Hole Expansion in Q&P, DP and TRIP Steel Sheets

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Abstract: Hole expansion tests of Q&P, DP and TRIP steel sheets with holes edges prepared by punching, milling and wire cutting were carried out with a conical punch having an angle of 60°. The hole expansion performance, the characteristics of the shear affected zone and the effects of mechanical properties on HER were studied. It shows that the HER of punched Q&P1180 is over 50%, which is much higher than that of the other steels. The HER of punched Q&P980 is close to 30%, which is similar as that of DP980 and a little higher than that of TRIP steels. The YS/TS ratio shows a strong positive effect on HER of the tested Q&P, DP and TRIP steels with punched edges. The punching process deteriorates the hole expansion performance when compared with milling and wire cutting. Q&P1180 shows the least HER loss between punched and wire cut edges. Q&P1180 also exhibits the smallest hardness increase at the sheared edge because of its low n-value. The TRIP steels with higher n-values exhibit greater HER loss as compared with Q&P steels.

Key Words: Quenching & Partitioning steel, Hole expansion

1. Introduction

Advanced high strength steels (AHSS) have been a significant focus in recent years. Varieties of AHSS have been developed to meet the requirements of improved passenger safety and reduced weight in the automotive industry. For example, the Quenching and Partitioning (Q&P) process has been recently proposed by Speer [1, 2] as a fundamentally new way of producing martensite steels containing a considerable amount of retained austenite. Q&P steel possesses a good balance of properties between tensile strength and elongation, i.e. it shows higher tensile strength than conventional TRIP steels and increased ductility as compared to martensitic steels and dual phase steels. Significant research achievements in Q&P steel have been made by ASPPRC and several other organizations. Industrial Q&P steels with tensile strength from 1000 to 1200 MPa and total elongation from 9.3 to 21.2% have been successfully developed using a conventional C-Si-Mn TRIP780 composition, processed via a special commercial line in Baosteel [3].

One of the concerns for AHSS in stamping operations is the failure of sheared edges in stretching modes [4]. Hole expansion ratio (HER) is usually used to characterize the sheared edge stretch-flangeability. The HER of commercial automobile steels has been studied by a number of investigators over the years. It has been reported that HER of steel sheets decreases dramatically as the tensile strength (TS) increases when the TS is less than 700 MPa, and it saturates at a low value of about 30% when the TS is beyond 700 MPa [5]. The effect of other mechanical properties such as yield strength (YS), total elongation (T.El.), n-value and r-value on HER has also been reported. Based on the literature [4-13], it is believed that sheared edge formability increases with increasing r-value. It is also clear that a higher YS/TS ratio results in higher HER for some steels [5, 7, 14-19]. However, the relationship between mechanical properties and HER is still not clear. Over a wide range of total elongation, it seems that the greater the elongation the better the HER. For instance,

the HER of IF or BH steel is better than that of DP or TRIP steel. Nevertheless, at a given level of total elongation, the difference between HERs can be very large for different steels. It is agreed by most authors [10, 12, 20] that steels having higher n-value show lower HER. However, Narayanasamy [9] presented an opposite trend based on the data of various steels including HSLA, HS-IF, C-Mn and IF steel. The effect of n-value on HER might therefore be complex and the reasons are still not clear.

The shear affected zone (SAZ), which means the deformed region adjacent to the sheared edge, has been recognized to play a critical role in the hole expansion process. The deleterious effect of SAZ on HER has been proved in a number of studies [7, 12, 14, 17, 19, 21]. Some characteristics, such as depth of SAZ, work hardening in the SAZ, shear strain and void nucleation between different phases, have been observed and studied by some investigators [13, 14, 19, 22]. It is pointed out by Levy and Van Tyne [23] that more detailed analysis of the SAZ would be desirable in studying sheared edge stretching.

The stretch-flangeability of commercially produced Q&P steel has not been reported yet. Different grades of industrially processed Q&P steels together with DP and some TRIP steels were therefore tested in the present work. Different hole preparation methods were also used to achieve different edge qualities. The HER and characteristics of the sheared edge and SAZ were studied and compared to that of the machined edges. The primary aim of this study is to improve the understanding of the stretch-flangeability of Q&P steel.

