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Shearing Technology for High-tensile-strength Steel

Takashi YASUTOMI*
Shigeru YONEMURA
Tohru YOSHIDA
Ryuichi NISHIMURA
Masahiro NAKATA
Masaaki MIZUMURA

Abstract

Hydrogen embrittlement cracking, burring, and tool wear in the shearing process are becoming increasingly important issues in the application of high-tensile-strength steel sheets for automotive body parts. In this paper, a new coining method with the aid of scrap parts and the cut-off punching process is introduced. The developed trimming die structure for suppressing the occurrence of burring on sheared surfaces is introduced. In addition, the mechanism of tool wear of shearing tools for high-strength steel is discussed, and the effect of coating on shearing tool life was investigated.

1. Introduction

High-tensile-strength steel sheets have been applied to automotive body parts to improve both the collision safety performance and fuel economy at the same time. The strength of steel sheets mainly applied to frame parts has, in particular, rapidly improved. Steel sheets of 1180 MPa have been developed although cold stamping is the precondition, and they have been used in practice for automotive body parts.[1, 2]

Steel sheets to be used for automotive body parts are cut from a coil into a blank shape using a blank die in the blanking process. Then, they are formed into a designated product shape by press-forming. After forming, a trim die is used to cut off extra sections other than the product shape and punch holes. In the course of manufacturing such automotive body parts, on the edge sections formed on steel sheets (hereinafter, sheared surface(s)), strain and residual stress occur in the aforementioned cutting process. Therefore, various characteristics of a sheared surface are lower than those of the base metal, so attention to this issue is required. Some researchers have pointed out that the stretch-flange-formability is lower at such sheared surfaces.[3] At the sheared surfaces of high-tensile-strength steel sheets with a strength of 1 GPa or more, cracks due to hydrogen embrittlement and burrs due to unexpected cracks and their advancement are of concern, in addition to such low stretch-flange-formability. In addition, the strength of steel sheets is becoming closer to that of the tool steel. Therefore, damage to cutting tools may be obvious, which may increase the production costs.

To solve these problems, an approach from the perspective of processing technologies is also important in addition to an approach considering the materials aspect. Many researchers have been studying measures to improve stretch-flange-formability among shearing methods.[4–7] This section introduces countermeasures against a particularly serious problems with 1-GPa or stronger high-tensile-strength steel sheets—mainly hydrogen embrittlement resistance at sheared surfaces, burrs on sheared surfaces, and damage to cutting tools.

2. Problems with Sheared Surfaces of High-tensile-strength Steel Sheets and Technologies for Solving Them (Countermeasures)

2.1 Technologies for improving hydrogen embrittlement resistance of sheared surfaces

Fracture due to hydrogen embrittlement is a phenomenon in which when hydrogen in a certain quantity or more permeates steel when static stress is applied, rendering it fragile and prone to breakage. Residual tensile stress due to processing remains at the sheared surfaces. In this state, hydrogen permeates the parts in processes for manufacturing automotive body parts or in environments where actual automobiles are used, so hydrogen embrittlement cracking is an issue. To prevent hydrogen embrittlement cracking, the quantity of hydrogen permeating the steel needs to be reduced and residual tensile stress needs to be reduced through processing technologies. This section introduces a simple coining method using scrap produced during shearing as a means to reduce residual tensile stress and a case in which the cutting-off punching method[8] was applied to high-tensile-strength steel sheets.

* Researcher, Integrated Steel-Solution Research Lab., Steel Research Laboratories
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

2.1.1 Coining method using scrap

General coining has problems in mass production: A punch of an appropriate shape needs to be selected based on the shape of the sheared surface because the improvement effects vary depending on the shape of the punch; and the tool needs to be aligned with the cutting plane line at high accuracy. The authors have developed a simple coining method in which scrap discharged after cutting is used as a coining punch.[9–11] **Figure 1** illustrates an outline of the proposed method. In shearing such as piercing and trimming, cut-out portions in the blanking process are discharged as scrap in general, but the proposed method utilizes such scrap. When a steel sheet is cut by shearing, the angle of the fracture surface of the scrap matches that of the product regardless of the shearing conditions. Therefore, the scrap steel sheet is used as a coining punch after shearing. The fracture surface of the scrap is pressed to that of the product with a cushioned pin or other tool to reduce the residual tensile stress on the sheared surface by the coining effects at the time of pressing.

