Phase transition kinetics and microstructures of A508-3 steel under continuous cooling process

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ABSTRACT
The phase transition kinetics of A508-3 steel during continuous cooling were studied by high temperature transition instrument which was based on thermodilatometry in this paper. The microstructures during continuous heating and cooling were also observed. The transition points were determined to be austenite formation temperatures, \( A_1 = 757^\circ\text{C} \), \( A_3 = 823^\circ\text{C} \), and martensitic transformation start and final temperatures, \( M_s = 382^\circ\text{C} \), \( M_f = 222^\circ\text{C} \) at the cooling rate of 5\(^\circ\text{C}/\text{s}\). The curves of Austenite transition fraction and time during continuous heating show a typical S shape. And the Austenite will show a maximum transition rate value at the middle temperature. The volume fraction of new phases translated from Austenite as functions of time and temperature during the cooling process can be obtained using the lever law. The pearlite transitions can occur in high-temperature regions at cooling rate smaller than 0.1\(^\circ\text{C}/\text{s}\). And Bainite can be gotten at a lower temperature region. The S-type curves can be used to describe the relationships between the transition volume fraction and time. Increasing the cooling rate enhances the volume fraction of Martensite at the cooling rate \( \geq 5^\circ\text{C}/\text{s} \). And only Martensite transition can be observed at the cooling rate \( > 10^\circ\text{C}/\text{s} \). And \( M_s \) and \( M_f \) increase with increasing cooling rate. The Martensite transition kinetics equation with changing temperature was obtained. Finally, the continuous cooling transformation curves of A508-3 steel were constructed, which can be used to predict the microstructure and design the heat treatment technologies.

INTRODUCTION

Over the last several decades, A508-3 steel has been applied in the pressure container of nuclear power station for its high strength, excellent low-temperature impact resistance and superb radiation resistance [1–7]. A508-3 steel still attracts a considerable amount of research interests [7–10] due to its good weldability, low ductility-brittleness transition temperature and high hardenability. The heat treatment of the pressure container in a fission reactor is very important to secure the application safety. The mechanical properties are closely linked with microstructures [11]. The phase transition thermodynamics and kinetics are basic theory for heat treatment design, which can provide important references for heat treatment design [12]. Heat treatment modification, mechanical properties, preparation and molding process and application and anti-radiation damage performance are research focus of A508-3 steel [9,10,13]. Different heat treatment modification methods can improve the fracture toughness of steel without significantly reducing its strength and obtain better comprehensive properties. In practical application, due to the large size of large forgings, the uneven modification of heat treatment becomes the primary consideration. Due to the service environment of A508-3 steel, the mechanism of irradiation embrittlement has been studied all the time. It is believed that irradiation produces dislocation rings and increases strength and toughness and brittleness transition temperature.

The phase transition kinetics would benefit research in actual production [12,14]. The determination of continuous cooling transformation curves correlates with the cooling rates of the microstructure transformation, which would guide the cooling process in actual production and would explain the corresponding mechanical properties [15–21]. It is necessary to refer to the CCT curve of the steel in the process of formulating the correct heat treatment process and obtaining the expected microstructure and properties. The CCT curve of SA508-3 steel has been measured, but the details have not been described [22]. On this basis, G. OBASI et al. further considered two unique thermal cycles in the welding-related phase transition behavior of A508-3 steel, and compared the complete

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transition evolution curve with the curve predicted by using the kinetic model [23]. The large forgings of A508-3 steel used in this experiment are large in size and modulated in use. The cooling rates in different parts of the large forgings are different during the quenching process, resulting in phase transformation uneven microstructure at room temperature. Therefore, our work of the continuous cooling phase transition dynamics of A508-3 steel has practical value for the full understanding of A508-3 steel, and provides an important basis for the establishment of its manufacturing and heat treatment system.

Although the microstructures, properties and heat treatment technologies of A508-3 steel were studied in detail, the phase transition kinetics under continuous cooling conditions has been unclear. In this work, microstructure transition point of A508-3 steel during heating and continuous cooling was measured by thermal expansion method, and the CCT curve of the steel was plotted with Rockwell hardness value. The Austenite transformation behavior during heating and ferrite, pearlite, bainite and martensite transformation behavior during continuous cooling were analyzed according to the regions divided by CCT curve and the lever principle. The transition curves under continuous condition of A508-3 steel were determined, the microstructures evolution and the transition kinetics from Austenite to Bainite and Martensite were analyzed.

