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Effect of Pre-strain on Microstructure and Stamping Performance of High-strength Low-alloy Steel

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Abstract: In this study, pre-strain ranging from 0 to 0.12 was applied through uniaxial tension on high-strength low-alloy (HSLA) specimens with four kinds of grain size. Effect of pre-strain and grain size on mechanical property was investigated through tensile tests. Microstructures of the pre-strained and tensile tested samples were analyzed, respectively. The 30.8° v-bending and following flattening, as well as Erichson cupping tests, were performed on the pre-strained samples. Results show the elongation ratio of grain and dislocation density increases with pre-strain. Yielding platform is removed when pre-strain is larger than 0.06 while yielding plateau period decreases with pre-strain less than 0.06 due to reduction of pinning effect. The 30.8° v-bending and the following flattening tests are successfully accomplished on all the pre-strained samples with different grain size. Decrease in grain size, along with increase in pre-strain, causes increase in strength and decrease in elongation rate as well as cupping value. Pre-strain causes very slight effect on bending ability, much less than that on mechanical property and cupping test value. Reciprocal impact of the pre-strain and grain size on HSLA steel deformability is inconspicuous.

Key words: strain hardening; dislocation; texture; bending; erichson cupping test

1 Introduction

The high-strength low-alloy(HSLA) steel is fabricated by adding tiny element such as Nb, Ti, and N, in the purpose of strengthening by grain refining and precipitation. It is therefore characterized as high strength level and good formability, which can be used to reduce thickness of automotive body parts to lessen fuel consumption and exhaust gas emission.

The strength and stiffness of HSLA steel can also be enhanced by applying a small amount of pre-deformation to achieve better crashworthiness. Nevertheless, the deformation ability shall be lowered due to strain hardening, especially in multi-pass stamping forming. Numerous experimental results show that dislocation pile-up occurs when metal plate is previously deformed, resulting in increase in both yielding strength (YS) and ultimate tensile strength (UTS), as well as decrease in elongation rate (ER)[1-3]. According to the work by Li *et al*[4], the production of UTS×ER of the pre-strained specimen is very near to that of the original one. Furthermore, Li found that sample with 0.1 pre-strain had lower yield/tensile ratio 0.79, compared to that of 0.89 without pre-straining. This provides an optional method of optimizing mechanical property. Pre-strain can also be used to eliminate the residual quenching stress through promoting dislocation density and resultant critical shear stress for dislocation slip aimed at the Al-Cu-Mg alloy, according to the work by Liu *et al*[5]. Zhou *et al* found that yielding strength of TA2 titanium alloy increased with increase in pre-torsion angle in a certain range, and dropped sharply when the pre-torsion angle exceeded 6π[6]. Pre-strain can also exert an effect on void generation and combination for AA5052 aluminum alloy[7]. Void growing rate increases with pre-strain, resulting in increase in yielding stress and decrease in ductility. As in terms of multi-pass sheet stamping, work hardening happens inevitably on blank in each pass. For example, nonlinear bending and straightening deformation happen when metal plate enters a die cavity or slides along radius direction before hemispheric bulging, which causes a negative impact

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on forming limit[8,9]. In multi-step drawing, hardening effect shall be caused in round corner and it can thus affect the following forming ability in the next pass. Nevertheless, the larger total ultimate forming limit and excellent forming quality can be achieved, compared to one-step forming[10,11].

Experimental study shows that grain size is a key influencing factor aimed at sheet forming ability[12,13]. Based on multi-directional rolling followed by annealing treatment, Jia *et al* developed a fine-grained (about 3.1 μm) Mg-2.0Al-0.8Sn-0.5Ca (wt%) alloy that owned a satisfactory compatibility of formability and strength[14]. The large cupping value was ascribed to the unique ring-characterized weak texture developed stretch forming and the high strength was related to the fine grain structure and nano-sized particles. Through stamping and electro-magnetic forming test, Lee *et al* found the finer grains enhanced aluminum alloy strength and yet decreased the formability due to increase in probability of grain boundary fracture[15]. From above, it is known that pre-strain and grain size each has an important influence on mechanical property and forming ability. However, the comprehensive effect of grain size and pre-strain on HSLA steel sheet forming property is less researched.

