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Hole expansion characteristics of ultra high strength steels

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Abstract

The hole expansion ratio is a key indicator to evaluate stretch flanging performance of steel sheets, which is usually obtained by hole expanding test using cylindrical or conical punch. According to ISO 16630-2009 (Metallic materials -- Sheet and strip -- Hole expanding test), hole expanding tests of 15 types of steel sheet were conducted using conical punch. The results indicated that there was obvious correlation between hole expansion ratio and tensile strength. While the tensile strength of steel is less than 700 MPa, hole expansion ratio of steel decreases linearly with the increase of tensile strength. While the tensile strength is greater than 700 MPa, hole expansion ratio tends to a constant value (about 30–40%). Steels with tensile strength of 700 MPa or more, including DP780, DP980, MS1180, have a common characteristic that they have relatively high volume of the hard phase (martensite phase). Therefore, it can be considered that, with large different deformation capacity during the forming process, the two-phase (ferrite & martensite) interface of these steels is prone to crack and expand. When the hard phase (martensite) reaches a certain volume fraction, there may be a limit of the damage energy during the microscopic damage of the two-phase interface.

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1. Introduction

High strength steels, especially ultra high strength steels are being used more widely in automobile industry. In the study of the ultra high strength steel (UHSS) forming characteristic, hole expansion ratio is an efficient method to evaluate stretch flanging performance of steel sheet, especially for advanced high strength steels. McEwan et al.

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(2009) proposed a method of integrating hole expansion ratio and forming limit to predict failure. With the continuous increase in strength of the developing steel, the FLC/HEC (Forming Limit Curve/Hole Expansion Capacity) integrated forming limit diagram may have wide application prospect. K. Mori et al. (2009) examined the effect of the quality of the sheared edge on the stretch flangeability of the high strength steel sheets from expansion of a sheared hole with a conical punch, and found that the limiting expansion ratio of the sheared ultra high strength steel sheet is dependent on the macroscopic unevenness and hardness of the sheared edge and not on the microscopic roughness. So the smoothing of the sheared edge is effective in improving the stretch flangeability of the ultra high strength steel sheet. Mori et al. (2010) developed a smoothing process of rough fracture surface of a sheared edge with a conical punch, and found that the limiting expansion ratio was improved by the smoothing even though the hardness was increased, and as the maximum elevation on the surface of sheared edge decrease, the limiting expansion ratio increased due to the delay of the propagation of the cracks.

In this study, hole expansion tests of high strength steels and ultra high strength steels manufactured by Baoshan Iron & Steel Co., Ltd (BaoSteel) were conducted. Hole expansion ratio of each steel was obtained to predict and evaluate the edge cracking tendency.

Nomenclature

D_0	Original hole diameter, mm
D_h	Average hole diameter after rupture, mm
d_p	Diameter of the punch used for punching a hole in the test piece, mm
D_d	Inside diameter of the die, mm
λ	Limiting hole expansion ratio, %

2. Experiment

2.1. Experimental materials

Cold and hot rolled auto sheets manufactured by BaoSteel were tested, as shown in Table 1. SAPH440 and SPFH590 are hot rolled steel sheets, the rest are cold rolled steel sheet. The thickness and mechanical properties of the tested materials are also listed in Table 1.

Table 1. Experimental materials.

Steel Grade	Thickness (mm)	Yield Stress (MPa)	Tensile Stress (MPa)	Elongation A_{80} (%)
H180YD+Z	0.7	189	351	42
H180BD+Z	0.7	199	319	43
H220BD+Z	0.8	256	385	38
B280VK	2.0	310	459	30
St37-2	2.0	287	392	33
H340LA	1.2	375	485	29
B1500HS	1.6	351	519	28
HC340/590DP	1.2	365	641	26
HC420/780DP	1.4	479	846	18
HC550/980DP	1.4	680	1053	12
HC950/1180MS	1.6	1074	1301	7
SAPH440	2.6	373	461	31
SPFH590	2.0	530	611	18

2.2. Experimental procedure

Hole expansion tests were conducted according to ISO 16630-2009 (Metallic materials -- Sheet and strip -- Hole expanding test) standard on the MTS810 forming test machine. Samples with a punched hole of 10mm diameter were used in the test. The geometry of the tools are shown in Fig. 1. A conical punch with an angle of 60° was used. Punch cylinder diameter d_p was 50 mm. Inner diameter of die was 50 mm. The driving speed of the

conical punch was 0.3 mm/s. During the test, the burr formed by hole expansion was along the normal direction of punch outside. The punch was moved up against the blank sample until the crack on the hole edge penetrating through the sample thickness could be observed by the optical instrument, as shown in Fig. 2.

