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Effect of Different Conical Punch Angle Geometries and the Initial Hole Diameters on the Hole Expansion Ratio of DP steels

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Abstract

In the recent decade, advanced high strength steels (AHSS) have gained a great popularity in the automotive manufacturing industries due to their high strength to weight ratio, which significantly improves the safety of the manufactured automobiles while reducing the weight and thus, enabling to improve the fuel efficiency. However, it is known that some types of AHSSs, especially DP steels, are highly susceptible to edge cracking behaviour during the forming operations. Edge cracking behaviour is generally investigated with a 600 conical punch as suggested by the ISO 16630 standard. However, in this study, to observe the behaviour of edge cracking ability of DP steels under different conical punch angles for different initial hole diameters, hole expansion tests have been performed with conical punches with three different angles (300 ,600 and 900) for three different initial hole diameters (14, 16 and 18 mm). The results have shown that the hole expansion ratio (HER) does not differ considerably with the variation of the conical punch angle and the initial hole diameter due to low fracture strain of DP steels observed after hole expansion tests. The major factor for the edge stretching ability of DP steels have been observed to be microstructure rather than geometrical factors such as conical punch angles.

Keywords: Advanced high strength steels; DP steels; Hole expansion ratio; AHSS

Research Article

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1. Introduction

The implementation of AHSSs in the automotive industry has resulted in great opportunities for manufacturers such as improved safety and weight reduction, which ultimately have led them to better comply with the stringent euro emission standards. However, high strength levels of AHSSs have also presented new issues in regards to their formability such as inferior edge-stretching ability [1]. The edge-stretching ability of materials are generally investigated by expanding a hole with an initial diameter of 10 mm by means of a 600 conical punch angle. However, depending on the forming application on the workshop, punches with a different angle or a different initial hole diameter may need to be expanded to form flanges. Main sections and subsections should be numbered consecutively.

There are many different factors affecting the edge-stretching ability of AHSSs such as edge condition, material microstructure, punch geometry and initial hole diameter [2-4]. In general, the initial edge condition of the hole significantly affects the HER behaviour of the material due to the resulting initial damage at the hole edge [5-8]. Therefore, the preparation of the initial hole by different means such as shearing, cutting, reaming, fine-blanking, water-jet cutting, laser cutting, electrical discharge machining and etc. result in considerably different HER values for the same material [9-12]. In terms of shearing, cutting clearance play a major role in determining the HER values since it directly impacts the four important zones on the sheared edge of the sheet, namely, rollover, burnish, fracture and burr zones [13-18]. Especially, the ratio of burnished zone over the fracture zone on the sheared edge is one of the controlling factors of the sheared edge ductility of materials. Since most of the micro-voids generated by the punching process are located at the fracture zone, the increase of the ratio of burnished zone over the fracture zone significantly improves the edge stretching ability of sheet metals [17]. These initial micro-voids or cracks propagates through the material during deformation and leads to final through-thickness crack formation. Zhou et al. [19], have investigated the effect of cutting clearance and shear angle on the quality of the sheared edges and tensile properties for QP980 steel and they have shown that smaller cutting clearance has provided a higher burnish zone on the sheared edge and resulted in higher total elongation as compared to the sheared edges with higher cutting clearance. The improvement of HER by decreasing the cutting clearance has also been mentioned in many different studies [14]. Even though HER can be improved by decreasing the cutting clearance, the amount of improvement on the HER is still limited due to the initial damage caused by the shearing process, therefore, the methods, which impart near zero damage at the hole edge, such as machining, laser cutting and water-jet cutting, etc. result significantly higher HER [11], [18], [20].

