Blanking Method with Aid of Scrap to Reduce Tensile Residual Stress on Sheared Edge

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Abstract. A simple shearing method to reduce tensile residual stress on a sheared edge is highly desired in the automotive industry because this type of stress deteriorates the fatigue property of automotive parts. In this study, the effect of a coining method with a shearing scrap material on a sheared edge was investigated. The scrap part of a sheared plate has a fracture surface shape similar to that of the product part since these parts are generated by separation of a single plate with crack propagation. Therefore, it is possible to impose plastic strain over the entire fracture surface by using the scrap part as a coining tool. Effectiveness of this method was investigated for high-tensile-strength steel. Using this method, the tensile residual stress on the sheared surface was significantly reduced and work hardening was slightly increased. The effects of shearing clearance and coining stroke were also investigated. Tensile residual stress decreased as the coining stroke increased; however, it saturated at a certain stroke. The stroke at which tensile residual stress saturated was relatively small at a large clearance. In particular, the amount of plastic deformation on fracture surface increased when coining stroke became large. These tendencies could be explained by the conditions of contact, which were investigated using finite element analysis.

1. Introduction

In recent years, the need for weight reduction of automobiles has increased owing to CO2 discharge regulations [1]. Although strengthening materials is an effective way to achieve it, there are several difficulties in using the high-strength steel, such as an increase in the spring back after forming process, lower formability, and deterioration of fatigue properties. In general, the fatigue property of steel is improved as materials are strengthened, however, it is known that fatigue strength does not increase linearly with tensile strength, especially in ultra-high-strength steels; therefore a new shearing method to improve fatigue properties is highly required.

The fatigue properties of steels are influenced by roughness and residual stress on sheared edges. Thun far, several shearing methods have been proposed and their effects have been shown. Shirasawa et al. reported that the fatigue properties of a sheared edge were improved by smoothing the fracture surface and reducing tensile residual stress on the sheared edge using the coining process; the effects of these processes depend on the shape of the fracture surface, which varies with changes in shearing clearance (CL)[2]. In addition, the coining punch may not contact the fracture surface, and expected effects are not achieved, if the blank is slightly out of alignment. Therefore, conventional coining methods require precise prediction of the shape of the sheared edge and precise alignment of the blank. These difficulties prevent the coining process from being used in commercial production process.
In the present study, a simple coining method that uses shearing scrap material after shearing is proposed. The effect of this method is investigated by measuring the residual stress and fatigue properties on the sheared edge.

2. Brief of the coining method

Figure 1 shows the conventional shearing method and the method proposed in this study. In the conventional shearing method, a scrap part generated during the shearing process is not used. On the contrary, in the proposed method, the scrap part is used as a coining tool and forced up by the counter punch. The scrap part of a sheared plate has a fracture surface shape similar to that of the product part because these parts are generated by separation of a single plate with crack propagations. Therefore, by using the scrap part as a tool for coining, it is possible to reduce the tensile residual stress on the entire fracture surface.

![Figure 1: Schematic of the conventional shearing method and the proposed method.](image)

(a) Conventional shearing method (b) Proposed method

Figure 1 Schematic of the conventional shearing method and the proposed method.
3. Experimental methods

3.1 Shearing test
A high-strength steel sheet (JSC980Y) with a thickness of 1.6mm was used in this study. The shape of shear line was a circle with a diameter of 10mm. The shearing punch and die used in this study were made of SKD11 alloy steel. The CLs were set to 5%t, 10%t, and 20%t, and the shearing angle was fitted at 0°. The punching velocity was set to 100 mm/sec.

3.2 Coining test
Figure 2 shows a schematic of a simple coining test conducted in this study to simulate the method described in Figure 1. The steel plate was divided into a scrap part (a disc) and a product part (a plate with a hole) by shearing. Using the punch and die used in the shearing process, the scrap part was pushed until it penetrated the hole. Coining stroke (s) was defined as 0 mm when the difference between height of product part and that of the scrap part was 1.6 mm (thickness). In this definition, s equals 0 mm just after piercing, 1.6 mm when the difference between the height of the product part and that of the scrap part is 0mm, and 3.2 mm when the scrap part penetrates the product part.

![Figure 2 Schematic of the simple coining test.](image)

3.3 Measurement of residual stress
Residual stresses on the sheared surface in each were measured using X-ray. For its simplicity, it is common to use a strain gage to measure residual stress. On the other hand, measurement of residual stress using x-rays is non-destructive and allows measurement of residual stress in a more local region. In the sheared edge, a large strain gradient is locally generated in the surface layer, and the roughness is also large, so it is difficult to accurately measure the residual stress by the x-ray. Therefore, in this paper, the change of relative residual stress value caused by coining are mainly discussed. The specimen was divided into two parts, and the measurements were carried out at three places as shown in Figure 3. The directions for the measurements were taken along the plate thickness and circumference. The diameter of the measured area was set to 500µm. In the present work, the measurement is based on the sin^2θ method, and (211) diffraction plane was used, which diffracts at 2θ=156° (CuKα radiation). The stress constant used in this study for calculation of residual stress is -318MPa.
3.4 Fatigue test
Plate-bending fatigue tests were conducted to evaluate the fatigue properties of the sheared edge. Figure 4 shows the design of the specimen with a hole, which was made by piercing. Some specimens were tested with an as-pierced hole (s = 0 mm), and the others had a hole treated with the coining process (s = 1.6 mm). The stress ratio was -1, and frequency was set to 25Hz. All tests were conducted at room temperature.

