Research on the SH-CCT and PWHT of improved new type SA738 Gr.B nuclear power steel

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Abstract. The Gleeble-3180 machine is used to determine the simulated HAZ continuous cooling transformation (SH-CCT) curves of improved new type SA738 Gr.B nuclear power steel by expansion method, metallographic method and hardness method. The t₈/₅ time increase from 5 s to 6000 s and the influence of cooling rate on microstructure and phase transition are analyzed. The hardness changes before and after tempering treatment are compared with the samples so as to analyze the process and function of tempering. This research provides theoretical and data support for improving welding technology and promoting the development of nuclear steel.

1. Introduction

Since the first use of nuclear power in 1951, the world's nuclear power industry has been more than 70 years. The application and development of nuclear power technology have reduced human dependence on and consumption of fossil energy such as coal and oil, reduced emissions of carbon dioxide and other greenhouse gases, and greatly promoted the development of environmental protection.

With the rapid development of nuclear power, higher and higher requirements have been put forward for nuclear steel[1,2]. At present, the new generation of nuclear power technologies (such as AP1000, Hualong, EPR) all adopt the steel containment structure, which is made of multiple groups of steel plates assembled by welding. Take the AP1000 for example, the material used for containment vessels is SA738 Gr.B steel[3], which is a mature low carbon steel[4,5].

However, in order to minimize the number of welds in the containment vessel and ensure its safety, the containment vessel has gradually developed into the direction of large-scale and integrated type[6]. Besides, there is the fine-tuning of chemical composition. For this improved new steel, it is necessary to re-measure its microscopic properties, such as SH-CCT curve and the effect of PWHT.

2. Experiment material and method

2.1. Materials and sample preparation

The chemical composition of the new type SA738 Gr.B steel is shown in Table 1. Compare with the previous materials, the content of Cr, Mo, Ni and Cu are significantly fine-tuned[7]. These changes in composition allow the SA738 Gr.B steel to have higher strength in thicker and thinner conditions.

| Element | w(C) | w(Si) | w(Mn) | w(P) | w(S) | w(Cu) | w(Ni) | w(Cr) | w(Mo) | w(V) |
|---------|------|-------|-------|------|------|-------|-------|-------|-------|------|
| Standard | ≤0.20 | 0.13–0.16 | 0.90–1.60 | ≤0.03 | ≤0.03 | ≤0.35 | ≤0.63 | ≤0.34 | ≤0.33 | ≤0.08 |
The microstructure of the material is shown in Figure 1, with its obvious tempered martensite structure and a small amount of proeutectoid ferrite. Because the base metal is tempered, which eliminates the residual stress in the rolling process, its hardness is relatively low. The hardness measured by HV5 with vickers hardness is only 262.3 HV5.

![Microstructure of SA738 Gr.B base material](image)

(a) 100 X  
(b) 500 X  

Figure 1. Microstructure of SA738 Gr.B base material

The material will be machined to a size of Φ10 × 100 before the testing. The heating zone is placed in the center of the sample. After the thermal cycle, the sample is cut along the heating center and processed into two Φ10 × 10 small samples for the subsequent tests and experiment.

2.2. Determination of equilibrium phase transition temperature

Ac1 and Ac3 respectively represent the begins and end temperature of austenitization at equilibrium state. Therefore, during the measuring of Ac1 and Ac3, it is necessary to reduce the heating rate as much as possible so that the phase transition can be completed at each temperature.

![Measurement of Ac1 and Ac3](image)

In this experiment, we use the speed of 0.05 °C/s to slowly heat up the sample to 1000 °C, and the expansion curve obtained through the experiment is shown in Figure 2. Two inflection points in the heating process is Ac1 and Ac3, we get that Ac1 is 715 °C and Ac3 is 880 °C. The values of Ac1 and Ac3 are higher than other low carbon steel. This is because that the content of Ni and Cr in SA738 Gr.B is lower. These two elements can lead to the increase of austenitic stability, and then the Ac1 and Ac3 is significantly reduced. It is mean that the austenitic can exist stably at a lower temperature.
2.3. Determination of SH-CCT curves

SH-CCT curves is a simulation of the heat cycle in the welding process, so the peak temperature rises and drop both very quickly, and the hold time is very short. The test process is shown in Figure 3, the sample is heated with the rate of 200 ℃/s to 1300 ℃ and hold on for 1 s. Then, it cool down to 900 ℃ with 40 ℃/s and continue to room temperature at different cooling rates.