One of the main reasons of the lower HER for DP steels stems from its unique microstructure. DP steels consist of ferrite and martensite phases. While the ferrite phase provides good formability characteristics to DP steel, the martensite phase contributes to its high strength. However, the combination of these phases, which have significantly different hardness values, creates stress concentration regions in between the phases due to the abrupt change of hardness and, therefore, cracks easily propagate through the phase boundaries during edge stretching [21]. In order to improve the edge-stretching capability of DP steels many researches have been conducted to obtain a more homogenous microstructure. Wu et al. [17], have developed series of different DP steels by different processing routes and investigated their microstructures, tensile properties and hole expansion behaviours. They have found that DP microstructure with a lower hardness difference in between the constituent phases has resulted in considerably higher HER values as compared to DP steels with high hardness difference between the phases. Similarly, Wu et al. [22], Hasegawa et al. [23] and Hu et al. [24], have also shown in their study that decreasing of hardness difference between the ferrite and martensite phases in DP steels results in higher HER values.

Along with the effects of properties of material and edge condition on the HER, it has been observed that the punch geometry also takes an important factor for the edge-stretching ability of the same material [25], [26], [27]. The reason of the variation of HER value for different punch geometries result mainly from the creation of different strain path on the sheet specimen for different punch geometries. Pathak et al. [25], have conducted hole expansion tests with a conical and flat-bottom punches for DP and CP steels with different initial edge conditions. They have observed that the initial edge condition for the hole expansion test conducted by flat-bottom punch doesn't significantly impact the HER, while it significantly does for the conical punch geometry. The authors have explained the reason of insensitivity of flat-bottom punch to initial edge condition by showing the position of initial crack formation on the sheet for both punch geometries. They have shown that while the initial crack occurs at the hole edge for conical punch geometry, it does at a location away from the hole edge for flat-bottom punch, therefore, flat-bottom punch geometry has been insensitive to initial edge conditions for the hole expansion test. Paul [27], has utilized finite elements analysis (FEA) to describe the reasons for the different HER values and the positions of the initial crack formation for different punch geometries such as flat-bottom, hemispherical and conical punches. The author has shown that while uniaxial type strain occurs at the hole edge for conical type punch, for flat-bottom and hemispherical punches plane-strain, which is the most critical type strain, occurs at a location slightly away from the hole edge, therefore, the author has concluded that the initiation of cracks for flat-bottom and hemispherical punches at a distance from the hole edge occurs due to the plane-strain condition, which also result in significantly lower HER, while the cracks initiate at the hole edge for conical type punch due to uniaxial type strain deformation. Accurate predictions of HER is significantly important to decrease the amount of try – error applications to form the desired part. However, simple forming limit diagrams (FLD) can't predict the edge cracking failure. For this reason Akinobu and et al. [4], have used different starting hole diameters for the hole expansion tests to observe the effects of radial and principal strain gradients as a failure criteria for edge-stretching failure. They have found that as the starting hole diameter increased, the amount of critical principal strain for fracture decreased and therefore larger initial hole diameters have resulted in lower HER values.

In this study, conical punch geometries with different angles (300, 600, 900) have been used to expand an initial hole diameter of 14 mm, 16 mm and 18 mm for DP600 and DP800 AHSSs to investigate the effects of conical punch angles and the initial hole diameter on the HER values.

2. Materials and methods

2.1 Materials

In this study, commercial DP600 and DP800 AHSSs, which have been provided by Swedish steel company, SSAB, with 1 mm thickness were used. The chemical compositions of the steels were investigated by energy-dispersive X-ray spectroscopy analysis and the results were given in Table 1. The mechanical properties of DP600 and DP800 were obtained by uniaxial tensile tests conducted at 0.005 s-1 strain rate and the results were given in Table 2. The microstructure of DP600 and DP800 were investigated by light optical microscopy under 1000x magnification and were shown in Figure 1. A more homogenous distribution of martensite particles throughout the ferrite matrix were observed for DP600, while a banded microstructure was seen for DP800. The percentage area of martensite and ferrite phases were analysed via image processing software, Image J, and the area fraction of martensite were found to be approximately 23.9 % and 54.2% for DP600 and DP800, respectively. The average grain size of ferrite was measured to be 4.8 microns for ferrite, 1.8 microns for martensite for DP600, while the ferrite and martensite grain sizes for DP800 were found to be 4 microns and 1.7 microns, respectively.