Materials and methods

A508-3 steel was adopted in this work, whose chemical compositions are listed in Table 1. The transition critical temperature and curves. The vacuum was made after the specimen loading. The sample was then heated to an austenitizing temperature of 880°C at a heating rate of 44°C/min and held at this temperature for 20 min followed by cooling to room temperature at a cooling rate of 0.1, 0.25, 0.5, 1, 2, 5, 10, 20 and 100°C/s, respectively. Figure 1(a) is the heating and cooling process of A508-3 steel when measuring the phase transition point. In our test, the specimens were heated to 940°C from room temperature in 20 min, then held for 20 min followed by cooling at 2°C/s in Figure 1(a). The changes in specimen diameter, temperature and time were recorded in detail. After test, the specimens were milled, polished and then corroded using 4% nital. The microstructures were observed using an optical microscope and scanning electron microscope (SEM). The equipment used in this experiment is HELIOS Nanolab 600i electron double-beam microscope, and its technical parameters are as follows: Secondary electron image resolution: 0.9 nm (15 kV), 1.4 nm (1 kV); magnification: 40~6 × 10^5; Accelerating voltage: 0.5~30 kV.

Results and discussion

Determination of transformation point

The thermal expansion curves of A508-3 steel during heating and cooling were obtained by using the changes of special volume and expansion coefficient. The transition point was determined by the tangent method. The tangent lines were drawn at abrupt points on temperature-expansion curves. And the temperature at which the tangent line begins to deviate from the temperature-expansion curve is determined to be a transition point. The thermal expansion curves at a cooling rate of 5°C/s are shown in Figure 1(b). Parameters Ac1, Ac3, Mf and Ms can be gotten in Figure 1 that Ac1 = 757°C, Ac3 = 823°C, Ms = 382°C, Mf = 222°C.

Transition kinetics

The lever law was used to deal with the curves of the diameter changes as functions of time at various temperatures to determine the relationships among austenite volume fraction, temperature and time. As shown in the thermal expansion curve in Figure 2(a), for a single organizational transformation, using the principle of leverage, the organizational transformation variable satisfies the following formula:

\[ f(T) = \frac{Bc}{AB} \times 100\% \]  \hspace{1cm} (1)

As shown in Figure 2(b), the transformation variable of one of the two organizational transformations satisfies the formula as follows:

\[ f'(T) = f(T) \cdot \eta\% = \frac{QM}{MN} \cdot \frac{AB}{AB + EF} \]  \hspace{1cm} (2)

where \( f(T) \) is a function of volume fraction and temperature calculated by a certain kind of organization according to the law of leverage, \( \eta\% \) is the maximum volume fraction of this tissue after the entire transformation. In addition, the extrapolation of the transformed and untransformed lines is used for this analysis.

Table 1. Compositions of A508-3 steel (wt.%).

| C   | Si  | Mn  | P   | S   | Ni  | Cr  | Mo  | Al  | Fe   |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| 0.22| 0.20| 1.43| 0.005| 0.002| 0.98| 0.13| 0.51| 0.017| Bal. |
The result at the heating rate of 0.75°C/s is shown in Figure 3. It is obvious that the curve of austenite transition fraction and time shows a typical S shape. And the relationships between transition rate and temperature can be obtained from the derivation of the austenite fraction to time. The results are shown in Figure 4. The austenite will show a maximum transition rate value at the middle temperature.

The volume fraction of new phases translated from austenite as functions of time and temperature can be obtained by using the lever law in the cooling process. The results show that pearlite transitions can occur in high-temperature regions at the cooling rate \( \leq 0.1°C/s \). And bainite can be gotten in a lower temperature region. The volume of pearlite and bainite as functions of time and temperature can be seen in Figure 5.

Pearlite begins to nucleate at 674°C. The nucleation ratio is low at high temperature due to the smaller supercooling degree, which results in lower transition rate. Increasing time results in the increase of nucleation ratio and transition rate. Although the supercooling degree is high at 606°C, the growth rate of pearlite is small, transition rate tends to zero. At this time, the total transition phase volume is 67.2%. If the temperature falls in the bainite transition region, residual austenite will translate into bainite. And an S-type curve can be used to describe relationships between the bainite volume fraction and time.

Figure 6 gives the volume fractions of Bainite and martensite as functions of temperature and time at the cooling rate of 5°C/s. Both bainite and martensite transition occur at the cooling rate of 5°C/s. In fact, our results show that there is no martensite transition

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**Figure 1.** Determination of phase transition points using thermal expansion method. Heating and cooling Technology; (b) Thermal expansion curves.

**Figure 2.** (a) Thermal expansion curve; (b) Schematic diagram of the law of leverage to calculate the transformation variables of the two organizations.

**Figure 3.** Austenite volume fraction as a function of time and temperature.

**Figure 4.** Austenite transition rate as a function of temperature.
at the cooling rate of 2°C/s. Therefore, the critical cooling rate of martensite transition is between 2 and 5°C/s. Only martensite transition can be observed at the cooling rate >10°C/s. And $M_s$ and $M_f$ increase with increasing cooling rate.

The martensite transition kinetics equation at changing temperature can be described using equation (3). The curves are drawn from Equation (3) in Figure 7, where give the relations between $\ln(1-f)$ and $(M_s-T_q)$.

$$\ln(1-f) = -\alpha(M_s-T_q)$$  \hspace{1cm} (3)

where $f$ is the martensite transition amount, $(1-f)$ is the austenite amount, $M_s$ is the beginning transition point, $T_q$ is the temperature during cooling process at a certain time.

