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INFLUENCES OF THERMOMECHANICAL PROCESSING ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF A HSLA STEEL

Yu Zhao, Songsong Xu, Yun Zou, Jinhui Li, Z.W. Zhang*

Key Laboratory of Superlight Materials and Surface Technology, Ministry of Education, College of Materials Science and Chemical Engineering, Harbin Engineering University, Harbin 150001, P R China

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Abstract

High strength low alloy (HSLA) steels with high strength, high toughness, good corrosion resistance and weldability, can be widely used in shipbuilding, automobile, construction, bridging industry, etc. The microstructure evolution and mechanical properties can be influenced by thermomechanical processing. In this study, themomechanical processing is optimized to control the matrix microstructure and nano-scale precipitates in the matrix simultaneously. It is found that the low-temperature toughness and ductility of the steels are significantly the matrix microstructure during enhancing the strength by introducing the nano-scale precipitates. The effects of alloying elements on the microstructure evolution and nano-scale precipitation are also discussed.

Introduction

High strength low alloy (HSLA) steel is developed on the basis of the research on ordinary carbon steel. Because of the high copper content in the steel, strength can be greatly improved by the precipitation of nano-phases. At the same time, the plastic property of the material can also be guaranteed. Meanwhile, the price of the steel is reasonable. So these kinds of steels can be widely used in the automobile industry, shipbuilding industry, marine engineering and so on [1-2]. Recently, HSLA steels with excellent properties has been required greatly, especially in the aspects of welding performance and low temperature toughness. HSLA steel with copper precipitation strengthening has received a wide range of attention, due to promising applications.

In 1930s, researchers have found that the strength of steel could be improved by adding copper [3]. When heat treatment temperature was set in the range of 450℃-600℃, it could lead to the precipitation of Cu element, and the yield strength could be increased by 100-200MPa. In 1980s, the HSLA-80 steel first appeared [4], and then was updated to HSLA-100 and HSLA-115 later. The yield strength of HSLA-80 steel is the same as that of HY-80 steel, about 550 MPa [5, 6]. It is shows that when the size of the nano-phase is 2.5-3.0nm, the precipitation hardening peak could be obtained [7, 8]. In general, when the nano particles grow to a larger size is larger size (>10nm), the crystal structure of the particles transforms form the body-centered cubic (BBC) structure to the face centered cubic (FCC) structure [8-10]. Some scholars also found that by optimizing the content of alloy elements and themomechanical processing, a proper copper rich precipitates and matrix microstructure can be obtained [11], leading to excellent mechanical properties [12,13].

During the preparation of HSLA steel, controlling both the matrix microstructure and copper rich precipitates becomes the main concerns of the process. The aim of this study is to elucidate the effect of aging temperature and time on the mechanical properties and microstructure of the HSLA steel.

Experimental

To ensure the accuracy of the experiment, and avoid the contamination of the impurity of the material, high purity alloying elements were used(Fe, 99.9%; Mn, 99.9%; Ni, 99.9%; Cu, 99.99%; Al, 99.99%; Ti, 99.995%; B-Fe(boron content, 17%;). The alloy composition is shown in Table 1

Table 1 Chemical compositions of steel (wt.%)

Fe	Cu	Mn	Ni	Al	B	Ti
bal	2.o%	1.0%	4.0%	1.0%	0.01%	0.30%

The cast ingots were obtained using high vacuum arc melting under the protection of high purity argon (>99.95%).The ingots were remelted several times with the magnetic stirring to ensure homogeneous distribution of alloying elements (180mm×20mm i.d.). The as-cast specimens with a diameter of 20 mm and 180 mm long were heated at 1000 ℃ in air for 1h, and then hot rolled to a total thickness reduction of ~80%, followed by water quenching. The hot rolled samples were then cold to a thickness reduction of ~50% after removing the surface oxides. The final size of as-rolled samples are 2mm. The as-rolled samples were solid solution treated at 900℃ for 30min, then quenched in water. Then the materials were aged at 500℃, 550℃ and 600 ℃ for 1h, 2h, 5h and 10h, respectively. The average Vickers hardness measurement was conducted applying 1000g load, and the samples were test over 10 locations. The sheet tensile samples were processed by electro-discharge machining (EDM) with a gauge size of 20.26mm×2mm×5mm. The tensile tests were conducted on INSTRON 5565 at room temperature with a strain rate of ~1×10^{-3}/s. The phase components of the specimens were determined by X-ray diffraction (XRD) with the following experimental parameters: a Cu Target K alpha ray, tube pressure is 40kV tube pressure, 20°-90°scanning angle, and 5°/min of scanning speed.