Table 1. Chemical Composition (wt.%) of DP600 and DP800 steel sheets

Material	Fe	C	Si	Mn	P	S	Al	Ti	Nb	V
DP600	98.2	0.108	0.195	0.878	0.012	0.002	0.045	0.001	0.016	0.016
DP800	97.9	0.142	0.190	1.489	0.007	0.003	0.038	0.001	0.016	0.012

Table 2. Chemical Composition (wt.%) of DP600 and DP800 steel sheets

Material	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Total Elongation	Strain Hardening Exponent (n)
DP600	425.6	646.6	0.20	0.15
DP800	550.3	851	0.19	0.16

2.2 Experimental methods

In order to eliminate any heat and initial damage effect on the hole edges, hole expansion test specimens were prepared by water-jet cutting method with 14 mm, 16 mm and 18 mm inner hole diameters and 80 mm outer diameters. Three different conical punches with different angles (300, 600, 900) were used to expand the holes in the experiments. The schematic representation of experimental setup and real die setup were shown in Figure 2. The dimensions of the punch diameter, $\emptyset d_p$, initial hole diameter, $\emptyset d_i$, die diameter, $\emptyset d_d$, die radius, r_d, and conical punch angle, α_i, were shown in Table 3. To determine the HER, initially created holes were expanded incrementally by increasing the punch stroke step by step and observing sheet edge at each increment. Increments were given according to the physical appearance of the hole edges after each step. Initially 6 to 8 mm of stroke were given and later were decreased smaller strokes to avoid inflicting excessive crack opening at the hole edges. After appearance of an instability at the hole edges, the stroke value was decreased to 1 mm to capture the initiation of crack. The experiments were stopped after a through-thickness crack was observed on the hole edge. Expansion of DP600 and DP800 sheets with a 600 conical punch angle for 14 mm initial hole diameter were shown in Figures 3 and 4, respectively. The diameters of the expanded holes were measured with De Meet 400 measuring device by creating 3 points around the hole edge. Percentage HER values were then computed according to the Eq. (1)

$$\%HER=\frac{\emptyset d_f-\emptyset d_i}{\emptyset d_i}*100 \quad (1)$$

where, the $\emptyset d_f$ and $\emptyset d_i$ represents the final and initial diameter of the hole edges.

The punch force and displacement data were taken from the pressure and displacement sensors existing in the hydraulic press machine and were recorded throughout the forming operation to observe the effect of conical punch angles on the forming force. The pressure values, taken as bars from the hydraulic press machine, were converted to force as kN.

Table 3. The dimensions of experimental die setup

Designation	Dimensions
Punch diameter, $\emptyset d_p$	37.6 mm
İnitial hole diameter, $\emptyset d_i$	14, 16, 18 mm
Die diameter, $\emptyset d_d$	40.04 mm
Die radius, r_d	5 mm
Conical punch angle, α_i	30^0, 60^0, 90^0