![Figure 3. Process of SH-CCT measurement](image)

The chose of $t_{8/5}$ time ranges from the shortest 5 s to the longest 6000 s. The inflection point temperature of the diameter expansion curve of each sample are measured by dilatometer and the microstructure is determined by metallographic observation. Besides, the hardness is test after thermal cycle with Vickers hardness. In the end, the result is shown in Table 2.

| No. | Cooling rate (℃/s) | $t_{8/5}$ (s) | Microstructure | Hardness (HV5) |
|-----|--------------------|---------------|--------------|----------------|
| 1   | 0.05               | 6000          | F+P+B       | 222.7          |
| 2   | 0.15               | 2000          | F+P+B       | 230.7          |
| 3   | 0.3                | 1000          | F+P+B       | 238.7          |
| 4   | 0.6                | 500           | F+P+B       | 240.3          |
| 5   | 1.2                | 250           | F+B         | 283.0          |
| 6   | 2.4                | 125           | F+B         | 321.0          |
| 7   | 4.7                | 64            | F+B         | 359.7          |
| 8   | 9.4                | 32            | F+B         | 374.0          |
| 9   | 18.8               | 16            | F+B         | 380.0          |
| 10  | 37.5               | 8             | F+B         | 394.3          |
| 11  | 60                 | 5             | F+B         | 395.0          |

2.4. Effect of PWHT

After the thermal cycle, the sample has a very high hardness. With the tempering treatment, the hardness can be reduced effectively. In this experiment, the temperature was raised to 300 ℃ at a higher rate of 300 ℃/h, and then raise to 580 ℃ at a rate of 120 ℃/h for hold on one hour. Finally, cool down with the furnace.

After tempering, the microhardness of the samples are tested again and compare with the untreated samples to analyze the effect of tempering treatment.

3. Result and analyze of experiment

3.1. Analyze of SH-CCT curve

The SH-CCT curve of SA738 Gr.B shown in Figure 4 is drawn by the data in Table 2. Each numbered curves represent different cooling rates. At the high temperature, the sample is completely...
austenitized. With the temperature decrease, the transformation from austenite to ferrite, pearlite or bainite occurs. The equilibrium phase transition temperature and hardness are noted on the curve.

![Figure 4. SH-CCT of SA738 Gr.B](image)

Both ferrite and bainite can both be formed in a wide range of cooling rate, but pearlite is only formed at low cooling rate. Therefore, the curve can be divided into two parts. One is in the case of a low cooling rate. At this condition, both ferrite, pearlite and bainite generate. With the increase of the cooling rate, there is only ferrite and bainite generate. Figure 5 show the the typical microstructure at different cooling rates with optical microscope.

At low cooling rate, ferrite and pearlite are dominated. Ferrite has the form of large block and it is still relatively uniform distribution, indicating that the homogeneity of the base material is also good. At this point, the soft lamellar pearlite leads to a lower hardness of the sample. The Vickers hardness is less than 250 HV5. With the increase of the cooling rate, the content of ferrite decreases and becomes finer and finer, the interval between lamellae of pearlite began to increase and there was a trend of transition to bainite structure.

![Figure 5. Microstructure of SA738 Gr.B at different cooling rate](image)

At the cooling rate higher than 1.20 °C/s, the pearlite has disappeared and obvious and typical bainite are present. The bainite produced is formed from the grain boundary and grows into the grain
boundary. In addition, the form of ferrite has become very small, and the content of ferrite has further decreased.

As the cooling rate continues to increase, the bainite has a tendency to transform into martensite, it gets thicker and thicker, the hardness of the sample also increases to more than 350 HV5. In particular, in the samples with a cooling rate of 60 °C/s, the needle-like structure has initially presented an angle of 60°, which conforms to the characteristics of lath martensite. However, considering that the structure is still small and not strong enough compared with martensite, and there is no obvious increase in hardness, it is not a complete martensite.

In addition, there is an obvious phenomenon of heterogeneous structure caused by the migration of carbon atoms. This is due to the fact that the cooling rate is too fast, leading to insufficient nucleation centers, which can only be nucleated in some areas and undergo phase transition. At this time, carbon atoms still have a certain migration capacity, resulting in this result.

3.2. Effect of tempering treatment

The tempering process plays a role in reducing the hardness of SA738 Gr.B steel in the HAZ. However, after tempering, the hardness still increases slowly with the increase of cooling rate. For samples whose cooling rate is less than 4.70 °C/s, tempering treatment has no obvious effect on reducing hardness. For high cooling rate, the hardness difference between before and after tempering can be up to 80 HV5.

![Figure 6. SA738 Gr. B hardness comparison before and after tempering](image)

From the results, there is a possibility that the tempering of the sample is not complete, and the hardness is not completely down. For high cooling rate samples, the thermal residual stress is not completely eliminated, and there is the possibility of brittle fracture.

4. Conclusion

(1) The SH-CCT curve of improved new type SA738 Gr.B steel is determined, which enrich the research of this steel, contribute to the optimization of welding process, and promoted the development of nuclear steel. To establish this curve, metallographic method, hardness method and expansion method are combined to analyze the microstructure and phase transition temperature at each cooling rate.

(2) Through experiment, the equilibrium phase transition temperature is obtained, the Ac1 is 715 °C and Ac3 is 880 °C. Bainite can be generated in all temperature ranges in this experiment. However, at high cooling rate, it has tendence that transform to martensite. The ferrite generate at cooling rate below 18.8 °C/s, and pearlite generate below 0.60 °C/s. The hardness of this structure is very low, with a minimum value of 227.7 HV5.
(3) After the tempering, the hardness of the sample increases slowly with the increase of the cooling rate. The tempering effect is obvious for the sample whose cooling rate is greater than 4.70 °C/s, and the maximum hardness reduce is 80 HV5.

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