The Effects of Piercing Methods on Burring Formability under Practical Hole Diameter

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Abstract. Advanced High Strength Steels (AHSS) sheets are used for automobile bodies to comply with the demands for weight reduction and collision performance. However, as the tensile strength is increasing, the ductility of steel sheets is decreasing. Therefore, forming defects such as fractures may occur. In case of chassis components, it is needed to prevent stretch flange fractures from burring edge. There are following methods to improve burring formability. 1) Double Punching Method (DPM): punching blank coaxially with a pre-punched hole. 2) Humped bottom Punch Method (HPM): punching blank under tension using a punch with a humped part. However, there isn't much previous evidence evaluating the burring formability of DPM and HPM under practical punching diameter for chassis components. In this study, the burring formability using DPM and HPM has been evaluated under 30mm punching diameter, through experiments and FEM analysis. The results showed that: 1) DPM: deforming mainly occurred in scrap side and equivalent plastic strain was reduced on the punched edge surface. 2) HPM: the burring formability requires both increasing stress triaxiality in blank and reducing equivalent plastic strain applied by the preceding bumped part. Under identical conditions, the same improvement effect of DPM was obtained with HPM.

1. Introduction
In the automobile industry, it is necessary to develop crash safety and body weight reduction to reduce fuel or electric costs. To accomplish these tasks, high strength steel (HSS) or advanced high strength steel (AHSS) sheets are used for automobile components. However, the ductility of steel sheets decreases with increasing tensile strength [1]. Necking or breaking may occur during molding. For example, chassis components have difficulty in press forming with HSS. Figure 1 shows the burring part of the chassis component. The rubber bush is press-fitted into the burring part, and it acts as a connection to the other part. Figure 2 illustrates the burring forming process. First, the sheet is punched out. Second, the formed hole is stretch-flange molded (expanding hole). In the stretch-flange process, cracks and fractures may occur at the edge of the hole. This forming limit is attributed to work hardening during the punching process. Figure 3 illustrates the formation of a punched edge surface. The work hardening between the edge of the punch and the edge of the die appears to increase with the length of the burnished surface in the blank thickness direction during punching. The long burnished surface after punching can be associated with a fractured surface with high hardness and a reduction in formability.

Certain punching methods have been developed to decrease the work hardening in punched edges [2-8]. These methods include the following. (1) Double punching method (DPM): punching blank coaxially with a pre-punched hole [2]. The work-hardened area can be shrunk using the DPM. (2) Humped bottom punch method (HPM): punching blank under tension using a punch with a humped part.
The high stress triaxiality $\sigma_T$ (mean stress $\sigma_{m}$/equivalent stress $\tilde{\sigma}$) breaks steel sheets with a low equivalent plastic strain $\tilde{\varepsilon}_p$ [9]. Thus, applying tension to the blank during punching causes a short burnished surface and low work hardening in the punched edge. Figure 4 illustrates the features of the DPM and HPM. Although these methods are simple and exhibit excellent performance, few studies have evaluated the burring formability of the DPM and HPM under practical punching diameters for chassis components. In this study, the burring formability using the DPM and HPM was evaluated under $\Phi$ 30 mm punching diameters through experiments and finite element method (FEM) analysis.

![Figure 1. Burring part of the chassis component](image1)

![Figure 2. Burring forming process](image2)

![Figure 3. Formation of the punched edge surface](image3)

![Figure 4. Features of (1) Double punching method: DPM, (2) Humped bottom punch method: HPM](image4)

### 2. Material

HSS sheets with a thickness of 3.2 mm and tensile strength of 780 MPa were used in this study. The mechanical properties in the rolling direction of these sheets are listed in Table 1.

| Steel grade (Japanese standard) | Thickness (mm) | Yield Stress (MPa) | Tensile Stress (MPa) | Total elongation (%) | Uniform elongation (%) |
|-------------------------------|----------------|-------------------|----------------------|----------------------|-----------------------|
| JSH780                        | 3.2            | 733               | 782                  | 15.8                 | 4.9                   |