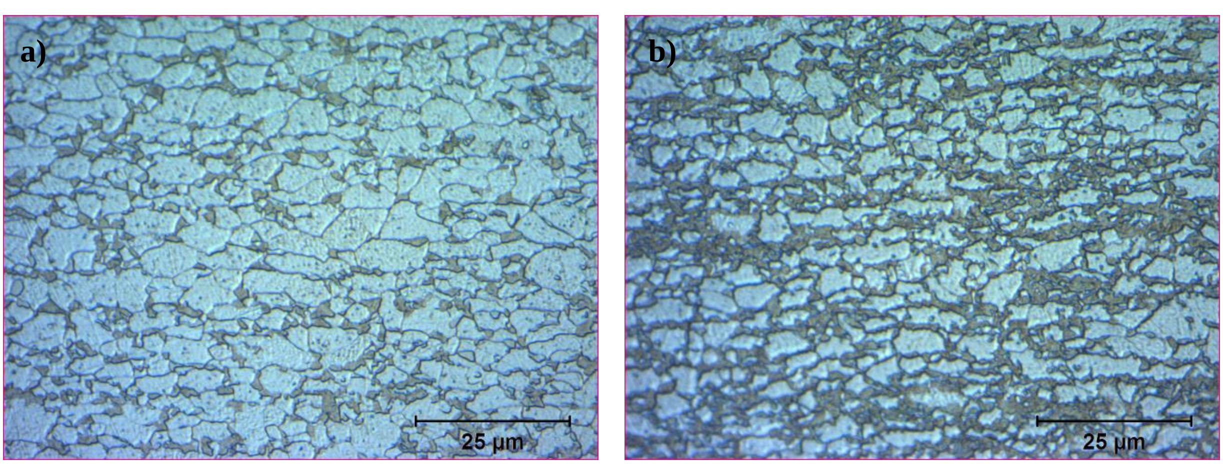

Fig. 1. The microstructures of a) DP600 and b) DP800 under light optical microscopy

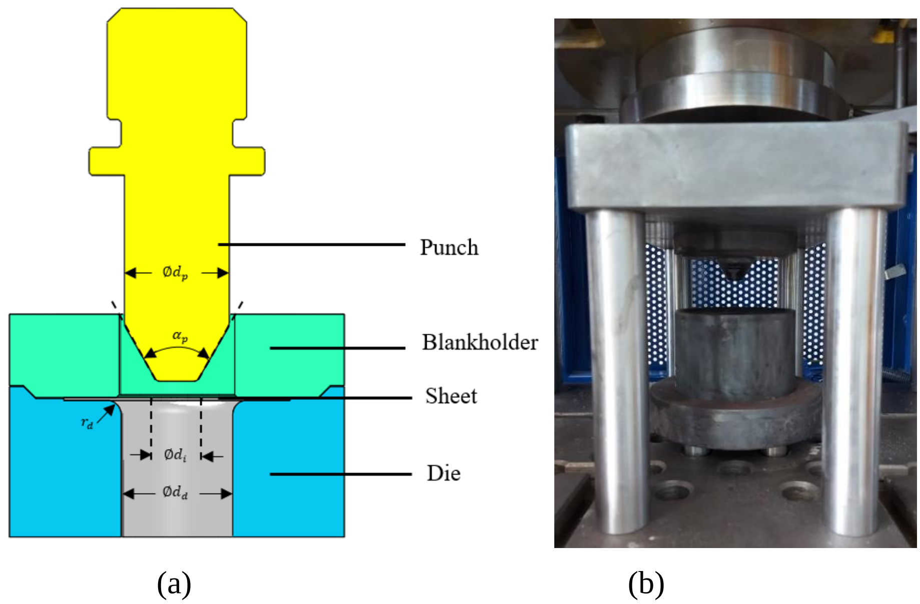

Fig. 2. a) Schematic representation of experimental setup for hole expansion test with different punch angles and initial hole diameters, $\emptyset d_p$, $\emptyset d_i$, $\emptyset d_d$, r_d, α_i designates the punch diameter, initial hole diameter, die diameter, die radius and conical punch angle, respectively
b) Experimental die setup

3. Results and discussions

During hole expansion test with a conical punch angle, uniaxial strain condition occurs at the hole edge, regardless of its punch angle [27]. However, the difference in conical punch angle causes different stress gradients on the hole edge during hole expansion tests. The higher the stress gradient on the hole edge, the more uniform the sheet deforms to a flange [28]. However, in this study, in case of DP steels the variation of conical punch angle and the change of initial hole diameter within 14 to 18 mm range haven't been found to cause a significant effect on the HER. The HER values of DP600 and DP800 steels for different conical punch angles and initial hole diameters have been shown in Figures 5 and 6, respectively. It seems that the variation of stress gradient at the hole edge caused by the change of conical punch angle and initial hole diameter don't cause a significant change for the HER values. Ito and et al. [28], have found in their study that the effect of conical punch angle on the HER values for materials which show low true thickness fracture strain is considerably low. When the fracture thickness strain has been calculated by measuring the thickness of the hole edge at the fracture region and calculating the strain with respect to the initial sheet thicknesses for DP600 and DP800 steels for different conical punch angles, it has been found that the fracture strain has been significantly low, varying around 0.2 and 0.3. Thus, the invariant response of HER values of DP steels to the change of conical punch angles might be because of their significantly low fracture strain values during hole expansion. The observed variations in HER values in Figures 5 and 6 might be due to the experimental errors, which might have occurred due to the variation of the surface quality of the edge condition, strength and etc. Nevertheless, the decrease of conical punch angle has resulted in a considerable decrease of forming forces as shown in Figure 7. This might be due to the slower increase of hole with a sharper punch such as with a 300 conical punch angle. The increase and decrease of force for 300 conical punch up to 10 mm stroke has possibly occurred due to the initial bending of the sheet edge since the edge of the 300 conical punch have not been small enough to fit into the initial hole of the sheets.