The aim of this study is to investigate the effect of pre-strain on microstructure evolution and mechanical behavior of HSLA steel with various grain size. Additionally, the stamping performance of HSLA steel specimens with different pre-strain is also explored through bending and bulging tests. This work may provide meaningful insight into optimization in HSLA steel sheet mechanical property and understanding of multi-step sheet metal forming.

2 Experimental

2.1 Material and pre-treatment

The 1.5 mm-thick as-rolled HSLA steel sheet was used in this study. The mass percentages of C, Si, Mn and Ti are 0.0658%, 0.014%, 0.418% and 0.036 2%, respectively. Then, this steel sheet was annealed at different temperature in order to obtain specimens with various grain size. The holding temperature ranging of 750-840 ℃ is selected and the soaking time was set as 2 min. Afterwards, all the specimens were slowly cooled down to 700 ℃ in the furnace, and then taken out for air cooling. The as-annealed specimens were wire cut along rolling direction to obtain two type of tensile specimens, namely the standard-gauge and the wide-gauge specimens, as shown in Fig.1. Using a Z150 Zwick-Roell machine with extensometer gauge of 50 mm, both the standard-gauge and wide-gauge specimens were respectively stretched to 1.5, 3, 4.5 and 6 mm, corresponding to the pre-strain of 0.03, 0.06, 0.09 and 0.12, respectively.

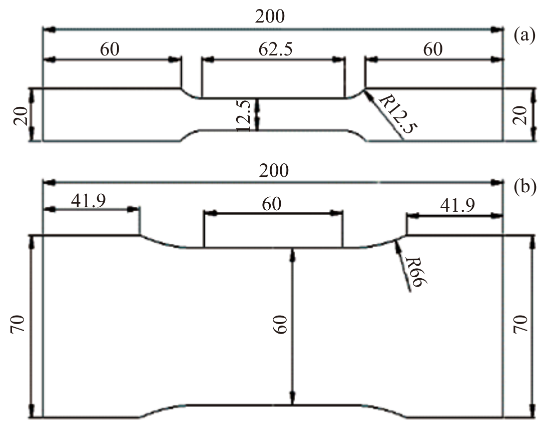

Fig.1 Geometric illustration of specimens used in tensile tests: (a) with standard gauge; (b) with wide gauge (in mm)

2.2 Mechanical property test

In order to reveal the effect of pre-strain on mechanical behavior, room temperature tensile tests were carried out on the standard-gauge specimens with pre-strain of 0-0.12. The same testing machine and extensometer gauge were used as above with strain rate of 0.006 7 s^{-1}.

2.3 Microstructure characterization

Specimens for microstructure examination were cut off the annealed and the pre-strained specimens along longitudinal direction. Optical observation was performed on an Olympus microscope for analysis on grain deformation. The OM samples were polished with abrasive paper and etched with 4% nital. TEM observation were conducted on the 810 ℃-annealed specimens using a Tecnai G2 F30 S-TWIN field-emission-gun microscope (FEG-TEM), in order to study sub-microstructure evolution. TEM samples were prepared by mechanical polishing and twin-jet electropolishing technique. Electron back-scatter diffraction(EBSD) analysis on texture, as well as analysis on surface morphology, was carried out using a JSM-7001F SEM.

2.4 Stamping test

V-bending tests were performed on the as-annealed and pre-strained specimens with standard-gauge through a bending machine. Each sample was first bent by a mould with opening angle of 30.8° and fillet radius of 0.5 mm, and then flattened by a flatting die. Since the original specimen thickness was quite close to the pre-strained ones, the same punch stroke was chosen to ensure full contact between dies and specimens, namely to ensure final bending angle of specimen outer layer equal to die opening angle. The outer surface morphology was observed by VEGA-3-SBH SEM.

Erichson tests were conducted on the wide-gauge specimens with different pre-strain using a Bup 600 Zwick-Roell machine. The punch diameter was 20 mm and blank holder force was 98 kN.