Optical microscopy (OM) and scanning electron microscope (SEM) were also used to characterize the microstructure of the specimens. The fracture surfaces of tensile samples were examined by SEM to evaluate the type of fracture.

Results and Discussion

Microstructure observation

The microstructures of the as-rolled and solid-solution-treated samples are show in Fig.1 After rolling, fibrous tissue is formed with fiber direction paralleling to the rolling direction (Fig.1a). After heat treatment at 900℃for 1h, the deformed fibrous structure transforms into irregular polygon ferrite due to recrystallization (Fig.2b).

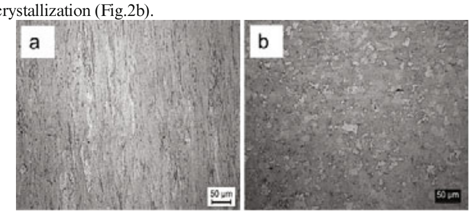

Fig.1 Microstructures of the samples, (a) as-rolled, (b) after solid solution treatment

Figure 2 shows the microstructures of the samples aged at 500℃ for 1h, 2h, 5h and 10h, respectively. It can be seen that the samples are mainly composed of polygonal ferrite with a average grain size.

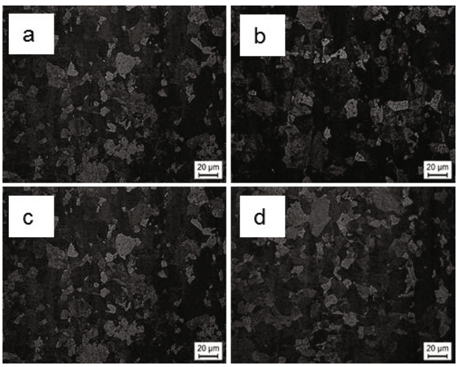

Fig.2 Micrstructures of the samples after aging at 500℃ for (a) 1h, (b) 2h, (c)5h and (d)10h

Figure 3 and 4 shows the microstructures of the samples aged at 550℃ and 600℃ for 1h, 2h, 5h and 10h, respectively. After aging at 550℃ and 600℃, the microstructures are similar to that after aging at 500℃, while the grain size grows slightly to ~20 μm and ~30 μm for 550℃ and 600℃, respectively. It can be concluded from Fig.2-4 that aging at different temperatures do not change the microstructures significantly.

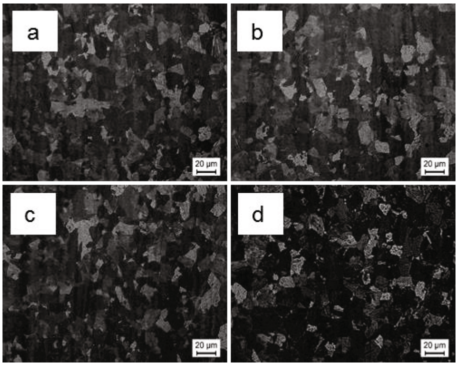

Fig.3 Micrstructures of the samples after aging at 550℃ for (a) 1h, (b) 2h, (c)5h and (d)10h

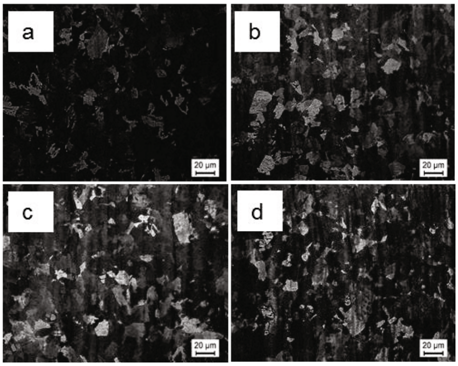

Fig.4 Micrstructures of the samples after aging at 600℃ for (a) 1h, (b) 2h, (c)5h and (d)10h

Phase analysis

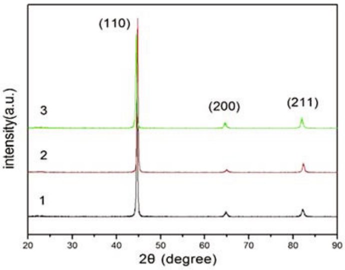

Fig.5 X ray diffraction spectra for different states of HSLA steel
(1-as-rolled; 2-solid solution treated; 3 after aging)

Figure 5 shows the diffraction spectra of HSLA steel after various treatments. It can be seen that the samples displays similar diffraction spectra, where only three peaks representing ferrite are found, revealing that no phase change has happened during various processing.