It seems that the main important factor for DP type steels is the microstructural factors rather than geometrical factors for conical type punches. As can be seen, the HER values of DP800 is quite lower than DP600 by an amount of approximately 25% on average. While the average HER value for DP800 has been found to be around 52%, it has been around 70% for DP600. The main reasons of such decrease of HER for DP800 as compared to DP600 might be due to its higher amount of martensite content and also its spatial distribution in the microstructure. As can be seen from Figure 1 that the DP800 consist of a higher amount of grain boundary area between the phases as compared to DP600, which causes easier crack propagation during edge stretching operation. Hence, new edge stretching methods might be investigated, which could relieve the high stress between the ferrite and martensite phases during the hole expansion and thus result in a better edge stretching ability for DP steels.

Fig. 3. Expansion of DP600 sheet with a 600 conical punch ange for 14 mm initial hole diameter at different punch distances a) 7.40 mm, b) 16.8 mm, c) 18.8 mm

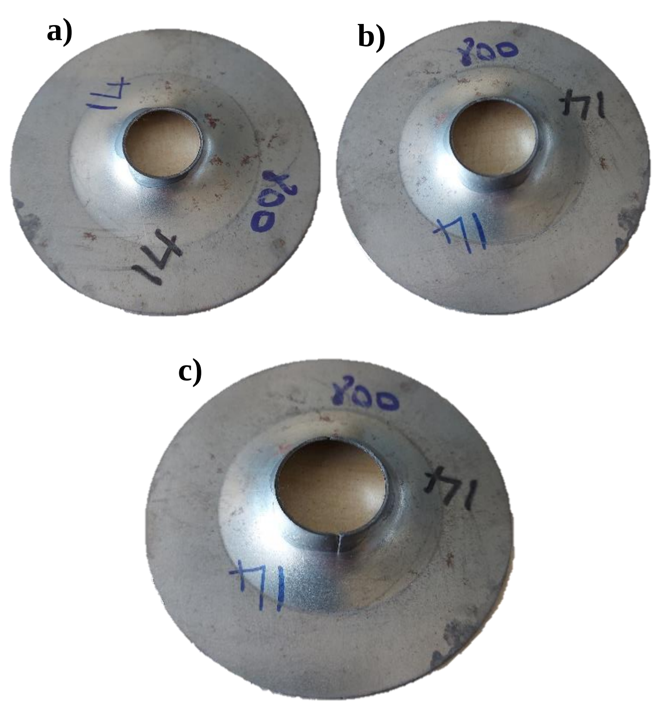

Fig. 4. Expansion of DP800 sheet with a 600 conical punch ange for 14 mm initial hole diameter at different punch distances a) 9.63 mm, b) 11.6 mm, c) 13.9 mm