3.5 Numerical analysis
To investigate the deformation behaviour of the sheared edge during the shearing and coining processes, numerical analyses were performed using the FEM (finite element method) code ABAQUS/implicit. Figure 5 shows the finite element models for the numerical analyses performed in this study.
Figure 5 FEM models for analysing the shearing and coining processes. 
(a) Shearing process (b) Coining process

The tools and the blank model composed of solid elements were used under the axial symmetry condition. A punch and a die have a round edge radius of 0.1 mm to avoid intrusion of tools into the blank mesh. To simulate the deformation behaviour of the material during a blanking and coining process as precisely as possible, fine elements with a size of 0.02 mm were used in the deformed area of the blank. The isotropic yield function proposed by Mises, the J2F plastic flow rule, and the isotropic hardening rule were applied to the blank deformation. The work-hardening characteristic of the material was approximated as

$$\bar{\sigma} = F(0.002 + \bar{e}^p)^n$$

where $\bar{\sigma}$ is the equivalent stress, $\bar{e}^p$ the equivalent plastic strain, $F$ the strength coefficient, and $n$ is the work-hardening exponent. The values used in this study were $F = 1864$ and $n = 0.122$. When the punch stroke increased in the shearing process, cracks occurred at the tool edges and propagated, thereby generating a fracture surface. The initiation of the crack was determined based on the observation result for the sheared edge, and the fracture surface was described by smooth lines for convergent calculation in the coining analysis. The coulomb friction rule was applied, and the frictional coefficient between the tools and the blanks was set at 0.2.

4. Results and discussion

4.1 Sheared surface

Figure 6 shows images of the sheared surface before and after the coining process. Sheared edges are composed of a roll over, a burnished surface and a fracture surface. Secondary shearing and a large burr were not observed under all CL conditions. The ratio of the rough fracture surface to the smooth burnished surface was high in this material because the onset of cracks in shearing occurred early because of the small ductility of ultra-high-strength steel. These characteristics were also confirmed by Mori et al.[3] and Matsuno et al.[5] for high strength steel.

As s increased, the fraction of the shiny area in the fracture surface increased. When the value of strokes reached 1.6 mm, almost all of the area of the fracture surface became shiny; this indicates that
the surface layer of the fracture surface was slightly deformed by a contact between the sheared edge of the scrap part and that of the product part. When the scrap part penetrated the hole in product part \( s = 3.2 \text{ mm} \), the sheared edge was largely deformed.

4.2 Residual stress

Residual stresses on the sheared edge before and after the coining process are shown in Figure 7 wherein tension is defined to be positive. Before the coining process, very high tensile residual stresses was observed along two directions. The value of tensile residual stress at some points were higher even than the ultimate tensile strength of the material used in this study. The plastic strain observed at a sheared edge was much higher than the uniform elongation measured in the tensile test. This has been confirmed by some authors via the Vickers hardness test on a sheared edge [3]. These high residual stresses could be due to severe deformation on the sheared edge during the sharing process. Residual stress varies depending measurement position in the plate-thickness direction. Higher tensile residual stresses were measured on the burr side of the specimen. As \( s \) increased, tensile residual stresses decreased drastically and reached almost 0MPa at \( s = 1.6 \text{ mm} \). It is notable that a decrease in residual tensile stress occurs with a smaller stroke on the burr side rather than on the roll over side and at the thickness center. For example, paying attention to the measurement result of residual stress in the thickness direction at CL=10\%t (Figure 6(c)), tensile residual stress mainly decreases after \( s = 1.4 \text{ mm} \) at roll over side and at the thickness center. Then these values saturate gradually until \( s = 2 \text{ mm} \). The value of \( s \) at which residual stress saturates seems to be affected by CL. The larger the CL, the smaller the \( s \) at which residual stress saturates. When CL = 5\%t, residual stress continues to decrease even after \( s = 1.6 \text{ mm} \) (Figure 6(a), (b)); however, when CL = 10\%t and 20\%t, residual stress is almost saturated at \( s = 1.6 \text{ mm} \) (Figure 6(c)-(f)). Similar tendencies were also observed in the result of residual stress along the circumferential direction.

4.3 Improvement in the fatigue property

The results of the fatigue test are shown in Figure 8. The fatigue properties were improved after the coining process proposed in this study was applied. The influence of the residual stress on the sheared edge on the fatigue property of the material investigated, and it was found that the fatigue property improved as the tensile residual stress on the sheared edge decreased by the proposed method. The improvement in the fatigue properties on the sheared edge could be explained by a decrease in tensile residual stress (Figure 7(e),(f)).

