Effects of Microstructure on Hole Expansion Ratio of AHSS

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INTRODUCTION

Advanced high strength steels (AHSS) are increasingly applied to automobile components to improve fuel efficiency and passenger’s safety. However, cracking during stretch flanging operation of some AHSS is one of the major concerns. Hole expansion ratio (HER) is one measurement that represents the stretch-flange-formability of a material required to form into a complex shaped component. Among four basic press forming modes, deep drawing ability, bulge-ability, bendability, and stretch-flange-formability, most of them can be sufficiently described by global formability—the conventional forming limit curves. But hole expansion and stretch-flange-formability are mostly governed by local formability.

Hole expansion ratio results can be heavily influenced by hole preparation method (punching, machining, or EDM, etc.), punch geometry, mechanical property (YS, UTS, uniform elongation, strain rate sensitivity, etc.), and microstructure (phase fraction, distribution, and strength difference, etc.) [1-4]. Different microstructures of AHSS show various mechanical properties, HER, and damage mechanisms. In this research, effects of microstructure on HER were studied on multi-phase (MP), and complex-phase (CP) AHSS, such as MP780, MP980, and CP980. In contrast to global formability depending on uniform elongation, HER of AHSS is mostly governed by its local microcrack initiation and growth resistance. The effect of microstructure (banding, microtexture, grain size, and bainite and martensite phases) on the microcrack growth resistance of AHSS HER samples have been investigated in detail.

EXPERIMENTAL PROCEDURE

Three AHSS sheet materials, multiphase 780, multiphase 980, and complex phase 980 (MP780, MP980 and CP980) produced in the continuous annealing and galvanizing line were chosen for this study. Nominal thickness was maintained between 1.3 and 1.8mm. Chemical compositions of the AHSS are shown in Table 1.

Table 1. Chemical compositions of steel investigated

<table>
<thead>
<tr>
<th>Steel</th>
<th>Chemical compositions (mass%)</th>
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<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>MP780-A, -B, -C</td>
<td>0.079</td>
</tr>
<tr>
<td>MP980</td>
<td>0.081</td>
</tr>
<tr>
<td>CP980</td>
<td>0.082</td>
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Stretch-flange-formability was evaluated by the hole expansion test. A hole of 10 mm diameter was pierced at the center of 100 mm square samples. The clearance of the 60° conical punch and die was 12%. The microstructures were observed by optical microscopy and scanning electron microscopy (SEM) after nital-etching. SEM and EBSD analyses were performed on a JEOL JSM 7000F field emission gun microscope equipped with a combined EDAX Pegasus EDX/EBSD system. The EBSD
data were evaluated with EDAX OIM 7.3 without additional data clean-up applied. For indexing purposes, the phases of α-Fe, γ-Fe and Fe₃C were chosen. The prior austenite grain (PAGs) reconstruction analysis was conducted by a MTEX software.

RESULTS AND DISCUSSION

Hole Expansion Ratio of MP980 and CP980

Tensile Property and Hole Expansion Ratio
The tensile property and hole expansion ratio (HER) of the MP980 and CP980 sheets are shown in Figure 1. The hole expansion ratios generally increased with increasing yield strength. Contrast to the strengths, the hole expansion ratios were decreased with the increase of total elongation.

![Figure 1](image)

**Figure 1.** (a) YS vs HER, (b) Total EL vs HER of MP980 and CP980

Microstructure and Hole Expansion Ratio
Microstructures of the hole expansion samples were characterized using secondary electron SEM images as shown in Figure 2. Two specimens were chosen to study the detailed microstructural difference between MP980 of low HER 24.4% and CP980 of high HER 44.6%. Both MP980 and CP980 showed uniform macrostructure at the low magnifications. However, MP980 showed some microstructural banding along the rolling direction. The microstructures of MP980 and CP980 consisted of tempered martensite and fresh martensite, as shown in Figure 2b and Figure 2d. MP980 had 30-45% fresh martensite, and small grains (visually observed). CP980 had 20-35% fresh martensite, and large grains (visually observed).