To study how the proposed method would work, scrap after blanking was simply pressed to the product to measure the residual stress on the sheared surface before and after coining. The test material was a 1.6-mm-thick steel sheet with a tensile strength of 1289 MPa. A servo press machine was used to pierce a hole with a diameter of 10 mm and the steel sheet was separated into the product and its scrap. At this time, the ratio of the clearance between the punch and die to the thickness (hereinafter, "CL/t") was set to 10%. After that, the scrap was placed at the hole section on the product. A piercing tool was used to apply a load to coin the hole section. To study the relationship between the coining stroke and the residual stress on the sheared surface, three stroke conditions were tested: Only the pierced state (S_0); the stroke in which the height of the scrap becomes the same as that of the product (S_1); and the stroke in which the scrap passes through the product hole section (S_2): The scrap was pressed to the hole section through conditions S_1 and S_2 and then removed.

Under each test condition, the residual stress at the center of the thickness at the hole section was measured by X-rays. The spot diameter was 500 μm and the $\sin^2 \psi$ method was used for measurement. In addition, for the stroke in which the scrap was pressed to the height of the product (S_1), the hydrogen embrittlement resistance of the sheared surface was evaluated in an immersion test using ammonium thiocyanate. **Figure 2** shows the residual stress in the thickness direction and circumferential direction in the coining. On the sheared surface in the only pierced state (S_0), the residual tensile stress observed was close to the tensile strength of the steel sheet both in the thickness and circumferential directions. On the other hand, on the sheared surfaces after the coining using the scrap (S_1 and S_2), the residual tensile stress was significantly lower. In addition, the evaluation results of hydrogen embrittlement resistance in the immersion test using ammonium thiocyanate show that the resistance to hydrogen embrittlement was significantly improved at the sheared surfaces coined by the proposed method (S_1 and S_2), as compared with the only pierced state (S_0). As described above, it has been confirmed that this method has robustness against changes in the pressed amount. This paper shows the effect of the proposed method targeting hole sections. The authors will study how the proposed method works on the cutting plane line shape other than that formed by piercing and will study a die structure appropriate for mass production.