The martensite transition amount changes as a linear function of decreasing temperature. The average value of the coefficient is determined to be 0.02267 by fitting the data at three cooling rates. And the fitting coefficient $R^2$ is larger than 0.99 for every line. Therefore, the martensite transition of A508-3 steel follows the martensite transition kinetics equation with changing temperature. The equation can be written as (4):

$$\ln(1-f) = -0.02267(M_s-T_q)$$  \hspace{1cm} (4)

Microstructures

Figure 8 shows the SEM micrographs of the microstructures obtained at various cooling rates. Ferrite shows massive shape, pearlite is distributed as lath shape at the cooling rate of 0.1°C/s, as shown by the arrow in Figure 8, and some austenite islands with more carbon or their transition produce islands can be observed in massive ferrite. Austenite translates into massive ferrite and some pearlite group, and some residual austenite translates into a small amount of bainite. Increasing the cooling rate will result in a decrease in the amount of pearlite and ferrite and an increase in the amount of bainite. And besides some...
granular structure, some transition produces show needle or strip characteristics. When the cooling rate increases to 0.5°C/s, pre-eutectoid ferrite, pearlite and bainite are observed. Ferrites are distributed as strips from Austenite boundary to the interior of grain, and some carbides are arranged as parallel short rods. Some carbides are distributed among the ferrite in the form of short rods, and some fine carbide particles are arranged at a certain angle to the long axis, showing the characteristics of needlelike lower bainite. The mixed microstructures of martensite and residual austenite can be gotten at a cooling rate of 5°C/s; some needle lower bainite is formed on austenite boundaries, the martensite in the austenite grain shows a lath shape, where the boundaries of ferrite in bainite show some steps. At this cooling rate, it is difficult for atoms to diffuse rapidly after cooling in the low-temperature zone of the bainite transformation. Large undercooling provides a high driving force for nucleation, and non-diffusion martensite transformation occurs. The width of the strands is different, and a small amount of granular bainite is also distributed. The untransformed austenite is stable due to the continuous enrichment of carbon, and finally retained as retained austenite to room temperature. The high cooling rate of 10°C/s can result in lathy martensite. In addition, since the start and endpoints of the martensite transformation are higher than room temperature, during the continuous cooling process, the martensite self-tempering occurred, and the characteristics of ε carbides were observed in its interior.

Continuous cooling transformation (CCT) curves of A508-3 steel

The CCT curves of A508-3 steel were gotten if we connect the corresponding points at the same cooling rate in the figure with the cross axle of logarithm of time and longitudinal axle of temperature, as shown in Figure 9, 'A' denotes the austenite region, 'F' denotes ferrite region, 'P' denotes the transition

Figure 8. SEM microscopy graphs of the microstructures at various cooling rates Cooling rate 0.1°C/s (a), 0.5°C/s (b), 1°C/s (c), 5°C/s (d), 10°C/s (e), 100°C/s (f).

Figure 9. CCT curves of A508-3 steel.
region from austenite to pearlite region, ‘B’ shows the transition region from austenite to bainite, ‘M’ shows the transition region from austenite to martensite in this Figure 9.

The CCT curves show that proeutectoid ferrite, bainite and perlite transition occur at the cooling rate <0.5°C/s. Only bainite transitions occur when the cooling rate reaches 2°C/s. And the transition temperature is 418–580°C. It can be seen that both bainite and martensite transition occur at the cooling rate of 5°C/s. Therefore, the critical cooling rate of martensite transition is between 2 and 5°C/s. Only martensite transition can be observed at the cooling rate >10°C/s. And Ms and Mf increase with increasing cooling rate. The organization transformation points at different cooling rates and the obtained room temperature structure, Rockwell hardness value and other information are summarized as shown in Table 2.

| Cooling Rate/°C/s | Ps | P2 | B2 | Mf | Mf | HRC | Microstructure |
|------------------|----|----|----|----|----|-----|----------------|
| 0.1              | 674| 606| 573| 403| –  | 26.0| F + P + B      |
| 0.25             | 655| 589| 589| 423| –  | 28.3| F + P + B      |
| 0.5              | 607.8| 583.1| 583.1| 423| –  | 31.0| F + P + B      |
| 1                | –  | –  | 585| 418| –  | 32.3| B             |
| 2                | –  | –  | 580.6| 418| –  | 34.5| B             |
| 5                | –  | –  | 551| 410| 357| 206| B + M         |
| 10               | –  | –  | –  | –  | 382| 222| 49.4| M            |
| 20               | –  | –  | –  | –  | 378.1| 228| 49.4| M            |
| 100              | –  | –  | –  | –  | 383| 228| 48.9| M            |

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