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Synergy effect of shear angle and anisotropic material ductility on hole-expansion ratio of high-strength steels

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ABSTRACT

This study investigated the effect of using a rooftop piercing punch on the hole-expansion ratio of high-strength steels. The holes made using the piercing punch showed very high hole-expansion ratios under certain conditions. Regarding the rooftop-vertical angles, the hole-expansion ratio increased at 80° and decreased at 45°. The sheet bending effect caused by the rooftop shape contributed to these results. The small amount of bending in the case of 80° induced tensile stress around the punch edge without plastic deformation, which accelerated the material fracture. This acceleration decreased the plastic strain on the pierced surface and led to a high hole-expansion ratio. In the case of 45°, a large amount of bending caused plastic deformation around the punch edge, which deteriorated the hole-expansion ratio. Regarding the material direction when set on a die face, the hole-expansion ratio increased when the material direction with the highest ductility on the pierced surface was at 90° to the rooftop line. In this condition, the ductility at the weakest position on the pierced surface resulting from piercing using the rooftop punch reaches a maximum in the other material directions.

1. Introduction

In recent years, carbon dioxide (CO_2) discharge emission regulations for the prevention of global warming have increased the need to reduce the weight of automobiles while increasing their crashworthiness. Using high-strength steels for automobile structural materials meets this need (Keeler and Ulintz, 2010).

To employ high-strength steels, we have to overcome their low formability (Woestmann et al., 2009). In particular, the hole-expansion ratio of pierced high-strength steels has to be improved. A common method to improve the hole-expansion ratio is to tune the piercing clearance (distance between the edge of the punch and that of the die). This method is easy for manufacturers because it does not require significant changes to conventional piercing processes. Some studies have already investigated the effect of the piercing clearance on the hole-expansion ratio. Mori et al. (2010) showed the monotonic increase in the hole-expansion ratio from 4 to 20%*t* clearance for high-strength steels having tensile strengths over 590 MPa, where %*t* indicates the percent thickness of the workpiece. Yoshida et al. (2010) confirmed this trend using SUS301-grade stainless steel. The hole-expansion ratios of high-strength steel workpieces with a clearance of 1.1%*t* (Konieczny and Henderson, 2007) and 0.6%*t* (Matsuno et al., 2010) are higher than those of pieces with a clearance between 4 and 6%*t* but lower than those with a clearance of 20%*t*. Sriram and Chintamani (2005) investigated the case of clearances above 20%*t*. According to their research, the hole-expansion ratio gradually decreases up to 30%*t* clearance, beyond which it becomes constant. These studies concluded that the optimum clearance for the hole-expansion ratio of high-strength steels is approximately 20%*t*.

Commonly, the shearing angle, i.e., the angle between the punch top and the workpiece surface, is designed to reduce noise and piercing force. The shearing angle is also effective for improving the stretch-flange formability, which represents the ductility of the sheared surface (Matsuno et al., 2015). The hole expansion represents the ductility of the pierced surface, similar to the stretch-flange formability; thus, tuning the shearing angle is also expected to improve the hole-expansion ratio. Although tuning the shearing angle does not require significant changes to conventional piercing processes—similar to tuning the clearance—its effect on the hole-expansion ratio has been rarely investigated. Because the shearing angle results in axial-nonsymmetric deformation of the material during piercing, the rotational orientation of the piercing punch