EBSD, Microtextures, PAGs and Hole Expansion Ratio
In Figure 3, low magnification EBSD images were compared between MP980 of low HER 24.4% and CP980 of high HER 44.6%. Microtextures were extensively observed in MP980, which were corresponding to the microstructural bands as seen in Figure 2a. In contrast, no microtextures were observed in CP980 of high HER 44.6%. The microtextures were playing an important role in affecting the hole expansion ratio. High magnification EBSD images of MP980 and CP980 in Figure 4a and 4c show the detailed difference between their microstructural features. The microstructure of MP980 was a mixture of large grains and numerous small grains. The microstructure of CP980 consisted of uniform equiaxed grains. The prior austinite grain (PAG) reconstructed images by the MTEX software analysis are shown in Figure 4b and 4c. The black lines represent PAG boundaries, while the blue and red lines represent sub-grain boundaries and dislocations. It can be clearly seen that the PAG sizes of MP980 varied from 2-3 microns to 15-20 microns (red circle in Figure 4b). The large PAGs contained some sub-grain boundaries and dislocations, causing to appear as small grains in the SEM images after Nital etching. The PAG sizes of CP980 were uniform, with an average of 5-8 microns. The sizes of PAGs had significant impact on the hole expansion ratio.

Microcracking Growth and Hole Expansion Ratio
Microcracking growth of the MP980 was investigated after hole expansion testing, as shown in Figure 5. The hole expansion cracking was initiated at the hole edges, and microcracks were formed ahead of the main crack tip in the stress concentrated regions. The main crack was propagated by microcracks linking together in the longitudinal direction. In the MP980 of low HER 24.2%, the microcracks were relatively straight, in a length of about 20-90 microns. The microcracking growth was governed by the microtexture size and orientation, which was associated with the large PAGs. Detailed difference in the microcracking growth between MP980 of low HER 24.2% and CP980 of high HER 44.6% was exhibited in Figure 6. MP980 showed relatively straight main crack, and no secondary cracks. CP980 exhibited zigzag cracking growth, accompanying with numerous secondary cracks. Some microcrack growth steps were in the range of PAG sizes, 5-8 microns, as marked by the red arrows in Figure 6b. The microtexture and PAGs sizes were one of the key factors to determine the hole expansion ratio.
Figure 2. Microstructure of (2a and 2b) MP980 (HER 24.2%) and (2c and 2d) of CP980 (HER 44.6%)

Figure 3. Low magnification EBSD showing (a) microtextures in MP980 and (b) no microtextures in CP980.
Figure 4. High magnification EBSD images and PAG analysis of MP980 (4a and 4b) and CP980 (4c and 4d)

Figure 5. Cracking growth in MP980, microcracks were formed ahead of the main cracks, and linked together
Hole Expansion Ratio of MP780

Tensile Property and Hole Expansion Ratio
The tensile property and hole expansion ratio (HER) of three MP780 sheets are shown in Table 2. No significant difference in YS, UTS, UEL, and TEL was observed among the three MP780 sheets. However, the hole expansion ratios were significantly different from 28.9% to 46.6%. The effects of tensile property on the hole expansion ratios were not observed.

<table>
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<tr>
<th>IDs</th>
<th>Tensile Property</th>
<th>HER, %</th>
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<tr>
<td></td>
<td>0.2 YS, MPa</td>
<td>UTS, MPa</td>
</tr>
<tr>
<td>MP780-A</td>
<td>530</td>
<td>855</td>
</tr>
<tr>
<td>MP780-B</td>
<td>541</td>
<td>864</td>
</tr>
<tr>
<td>MP780-C</td>
<td>550</td>
<td>852</td>
</tr>
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</table>

Microstructure and Hole Expansion Ratio
The macro/microstructures of the three MP780 sheets are shown in Figure 7. At the low magnifications, severe microstructural banding was observed in the MP780-A which had the lowest hole expansion ratio of 28.9%. Some banding was observed in the MP780-B that had a hole expansion ratio of 33.3%. The MP780-C had the best hole expansion ratio of 46.6%. No banding was observed in this sheet. The microstructures of MP780 consisted of 20-35% fresh martensite, 30-45% ferrite and 10-25% bainite. Both the MP780-A and B showed large ferrite grains compared to the MP780-C. Uniform microstructures were observed in the MP780-C, with the best hole expansion ratio 46.6%.

EBSD, PAGs and Hole Expansion Ratio
EBSD images of the three MP780 sheets and their prior austenite grain (PAG) reconstructed images by the MTEX software analysis are shown in Figure 8. MP780-A of the lowest HER 28.9% had a mixed microstructure of large, elongated grains and numerous small grains (Figure 8a). In contrast, MP780-C of the highest HER 46.6% had uniform, equiaxed grains (Figure 8e). Further analysis of the PAG reconstruction images by the MTEX software was shown in Figure 8b, 8d, and 8f. In the PAG reconstructed images, the black lines represent PAG boundaries, the blue lines represent sub-grain boundaries, and the red lines represent dislocations. The PAGs varied from elongated and non-uniform to equiaxed and uniform shapes, causing the HER increasing from 28.9%, to 33.3%, and to 46.6%. The observation of PAGs was consistent to the variations of banding. Severe banded microstructure was associated with large elongated PAGs in the rolling direction, causing the lowest hole expansion ratio. Non banded microstructure was associated with uniform and equiaxed PAGs, leading to significant improved hole expansion ratio. The phenomenon can be explained by cracking growth resistance of different microstructures.