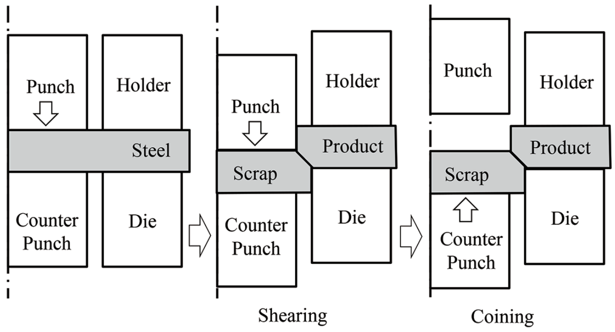

Fig. 1 Schematic of coining method with aid of scrap

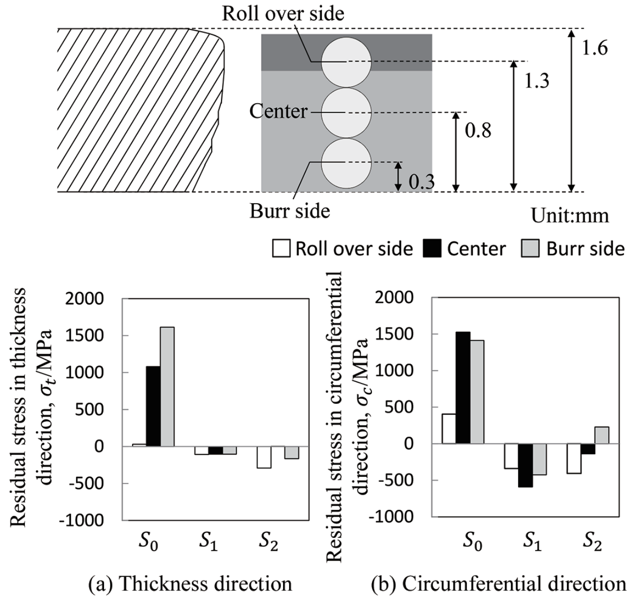

Fig. 2 Residual stress at each coining stroke

2.1.2 Cut-off punching method

The cut-off punching method[8] is known as a simple shaving method. The method can achieve excellent stretch-flange-formability by suppressing the thickness of work-hardened layers. This section studies hole expansion ratios and hydrogen embrittlement resistance of surfaces processed by the cut-off punching method targeting punching of high-tensile-strength steel sheets. The test material was a 1.6-mm-thick steel sheet with a tensile strength of 1289 MPa. The diameter of the die was determined as 10.64 mm. To study how the cutting width affects the hole expansion ratio, cylindrical punches (**Fig. 3** (a)) with the dimeters shown in **Table 1** were used to cut off the sheet in two-step punching. In addition, a punch in the shape shown in Fig. 3 (b) was used to cut off the sheet in one step under condition No. 3. After punching, the hole expansion ratios at the hole sections were measured for all the conditions. Under conditions Nos. 1 and 3, residual stress was measured by X-rays and an immersion test using ammonium thiocyanate was conducted.

Figure 4 shows an example sheared surface of the conventionally pierced surface (No. 1) and another surface processed by the cut-off punching method (No. 3). For the conventionally pierced surface, the shear plane is small and the ratio of the fracture surface is large. On the other hand, for the surface processed by the cut-off

Table 1 Punching conditions

No.	D_1 [mm]	D_2 [mm]	Cut-off width [mm]
1	10.32	–	0
2	10.32	10.48	0.08
3	10.00		0.24
4	9.68		0.40

