Journal of Materials Processing Technology 223 (2015) 98–104

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Effect of shearing clearance and angle on stretch-flange formability evaluated by saddle-type forming test

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ARTICLE INFO

Article history:
Received 23 February 2015
Accepted 28 March 2015
Available online 7 April 2015

Keywords:
Shearing
Blanking
Punching
Stretch-flange forming
High-strength steel
Tool design

ABSTRACT

In this study, the effects of shearing clearance and shearing angle on stretch-flange formability are investigated. The saddle-type forming test is adopted for this investigation. A notch-type shearing line, which comprises straight and circular arcs, is used for this test. The results show that stretch-flange formability is improved in narrow clearances. This tendency is different from that obtained by the hole expansion test, wherein stretch-flange formability is improved in large clearances. This improvement might be caused by the increase in the area of the fractured surface in narrow clearances. Generally, the larger the fractured surface, the smaller the work hardening on a sheared edge. Furthermore, the investigation reveals the existence of an optimum shearing angle for excellent stretch-flange formability. FE simulation shows that the optimum shearing angle increases hydrostatic stress in materials during shearing. Compressive stress across the material thickness is mainly affected by shearing angle. The result of the analysis suggests that the optimum shearing angle increases the area of the fractured surface to improve stretch-flange formability.

1. Introduction

In recent years, CO_2 discharge regulations for the prevention of global warming have increased the need for weight reduction of automobiles, which has to be compatible with increased crashworthiness. Strengthening of automobile structural materials is effective for fulfilling these needs. As for steels, Keeler and Ulintz (2011) have reported on the rapid substitution of conventional mild steels with high-strength steels as structural materials for the automobiles.

In contrast, as reported by Woestmann et al. (2009), the lower formability of high-strength than that of mild steels is a subject of concern regarding its further utilization. Especially, cracking of sheared surfaces during stretch-flange forming, hereafter called as “stretch-flange cracking,” has been identified as main aspect requiring improvement. In fact, steel developers have proposed advanced high-strength steels that provide high resistance against stretch-flange cracking (hereafter, “stretch-flange formability”). Examples of such steels include tempered dual-phase (DP) steels reported by Fang et al. (2003) and transformation-induced plasticity (TRIP)-aided steels reported by Kobayashia et al., 2014. In parallel, techniques have been also developed to improve the stretch-flange formability during the formation process. Examples of such techniques include smoothing of sheared surfaces (Mori et al., 2010), modification of the cutline shape (Kurosawa et al., 2012), and gradual stretch-flange forming (Abe et al., 2013). Additionally, Golovashchenko (2008) has reported that shearing using obtuse-angled punch and die edges improve the ductility of sheared edges; however, this study has not directly dealt with stretch-flange forming.

Nevertheless, the abovementioned forming techniques demand additional processes or new design of the shearing tools, which increase the forming cost. Therefore, to minimize the escalation in cost, stretch-flange forming should be improved by simple tuning of the shearing tools. The factors relevant for such tool tuning include the shearing clearance (distance between punch and die edges) and shearing angle (angle between punch bottom and workpiece surface). Generally, shearing clearance is the key factor for the smoothness of sheared surfaces, and the shearing angle is crucial for low noise and shearing force.

Many research papers have presented the effect of the shearing clearance on the hole–expansion ratio, which is a kind of stretch-flange forming for a circular hole (effects of the shearing angles

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http://dx.doi.org/10.1016/j.jmatprotec.2015.03.041
0924-0136/

on the hole–expansion ratio have been rarely reported). Mori et al. (2010) have shown a monotonic increase of the hole–expansion ratio from 4%*t* to 20%*t* clearances for high-strength steels belonging to classes above 590 MPa, where %*t* indicates the percentage of the workpiece's thickness. Yoshida et al. (2010) have confirmed this behavior of the hole–expansion ratio using another material, namely stainless SUS301. In terms of high-strength steels with minute clearances, the hole–expansion ratios for 1.1%*t* (Konieczny and Henderson, 2007) and 0.6%*t* clearances (Matsuno et al., 2010) are higher than those for 4–6%*t* clearances but lower than those for around 20%*t* clearance. High-strength steels with large clearances above 20%*t* have been investigated by Sriram and Chintamani (2005). According to their investigation, the hole–expansion ratio gradually decreases with clearance until approximately 30%*t*, after which the ratio levels off. These reports concluded that the optimum clearance to achieve the largest hole–expansion ratio is approximately 20%*t* for high-strength steels.