3 Results and discussion

3.1 Analysis on microstructure

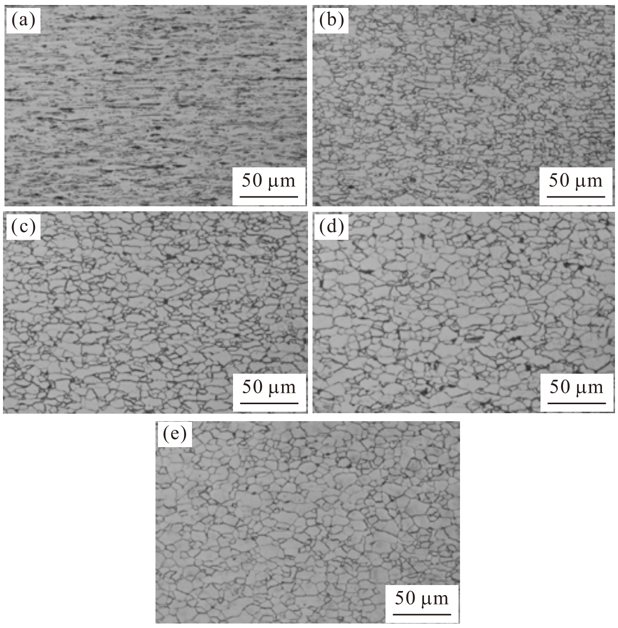

Fig.2 Microstructure of (a) the as-rolled specimen and the specimens annealed at (b) 750 ℃, (c) 780 ℃, (d) 810 ℃, and (e) 840 ℃

Microstructures of the as-received and the annealed specimens are shown in Fig.2. It is found the original grains are severely damaged after cold rolling and changed into fiber-like (in Fig.2(a)) or equiaxed structures (in Figs.2(b)-2(e)), depending on annealing temperature. Recrystallization at annealing temperature of 750 ℃ is incomplete since a few narrow grains still exist, as seen in Fig.2(b)). Based on Fig.2, average grain size of these specimens annealed at 750, 780, 810 and 840 ℃ is calculated as 5.5, 6.2, 7.9 and 7.6 μm, respectively. With annealing temperature increasing, grain size increases to peak at 810 ℃ and then decreases gradually. The reason for slight decrease in average grain size at 840 ℃ is due to that ferrite grain boundary is pinned in growing period by precipitates like $(NbTi)_x(CN)_{1-x}$ developed in hot rolling stage[16,17].

Fig.3 shows microstructure of the annealed specimens after tensile testing without pre-strain. Grains of all the specimens are stretched to narrow shape, but grain boundary still remains undamaged regardless of grain size, compared to the as-rolled specimen in Fig.2(a). The reason lies that cold rolling yields a large reduction ratio up to 70% under the compressive stress, which thus causes much larger deformation than tensile deformation less than 35% under the tension stress. Due to the incomplete recrystallization at 750 ℃, a few carbides also distribute in chain along tensile direction, as seen in Fig.3(a). Microstructures of the pre-stretched specimens with grain size of 6.2 μm are shown in Fig.4. Grains of all the pre-strained specimens are stretched to different extent and elongation ratio is nearly linear with pre-strain value. It also implies the equiaxed grains take part in deformation when it enters into plastic stage even at small strain of 0.03. Moreover, grain orientation is more and more towards to elongation direction with increasing pre-strain.

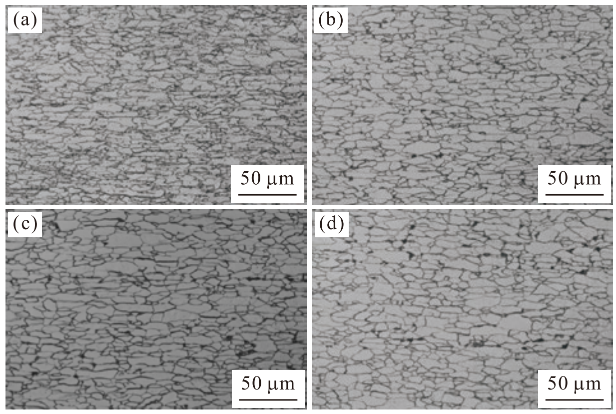

Fig.3 Microstructure of the tensile tested specimens with grain size of (a) 5.5 μm, (b) 6.2 μm, (c) 7.6 μm and (d) 7.9 μm

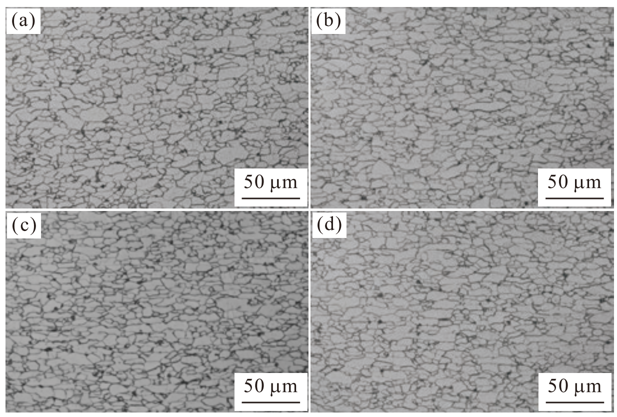

Fig.4 Microstructure of specimens of 6.2 μm grain size after pre-straining with (a) 0.03, (b) 0.06, (c) 0.09 and (d) 0.12