D_1: Punch diameter in the first step
D_2: Punch diameter in the second step

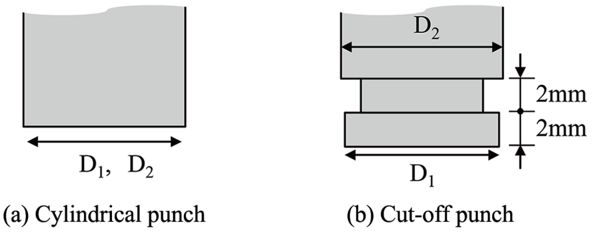

Fig. 3 Schematic figure of piecing tools

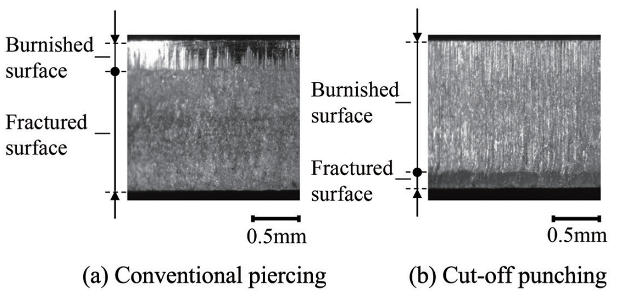

Fig. 4 Sheared surface of conventional piercing and cut-off punching

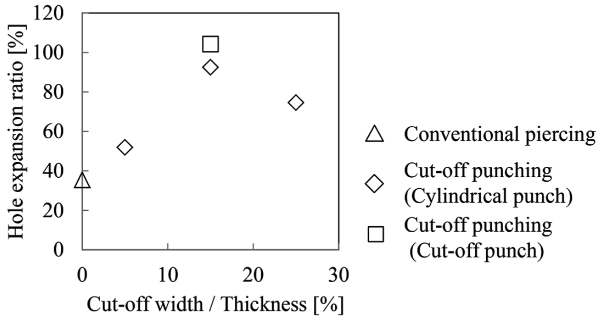

Fig. 5 Hole-expansion ratio of cut-off punched hole

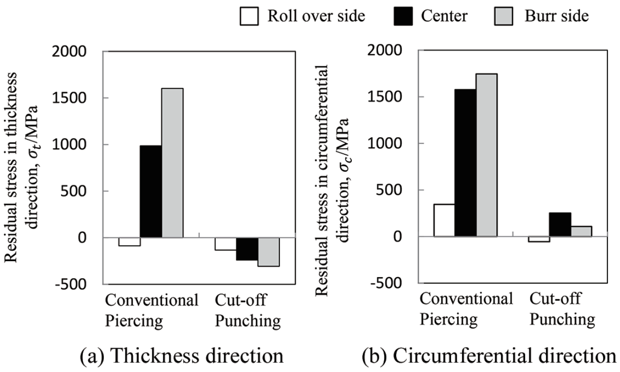

Fig. 6 Measurement result of residual stress

punching method, the ratio of the shear plane is large. **Figure 5** shows the hole expansion ratios of the surfaces processed by the cut-off punching method against the conventionally pierced surface with a CL/t of 10%. Compared with the conventionally pierced hole under a CL/t of 10%, the hole expansion ratio of the surface processed by the cut-off punching method was significantly improved. For the hole processed by the punch shown in Fig. 3 (b), since the punching was performed in one step, the surface was uniform in the circumferential direction. The hole expansion ratio measured was approximately three times that of the conventionally pierced hole under a CL/t of 10%.

Figure 6 shows measured residual stress for the conventionally pierced surface (No. 1) and the surface processed by the cut-off punching method (No. 3). For the conventionally pierced surface, the residual stress on the fracture surface is higher than the tensile strength. On the other hand, on the surface processed by the cut-off punching method, the residual tensile stress was significantly low.

In addition, the evaluation results of hydrogen embrittlement resistance in the immersion test using ammonium thiocyanate showed that the resistance of the surface processed by the cut-off punching method to hydrogen embrittlement is significantly higher than that of the conventional piercing. As described above, the surface processed by the cut-off punching method has excellent stretch-flange-formability and hydrogen embrittlement resistance even for high-tensile-strength steel sheets. The cut-off punching method has problems in mass production (e.g., chipping). Solving these problems could dramatically enhance the characteristics of surfaces for high-tensile-strength steel sheets.

2.2 Technologies for suppressing burrs on sheared surfaces

In shearing, when the CL/t value is appropriately determined, the sheared surface consists of a round edge, shear plane, and fracture surface. Meanwhile, when the CL/t is too large, convex (burred) portions may form on the die side. This section shows the CL/t range in which a burr is formed in various cutting plane line shape types targeting high-tensile-strength steel sheets. This section also introduces a blanking die structure that can suppress the formation of burrs in a wider CL/t range. In this paper, among burrs, relatively larger burrs exceeding 5% of the thickness are referred to as excessive burrs.

The test material was a 1.4-mm-thick, 980-MPa steel sheet. For the cutting plane line shape shown in **Fig. 7**, the distribution ratios on the sheared surfaces (ratio of the thicknesses of the round edge, shear plane, fracture surface, and burr) were studied after the sheet was blanked while the CL/t was changed from 7 to 25%. **Figure 8** shows the results of the convex portion after blanking. When the CL/t was equal to or larger than 18%, excessive burrs were seen.

Next, the influence of the CL/t on the height of a burr was compared between various cutting plane line shape types (**Fig. 9**). The minimum CL/t at which an excessive burr was formed is 18% for the convex portion and 21% for the straight line. On the other hand, for the concave portion, even when the CL/t is 25%, no excessive burrs were seen. These results show that, for convex portions and straight lines, an excessive burr is more easily formed as compared with concave portions. This may be because, when a cutting plane line is in a straight line or close to the end of the blank, excessive