These investigations provide effective knowledge for practical forming processes; however, we must keep in mind that these results are limited to circular holes. In particular, the shear geometry generally affects the properties of sheared surfaces. Thus, the optimum clearance derived from hole–expansion tests is not directly applicable to other shear geometries, for example being straight, semicircular, or having combined shape. However, other types of stretch-flange formability than the hole–expansion ratio have rarely been investigated with regard to the shearing conditions owing to the absence of standards for the evaluation tests.

With the above background information in place, the present study investigated the effects of shearing clearances and angles on the stretch-flange formability; the evaluations were done by saddle-type forming tests. Nitta et al. (2008) proposed this type of test to evaluate stretch-flange forming, since this is much more frequently done than hole expansion. Furthermore, morphological observations and measurement of the hardness of the sheared surfaces were performed for the interpretation and discussion of the results of the saddle-type forming tests. Additionally, finite element (FE) simulations were performed to analyze the mechanism behind the shear-edge differences in terms of the shearing clearances and angles. We aim at deriving a general guideline regarding the shearing conditions by adding our contribution to the previous investigations on the hole–expansion ratio.

2. Stretch-flange forming test

2.1. Experimental conditions

2.1.1. Material

Three types of high-strength steel sheets were used for this study. Table 1 shows the mechanical properties, hole–expansion ratios, and thickness of these materials. Regarding the hole–expansion ratios, the holes punched in specimens with 10%*t* clearance were expanded using a conical punch until a crack generated on the punched surface percolated across the entire material thickness, according to ISO16630 (2009). Five values of the hole–expansion ratio were averaged for each material.

Table 1
Material properties.

Material ID	A	B	C
Tensile strength [MPa]	446	626	639
Yield stress [MPa]	294	467	367
Elongation [%]	36	34	31
Hole–expansion ratio [%]	116	48	52
Thickness[mm]	1.6	1.6	1.6

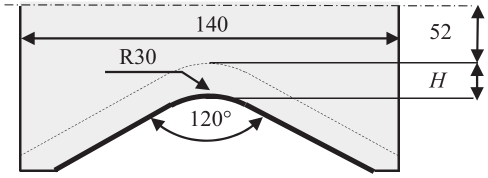


Fig. 1. Specimen geometry used for the stretch-flanging tests.

In Table 1, Material A presents the lowest tensile strength and the highest elongation and hole–expansion ratio. Materials B and C exhibit roughly the same tensile strength, elongation, and hole–expansion ratio. The yield stress of Material B is higher than that of Material C.

2.1.2. Shearing

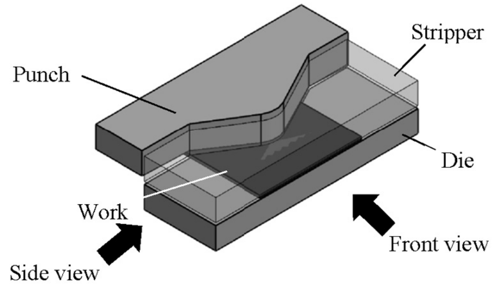
Fig. 1 shows the specimen geometry used for the saddle-type forming tests. As shown in Fig. 1, the specimen width is 140 mm. The shape of the shear line, shown as the thick line in Fig. 1, comprises straight lines at the left and the right, connected by a curve with a radius of 30 mm. This shape was sheared using the tools shown in Fig. 2. The shearing clearances shown in Fig. 2c were set to 5.0%*t*, 11%*t*, and 14%*t*, and the shearing angles θ shown in Fig. 2b were fixed at 0.0°, 0.5°, 1.0°, 1.5°, and 2.0°.

As for the other shearing conditions, the punching velocity was set to 60 mm/s and Z3 lubrication oil produced by Idemitsu Kosan Co., Ltd. was used. Any special methods, such as a counter punch, were not applied.

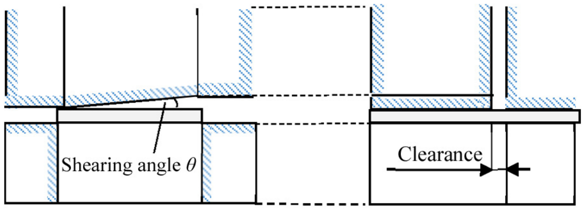
The main difference in the shearing conditions between a circular hole and the presently used geometry is the way the workpiece is held. The holding condition in the case of circular holes depends on the axial symmetry, but the condition for the saddle-type forming test is cantilevered clamping.

2.1.3. Saddle-type forming test

Fig. 3 shows schematic images of the saddle-type forming test. As shown in Fig. 3a, the specimen is first set on the die so that the burr side of the sheared edge is directed toward the punch. Then,



(a) Over view



(b) Front view (c) Side view

Fig. 2. Schematic image of shearing tools.