2. Experimental Procedure

2.1 Material

In the present work, two grades of Q&P steel were studied by hole expansion testing according to ISO/TS16630:2009 [24]. The hole expansion properties of the Q&P steel were compared to three grades of TRIP steel and one grade of DP steel. The compositions of Q&P1180, Q&P980, TRIP780 and TRIP900 are almost the same, but they are different from that of TRIP690 and DP980. Table 1 shows the tensile properties acquired using tensile specimens having a gage width of 25 mm and gage length of 50 mm. All the tensile samples were tested in the transverse direction. Some typical strain stress curves are plotted in Fig.1.

Table 1 Mechanical Properties of the Steel Sheets

	thickness (mm)	YS (MPa)	TS (MPa)	U.El. (%)	T.El. (%)	n-value*	r-value**
Q&P1180	1.0	1070	1204	6.3	11.3	0.064	0.81
Q&P980	1.2	701	992	12.8	19.1	0.13	0.82
Q&P980	2.0	656	989	11.8	19.1	0.15	0.89
DP980	1.4	613	975	8.3	14.6	0.093	0.75
TRIP900GI	1.7	576	900	18.0	24.8	0.17	1.16
TRIP780	1.8	494	817	22.5	28.7	0.23	1.16
TRIP690GI	1.7	476	700	25.2	37.0	0.20	0.87

* The n-values were determined using the stress-strain data between 4% and uniform elongation.
** The r-values were determined at 7% elongation, transverse direction.

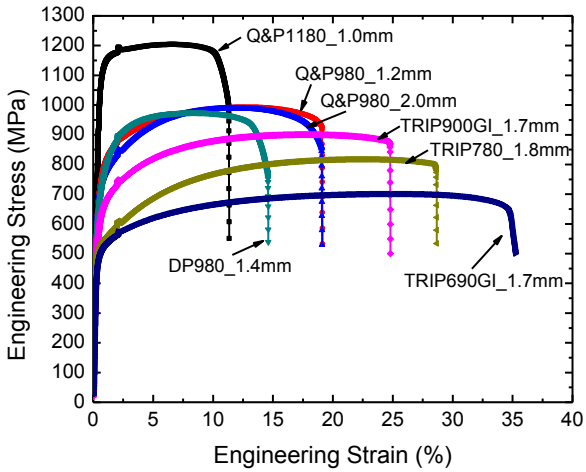


Fig.1 Strain stress curves of the steels. Q&P1180 shows the highest TS and lowest total elongation among all the tested steels. DP980 has the same TS level as Q&P980 and lower total elongation than Q&P980. The total elongation of the TRIP steels is higher, corresponding with its lower tensile strength.

2.2 Hole Preparation for Hole Expansion Testing

130mm*130mm sheet specimens were used and a 10 mm hole was machined in the center of the sheets by one of three different methods: punching, milling or wire cutting. When comparing the influence of preparation method on the hole expansion properties, a particular die clearance (12±2%) suggested in ISO/TS16630:2009 [24] was selected for the punched specimens. Because the thickness of the studied steel sheets ranges from 1.0 mm to 2.0 mm, different inside diameters of the die were used for different sheet thickness in the hole punching process. In order also to study the effect of die clearance on the hole expansion properties, the outer punch diameter was equal to 10mm and kept constant.

2.3 Hole Expansion Testing

Hole Expansion (HE) tests were performed on a MTS tester at Baosteel Research Institute with a conical punch having an angle of 60° as shown in Fig.2. Burrs were placed in the "up" position in which the burr was not in contact with the conical punch. The tests were carried out with a punch velocity of 1mm/s. A minimum of three specimens was tested for each condition. A digital camera was used to detect the initiation of the cracks. The HE tests were terminated as soon as the crack extended through the thickness of the test piece. As the expanded hole was often not symmetric after cracking, the final hole diameter was measured in two perpendicular directions by using a slide caliper. The Hole Expansion Ratio (HER) was then calculated by

$$HER=(d_f-d_0)/d_0\times 100\%$$

where d_0 and d_f are the initial and final hole diameter, respectively.