3.2 TEM microstructure of specimens with different pre-strain

TEM images of the pre-strained specimens of grain size 7.9 μm are shown in Fig.5. There are a few of dislocations within *α* grains for the annealed specimen. This is due to that annealing at 810 ℃ is not fully completed in short stage of 2 min. As for specimen with 0.03 pre-strain, a few dislocations start to move under shear stress and high density of dislocations are formed, as shown in Fig.5(b). With pre-strain increasing, more and more dislocations are initiated to slid. Therefore, dislocation tangling is caused at pre-strain of 0.06 and sub-grains are even generated at pre-strain of 0.09, as shown in Figs.5(c)-5(d). It is known pre-straining is essentially plastic deformation. Thus, microstructure evolution is highly dependent on pre-strain value.

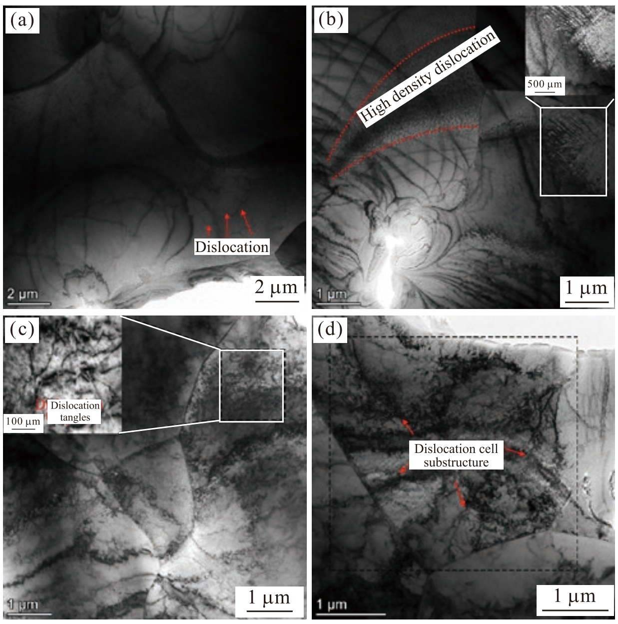

Fig.5 TEM microstructure of the specimens with 7.9 μm grain size without pre-strain and after pre-straining with (b) 0.03, (c) 0.06 and (d) 0.09

3.3 Mechanical behavior

Fig.6 describes engineering stress-strain curves of the pre-strained specimens with grain size of 5.5 and 7.9 μm, respectively. It clearly shows that yielding platform is eliminated when pre-strain is larger than 0.06, regardless of grain size. This finding differs from other research works[18,19], in which yielding platform can be eliminated by applying 0.05 pre-strain for HC340 steel and 0.01 pre-strain for TRIP steel. It shows threshold pre-strain varies with different material or with different preparation process even using the same material. As pre-strain is larger than 0.06, high density of dislocation can not only restrain Luders band to eliminate yielding platform but result in remarkable increase in YS, as seen in Fig.6. As pre-strain is less than 0.06, yielding plateau exists because pinning effect of Cottrell atmosphere is dominating[1]. Nevertheless, the platform period is still proportional to pre-strain value. Within such pre-strain range, the smaller the pre-strain is, the easier the Luders band occurs, which means that the original specimen yields the longest yielding platform, as shown in Fig.6. Similar phenomenon is also found for the specimens with grain size of 6.2 and 7.6 μm.

Variation of YS, UTS and ER with pre-strain is shown in Fig.7. As pre-strain is smaller than 0.06, variation trend of YS is inconsistent for the large-grained specimens. This can be ascribed to that YS collection is inaccurate because of long yielding platform in such pre-strain range, as shown in Fig.6. Beyond this range, YS value, replaced by $\sigma_{0.2}$, increases gradually with pre-strain. Fluctuation of UTS with pre-strain is slight since pre-strain has a limited impact on UTS. Thus, the larger yield ratio is obtained with larger pre-strain. Besides, the highly pre-strained samples endure small elongation before fracture, as shown in Fig.7(c).