Mechanical properties

The microhardness of samples after various treatments are shown in Fig.6. After solid-solution-treated, the microhardness of the samples is ~267 HV. Upon aging, the microhardness increases significantly. With the three aging temperatures, three aging stage can be observed, i.e. under aging, peak aging and over aging. After aging at 500℃, the samples have the highest microhardness and the aging peak appears at 5 h. Increasing the aging temperature, the microhardness drops and the aging peak moves towards to short aging time. These phenomena are similar to the traditional aging processes in aged-strengthened alloys. The changes in microhardness can be attribute to the formation of precipitates in the steels. After solid-solution treating, there is few precipitates in the matrix, leading to a low microhardness. Upon aging, the nucleation and growth of the precipitates leads to the significant increase in hardness.

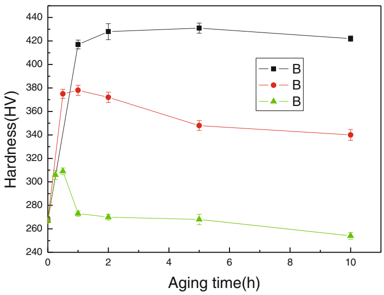

Fig.6 The microhardness of samples (the time 0h is solid solution sate） aged at different temperature(500℃, 550℃, 600℃) for 1h, 2h, 5h and 10h

When aging temperature was set at 550℃ and 600℃, the aging peak appeared at 1 h and 0.5h, respectively (Fig.6). With the increase of aging temperature, the aging peak of HSLA steel moves towards shorter aging time, and the hardness of samples decreases as well. This is because aging temperature directly affects the diffusion coefficient of copper in the matrix, following the diffusion formula:

$$D = D_0 \exp(-\frac{Q}{RT}) \quad (1)$$

Where R is the gas constant, T is temperature, D is the diffusion coefficient, Q indicates the diffusion activation energy. When the copper element diffuses in the crystal, they need additional energy to overcome the barriers to transfer and to strengthen the material [16]. It can be seen from Eq. (1) that the diffusion coefficient D and temperature T is exponential interrelated. When increasing the aging temperature, the copper atoms will diffuse quickly and so does the precipitation rate. Then the aging peak anticipated.

The tensile properties under various aging temperature and time are show in Fig.7. Fig7-a describes the tensile properties of samples aged at 500℃ for 1h, 5h, 10h and solid solution. From Figure 7-a, it can be seen that the highest tensile properties of 1206MPa can be obtained after aging for 5 h. Zhang Z W [17] has reported that aging process leads to the formation of nano-scale Cu-rich precipitates, which can enhance the strength significantly by pinning the dislocation during deformation.

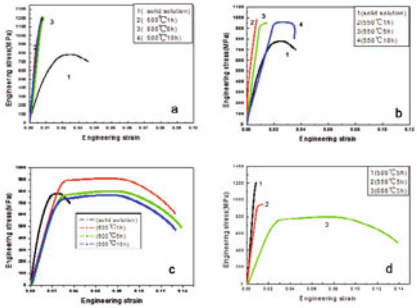

Fig.7 Tensile properties of steel at various aging temperature and time

From figure 7-b, it can be concluded that the strength of sample reaches the peak at 550℃for 1h (983MPa). And as aging time prolonged, the strength of the steels decreased with an increase in elongation. Figure 7-c shows the tensile stress-strain curves of samples after aging at 600℃. It shows that the plastic properties of the samples after different aging time were all significantly improved. The extension rate increases to 14% after aging for 5 h. When aging for 10 h, both the elongation and strength decreased. This is because the higher temperature and longer time lead to the rapid growth of nano-sized precipitates [18]. Taking overall mechanical a property into account, the better steel is the one aged for 1h, whose strength is 900MPa and percentage elongation is 13%.

Fig.7-d shows the effect of aging temperature on the tensile properties. As the aging temperature increases, the strength of the material decreases, and the plasticity of the material gradually increases. This is because the growth rate of the precipitates accelerated and its ability to block the dislocation movement is reduced, resulting in a decrease of the hardness and strength. The deformation mode of the material transferred from brittle deformation to plastic deformation.

Fracture analysis

Figure 8 shows the fracture surface of the sample after solid-solution treatment. It can be seen that the fracture morphology of the HSLA steel at solid solution state is a dimple pattern. As we know, the mainly micro-morphology of the ductile fracture metal is the existence of the dimples which are formed by the aggregation of the holes. When the external load is applied, these cavities went through nucleating, growing up and then gather to the fracture. It is clear that the fracture mode of the solid solution is microvoid coalescence fracture, which belongs to plastic fracture.