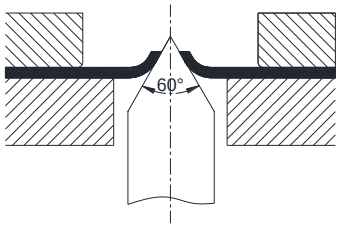


Fig.2 Schematic diagram of the hole expansion test with a conical punch.

2.4 Hole Edge Characterization

The characteristics of the hole edges were analyzed using a light optical microscope (LOM), scanning electron microscope (SEM), and microhardness testing. The depths of the roll-over, burnish, and fracture regions of the sheared edges were measured using image analysis software.

Microhardness tests were performed with a 200 gram-force load with a 10s dwell time using a Vickers indentor. The work hardening behavior of the edges prepared by different methods for different steels was evaluated by performing microhardness measurements at a 30-100 micron increments starting from the hole edge at the mid thickness.

3. Results and Discussion

3.1 Hole Expansion Ratio

The hole expansion test results are presented in Fig.3. The results show that wire cut edges typically had highest HER for most of the tested steel sheets followed by milled and punched edges, respectively. Except for DP980, the HER of specimens with milled edges was very close to or a little lower than that of specimens with wire cut edges. The results demonstrate that the edge qualities of the milled and wire cut edges are similar. When the holes were punched, Q&P1180 showed the highest HER, Q&P980 showed similar HER as DP980, and the TRIP steels showed the lowest HER.

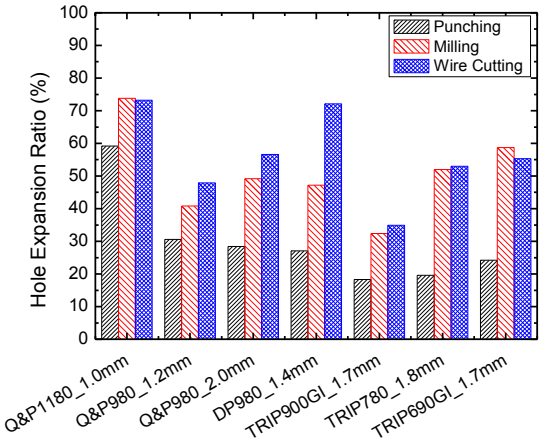
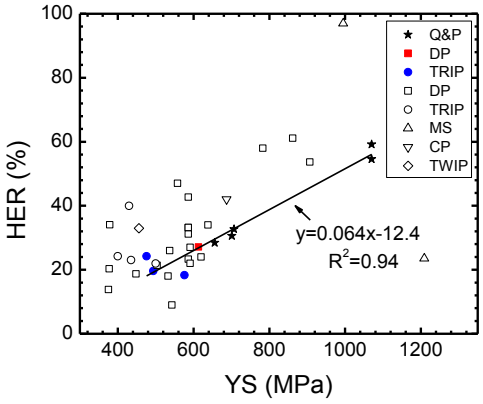
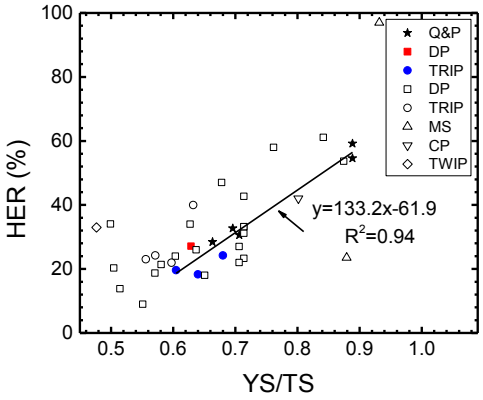