Grain size also causes a remarkable effect on mechanical performance. With grain size increasing, both YS and UTS decrease while ER increases, as pre-strain value keeps constant. It shows good agreement with

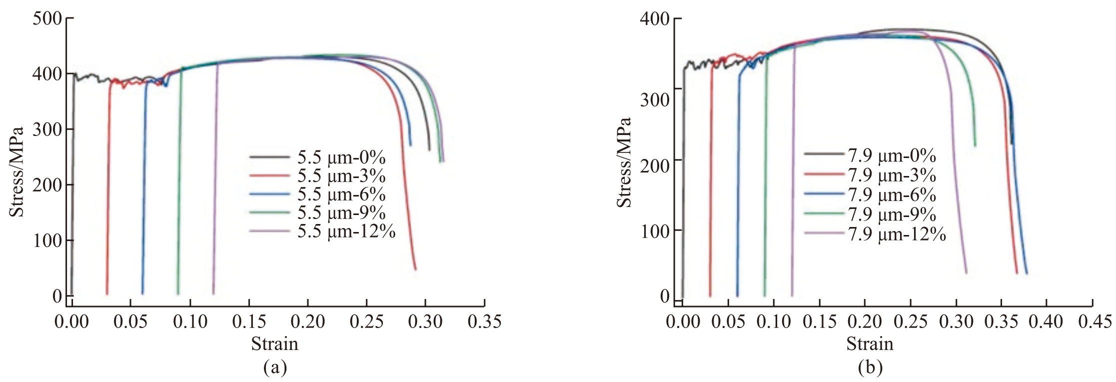

Fig.6 Stress-strain curves of the pre-strained specimens with grain size of (a) 5.5 μm and (b) 7.9 μm

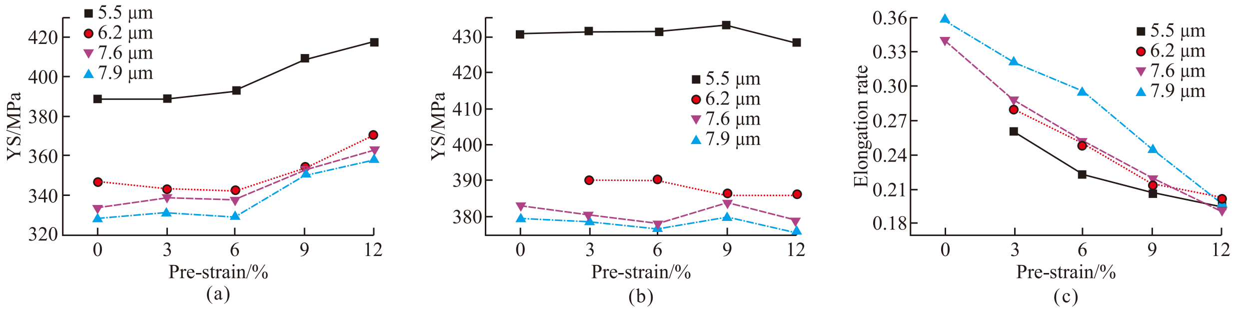

Fig.7 Curves of (a) YS, (b) UTS, and (c) ER *versus* pre-strain for specimens with different grain size

many research works[20,21]. Grain size of 5.5 μm yields much higher YS and UTS than others. This can be ascribed to two reasons. One is that it confirms to the Hall-Petch relationship. The other is that recrystallization is incomplete and work hardening is not fully eliminated after annealing at 750℃, as shown in Fig.2(b)).

3.4 Influence of pre-strain on stamping ability

3.4.1 Bending ability

The bent specimens, as well as SEM graphs of typical specimen outer surfaces, are shown in Fig.8. No microcrack is observed in these outer surfaces. This implies that v-bending can be successfully accomplished, regardless of pre-strain value and grain size.