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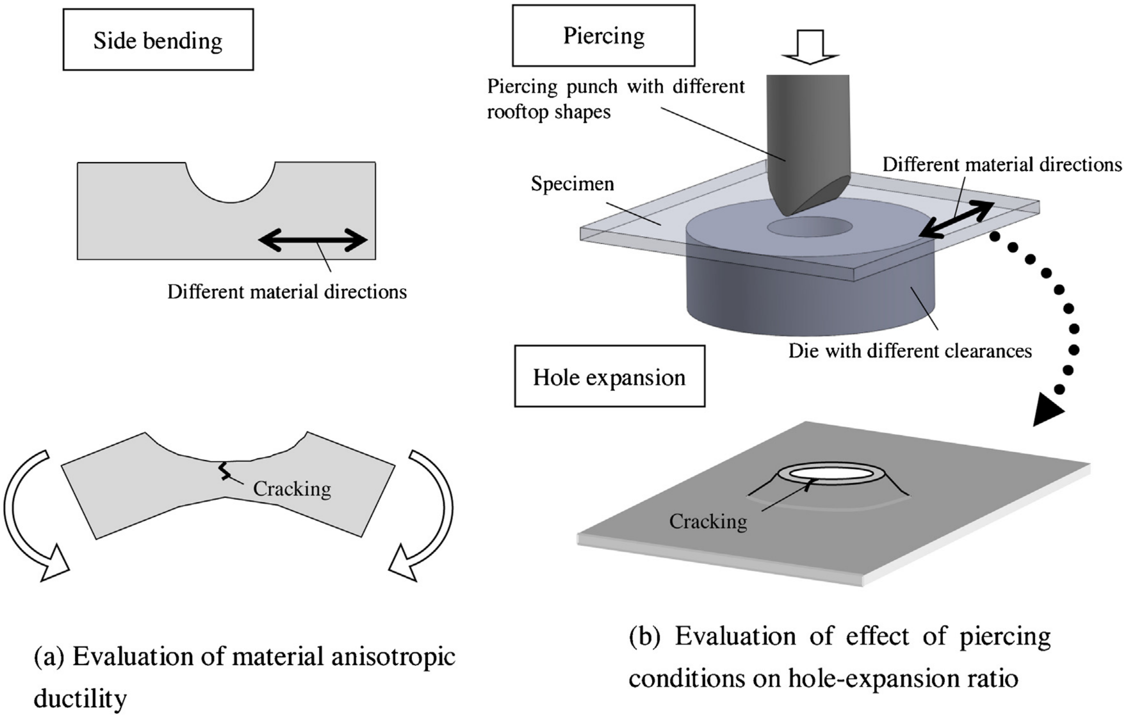

(a) Evaluation of material anisotropic ductility

(b) Evaluation of effect of piercing conditions on hole-expansion ratio

Fig. 1. Overall sequence of operations being investigated.

can also be tuned. The rotational angle between the material direction of the workpiece (e.g., rolling direction or transverse direction) and the piercing punch with its shearing angle affects the hole-expansion ratio if the properties of the workpiece are anisotropic. This effect of the rotational angle of the piercing punch has never been reported before. With this background information, this study aims to clarify the synergetic effects of shearing and rotational angles on the hole-expansion ratio for three high-strength steels with tensile strengths up to 980 MPa.

The paper consists of the material anisotropy evaluation and the hole-expansion test. Fig. 1 presents overall sequence of these operations. The mechanism of hole-expansion behavior is discussed in terms of the shapes and work hardening of the pierced surfaces and the material anisotropy.

To evaluate steel anisotropy, we adopted in-plane bending tests, or “side-bending” (Yoshida et al., 2013) using notched specimens with different material directions because material elongation does not represent the hole-expansion ratio (Takahashi, 2003). In the side-bending test, the notch was formed by shearing using a conventional flat punch to directly evaluate the ductility of the pierced surface in each material direction. Hereafter, we refer to this difference in ductility of the pierced surface with respect to the material direction as “material anisotropy.”

The piercings before the hole-expansion tests were carried out for different shearing angles, clearances, and material directions. The shearing angle was introduced using a piercing punch with a rooftop. The rooftop is commonly used because its line-symmetric shape provides low dynamic eccentricity during the piercing process as compared to the other types of shear angles.

2. Experimental conditions

2.1. Material

Three high-strength steels with different tensile strengths, Materials A, B, and C, were used for this study. These three high-strength steels correspond to the 590, 780, and 980 MPa classes, respectively. Table 1 shows the mechanical properties measured by tensile tests along the rolling direction (RD) and the transverse direction (TD) and the hardness and thickness of each material. Material A has the lowest tensile strength and yield stress and the highest uniform and total elongation. Material C has the highest tensile strength and yield stress but the lowest uniform and total elongation. Material B presents intermediate mechanical properties. All the materials show isotropic mechanical properties, i.e., the differences along the RD and the TD are very small. In addition, we confirm that the hardness is proportional to the tensile strength from Table 1.

Table 1
Material properties.

Material ID		A	B	C
Tensile strength [MPa]	RD	626	786	1051
	TD	627	795	1049
Yield stress [MPa]	RD	407	477	730
	TD	413	494	740
Uniform elongation [%]	RD	19.7	14.8	8.3
	TD	18.7	14.1	7.8
Total elongation [%]	RD	31.5	23.4	16.5
	TD	31.9	21.2	15.0
Hardness [Hv0.05]		198	239	301
Plate thickness [mm]			1.6	

2.2. Side-bending test for the evaluation of material anisotropy

For the side-bending tests, we prepared a sample with a semi-circular notch with a curvature radius of 15 mm. The shape of the specimen is shown in Fig. 2. The notch was formed by shearing with a conventional flat punch and a clearance of 10%*t*.

In the side-bending test, the specimen was subjected to in-plane bending, as shown in Fig. 3; the bending was stopped when a crack initiated on the sheared surface penetrated the material thickness.