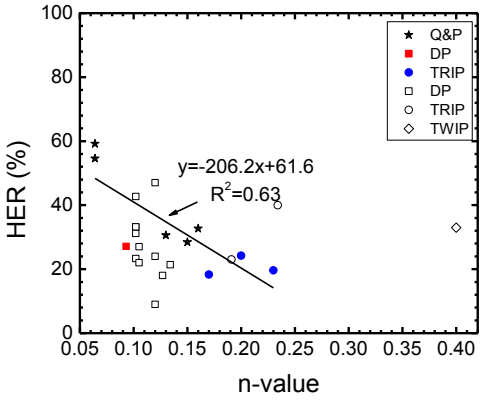
Fig.3 HER of the tested steel sheets with holes prepared by different methods.



a)



b)



c)

Fig.4 Relationship between mechanical properties and HER. The values in current study are shown by solid symbols and those in literature [4, 5, 7, 10, 12, 14, ,15, 19] are shown by open symbols. The linear regression analysis was carried out only for the values measured in the current study.

The relationships between some mechanical properties and HER of the punched edges are presented in Fig.4. Results of some AHSS steels in the literature [4, 5, 7, 10, 12, 14, 15, 19] having a

tensile strength greater than 700MPa are plotted in Fig.4 as well. All the edges were punched with die clearances between 10-15% and the hole expansion tests were performed with a conical punch. Therefore the values can be compared to each other to some extent. At the tensile strength level of 980MPa, Q&P980 shows higher HER than DP980 [7] and JSC980Y [15], but lower HER than another DP980 steel and MS980 [5, 14]. Q&P980 shows the same hole expansion performance as TWIP1000 [12] and DP980 having 34% volume fraction of martensite [14]. It should be noted that the HER of Q&P1180 is higher than most of the specimens tested in literature except for MS980 [14], presumably due to its uniform microstructure. However, the total elongation of MS980 tested by Hasegawa [14] was only 5%, which was much lower than that of Q&P980 and even lower than that of Q&P1180, so the Q&P microstructure seems clearly to offer a better balance of properties. The effects of TS, T.El. and r-value on HER for Q&P, DP and TRIP steel sheets are not as clear as for YS, YS/TS or n-value.

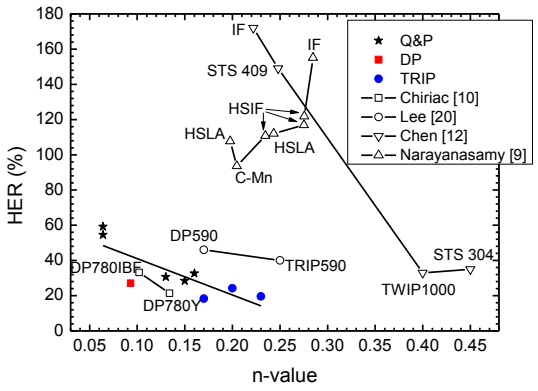


Fig.5 Effect of n-value on HER of punched edges.

In order to study the effect of edge preparation method on HER, the HER loss of punched edges relative to wire cut edges is expressed as:

$$HER\ loss=(HER_w-HER_p)/HER_w\times 100\%$$

where HER_w and HER_p are HER of the wire cut edge and punched edge respectively. Some materials show a significant HER loss. For example, the TRIP780 and DP980 materials showed a 63% reduction and TRIP690GI showed a 56% reduction. It is clear that the punching process significantly decreases the edge stretchability of the tested steels. It is worth noting that Q&P1180 shows the least HER loss among all the tested steel sheets.

Among all the mechanical properties, the linear dependence of the HER loss on n-value is the strongest. Excluding the DP980, the square of the correlation coefficient (R^2) for the linear regression equation between HER loss and n-value is 0.95. A similar effect of n-value on the HER loss for punched edges relative to machined edges was also observed by Comstock [8] and can also be obtained from the data of Konieczny [7], as shown together with the current work in Fig.6a. While the measured values of HER loss varied between the different studies, the trends of the effect of n-value on the HER loss are nevertheless very similar. It is believed that higher n-value results in higher strength material at the sheared edge [8]. This increase in strengthening would lead to a larger difference between punched edge and machined edge performance, because strength is generally inversely proportional to hole expansion performance. A strong relationship between the YS/TS ratio and HER loss is also found, as shown in Fig.6b, the data of current study and that of Comstock [8] show a similar obvious trend that higher YS/TS ratio is associated with lower HER loss. However, the data of Konieczny [7] does not show a clear effect of YS/TS ratio on HER loss. For the materials in this study, Q&P1180 had the lowest n-value and highest YS/TS ratio, and also the lowest HER loss.

