process, e.g. roughness and friction coefficient of the sheared edge which seems to affect the coining behavior hasn’t established. Thus, in this study, the numerical analyses are performed to discuss the generation mechanism of residual stress, qualitatively.

The model used in this study are shown in Figure 4. First, the analysis of the shearing hole expansion and reduction was performed. The 0.03 mm of enforced displacement on the in-plane direction was imposed at node set a of the product and scrap part, then eliminated to investigate the effect of the shearing hole expansion and reduction without contact of the product and scrap part. The cross-sectional shape of the product and scrap part was extracted from images obtained by experiment. Secondly, the analysis of the whole scrap-used coining process including contact of the product and scrap part was performed. In this analysis, the fracture surface was defined as straight line. In the model, two-dimensional solid elements were used under the axial symmetry condition. The tools and blank are defined as rigid and elasto-plastic solid, respectively. The edges of the tools rounded with the radius of 0.1 mm to avoid intrusion into blank mesh and ensure stability of a numerical analyses. Regarding the blank, CAX4R elements was used and the rectangle region between edges of punch and die where large strains occur by shearing has fine lattice mesh with a size of 0.02 mm to improve the analyses accuracy. The von Mises yield criterion for isotropic material, the associated plastic flow rule, and the isotropic hardening rule were applied to the blank deformation. The work-hardening characteristic of the material was approximated as:

\[
\bar{\sigma} = F (0.002 + \bar{\epsilon}_p)^n
\]

(1)

where \(\bar{\sigma}\) is the equivalent stress, \(\bar{\epsilon}_p\) the equivalent plastic strain, F the strength coefficient, and n is the work-hardening exponent. The values F = 1864 [MPa] and n = 0.122 were used in this study. The Coulomb friction rule was applied, and the friction coefficient between the tools and the blank was set
at 0.2. In the both analyses, the 1209 MPa of stress in circumferential direction, 966 MPa of stress in thickness direction and 0.102 of equivalent plastic strain are given as initial condition to the elements of outermost layer corresponding to the fracture surface shown as element set b in Figure 4. The values are defined from experimental results of the product part after shearing by 10 mm diameter punch. The values of residual stress are measured by X-ray and the value of equivalent plastic strain is calculated from average Vickers Hardness of sheared edge and equation (1) assumed that equivalent stress is 3.3 times Vickers Hardness[2].

![FEM model for analyses of the coining process.](image)

**Figure 4.** FEM model for analyses of the coining process.

4. Results and discussion

4.1. Sheared surface

The surface of sheared edge of the product and scrap part after shearing by punches with a diameter of 10 and 20 mm and coining by the flat shaped counter punch are shown in Figure 5. The roll over, burnished surface and fracture surface are formed on sheared edge by shearing. After shearing and coining at each coining stroke condition, the appearance of sheared surface including the ratio of each surface is almost the same regardless of punch diameter and the product or scrap part, namely the size and, positive or negative sign of shearing line curvature. These results suggest that almost the same constraint state occurred in these conditions. After coining, sheared edge of the product and scrap part are deformed and looks shiny. At $s = 1.6$ mm, the burnished surface and fracture surface formed by shearing seems to remain. At $s = 3.2$ mm, the fracture surface is deformed largely. The burr occurred in part of the shearing line and the boundary between the burnished surface and the fracture surface is almost disappeared. These deformation and the change of appearance occurred by contact of the product and scrap part during coining.

Sheared surface of the product part after shearing by punch with a diameter of 30 mm and coining with the flat and dome shaped counter punch are shown in Figure 6. In the conditions of Figure 6(b) – (e), the scrap part penetrated the product part completely. In the coining by the flat shaped counter punch, the entire sheared surface was deformed largely and the boundary between the burnished surface and fracture surface is disappeared. In the coining by the dome shaped one, the deformation of sheared surface decreases as $h$ gets higher. At $h = 0.8$ mm, the boundary between the burnished surface and fracture surface has disappeared. However, part of the burr side of the fracture surface is not deformed. At $h = 1.6$ mm, although the large part of the sheared surface is deformed, part of the boundary and the burnished surface is not deformed. At $h = 2.4$ mm, the deformed area decreases furthermore. These difference of sheared surface after coining by the flat and dome shaped counter punch be caused by rigidity of the scrap part during coining. During coining by the flat shaped counter punch, the scrap part is rigid due to constraint by the product part and counter punch. On the other hand, during coining by
the dome shaped one, the scrap can flex along with the counter punch head and become more flexible as \( h \) gets higher. Therefore, after coining by the flat shaped one, the deformation of sheared surface is larger than by the dome shaped one, and the deformation reduces as \( h \) gets higher.