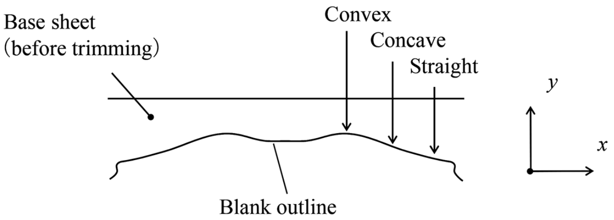

Fig. 7 Cutting line shape

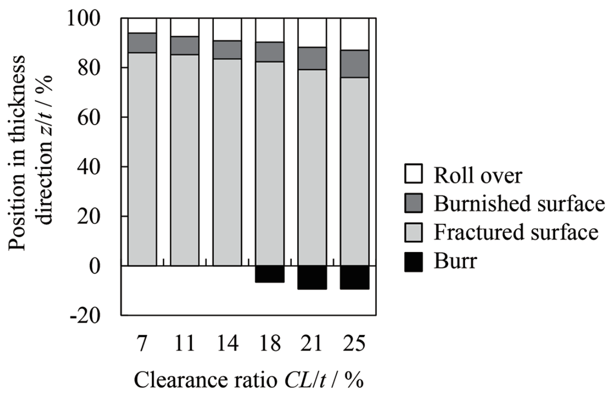

Fig. 8 Effect of piercing clearance on pierced edge quality

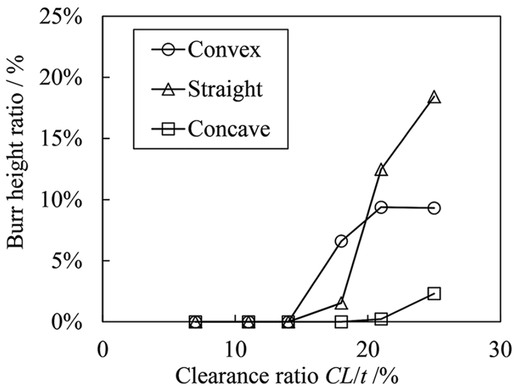

Fig. 9 Comparison of effect of shearing clearance on burr height among different trimming line curvatures

collapse of the material may occur, which may form an excessive burr although this is not shown in a figure.

The stretch-flange-formability of the test material was evaluated by flange-up forming with various CL/t values. Under conditions where an excessive burr was formed, the stretch-flange-formability was significantly low. **Figure 10** shows the trimming die structure that we conceived to suppress excessive burrs when the CL/t is larger. To reduce excessive collapse of the material that forms excessive burrs, the sheet was trimmed while the underside of the material was pressurized at the section to be trimmed by a die directly connected to a gas cylinder in the structure. **Figure 11** shows the relationship between the absolute value of the finite thickness strain in the flange-up forming and CL/t. Thanks to the designed trimming die structure, even when the CL/t is large, excessive burrs were suppressed, which has made it possible to achieve stable and good formability.[12)]

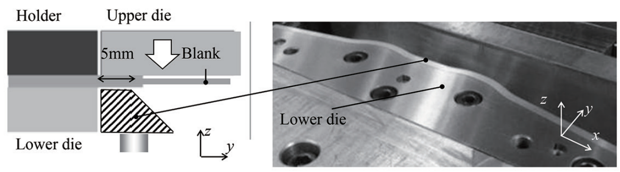

Fig. 10 Developed trimming die structure for suppressing excessive bending behavior around trim edge line