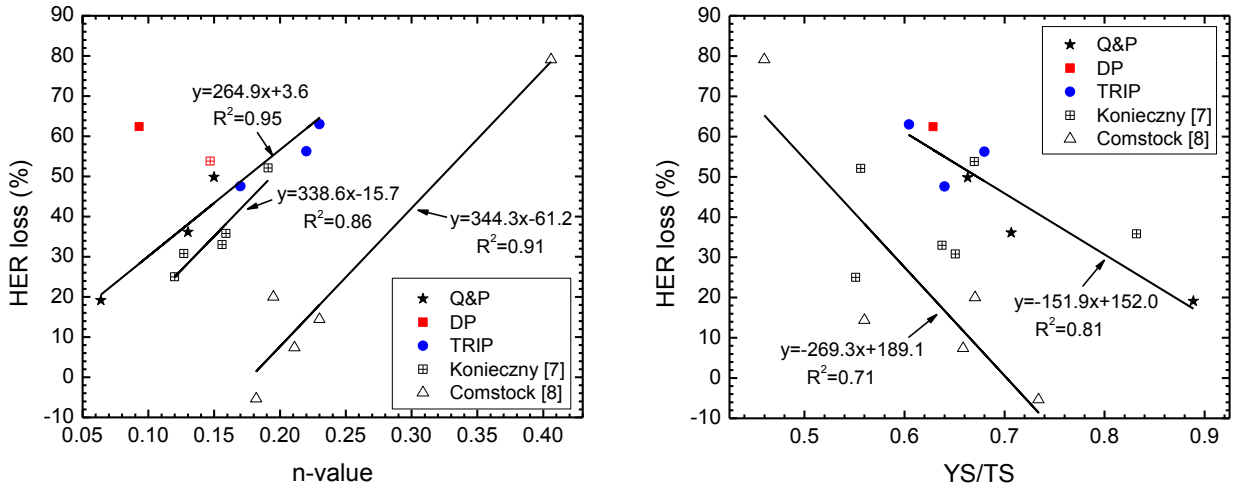


Fig.6 Effect of n-value (a) and YS/TS ratio (b) on the HER loss. DP980 was excluded from the regression analysis of current data. The steels studied in Konieczny's work [7] included DP980, DP780, DP590, TRIP780, 590R and 50XK. 590R was excluded from the regression analysis. The steels studied in Comstock's work [8] were ferritic stainless steels including 409, 18 SR and 18 Cr-Cb and austenitic stainless steel 304L.

3.2

Edge Characteristics

Representative images for the sheared surface and cross-section of punched, milled and wire cut edges are shown in Fig.7. Different machining methods clearly resulted in different edge characteristics. The punched edges show four different zones: rollover, burnish, fracture and burr. Unlike the punched edges, there are no distinct zones in the milled or wire cut edges. The milled edge surface has horizontal lines across the surface and is straight and smooth, with some slight bulging at the top and bottom of the sheet from the milling process. The wire cut edge surface is also smooth and had some small round dimples resulting from the wire electro-discharge cutting process.

Microhardness measurements were made to characterize local changes in properties resulting from edge preparation. The microhardness profiles along the mid-thickness near the edge surface for different steel samples are shown in Fig.8. It can be seen that the hole preparation methods have different effects on the work hardening in the edge area. For all materials, the punching process resulted in a significant hardness increase while only a slight hardness increase was detected for milled edges and almost no hardness increase was observed for wire cut edges. The differences between the maximum hardness at the sheared edge and the average hardness far from the edge were calculated and shown in Fig.9a. It is interesting to note that Q&P1180 shows the lowest hardness increase at the sheared edge, and the TRIP steels show the highest hardness increase. Because the original hardness values of the base steels are different from each other, the percentage of the hardness increase was also calculated. The relationship between the hardness increase and the HER loss is drawn in Fig.9b. For the Q&P and TRIP steels, the slope of the linear regression line is 0.93 which is very close to 1. It indicates that a 10% increase in hardness at the punched edge appears to be associated with a decrease in HER of approximately 9%. Thus it appears that higher n-values cause higher hardness increases at the sheared edge, which reduce HER.