### 3. Experimental Procedures

The single punching method (SPM, a conventional method), DPM, and HPM were adopted for the punching process, as demonstrated in Figure 5. The cut-off ratio $\delta_1$ (%) of the DPM was 30 % ($\delta = (D_{p2} - D_{p1})/2$, the punch diameter of the first punching is $D_{p1} = 28$ mm, and the punch diameter of the second punching is $D_{p2} = 30$ mm), which is desirable for the improvement effect of burring formability [2]. The humped bottom punches with the following diameters of the humped part, $D_{h1}$, and heights of the humped part, $H_{h1}$, respectively, were prepared—(A): (28 mm, 0.1 mm), (B): (28 mm, 0.4 mm), (C): (26 mm, 1.0 mm).
mm), and (D): (26 mm, 0.4 mm). The punching clearance CL/t (%) of all methods was 12.5 % (CL = (D_0 - D_P)/2, where D_0 denotes the diameter of the die, and D_P denotes the diameter of the punch). The D_P of all the methods was 30 mm. The punched holes were expanded with a conical punch (a 60° angle at the top of a cross section and a diameter of 100 mm) and die (a shoulder radius of 14 mm and diameter of 107 mm). The hole expansion ratio λ (%) = 100 × (D_C - D_0)/D_0 (D_0 = 30 mm denotes the diameter of the punched hole, and D_C denotes the diameter of the expanded hole when a crack penetrating thickness was generated) was evaluated as burring formability.

Figure 5. SPM, DPM, and HPM adopted in this study

4. Numerical Analysis Conditions
The two-dimensional solid finite element models of the SPM, DPM, and HPM were analyzed using Abaqus/Explicit (axial symmetry). Figure 6 presents the FEM model of the SPM. The shoulder radius of the cutting edge of the punch and the die was 0.05 mm. To prevent finite element from excessive deformation, an adaptive mesh (rectangle, 0.07 mm in the thickness direction, and 0.03 mm in the plane direction) was used near the cutting edge of the punch and the die. The stress triaxiality σ_T, as an index of the length of the burnished surface, and the equivalent plastic stress σ_p, as an index of work hardening, were evaluated when the (1) punch was stroked (St = 0.4 mm) because the cutting edge of the punch touched and (2) punch was stroked that equaled the sum of the length of the roll over and burnished surface from experimental results.

Figure 6. FEM model of the SPM

5. Results and Discussion
5.1. Experimental Results
Figure 7 depicts the cross-sectional images of the punched edge and scrap. A coin-shaped scrap was generated using the SPM, and the length of the burnished surface (red two-headed arrow) was 1.22 mm. A ring-shaped scrap was generated in the second punching process using the DPM, and the length of the burnished surface was 1.37 mm. However, the length of the burnished surface obtained using the HPM (A–D) was shorter than that obtained using the other methods. In the case of narrower D_H or higher H_h, particularly using HPM: A or C, short burnished surfaces were formed. It was estimated that the work hardening was suppressed when the HPM was used. Figure 8 presents the length of the roll over, burnished surface, and fractured surface. This bar graph was measured using the images of Figure 9. Focused on the length of the burnished surface, the burring formability of the HPM was assumed to be the best, followed by that of the SPM and the DPM. Nevertheless, it cannot to be confirmed that the burring formability and length of the burnished surface are related to negative correlation in this study.
Figure 9 presents the relation between the hole expansion ratio \( \lambda \) and the burnished surface ratio. The burnished surface ratio is the percentage of the length of the burnished surface in the thickness. All plots were scattered and lacked regularity. The hole expansion ratio \( \lambda \) achieved using the DPM was high although the burnished surface ratio was high. On the other hand, the ratio \( \lambda \) achieved using the HPM (B–D) was high with low burnished surface ratio. Moreover, the performance exhibited by using the HPM (C) was same as that by using the DPM. However, the performance exhibited by using the HPM (A) was low while the burnished surface was short. Subsequently, a consideration was added to these experimental results by FEM analysis.