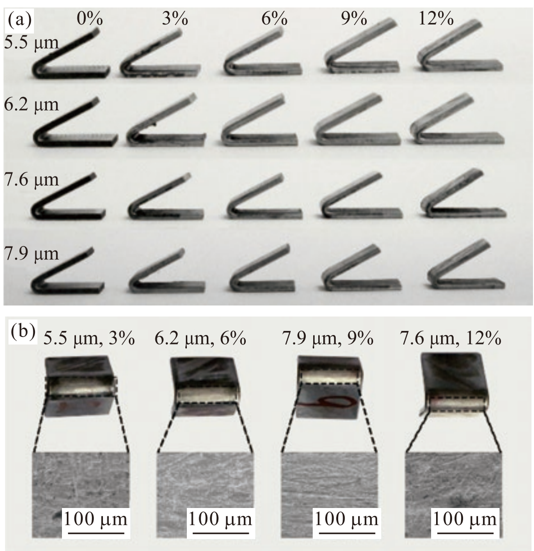

Fig.8 The bent specimens: (a) with different pre-strain and grain size; (b) SEM graphs of outer surface of typical specimens

Fig.9 shows the flattened specimens, as well as outer surface SEM graphs of the same specimens, as mentioned above. Similarly, no apparent microcrack is yet seen in outer surface. It proves HSLA steel flattening ability is excellent even when large strain of 0.12 is applied previously, regardless of grain size. Fillet radius of 0.5 mm and bending angle 30.8° is considered to result in quite large tensile strain in outer layer, under which circumstance crack could be caused in this layer. However, partial transition zone participates in bending deformation with such small fillet radius[22,23]. Correspondingly, unstable deformation in outermost layer can be relieved by its adjacent layer due to large tensile strain gradient caused by thin specimen. Therefore, bending can be successfully accomplished by using such radius/thickness ratio.

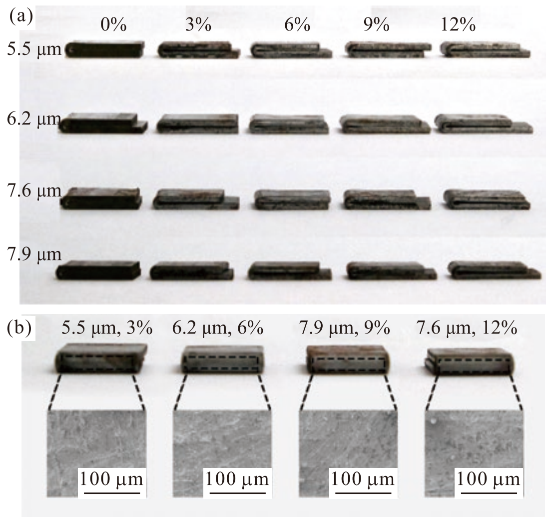

Fig.9 The flattened specimens: (a) with different pre-strain and grain size; (b) SEM graphs of outer surface of typical specimens

In flattening stage, deformation mainly happens in bending area which is also the main deformation zone in bending stage. Thus, it is believed that the former 30.8° v-bending causes a second strain hardening on the main deformation zone in flattening stage. The good bending and flattening ability proves that former pre-deformation causes very limited effect on the follow-up forming ability. As for further experiment, much larger pre-strain can be applied to investigate its effect on bending performance and determine the limiting pre-strain with which crack could occur in outer layer of HSLA sheet. Furthermore, emphasis can be put into springback upon unloading since work hardening and such small fillet radius would cause complicated effect on springback behavior.

3.4.2 Cupping ability

Variation of cupping value, IE, with pre-strain is shown in Fig.10. It is clearly found that IE decreases gradually with pre-strain increasing. One reason is that formability is weakened by high dislocation density, as discussed in Section 3.2. The other is that texture is another important influencing factor. It is known the as-annealed specimens contain many {111} textures that are beneficial to improve sheet forming ability[24]. For original sample of grain size 7.9 μm, the maximum pole density, f_g (max), of {111} texture is found to reaches the peak, according to the previous work[25]. Thus, the original specimens yield the largest IE, regardless of grain size. After specimens are stretched with different pre-strain, proportion of the {111} and other grain-oriented textures is switched. With pre-strain increasing, f_g (max) of the dominant {111} texture decreases. Rotation cubic texture {001} <110> harmful to stretching ability is developed. As a result, it weakens stretching ability of the pre-strained specimens. Besides, more and more sub-grains are generated when specimens are stretched by increasing pre-strain[25], compared to the as-annealed one, as shown in Fig.11. Obviously, the newly formed sub-grains are also responsible for reduction in IE value.