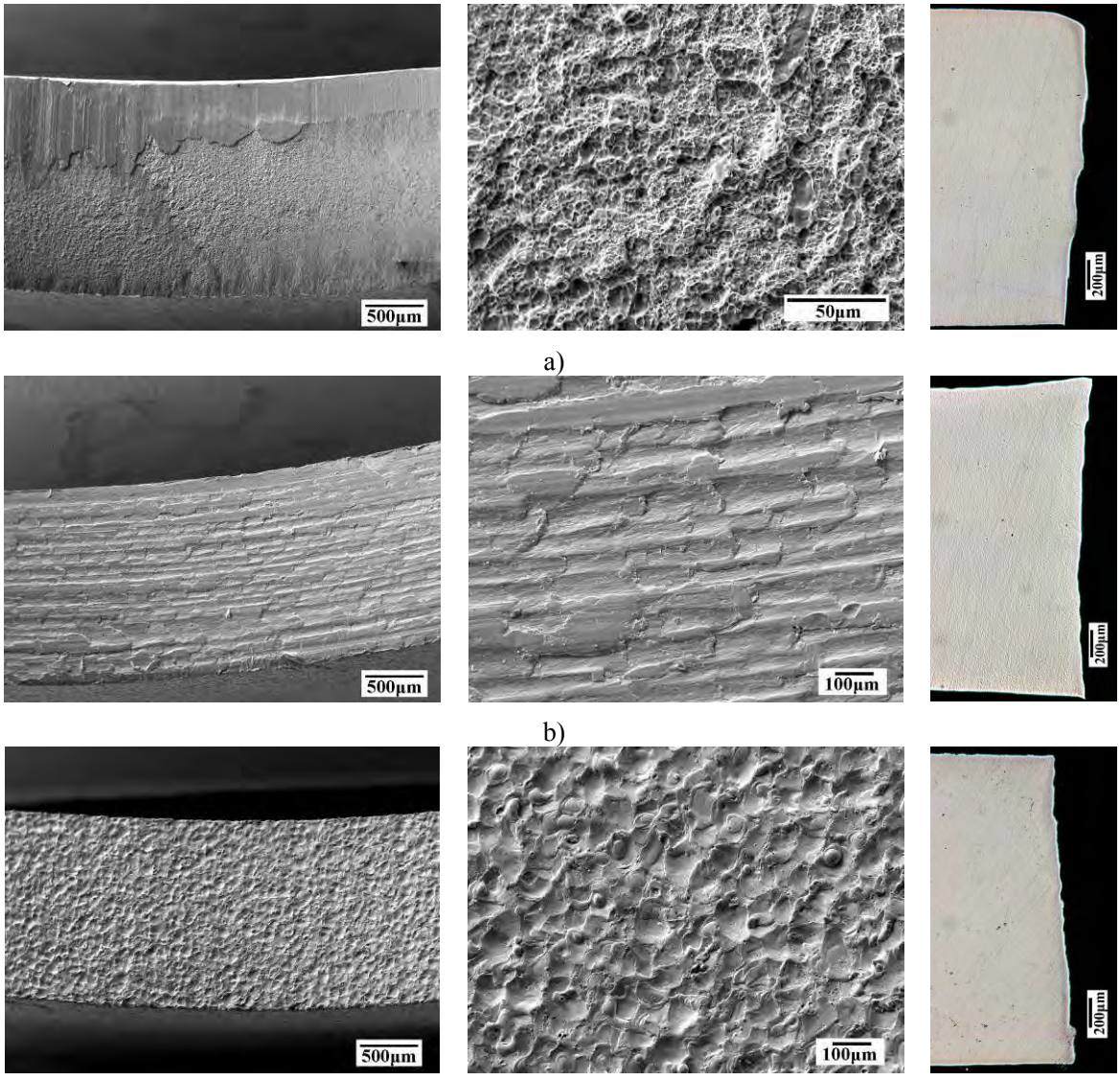


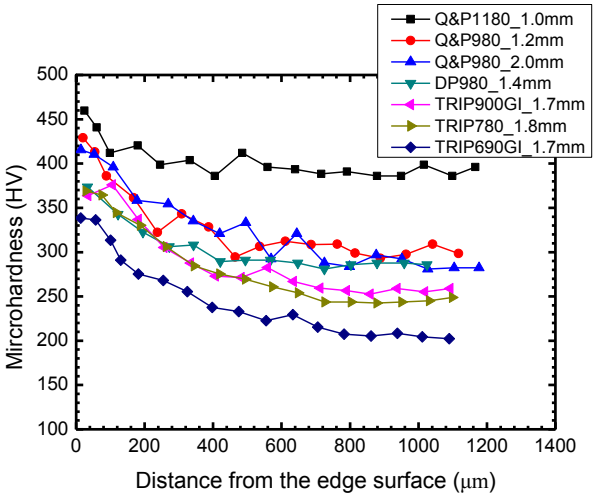
Fig.7 Surface and cross-section characteristics of the hole edges made by a) punching, b) milling and c) wire cutting processes.

The depth of the SAZ was determined by the distance from the sheared surface to the point where the hardness remains unchanged after the punching process. The depth and the percentage of the depth divided by sheet thickness are shown in Table 2. Because the ranges of sheet thickness and the tensile strength widely vary from 1.0 to 2.0 mm and 700 to 1200 MPa respectively, and the actual die clearances during the punching process also differ slightly for different steel sheets, the depth of SAZ varies from 0.27 to 0.74 mm. However, the percentage of depth to thickness only ranges