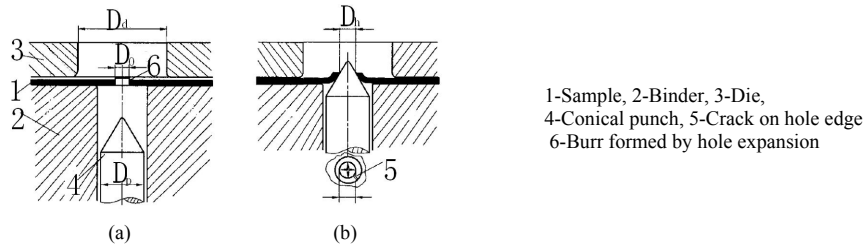


Fig. 1. Schematic diagram (a) before and (b) after the hole expansion test.

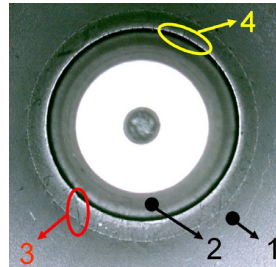


Fig. 2. Schematic diagram of hole expansion test observed by optical instrument.

2.3. Experiment validation and repeated experiment

The hole edge morphology of each specimen was observed by stereo microscope after hole expansion test to validate the crack determination, as shown in Fig. 3.

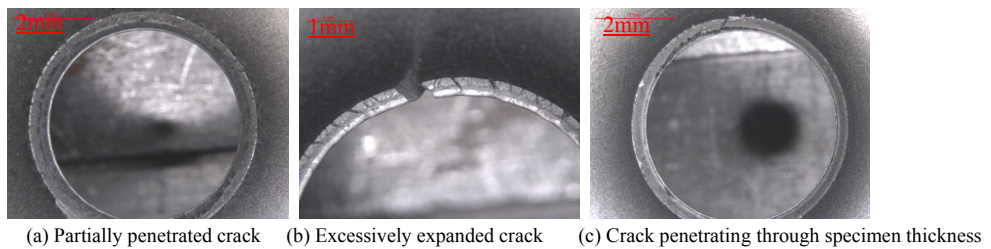


Fig. 3. Hole edge morphology observed by stereo microscope

The crack in Fig. 3(a) was formed but not through the full thickness of the test specimen. The crack in Fig. 3(b) is excessively expanded since the movement of the punch failed to stop when the crack penetrated through the full thickness of test specimen. For the above two kinds of specimen, the test was determined to be invalid. Only the specimen with crack just appeared through the full thickness was accepted. Two or three valid tests were conducted for each steel grade.

3. Measurement and analysis

3.1. Measurement and calculation of hole expansion ratio

For each valid tested specimen, the average diameter of the ruptured hole D_h was determined by measurement in two directions, perpendicular to each other, avoiding the crack. Using the average diameter of the ruptured hole, the limiting hole expansion ratio for each of the two or three test specimen was calculated by the following equation:

$$\lambda = \frac{\overline{D_h} - D_0}{D_0} \times 100 \quad (1)$$

The measured data and calculation results are listed in Table 2.

Table 2. Experiment results.

Steel grade	Average hole diameter after rupture, mm			Hole expansion ratio λ , %		
	1#	2#	3#	1#	2#	3#
H180YD+Z	22.74	21.24	/	127	112	/
H180BD+Z	21.97	19.68	/	120	97	/
H220BD+Z	20.75	20.61	20.38	108	106	104
B280VK	19.54	22.73	21.79	95	127	118
St37-2	17.61	19.28	20.08	76	93	101
H340LA	15.93	17.83	16.06	59	78	61
B1500HS	15.98	16.47	15.80	60	65	58
HC340/590DP	15.17	14.41	14.53	52	44	45
HC420/780DP	13.20	13.15	13.48	32	31	35
HC550/980DP	13.28	13.49	13.50	33	35	36
HC950/1180MS	13.52	13.74	14.20	35	37	42
SAPH440	19.54	18.49	20.60	95	85	106
SPFH590	19.39	16.34	17.33	94	63	73

3.2. Correlation between hole expansion ratio and tensile strength of materials

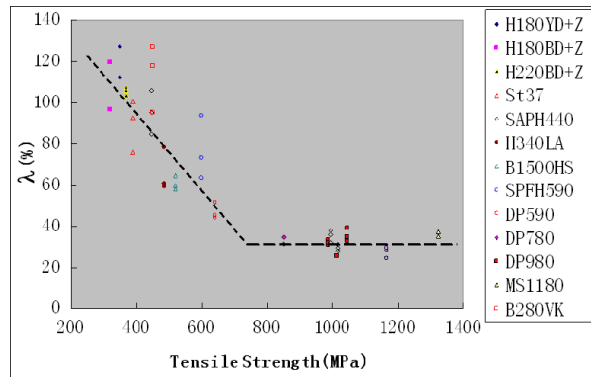


Fig. 4. Correlation between hole expansion ratio and tensile strength of test steel sheet.