| SPM | Burnished surface 1.22mm | DPM | 1.37mm |
|-----|-------------------------|-----|--------|
| Scrap | Blank | Scrap | Blank |

- **HPM: A**
  - \( (D_H, H_H) = (28mm, 1.0mm) \)
  - Indentation by humped part
- **HPM: B**
  - \( (28mm, 0.4mm) \)
  - Roll over
- **HPM: C**
  - \( (26mm, 1.0mm) \)
  - Fractured surface
- **HPM: D**
  - \( (26mm, 0.4mm) \)
  - Fractured surface

**Figure 7.** Cross sectional images of the punched edge and scrap

**Figure 8.** Length of the roll over, burnished surface, and fractured surface

**Figure 9.** Relation between the hole expansion ratio \( \lambda \) and the burnished surface ratio
5.2. Analytical Results

Figure 10 displays the stress triaxiality $\sigma_T$ of the punched edge during punching (0.4 mm stroke because the cutting edge of the punch touched). The contour of stress triaxiality $\sigma_T$ between the cutting edge of the punch and the die obtained using the SPM or DPM were similar. Meanwhile, the stress triaxiality $\sigma_T$ obtained was higher when using the HPM (A–D) than the other methods, particularly using the HPM (A, C) with narrower $D_H$ or higher $H_H$. These results correspond to the length of the burnished surface in Figure 8.

Figure 11 depicts the equivalent plastic strain $\varepsilon^p$ of the punched edge during punching (0.4 mm punch stroke because the cutting edge of the punch touched). The equivalent plastic strain $\varepsilon^p$ was concentrated between the punch and the die using the SPM, whereas the equivalent plastic strain $\varepsilon^p$ was concentrated mainly in the large deforming scrap side using the DPM. Using the HPM (A), equivalent plastic strain $\varepsilon^p$ between the punch and the die was increased by the preceding humped part because of the short distance between the shoulder of the humped part and the die. However, the distance between the humped part and the die was larger when using the HPM (C) than the HPM (A), and the equivalent plastic strain $\varepsilon^p$ between the punch and the die was small.

Figure 12 shows the equivalent plastic strain $\varepsilon^p$ of the punched edge (punch stroke equals the sum of the length of the roll over and burnished surface from experimental results). The equivalent plastic strain $\varepsilon^p$ obtained after punching was lower when using the DPM than the SPM. The equivalent plastic strain $\varepsilon^p$ obtained using the HPM (A) and the SPM was similar. However, when using the HPM (C), the plastic strain $\varepsilon^p$ by the preceding humped part was suppressed. It was assumed that the work hardening in the punched edge did not advance.

First, according to these results, the improvement effect of burring formability when using the DPM was expressed by the deformation of the scrap side and the depression of work hardening in the punched edge. Second, the improvement effect of burring formability when using the HPM was expressed by both the increasing stress triaxiality $\sigma_T$ of the blank by the humped part and depressing work hardening owing to the preceding humped part.

| SPM       | DPM       |
|-----------|-----------|
| Punch     | Die       |
| $\sigma_T$ | $\sigma_T$ |
| -0.5      | 0.5       |

**Figure 10.** Stress triaxiality $\sigma_T$ of the punched edge during punching (0.4 mm stroke because the cutting edge of the punch touched)

**HPM: A**

$D_H$, $H_H$ = (28mm, 1.0mm)

**HPM: B**

(28mm, 0.4mm)

**HPM: C**

(26mm, 1.0mm)

**HPM: D**

(26mm, 0.4mm)
Figure 11. Equivalent plastic strain $\varepsilon^p$ of the punched edge during punching (0.4 mm punch stroke because the cutting edge of the punch touched)

Figure 12. Equivalent plastic strain $\varepsilon^p$ of the punched edge (Punch stroke equals the sum of the length of the roll over and burnished surface from experimental results)
5.3. The effects of the hole diameter on burring formability