from 27 to 44%. Based on the analysis of the available data in literature, Levy [23] had concluded that the effective depth of the SAZ is less than the thickness and probably less than half the thickness with variations due to differences in shearing conditions. The current results appear to be consistent with this conclusion [21, 23]. No obvious relationship between the depth of SAZ and the HER was observed, however, suggesting that the hardness increase near the edge is more influential than the depth of hardening. Among all the materials in this study, the depth of SAZ of

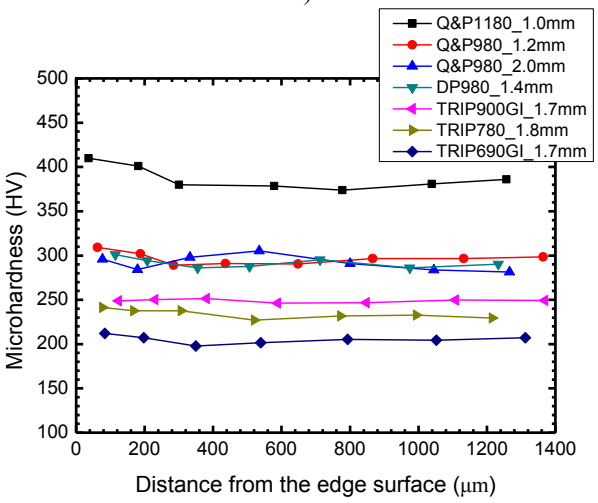
TRIP690GI is the largest, but the HER of TRIP690GI is not the worst. Moreover, the depth of SAZ of Q&P1180 which has the best HER is very close to that of Q&P980 and TRIP900GI.



