Microstructure and Mechanical Properties Evolution of 0.2C-1.8Si-2Mn Low-Alloy Steel Under Different Quenching and Partitioning Treatment

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ABSTRACT

The effect of quenching and partitioning heat treatment at different annealing temperature and partitioning time on microstructure and mechanical properties of low alloy Si-Mn steel was studied. The results show that the comprehensive mechanical properties of the material are improved greatly after Q&P treatment. The analysis shows that the stability of the carbon-rich residual austenite plays a major role in improving the mechanical properties of the materials. With the increase of annealing temperature and partitioning time, the content of RA firstly increases first and then decreases, but the effect of distribution time is more significant. With the increase of austenitizing temperature, the tensile strength increases and the elongation decreases. With the extension of the partitioning time from 120s to 480s, the tensile strength and elongation both increases first and then decreases. When the austenitizing temperature is 950°C and the partitioning time is 300s, the comprehensive mechanical properties are the best (tensile strength: 1167MPa, elongation: 18.8%, the product of strength and plasticity: 22GPa%). The analysis shows that the carbon-rich residual austenite retained to room temperature plays a major role in improving the plasticity of the material after Q&P treatment.

Keywords: Quenching and Partitioning, Microstructure evolution, Retained austenite, Mechanical property

1. INTRODUCTION

With the continuous improvement of the performance requirements of automobile steel plate, advanced high strength steels (AHSSs) have gradually developed from the first generation of AHSSs represented by dual-phase steels, the second generation of AHSSs represented by twin-induced plastic steels, to the third generation of AHSSs represented by quenching and partitioning steels1,2. This evolution shows that the design of AHSSs pays more and more attention to the interaction of multiple phases and the ability of coordinated deformation. Therefore, the study on the relationship between microstructure and mechanical properties is increasingly important. Some studies have shown that the deformation coordination between soft phase and hard phase matrix can significantly improve the comprehensive mechanical properties of the material3. In 2003, Speer et al. first proposed the concept of quenching and partitioning (Q&P) on the basis of traditional martensitic and TRIP steels for the development of the third generation of austenitic stainless steels as a new method to produce martensitic steels with high austenitic content4. The core idea is to obtain a certain amount of martensite and austenite duplex structure by quenching the steel to the martensite transformation zone, and to achieve the redistribution of carbon from martensite to austenite in the subsequent holding stage, so that the residual austenite can be stable to room temperature, and finally achieve the combination of high strength and excellent plasticity5,6. The high strength of Q&P steel comes from the hard phase martensite in the structure, and its good ductility is due to TRIP effect of retained austenite.

TRIP effect is closely related to the content and stability of residual austenite. During Q&P treatment, effective inhibition of carbide precipitation is the key to control the process, because any carbide precipitation will consume the limited carbon in the steel, thus reducing the carbon that can be diffused into the austenite and ultimately affecting the amount of residual austenite7,8. Therefore, it is of great significance to explore the effects of different heat treatment processes on the content and stability of residual austenite. Austenitizing temperature determines the grain size in the room temperature structure, while carbon partitioning time and temperature are related to the quantity and stability of residual austenite in the final structure, which has an important influence on the structure and properties of Q&P steel9,10. Therefore, the main purpose of this paper is to explore
the influence of different austenitizing temperatures and carbon partitioning time on the final microstructure and mechanical properties, in order to provide theoretical and practical experience for the further development of AHSSs.

2. EXPERIMENTAL PROCEDURE

The chemical composition of the studied Q&P steel is Fe-0.2C-1.8Si-2Mn (wt.%). Firstly, the phase transition temperatures of the experimental steel samples was measured by thermal expansion method, and the measured results were as follows: Ac1=754°C, Ac3=870°C, Ms=388°C and Mf=250°C. The thermal simulation experiment was carried out on Gleeble-3800 thermal simulation experiment machine. Figure 1 shows the heat treatment process of this experiment. A critical zone and two austenitic single-phase zones were selected for annealing at three different temperatures. The specific process is as follows: the steel was first heated to 850°C, 950°C and 1050°C respectively at a rate of 30°C/s and held for 3min. Then quenched to 300°C at a rate of 30°C/s and kept for 30s, then heated to 450°C at a rate of 50°C/s and kept for 180s, and finally cooled to room temperature at a rate of 10 °C/s to obtain AT850, AT950 and AT1050 samples. In order to further explore the effect of holding time on the final microstructure under the same conditions, the distribution time of austenitizing samples at 950°C was further extended to 300s and 480s, respectively, and Pt300 and Pt480 samples were obtained.