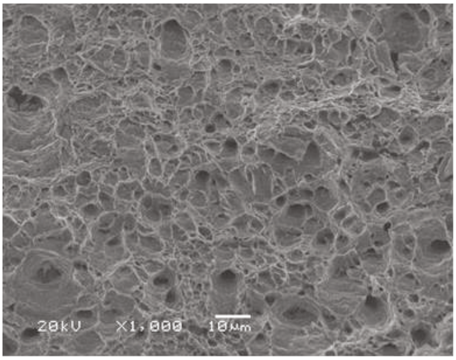

Fig.8 The fractograph of steel after solid solution treatment

Figure. 9 shows the fracture surface of samples aged at 500 ℃ with various aging time. It can be seen from Fig.9 that all the samples show a brittle intergranular fracture along with a few of cleavage fracture.

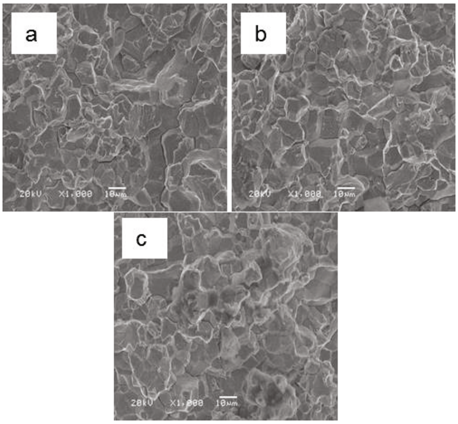

Fig.9 Tensile fracture morphologies of the samples aged at 500 ℃ for 1h (a), 2h (b) and 5h (c)

As shown in Fig.10, the fracture surface of the steel is still typical intergranular fracture after aging at 550℃ for 1h and 5h (fig. 10a and b). When aging for 10h, the fractograph exhibits a small part of cleavage step and a few dimples, contributing some plasticity.

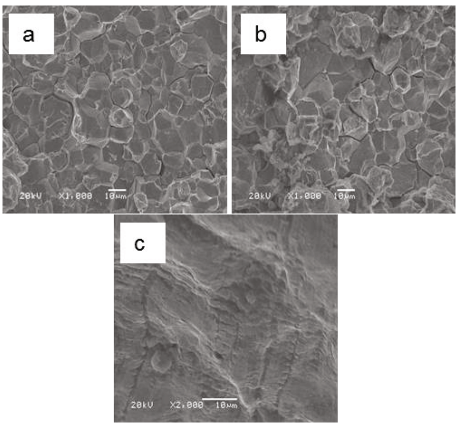

Fig.10 Tensile fracture morphologies of the sample aged at 550 ℃ for 1h (a), 2h (b) and 5h (c)

When aging process is set at 600℃(Fig. 11 a-c), the tensile fracture mode of the material is typical microvoid coalescence fracture with different size of dimples. Therefore, the elongation of the material is improved greatly.

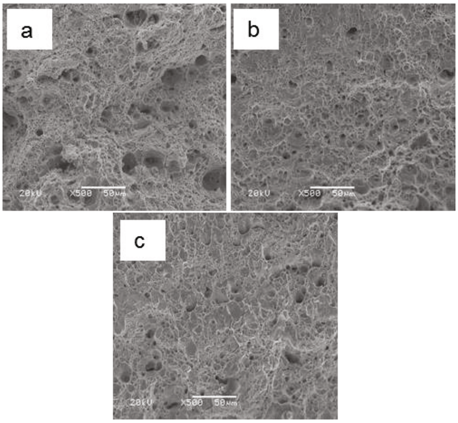

Fig. 11 Tensile fracture morphology of the sample aged at 600 ℃ for 1h (a), 2h (b) and 5h (c)

Conclusions

1 After rolling treatment, the microstructure is elongated and aligned along the rolling direction. After the process of solution treatment at 900℃ for 1h, the microstructure is polygonal ferrite. Aging treatment has no significant effect on the microstructure.
2 Aging treatment can improve the hardness of the metal significantly. With increasing the time of aging, the aging peak appears earlier, and the hardness decreases.
3. At the same temperature, the change in the strength under various aging time is consistent to the change in hardness. At 500℃ for 5 h, the maximum strength was obtained (1206MPa). At 550℃ and 600℃, the maximum strength appeared at 1h, which were 983MPa and 900MPa, respectively. With the increase of aging time, the elongation rate also increased. When aging time is the same, the tensile strength decreased and the elongation increased with the increase of aging temperature.
4. When aging temperature is 500℃, increasing aging time does not change the fracture mode. All of them are intergranular fracture. When aging at 550℃ for 1h and 2h, the fracture mode of the material is also intergranular fracture. 10 h of aging at 550℃ leads to the cleavage fracture. When the aging time goes up to 600 ℃, the fracture mode of the material transfers to ductile mode, i.e. microporous gathered fracture mode.

Acknowledgements

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