![Figure 5](image)

**Figure 5.** Sheared surface after shearing and coining. (a) Product part. (b) Scrap part. Shearing by 10 mm diameter punch. (c) Product part. (d) Scrap part. Shearing by 20 mm diameter punch.

![Figure 6](image)

**Figure 6.** Sheared surface of the product part after shearing and coining with the flat and dome shaped counter punch. (a) After shearing. (b) \( h = 0 \) (Coined by the flat shaped one). (c) \( h = 0.8 \) mm. (d) \( h = 1.6 \) mm. (e) \( h = 2.4 \) mm.

The circumferential view of the sheared edges of the product after shearing and coining by 10 mm diameter punch are shown in Figure 7. Just like Figure 5, the roll over, burnished surface and fracture surface can be seen on sheared edge after shearing. After coining, the cross-sectional shape is changed. At \( s = 1.6 \) mm, the unevenness on sheared edge occurs and the burnished surface formed by shearing is lifted by coining from below, and by this, the small burr is formed on the side that was originally on the roll over side. At \( s = 3.2 \) mm, the deformation and the unevenness becomes larger on the entire sheared surface. These trends are seen regardless of the product and scrap part, and punch diameter.

The entire sheared edges of the product and scrap part sheared by 10 mm diameter punch after coining at \( s = 1.6 \) and 3.2 mm, which are shown in Figure 5 partially, are shown in Figure 8 and 9, respectively. The top and bottom images are combined to form the entire sheared edge in the circumferential direction. As to the scrap part, not all, but most of the sheared edge is shown. It can be seen that the appearance of the entire sheared edge is the same state as mentioned with respect to Figure 5. In other words, the entire sheared edge is coined uniformly in the circumferential direction. This tendency is seen regardless of punch diameter.

![Figure 7](image)

**Figure 7.** Circumferential view of the sheared edge of product part sheared by 10 mm diameter punch. (a) After shearing. (b) After coining at \( s = 1.6 \) mm. (c) After coining at \( s = 3.2 \) mm.
4.2. Residual stress
Residual stress on sheared edge in circumferential direction after coining at each shearing line conditions are shown in Figure 10. Two graph symbols at each $s$ condition shows the residual stresses at the both sides of diameter position in the shearing hole edge. Regardless of the shearing hole diameter and the product or scrap part, namely the size and, positive or negative sign of shearing line curvature, residual stress is maximum after shearing and reduces as $s$ increases. In addition, the residual stresses decreases at the both sides of diameter position in the shearing hole edge. Thus, it is assumed that the sheared edge is coined successively in this study. And it is thought that the variation of the residual stresses in the circumferential direction of the sheared edge fits in the range of these two values because these values are the ones at the farthest spots in the sheared edge which seems to most likely reflect variation.

Figure 8. Sheared surface after shearing and coining by 10 mm diameter punch at $s = 1.6$ mm. (a) Product part. (b) Scrap part.

Figure 9. Sheared surface after shearing and coining by 10 mm diameter punch at $s = 3.2$ mm. (a) Product part. (b) Scrap part.
Residual stress on sheared edge after shearing and coining by the flat and dome shaped counter punch are shown in Figure 11. In the 30 mm of punch diameter, the residual stress of 654 MPa after shear decreases to -28 MPa after coining by the flat shaped counter punch. The reduction of the tensile residual stress is almost equivalent regardless of the shape, flat or dome, and the value of h although the deformation of sheared surface by the dome shaped counter punch is smaller than by the flat shaped one.

4.3. Coining Load
The proposed scrap-used coining method requires the cushion pin to get the reaction force for the coining. The number of cushion pin corresponding to the coining load is required. Therefore, to reduce the tool cost, the coining load must be reduced. The maximum coining load of each coining test shown in Figure 11 are shown in Figure 12. At h = 1.6mm and above, the maximum coining load reduced more than 36% against the flat shaped one. It is assumed that the reduction of the coining load by the dome shaped counter punch is because the scrap part could be flex along with the counter punch head.

Figure 10. Residual stress on sheared edge after coining at each punch diameter. Result after shearing is plotted as s = 0. (a) Product part. (b) Scrap part.

Figure 11. Residual stress on sheared edge of the product part after shearing and coining by the flat and dome shaped counter punch. Result of the flat shaped one is plotted as h = 0.