Figure 6. Comparison of cracking growth of (a) MP980 and (b) CP980

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Microcracking Growth and Hole Expansion Ratio

Microcracking growth of the MP780-A HER samples was investigated, as shown in the optical micrographs (Figure 9). The microcracks were generally initiated and propagated in the longitudinal direction, in the direction of the banding. The microcracks were relative straight, and no secondary cracking was observed (Figure 9a). Detailed observations indicated that the microcrack was easily propagated in a certain crystal orientation. In Figure 9b, the three-yellow marked microcrack-sections were in the same crystal orientation, and the two-red marked microcrack-sections were in another crystal orientation. The two orientations were easy-microcrack-growth-orientations, just slightly different. The microcrack was propagated along the easy orientations, and then the microcrack-sections were linked by some hard orientations. Those easy-microcrack-growth-orientations can be explained by the large elongated PAGs, illustrated in Figure 8b. The severe rolling banding and large elongated PAGs had less microcracking growth resistance, leading to low hole expansion ratio.
Figure 7. Macro/Microstructures of MP780-A (7a and 7b), MP780-B (7c and 7d), and MP780-C (7e and 7f).
**Figure 8.** High mag EBSD images and PAGs analysis of MP780-A (8a and 8b), MP780-B (8c and 8d), and MP780-C (8e and 8f)

**Figure 9.** Cracking growth in MP780-A of HER 28.9%, microcracks formed in the easy orientations, and linked together

**Improved Hole Expansion Ratio by Increased Crack Initiation and Growth Resistance**

Improved hole expansion ratio is dependent upon resistance to microcrack initiation and growth. Hole preparation has significant impacts on microcrack initiation resistance. In the present study, all the sample holes were prepared by piercing. The microcrack initiation resistance was governed by the resistance of dislocation pileups at PAGs boundaries. In large elongated PAGs, dislocation pileups can be readily formed at the boundaries, causing a microcrack to be initiated in the rolling directions. Once the single microcrack was initiated, it can be easily propagated, relatively straight and no secondary microcracks in the microtextures regions. In samples with less microtextures and equiaxed PAGs, dislocation pileups occurred in multiple PAGs in different orientations, delaying the microcrack formation. In general, the microcracks were initiated in all orientations around the hole. The cracks can be propagated in a zigzag cracking growth path, and it is possible that secondary microcracks may be initiated. The microcrack growth resistance is attributed to large crystal orientation difference among the neighboring PAGs in the no microtextures microstructure. The large angle PAGs boundaries are efficient barriers to dislocation pileups and microcrack initiation. They are also efficient barriers to microcrack growth, causing zigzag cracking with numerous secondary microcracks. The effect of microstructure on hole expansion ratio of AHSS can be explained in the schematic in Figure 10. The low HER samples had a mixed microstructure of large elongated PAGs and numerous small grains, with banding and microtextures. Generally, the samples had a single straight crack in the rolling direction. The high HER samples had a microstructure of uniform equiaxed PAGs, without banding and microtextures. They generally had multiple cracks, zigzag cracking growth paths plus secondary microcracks.

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Figure 10. Schematics of crack initiation and growth in (a) low HER and (b) high HER

CONCLUSIONS

The effect of microstructure on the hole expansion ratio of MP780, MP980, and CP980 was investigated. The microstructure of MP780 consisted of 20-35% fresh martensite, 30-45% ferrite and 10-25% bainite. The microstructures of MP980 and CP980 consisted of 20-45% fresh martensite and 55-80% tempered martensite. The microstructure had significant impact on hole expansion ratio. The microstructural banding, microtextures, and large elongated PAGs negatively impacted the hole expansion ratio. The hole expansion ratio could be improved by increased microcrack initiation resistance and microcrack growth resistance. The higher hole expansion ratio could be achieved in a microstructure of uniform equiaxed PAGs, without banding and microtextures.

ACKNOWLEDGMENTS

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REFERENCES