The relationship between expanding rate and tensile strength of each test steel is shown in Fig. 4. As shown in Fig. 4, the correlation between the hole expansion ratio and tensile strength had an obvious turning point:

While the tensile strength of steel was less than 640 MPa (HC340/590DP steel sheet sample with tensile strength of 641 MPa), hole expansion ratio of steel decreased linearly with the increase of tensile strength. There was a strong inverse correlation between hole expansion ratio and tensile strength.

While the tensile strength was greater than 840 MPa (HC420/780DP steel sheet sample with tensile strength of 846 MPa), hole expansion ratio tended to a constant value (about 30~40%) with the increase of tensile strength.

3.3. Morphology of hole edge after hole expansion test

The hole edge of each test specimen was observed by 50× stereo microscope. The hole edge morphology of the punched specimen are shown in Fig. 5.

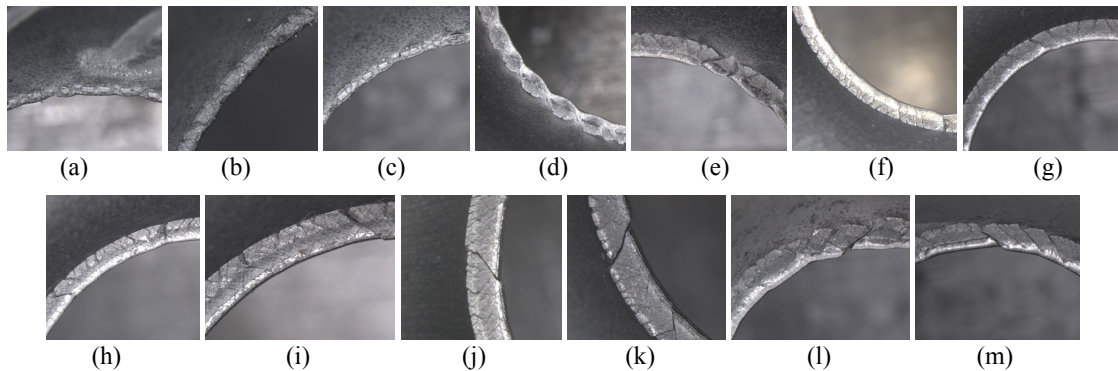


Fig. 5. Hole edge morphology (a)HC180YD+Z, (b)HC180BD+Z, (c)HC220BD+Z, (d)B280VK, (e)St37-2, (f)HC340LA, (g)B1500HS, (h)HC340/590DP, (i)HC420/780DP, (j)HC550/980DP, (k)HC950/1180MS, (l)SAPH440, (m)SPFH590.

Hole edge morphology characteristic of steels with relatively low tensile strength and high ductility were very similar, as shown in Fig. 5(a), (b) and (c). From the hole edge morphology, we can see diffuse instability occurs almost uniformly around the hole edge. A series of “groove” thinning area were formed. These thinning area appeared through the full thickness section of the test specimen but passivated at the crack tip and therefore restrained the crack propagation to increase the limiting hole expansion ratio.

Fig. 5(d) shows a typical steel grade with relatively high hole expansion ratio. As can be seen in the morphology, instability occurred uniformly along two directions, perpendicular to each other, 45° to the hole radial direction.

The hole edge morphology characteristic in Fig. 5(e) - 5(k) changed regularly. The crack on the hole edge developed from “island” and “groove” shape to clear micro crack shape gradually. Crack basically formed on the edge of test specimen with relatively low tensile strength. However many micro cracks formed in the middle of the thickness direction on the cross section of test specimen with relatively high tensile strength.

Fig. 5(l) and 5(m) demonstrates hole edge morphology of hot rolled steel sheet. Brittle crack propagation characteristic can be clearly seen although the tensile strength of these two steel grade is not very high.

3.4. Corner feature analysis of AHSS hole expansion ratio

Experiment results in Item 3.2 indicated that while the tensile strength of steels was less than 640 MPa, there was a strong inverse correlation between hole expansion ratio and tensile strength. While the tensile strength of steel was more than 840 MPa, hole expansion ratio tended to a constant value. The turning point of these two kinds of correlation was tensile strength of about 700 MPa.