Leica DM4000M metallographic microscope was used to observe the microstructure of the test steel, and the metallographic samples were prepared by conventional means. The specific process is as follows: firstly, the samples were mechanically ground with sandpaper (400#~2000#) of different roughness successively, and then polished with diamond grinding paste of 1um. The polished samples were rinsed and blow-dried with distilled water and alcohol successively, and finally corroded. The corrosive agent is 4% nitric acid alcohol solution, and the corrosion time is about 3~5s. The samples preparation for field emission scanning electron microscopy (ZEISS RIGMA) were the same as the metallographic sample. The content of RA was determined by X-ray diffractometer (D/max 2550VB). The experimental parameters were: Cu-Kα, the scanning range was 40-95 °, the step size was 0.02°, and the scanning speed was 5°/min. In order to avoid the influence of texture and ensure the accuracy of calculation, the paralympic content is calculated by contrast method. Five diffraction peaks of (200)γ, (220)γ, (311)γ, (200)α and (211)α were paired to calculate the corresponding paralympic content, and the average value was taken as the final Paralympic content. The calculation formula is11,12:

$$f_\gamma = \frac{I_\gamma C_\alpha}{(I_\gamma C_\alpha + I_\alpha C_\gamma)}$$

In the formula, $f_\gamma$ is RA content, $I_\alpha$ is the integral intensity of the diffraction peak of martensite crystal surface, $C_\alpha$ is the correlation coefficient of martensite, $I_\gamma$ is the integral intensity of the diffraction peak of austenite crystal surface, and $C_\gamma$ is the correlation coefficient of Paralympic.
3. DISCUSSION

3.1 Microstructure Evolution

Figure 2 shows the initial microstructure of the sample before heat treatment, where (a) is the SEM structure and (b) is the OM structure. It can be seen from Figure 2 that the initial structure of the sample is bi-phase structure of pearlite and ferrite. Figure 3 and Figure 4 show the metallographic and SEM structures of the samples after different Q&P heat treatments respectively, and (a) ~ (e) are AT850, AT950, AT1050, Pt300 and Pt480 respectively. Compared with Figure 2, it is easy to observe that the microstructure of the sample after Q&P treatment has changed significantly, and the microstructure has changed from the initial pearlite + ferrite to the composite structure mainly composed of martensite, ferrite and residual austenite.

According to the comparison in Figure 3(a) ~ (c), it can be found that with the increasing of austenite temperature from the critical zone (850°C) to the austenite single-phase zone (950°C, 1050°C), the increase of original austenite grain size and the obvious coarsening of martensitic lath can be seen. It can also be observed that with the increase of annealing temperature, the martensite proportion increases and the ferrite proportion decreases obviously, among which the ferrite proportion in AT850 is higher. From the comparison of Figure (b), (d) and (e), it is not difficult to find that the microstructure does not change significantly with the extension of carbon partitioning time. Carbon partitioning is a process in which carbon diffused from supersaturated martensite to austenite in order to obtain a certain proportion of stable residual austenite at room temperature. Therefore, the microstructure of AT950, Pt300 and Pt480 has little difference because the annealing temperature has a more significant effect on the microstructure and the proportion of Paralympic in the microstructure is relatively small.
It can be clearly observed from the SEM structure in Figure 4 that different martensitic lath blocks present different distribution orientations, and ferrite is mainly distributed at the original austenite grain boundary in the form of polygons. In addition, it can be observed that in the same lath martensitic bundle group, the lath is basically parallel and the width of the lath is very uniform. It can also be observed from Figure 4 that with the increase of austenitizing temperature, the microstructure shows an obvious coarsening trend, and the martensitic lath bundle of AT1050 is the largest. (Figure 4-c). AT850 samples contain a large amount of ferrite and the proportion of soft phase is the highest. When austenitizing temperature is 950°C, the microstructure is finer, the width of martensite strip bundle is smaller and the arrangement is more compact.

In addition, it can also be seen from Figure 4 that carbide precipitation is found in the microstructure of most samples, and the precipitated carbide is linearly distributed in the massive martensite, and there is a certain Angle between the precipitated carbide and martensite lath. Among them, AT850, AT950 and AT1050 have relatively more carbide precipitates, Pt480 has relatively less carbide precipitates, and Pt300 has almost no carbide precipitates. Although there is a certain amount of non-carbide forming element Si in the steel composition in this study, the distribution stage can effectively inhibit the generation of carbide precipitates to a certain extent, but the improper holding time will lead to the decomposition of martensite and the formation of tempered martensite and carbide precipitates. The formation of the carbide precipitates can be explained as follows: After the initial quenching, there is a stress field near the defects such as dislocation and substructure of the carbon-rich martensite, which makes the energy of some gap positions around these defects lower than that of the normal lattice gap positions, so that C atoms are easy to redistribute in these positions with lower energy. As a result, a large number of C atoms converge and precipitate in the form of carbides between martensite lath during the subsequent partitioning process.