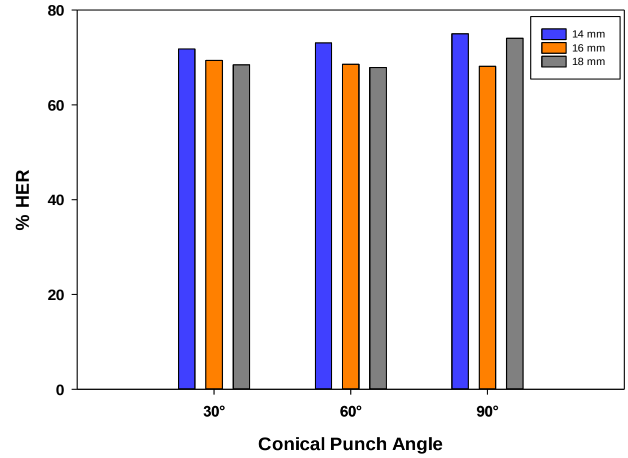

Fig. 5. Effect of conical punch angle and initial hole diameter on the HER behaviour of DP600

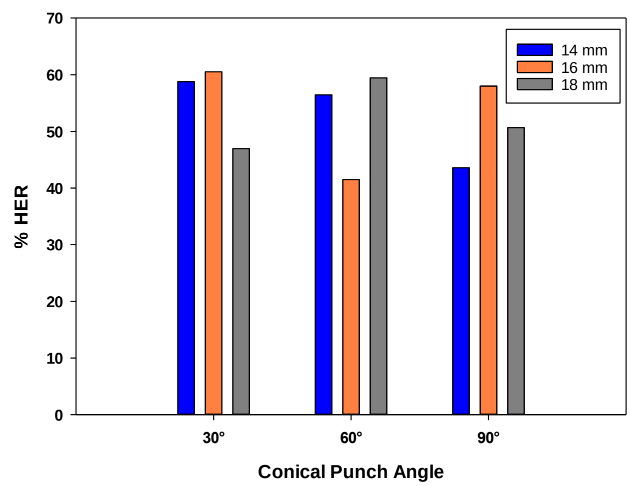

Fig. 6. Effect of conical punch angle and initial hole diameter on the HER behaviour of DP800

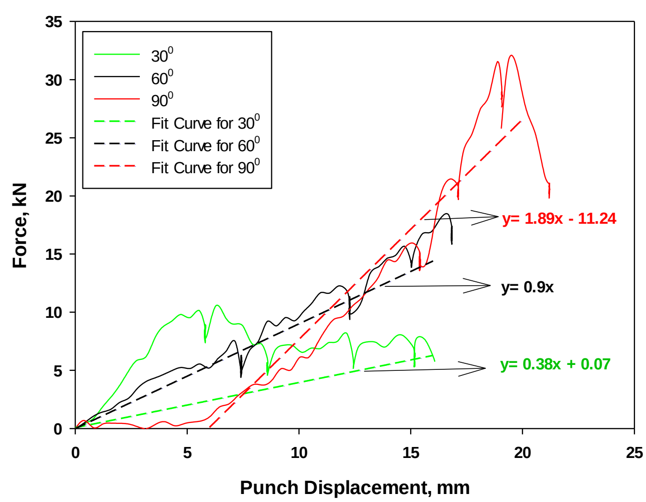

Fig. 7. The variation of force displacement curves with respect to different conical punch angles for 14 mm initial hole diameter

3. Conclusions

In this study, conical punches with different angles have been used for hole expansion tests of DP steels for a three different initial hole diameters and the following conclusions have been drawn:

•The change of conical punch angles and the initial hole diameters have not resulted in a considerable change in HER values of DP steels. This has been attributed to the low fracture strain of DP steels observed after the hole expansion tests.

•The decrease of conical punch angle has significantly reduced the forming forces due to the slower expansion of initial holes during the hole expansion test.

•The effect of microstructural factors for DP steels on the HER have been found to be more profound as compared to the geometrical factors such as conical punch angles. The average HER value for DP800 has been found to be 25% lower than DP600, which has been attributed to higher amount of martensite phase in DP800 steel, which has resulted in a higher grain boundary area between the martensite and ferrite and thus, resulting in an easier crack propagation.

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Conflict of Interest Statement

The authors have no conflicts of interest to declare.

CRediT Author Statement

Nuri Şen: Conceptualization, Supervision
Tolgahan Civek: Conceptualization, Writing-original draft
Necati Bektaş: Data curation, Formal analysis

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