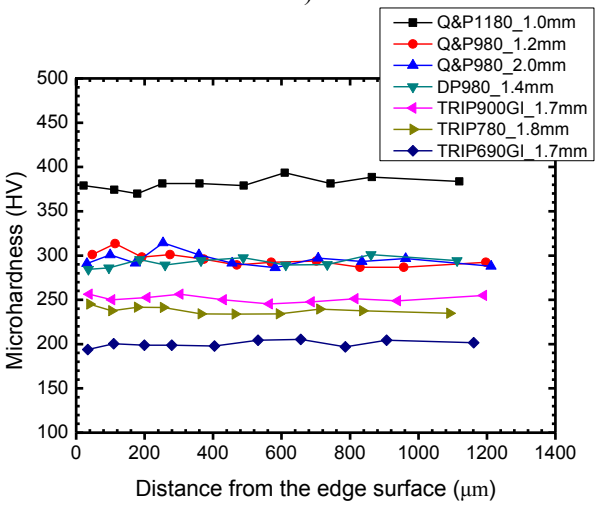
a)



b)

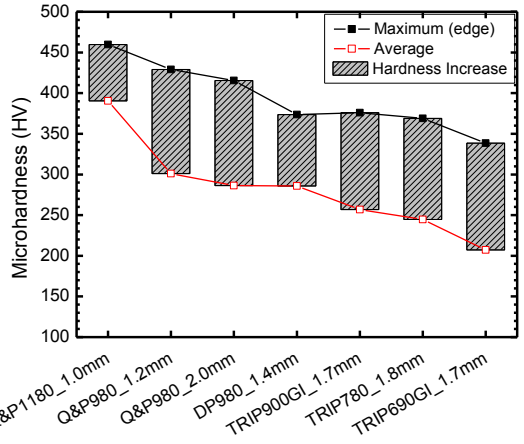


c)

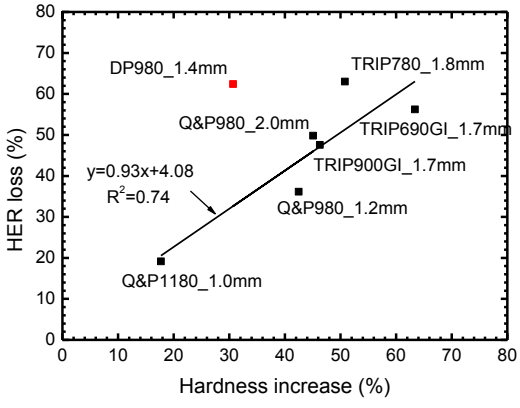


d)

Fig.8 Microhardness profiles at mid-thickness. a) an example of punched Q&P980 after microhardness testing, b) punched edges, c) milled edges and d) wire cut edges.



a)



b)

Fig.9 a) Hardness increase at the punched edges and b) Relation between the hardness increase at the sheared edge and

the HER loss. DP980 was excluded from the regression analysis.

Table 2 Depth of Shear Affected Zone

	thickness (mm)	depth (mm)	depth to thickness (%)
Q&P1180	1.0	0.37	37
Q&P980	1.2	0.43	36
Q&P980	2.0	0.68	34
DP980	1.4	0.38	27
TRIP900GI	1.7	0.67	40
TRIP780	1.8	0.69	38
TRIP690GI	1.7	0.74	44

4. Conclusion

Hole expansion tests of Q&P, DP and TRIP steel sheets with hole edges prepared by punching, milling and wire cutting were carried out. The hole expansion performance, the characteristics of the shear affected zone and the effects of mechanical properties on HER were studied. The main results are presented in the following conclusions.

1. The HER of punched Q&P1180 is over 50%, which is much higher than that of the other steels. The HER of punched Q&P980 is close to 30%, which is similar as that of DP980 and a little higher than that of TRIP steels.

2. The YS/TS ratio shows a strong positive effect on HER of the tested Q&P, DP and TRIP steels with punched edges. One possible explanation of the high HER of Q&P1180 is due to its high YS/TS ratio.

3. The punching process deteriorates the hole expansion performance when compared with milling and wire cutting. Q&P1180 shows the least HER loss between punched and wire cut edges. Q&P1180 also exhibits the smallest hardness increase at the sheared edge because of its low n-value. The TRIP steels with higher n-values exhibit greater HER loss as compared with Q&P steels. There is a strong relationship between n-value, hardness increase at the sheared edge and the HER loss.

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