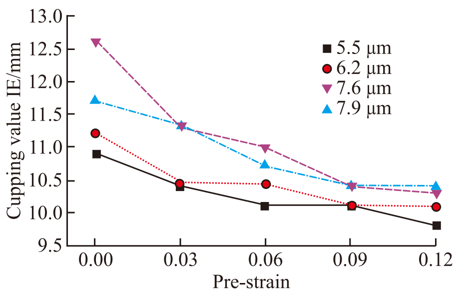

Fig.10 Curve of IE *versus* pre-strain of specimens with various grain size

The influence rule of grain size on cupping ability is not noticeable. The specimen with grain size of 7.6 μm is seen to achieve the highest IE, as pre-strain keeps constant. It is due to that this specimen is obtained through annealing at the highest temperature of 840 ℃ and thus it has much more {111} textures than those annealed at lower temperature[26]. Except for this grain size, specimens with larger grains yield higher cupping value, for each pre-strain value. It is mainly due to that larger deformation can be achieved by coarse-grain because of small strength ratio.

The effect of pre-strain on bulging performance is much larger than that on bending ability. It is mainly because the pre-strained specimens can possess good extension capacity, as shown in Fig.6. Besides, the small fillet radius and large width/thickness can promote bending and flattening ability. Unlike bending formation, the bulging ability is weakened due to decrease in {111} texture and increase in sub-grains.

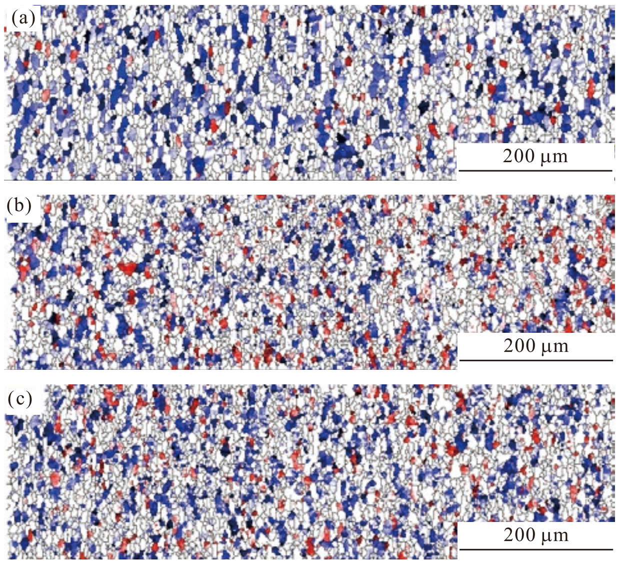

Fig.11 {111} texture (in blue color) and {001}<110> texture (in red color) of samples of 7.9 μm grain size with pre-strain of (a) 0, (b) 0.09 and (c) 0.12

From the discussion above, it is known that pre-strain and grain size each has influence on mechanical property and cupping ability of HSLA steel. Nevertheless, reciprocal impact of the two factors on mechanical property and forming ability is inconspicuous. The cross-effect may be profound if the larger pre-strain is applied. By this way, sheet thickness can be highly reduced and it can become an important influencing factor on forming ability.

4 Conclusions

With annealing temperature increasing from 750 to 840 ℃, grain size increases to peak 7.9 μm at 810 ℃ and then decreases gradually. The annealing temperature should be high than 750 ℃ in order to eliminate hardening effect.

Elongation degree of grains is in direct proportional to pre-strain value, regardless of grain size. Dislocation density increases gradually and {111}-based texture decreases with pre-strain. Dislocation tangling and sub-grain generation occur when using large pre-strain.

When pre-strain is larger than 0.06, yielding platform is eliminated and YS increases gradually, regardless of grain size. When pre-strain is less than 0.06, yielding plateau period reduces gradually with pre-strain increasing. With grain size increasing, both YS and UTS decrease and elongation rate increases as pre-strain keeps constant.

The 30.8° v-bending, as well as the follow-up flattening, can be successfully accomplished on all the specimens, regardless of pre-strain and grain size. The effect of pre-strain on bending and flattening ability is very limited even large pre-strain of 0.12 is applied. With pre-strain increasing, cupping value decreases. As pre-strain stays constant, cupping value increases with grain size, except for specimens obtained by annealing at temperature higher than 840 ℃. The effect of pre-strain on bulging performance is much larger than that on bending ability.

Pre-strain and grain size each has regular influence on mechanical performance and stamping ability. However, reciprocal impact of the two factors on mechanical property and stamping ability of HSLA steel is not remarkable.

Conflict of interest

All authors declare that there are no competing interests.

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