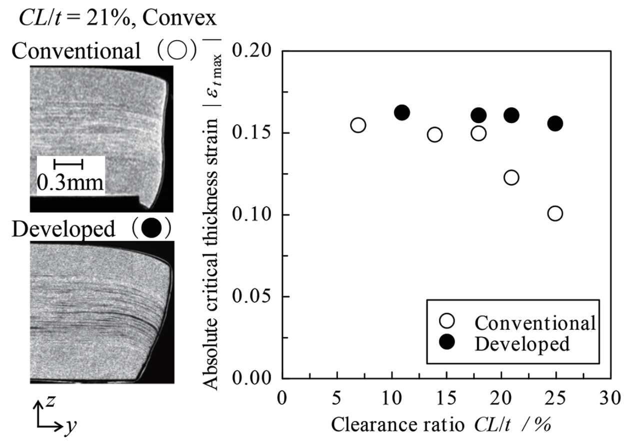

Fig. 11 Effect of developed trimming die structure on flange-up formability

3. Work on the Durability of Cutting Tools for High-tensile-strength Steel Sheets

The hardness of high-tensile-strength steel sheets is becoming closer to that of tool steel, which raises concerns that tools used in shearing may be significantly damaged. The height of burrs formed on a sheared surface is one index to evaluate the life of the cutting edge in shearing. The main causes of increase in the height of burrs are changes in the shape of the cutting edge and changes in the CL/t due to wear of the side of the tool. This section describes the mechanism in which the shape of a tool cutting edge changes for high-tensile-strength steel sheets and the influence of shearing conditions on such changes. This section also shows the results of the test on the durability of various coating treatments that are effective in suppressing wear on the sides of tools.

3.1 Causes of damage to shearing tools for high-tensile-strength steel sheets

Causes of changes in the shape of cutting edges for high-tensile-strength steel sheets were studied. To observe deformation of a cutting edge during shearing, a hole with diameter of 10 mm was bored on a steel sheet inclined 3° toward the punch and a sample where the end of the punch had cut the steel sheet was taken in order to observe the cross section of the tool. The test materials were 590-MPa and 1180-MPa steel sheets of 1.4 mm thick each. **Figure 12** shows the observation results of the tool cutting edges. For the tool that cut the 590-MPa steel sheet, the cutting edge is little deformed. On the other hand, for the tool that cut the 1180-MPa steel sheet, the shape of the cutting edge has clearly changed. The shape changed in the first shot, so this is neither low-cycle fatigue of the cutting edge nor separation of the cutting edge section due to adhesion with the workpiece (problems that have been pointed out); the deformation may be plastic deformation of the tool steel.

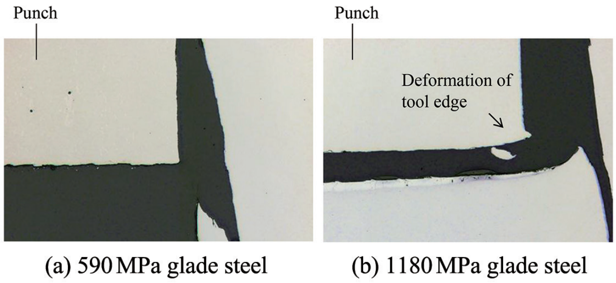

Fig. 12 Deformation of sheared tool edge

Table 2 Analysis conditions

Shearing conditions	Reference conditions	Analysis conditions
Thickness, t [mm]	1.6	0.8 – 2.4
Clearance/Thickness, CL/t [%]	10	1 – 30
Blank inclination angle, θ [°]	0	0 – 20
Curvature radius of tool edge, R [mm]	0.1	0.02 – 0.5

To study the influence of various shearing conditions on the plastic deformation of cutting edges, numerical simulation by the finite element method was carried out. The static implicit FEM software ABAQUS/Standard was used as the solver. The tool was determined as an elastic body, Young's modulus was set to 206 GPa, and Poisson's ratio was set to 0.3. The cutting edge was rounded to prevent the tool cutting edge from becoming caught in the mesh. To study the influence of various shearing conditions, the analysis factors were changed in the ranges shown in **Table 2** in reference to the standard conditions. The loads to the cutting edges during shearing were evaluated using the maximum equivalent stress values that correlate with plastic deformation.