3.2. Stability of Retained Austenite

The X-ray diffraction spectrum and its calibration after heat treatment are shown in Figure 5. It can be easily observed from Figure 5 that the four diffraction peaks of austenite between 45° and 95° appear obviously, indicating that there is a certain proportion of residual austenite in the steel. When the sample is subjected to stress, the residual austenite transforms into martensite, which simultaneously improves the strength and plasticity of the steel, namely TRIP effect. According to formula 1, the volume fractions of RA after QP treatment of AT850, AT950, AT1050, Pt300 and Pt480 were 10.3%, 11.4%, 9.7%, 14.3% and 13.5%, respectively. With the increase of austenitizing temperature, the content of RA increases first and then decreases, but the overall content has little change. With the extension of partitioning time from 120s to 480s, the content of RA also showed a trend of first increasing and then decreasing, among which the RA content of Pt300 was the highest (14.3%). The RA content of Pt300 is relatively higher than that of Pt480, indicating that prolonged partitioning time cannot continuously...
increase the carbon content in RA, but changes within a range and there is a limit value. Once the extreme value is exceeded, carbon will be precipitated in the form of cementite, resulting in the stability of the corresponding RA decreased.

The above experimental results show that the RA content is higher under the annealing temperature of 950°C and the carbon distribution time of 300s and 480s, and RA in Pt300 has the best stability (with the least carbonated precipitates), which proves that the relatively higher annealing temperature and longer distribution time are favorable for carbon diffusion. However, too high annealing temperature will lead to too large size of original austenite, and too long partitioning time will lead to the tempering of martensite, which will precipitate carbides and ultimately reduce the stability of RA.

3.3. Mechanical Property

Figure 6 is a summary of the mechanical properties of the five groups of samples mentioned above. It can be seen from the figure that with the increase of austenitizing temperature, the tensile strength increases and the elongation decreases gradually. AT850 has the highest elongation but the lowest tensile strength, because annealing in the critical region results in a large amount of ferrite in the microstructure and a high proportion of soft phase. AT1050 has the highest strength but the worst plasticity, because the higher austenitizing temperature makes the grain size too coarse. With the extension of the partitioning time from 120s to 480s, the tensile strength and elongation both increases first and then decreases. Among all the samples, Pt300 has the best comprehensive mechanical properties, with tensile strength of 1164 MPa, elongation of 18.8% and the product of strength and plasticity of about 22GPa%.

Figure 5. X-ray diffraction pattern after Q&P treatment before the tensile test.

Figure 6. The mechanical properties after different Q&P treatment.

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Figure 7. The tensile fracture morphology: (a) AT850, (b) AT950, (c) AT1050, (d) Pt300 and (e) Pt480.

Figure 7(a) ~ (e) show the tensile fracture morphology of AT850, AT950, AT1050, Pt300 and Pt480, respectively. It can be observed that the tensile fracture of the samples is mainly composed of a large number of dense circular or elliptical equiaxial dimples, among which AT850 fracture has the largest and deepest dimple size, followed by Pt300 and Pt480. The number of dimples in AT950 and AT1050 fracture is significantly reduced, and the dimples are smaller in size and shallower in depth. At the bottom of the dimple, some small round particles can be observed, which may be impurity particles located in the crystal or at the phase interface, second phase particles and solid solution. When these particles are subjected to high stress and strain, they will continuously nucleate, grow and aggregate, and then evolve into crack sources. The morphology of the dimple can reflect the plastic deformation degree of the specimen under the action of external force to a certain extent. The larger and deeper the dimple is, the larger the plastic deformation can be produced under the action of external force, and to some extent, it also indicates that the dimple has better plasticity. By comparison, it can be found that the observed fracture morphology is corresponding to its elongation. AT850 has the highest elongation, which can produce greater plastic deformation when subjected to external forces, followed by Pt300 and Pt480.

CONCLUSIONS

The effect of quenching and allotment heat treatment at different annealing temperature and allotment time on microstructure and mechanical properties of low alloy Si-Mn steel has been studied. The results show that after Q&P treatment under different conditions, the microstructure of the sample changes from pearlite + ferrite to martensite, ferrite and RA composite microstructure, and the comprehensive mechanical properties of the material are greatly improved. With the increase of annealing temperature and partitioning time, the content of RA firstly increases first and then decreases, but the effect of distribution time is more significant. With the increase of austenitizing temperature, the tensile strength increases and the elongation decreases. With the extension of the partitioning time from 120s to 480s, the tensile strength and elongation both increases first and then decreases. When the austenitizing temperature is 950°C and the partitioning time is 300s, the comprehensive mechanical properties are the best (tensile strength: 1167MPa, elongation: 18.8%, the product of strength and plasticity: 22GPa%). The analysis shows that the carbon-rich residual austenite retained to room temperature plays a major role in improving the plasticity of the material after Q&P treatment.
REFERENCES