The burring formabilities under different hole diameters (Φ = 10 mm and 30 mm) were compared. The punching tests of hole diameter Φ = 10 mm were conducted with the same clearance CL/t = 12.5 % (punch diameter DP₁₀ = 10 mm). The cut-off ratio δ/t (%) of the DPM was 30 %, (δ = (DP₂ - DP₁)/2, DP₁ = 8 mm, DP₂ = 10 mm). The punches of HPM were prepared—(A): (8 mm, 1.0 mm), (B): (8 mm, 0.4 mm), (C): (6 mm, 1.0 mm), and (D): (6 mm, 0.4 mm). The hole expansion tests of hole diameter Φ = 10 mm were conducted with a conical punch (a 60° angle at the top of the cross section and a diameter of 50 mm) and die (a shoulder radius of 5 mm and diameter of 57 mm). Figure 13 presents the relation between the hole expansion formability improvement ratio (λ/λₛ) by using SPM and the burnished surface ratio (Φ =10 mm). Figure 14 presents the relation between the hole expansion formability improvement ratio (λ/λₛ) and the burnished surface ratio (Φ = 30 mm). The relationship between the tendency of tests under Φ = 30 mm using the SPM and the DPM was similar to that of tests under Φ = 30 mm. Contrary to the results of the HPM for Φ = 30 mm, the lengths of the burnished surfaces for Φ = 10 mm were equivalent to those of the SPM and DPM.

Figure 15 shows the sectional images of the scrap using the HPM (A, C) under hole diameters Φ = 10, 30 mm. Under Φ = 10 mm, the deep indentation was generated by the humped part. It implied that under Φ = 10 mm, it was difficult to be punched by applying tension. On the other hand, the indentation shown in the scrap using HPM (A, C) was shallower under Φ = 30 mm than under Φ = 10 mm.

Figure 16 illustrates the effects of the hole diameter on the burring formability of the HPM. To summarize the above, the stiffness of the punching face of the blank affects the ease of warping (giving tension to) the blank when the HPM was used. The high stiffness of the punching face (a small punching diameter or large thickness of the blank) does not allow the blank to warp and causes deep indentation by the humped part. In contrast, the low stiffness of the punching face (a large punching diameter or small thickness of the blank) eases providing tension while punching and avoids increasing work hardening in the punched edge.

![Figure 13](image1.png)

**Figure 13.** Relation between the hole expansion formability improvement ratio (λ/λₛ), and the burnished surface ratio (Φ = 10 mm)

![Figure 14](image2.png)

**Figure 14.** Relation between the hole expansion formability improvement ratio (λ/λₛ), and the burnished surface ratio (Φ = 30 mm)
Hole diameter Φ = 10 mm

| HPM: A (D_{1t}, H_{t}) = (8mm, 1.0mm) |
| Indentation |
| 1mm |

Hole diameter Φ = 30 mm

| HPM: A (28mm, 1.0mm) |
| Indentation was formed by the humped part |

| HPM: C (6mm, 1.0mm) |

| HPM: C (26mm, 1.0mm) |

| Punching face has high stiffness |
| Indentation was formed by the humped part |

| Punching face has low stiffness |
| Tension was applied to the blank by the humped part |

Figure 15. Sectional images of the scrap using the HPM (A, C) under hole diameters Φ = 10, 30 mm

Figure 16. Effects of the hole diameter on the burring formability of the HPM

6. Conclusions
The results of the experiments and FEM analysis conducted in this study were as follows:
(1) The improvement effect of burring formability by using the DPM was expressed by the large deformation of the scrap side and depressing plastic strain in the punched edge.
(2) The improvement effect of burring formability by using the HPM was expressed by both the increasing stress triaxiality of the blank by the humped part and depressing work hardening owing to the preceding humped part.
(3) The stiffness (changes with the punching diameter and the thickness of the blank) of the punching face of the blank affected the ease of warping (giving tension to) the blank when the HPM was used. The low stiffness of the punching face was suitable to the HPM.
(4) Under a punching hole diameter Φ = 30 mm, the burring formability of the HPM satisfying the condition of (2) equals those of the DPM with fewer manufacturing steps.

7. References
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