4.4 Results of the FEM simulations

Figure 9 shows the plastic strain distribution during the coining process at CL = 10\%t. The fracture surface of the sheared edges contact each other at \( s = -1.1 \text{ mm} \). The surface area of the fracture surface of the product part was mainly deformed at the burr side at a small stroke, and the mainly deformed area gradually moved from the burr side to the roll over side as \( s \) increased (Figure 9(b)). This should be the reason why tensile residual stress decreased at the burr side, and that at roll over side decreased after \( s \) became large. Figure 10 shows the distributions of hydrostatic pressure during the coining process at \( s = 1.6 \text{ mm} \). A higher hydrostatic pressure was applied to the sheared edge at a larger CL because the larger the clearance is, the larger the angle of the fracture surface with respect to the coining direction is. This may cause an early decrease in tensile residual stress at a larger CL. When the coining load was applied to the scrap part, the hole in product part expanded slightly in the x direction with elastic plastic; therefore, the distribution of plastic strain did not change significantly at \( s = 1.6 \text{ mm} \) (Figure 11(b)). However, when the scrap part penetrated the hole in the product part at \( s = 3.2 \text{ mm} \), the sheared edge was largely deformed and the area and amount of plastic strain increased (Figure 11(c)). This tendency was confirmed by observing the sheared edge (Figure 6). As mentioned by several authors, the amount and area of plastic strain on the sheared edge causes deterioration of the stretch-flange formability [3]-[6]. Therefore, it is recommended that coining should be stopped before penetration to avoid a large plastic deformation on a sheared edge where high stretch-flange formability is required.
Figure 6  sheared surface before and after coining.
(a) s = 0 mm(CL =5%t) (b) s = 0 mm(CL = 10%t) (c) s = 0 mm (CL = 20%t)
(d) s = 1.6 mm(CL = 5%t) (e) s = 1.6 mm(CL = 10%t) (f) s = 1.6 mm (CL = 20%t)
(g) s = 3.2 mm(CL = 5%t) (h) s = 3.2 mm(CL = 10%t) (i) s= 3.2 mm (CL = 20%t)
Figure 7  Residual stress at each coining stroke.
(a) $\sigma_t$ (CL = 5%t)  (b) $\sigma_c$ (CL = 5%t)
(c) $\sigma_t$ (CL = 10%t)  (d) $\sigma_c$ (CL = 10%t)
(e) $\sigma_t$ (CL = 20%t)  (f) $\sigma_c$ (CL = 20%t)
Figure 8 S-N fatigue curve for the specimen with a hole before and after coining (CL = 20%t).

Figure 9 The shape of sheared edge during coining process (CL = 10%t).
(a) s = 1.1 mm (b) s = 1.6 mm

Figure 10 Hydrostatic pressure during coining process (s = 1.6 mm).
(a) CL = 5%t (b) CL = 20%t
5. Summary and Outlook

Using shearing scrap material, the effect of the proposed coining method on a sheared edge was investigated. As a result, the following facts were clarified:

1. Using the proposed method, tensile residual stress on the sheared edge reduced in a wide range of shearing clearances (CL=5%t ~ 20%t).

2. The sheared edge was gradually treated by the scrap part form the burr side to the roll over side when using proposed method.

3. As the coining stroke increased, the shiny area on the fracture surface increased and the residual stress at the sheared edge decreased. The coining stroke at which residual stress on the sheared edge saturated decreased as the shearing clearance became larger.

4. When the scrap part penetrated the hole in the product, the deformed area and amount of plastic strain on the sheared edge increased. To avoid deterioration of stretch-flange formability on the sheared edge, the coining stroke should not be too large.

5. The sheared edge treated with the proposed method showed a better fatigue property owing to the reduction in tensile residual stress on the sheared edge.

In the method proposed in Figure 1, a press machine with two axes is required. Press machines with two axes are expensive; therefore, for their feasible application in the automobile press line, it is necessary to establish a simpler method, if the counter punch is placed in appropriate position, it can be implemented with single-axis press machine, which is a suitable candidate. It is considered that the residual stress after punching is affected by the position and force of the counter punch; therefore, further investigation is necessary. Also, with the counter punch, it is necessary to consider the discharge method of scrap.

In the case of a circular piercing, such as that used in the proposed method, because the scrap part is a disk, a uniform effect can be obtained on the shear surface merely by pushing up the scrap part; however, when the punching shape is non-axisymmetric, the effect of reducing the residual stress is non-uniform. In the case of trimming, it is necessary to consider the method of restraining scrap so that the material for pushing up does not shift during coining.

Figure 11  The distribution of plastic strain on sheared edge at each coining stroke (CL = 10%t).

(a) s = 0 mm  (b) s = 1.6 mm  (c) s = 3.2 mm
Despite the above-mentioned problems, this method is considered to be a powerful method for reducing residual stress, because it does not require a high press rigidity and a mold accuracy, as is the case with precision blanking method, normal coining, and shaving.

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