From hole edge morphology in Item 3.3, we can see that with the increase of tensile strength, the original crack formed not only on the edge but also in the middle of thickness direction of specimen. The crack formed from the center was most likely originated from the compatible deformation between hard and soft phase of test specimen.

The martensite volume fraction of four steel sheet HC340/590DP, HC420/780DP, HC550/980DP and HC950/1180MS was measured. The specimen was etched with Lepera reagents (1:1 mixture of 4% picric acid in methanol and 1% Na₂S₂O₅ in water). The microstructure was observed by Leica DM6000M microscope. As shown in Fig. 6, martensite was white after etching. Image-analysis software Leica Qwin V3 was used to determine the spatial distribution of martensite phase. The volume fraction of martensite phase of measured specimen was listed in Table 3.

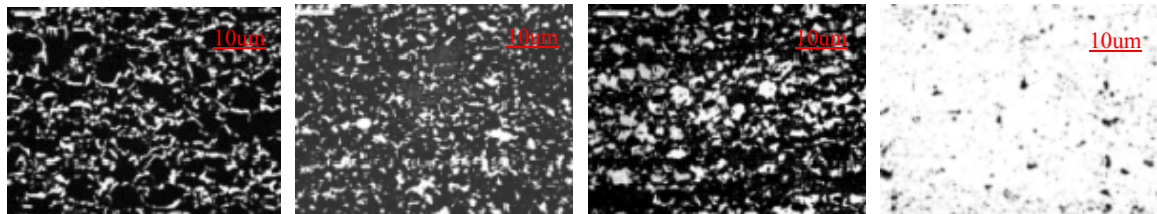


Fig. 6. Microstructure of (a) HC340/590DP, (b) HC420/780DP, (c) HC550/980DP, (d) HC950/1180MS.

Table 3. Martensite volume fraction of measured four steel grades.

Steel grade	Measurement area						Average value
	1#	2#	3#	4#	5#	6#	
HC340/590DP	18.98	19.02	19.49	18.56	21.91	20.55	19.75
HC420/780DP	27.83	27.95	24.30	23.93	24.03	21.11	24.86
HC550/980DP	32.41	37.97	33.41	28.27	28.28	31.77	32.03
HC950/1180MS	90.65	87.75	95.15	95.87	90.65	94.31	92.40

From the measurement, we can see that steels with tensile strength of 780MPa or more, including DP780, DP980, MS1180, have a common characteristic that they have relatively high volume of the hard phase (martensite phase). Therefore, it can be considered that, with large different deformation capacity during the forming process, the two-phase (ferrite & martensite) interface of these steels is prone to crack and expand. When the hard phase (martensite) reaches a certain volume fraction, the micro damage on the interface of hard and soft phase may have a limiting damage energy.

4. Conclusion

Hole edge morphology characteristic of steels with relatively low tensile strength indicated that diffuse instability occurred uniformly around the hole edge forming a series of “groove” thinning area. The crack on the hole edge developed from “island” and “groove” shape to clear micro crack shape gradually with increasing tensile strength. Cracks basically formed on the edges of test specimens with relatively low tensile strength. However, with the increase of tensile strength, the original micro crack formed not only on the edge but also in the middle of thickness direction of specimen. For steels with relatively high hole expansion ratio, instability occurred uniformly along two directions, perpendicular to each other, 45° to the hole radial direction.

While the tensile strength grade was less than 590 MPa, the hole expansion ratio of steel decreased linearly with the increase of tensile strength. There was a strong inverse correlation between the hole expansion ratio and tensile strength. However, while the tensile strength grade was greater than 780 MPa, the hole expansion ratio tended to a constant value (about 30–40%) with the increase of tensile strength. That may be because when the hard phase (martensite phase) reaches a certain volume fraction, there may be a limit of the damage energy during the microscopic damage of the two-phase interface.

References

- C. McEwan, R. Underhill, N. Langerak, G. Botman, M. de Bruine, 2009, A new approach to predicting edge splits - The combined FLD/HEC diagram, IDDRG 2009 Proceedings, 1-3 June 2009, Golden, CO, USA, 65–72.
- K. Mori, Y. Abe, Y. Suzui, 2010, Improvement of stretch flangeability of ultra high strength steel sheet by smoothing of sheared edge, Journal of Materials Processing Technology, 210-4, 653-659.
- K. Mori, Y. Abe, Y. Ikeda, 2011, Improvement of formability for expansion of punched hole of ultra-high strength steel sheets by smoothing of sheared edge, Steel Research International, Special Edition, 604-609.
- GB/T 15825.4-2008, Sheet metal formability and test methods--Part 4 : Hole expanding test.
- ISO/TS 16630-2003, Metallic materials - Method of Hole Expanding Test.