Figure 13 shows the maximum equivalent stress values at the tool cutting edges under the various shearing conditions. The results under the various analysis conditions have been normalized by the results under the reference conditions. Firstly, the results under the conditions where the thickness was changed (Fig. 13 (a)) show that, even when the thickness is larger, the stress working on the tools does not greatly change. Secondly, the results under the conditions where the curvature radius of the tool cutting edge was changed (Fig. 13 (b)) show that, when the curvature radius of the tool cutting edge is larger, the stress occurring at the cutting edge is lower, showing that plastic deformation can be suppressed. Thirdly, the results under the conditions where the CL/t was changed (Fig. 13 (c)) show that the stress occurring at the cutting edges hardly depends on the CL/t. Lastly, the results under the conditions where the blank angle (θ) was changed (Fig. 13 (d)) show that the stress occurring at the cutting edge is strongly affected by the blank angle (θ): It shows that, as compared with the case where the blank angle is zero, when the angle is approximately 20°, the load to the cutting edge is approximately 1.5 times.

As described above, to suppress deformation at a shearing tool cutting edge, it is important to suppress the stress occurring at the cutting edge by changing its shape and to make the blank angle smaller. When the shape of a cutting edge is changed, both the durability of the tool and various characteristics demanded for the sheared surface need to be satisfied at the same time. In addition, while the blank angle is almost zero in the blanking process of coils, inclined blanks need to be cut in the trimming process after forming. In addition, when the shape of the part is different from that of the die due to changes in the shape of the formed part due to springback, the inclination of the blank becomes larger. To suppress such a problem, countermeasures against springback like those introduced in the previous technical report[13)] need to be used and such technologies need to be improved.

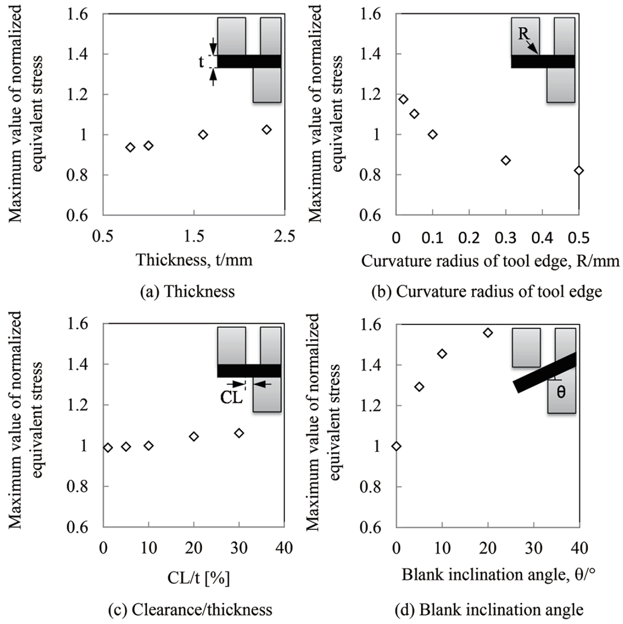

Fig. 13 Influences of shearing conditions on tool edge stress

3.2 Coating technology for enhancing the durability of cutting edges

The surfaces of cold-pressed dies for processing high-tensile-strength steel sheets are often treated before use these days to improve wear resistance and prevent galling. This section studies the life of coatings of various surface treatment targeting shearing tools.[14)] **Figure 14** is a schematic diagram of a cold-piercing test. In this test, the CL/t values were set to 3% and 6%. The workpieces were inclined 3°, and the test was carried out without lubrication. The test speed was 50 to 55 spm. The test material was a 1.6-mm-thick, 1180-MPa high-tensile-strength steel sheet. The steel for the die was cold-tool steel (improved SKD11). Three punches with different coating treatment performed–thermo reactive deposition and diffusion (TRD) treatment, chemical vapor deposition (CVD) treatment, and physical vapor deposition (PVD) treatment–were used and the results were evaluated.

For the PVD treatment, a coating for which nitriding at a depth of 50 μm was applied as the primary coating was also evaluated (nitriding + PVD). The punch cutting edges were chamfered to prevent chipping. A sample was taken from the workpiece for each shot to observe the sheared surface. When galling formed on the punch, a striped pattern was seen on the shear plane. The life of a tool in shearing is evaluated based on the height of burrs formed on the opening made by cutting and the characteristics of the section.