Figure 12. Maximum coining load by the flat and dome shaped counter punch. Result of the flat shaped one is plotted as h=0.
Also, the reason why in the coining by the dome shaped counter punch residual stress reduces regardless of decreases of coining load especially at \( h = 1.6 \) mm and above is considered as follows. In the coining by the dome shaped counter punch, the deformation of sheared edge decreases as increase of \( h \) and gets closer to the one at \( s = 1.6 \) mm by the flat shaped counter punch where sheared edge is deformed, but the fracture surface and the boundary between the burnished surface and fracture surface almost keeps the appearance after shearing as shown in Figure 5 and 6. At \( s = 1.6 \) mm and above by the flat shaped counter punch, the amount of reduction of residual stress is saturated[3]. Thus, in the scrap-used coining, residual stress reduces enough by the deformation equivalent to the one at \( s = 1.6 \) mm by the flat shaped counter punch. Therefore, it is assumed that in the present study the reduction of residual stress at \( h = 1.6 \) mm and above by the dome shaped counter punch regardless of decrease of coining load is because sheared edge is deformed to the same extent as the one at \( s = 1.6 \) mm by the flat shaped counter punch.

4.4. Results of the FEM simulations

Average circumferential stress of the elements of outermost layer corresponding to the fracture surface during coining process calculated by FEM is shown in Figure 13. Regarding the product part, in the analyses of the shearing hole expansion and reduction, as the hole diameter expands, the average circumferential stress increases slightly, then flattened. And as the hole diameter reduces, the average circumferential stress decreases linearly to 259 MPa by elastic recovery. Therefore, residual stress on sheared surface can decrease by the shearing hole expansion and reduction by penetration of the scrap part. On the contrary, the analyses of the whole scrap-used coining process shows the sheared edge compression by contact of the product and scrap part lower the stress overall. As for the scrap part, the average circumferential stress decreases linearly as the hole diameter reduces. Then, the stress increases linearly by elastic recovery as the hole diameter expands. However, the 560 MPa of final stress is lower than the initial value. The reason the stress doesn’t recover to the initial value in spite of the elastic behavior of stress is assumed that the amount of elastic recovery in the whole scrap decreased because plastic deformation occurred in the elements other than the outermost layer. As in the case of the product part, the stress is lowered overall by the sheared edge compression by contact. In conclusion, it is turned out that both of the shearing hole expansion and reduction and the sheared edge compression by contact of the product and scrap part during the scrap-used coining contribute the reduction of residual stress on sheared edge of the product and scrap part.

![Graph](image)

**Figure 13.** Average circumferential stress on fracture surface during coining process.
(a) Product part. (b) Scrap part.
5. Summary and Outlook
In the present study, the scrap-used coining method was applied to high strength steel, and the effects of the size of shearing line curvature, positive and negative sign of curvature and shape of counter punch head on residual stress on sheared edge were investigated by experiments and numerical analyses to clarify the range of conditions the method could reduce residual stress. As a result, following things are revealed.

1. In the actual manufacturing process, the coining process is performed successively after shearing. On the other hand, in this study, the shearing and coining process are performed separately to process the method simply. It is turned out that even in the case of processing the shearing and coining separately, the sheared edge could be coined uniformly in the circumferential direction.

2. The scrap-used coining could reduce residual stress on sheared edge regardless of the shearing hole diameter and the product or scrap part, namely the size of shearing line curvature and positive and negative sign of curvature in the range of 10 to 20 mm of punch diameter. The

3. The dome shaped counter punch could reduce coining load in addition to the same extent of reduction of residual stress as the flat shaped one. In this study, at h = 1.6 mm and above, coining load reduced more than 36% against the flat shaped one. It is assumed that the coining load decreases because the scrap can flex along with counter punch head and the reason why residual stress decreases regardless of reduction of coining load is sheared edge is deformed to the same extent to the one at s =1.6 mm by the flat shaped counter punch where reduction of residual stress is equivalent to the one after scrap penetration.

4. It is thought that the tool cost of the scrap-used coining could be reduced using the dome shaped counter punch because the number of cushion pin required to get the reaction force for coining could be reduced.

5. From the result of analyses, during the scrap-used coining, the residual stress changes by two mechanisms, the shearing hole expansion by the scrap penetration and reduction by elastic recovery after scrap penetration and the sheared edge compression by contact of the product and scrap part.

And, following things are considered issues for the practical use. In the actual manufacturing process, the shearing and coining process are performed successively pushing the counter punch with the reaction force of shearing by cushion pin. Thus, the way of removal of the scrap penetrating above the shearing hole is needed. In addition, in the trimming condition, other challenges different from piercing condition may arise because of difference in constraint conditions. Also, to perform the analysis of this method and discuss the value of residual stress quantitatively, the modeling of the experimental conditions of coining process, e.g. roughness and friction coefficient of the sheared edge which seems to affect the coining behavior is required.

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