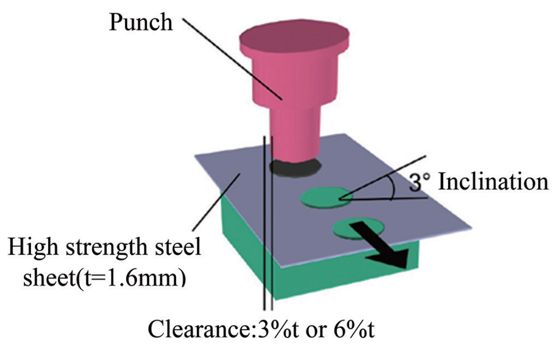

Fig. 14 Schematic diagram of pierce processing test

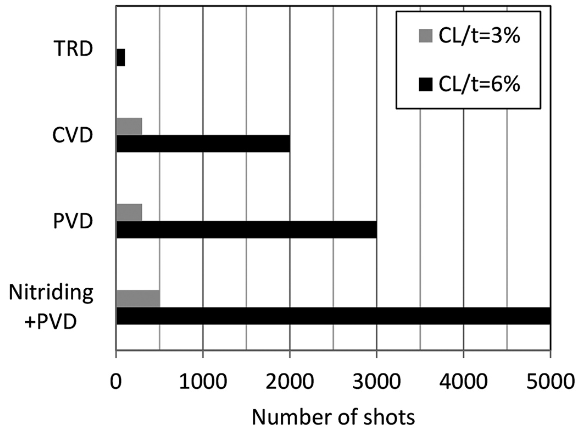

Fig. 15 Coating life comparison

Therefore, the occurrence of galls does not always match the life of the die. This section compares the number of shots until a striped pattern was seen on the shear planes as a relative index for the life of the coatings.

Figure 15 shows the evaluation results of the life of the coatings under the various conditions. For all the coatings, the life of the coatings is longer when the CL/t is 6% than that when the CL/t is 3%. When comparing the lives of the various coatings, the life is longer in the order of PVD coating, CVD coating, and TRD coating. In addition, the life of the PVD coating with nitriding as the primary coating was increased by 1.5 times or longer as compared with that without nitriding. These results show that, in cutting of high-tensile-strength steel sheets, appropriate coating treatment can extend the life of tools.

4. Conclusions

Steel materials have been made stronger both to reduce CO_2 emissions by reducing the weight of automobile bodies and to secure collision safety performance at the same time. This paper introduced, among problems with shearing, our work to solve problems that are critical when high-tensile-strength steel sheets with a tensile strength of 1 GPa or more are cut, particularly the formation of cracks due to hydrogen embrittlement on sheared surfaces, burrs on surfaces, and damage to tools. When the strength of steel sheets is further enhanced in the future, cutting technologies including laser cutting may need to be considered even for cold-rolled steel sheets, in addition to the technologies introduced in this paper. We will continue developing such technologies to produce steel sheets with higher performance and developing use and processing technologies that make application to automotive body parts possible.

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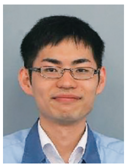

Takashi YASUTOMI
Researcher
Integrated Steel-Solution Research Lab.
Steel Research Laboratories
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

Ryuichi NISHIMURA
Senior Researcher, Dr. of Energy Science
Integrated Steel-Solution Research Lab.
Steel Research Laboratories

Shigeru YONEMURA
Senior Researcher, Dr. of Engineering
Integrated Steel-Solution Research Lab.
Steel Research Laboratories

Masahiro NAKATA
Chief Researcher
Integrated Steel-Solution Research Lab.
Steel Research Laboratories

Tohru YOSHIDA
Chief Researcher, Dr. of Information Science
Integrated Steel-Solution Research Lab.
Steel Research Laboratories

Masaaki MIZUMURA
Executive General Manager, Dr. of Engineering
Structural Mechanics Solution Div., Futtsu Unit
Nippon Steel Technology Co., Ltd.
(Former Chief Researcher, Integrated Steel-Solution Research Lab., Steel Research Laboratories)