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In Situ Observation of Austenite Grain Growth and Phase Transformation of A517GrQ Rack Steel for Jack-Up Offshore Platform

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Abstract. Austenite grain size plays an important role for quenched and tempered A517 GrQ rack steel. In order to investigate the austenite grain growth behavior, in-situ austenizing experiments were conducted at different temperatures with varied holding time. Austenite grain growth, and subsequent bainite and martensite transformation were observed by a confocal laser scanning microscope (CLSM). The average austenite grain size increased rapidly from 32.7 μm to 137.9 μm with increasing temperature from 1100 °C to 1250 °C, and abnormal grain growth occurred at 1250 °C for 15 min. While holding from 5 min to 20 min at 1200 °C, the grain size grew gradually from 70.2 μm to 84.8 μm. The grain size distributions under different conditions all obey lognormal function. After austenizing, the rate of subsequent cooling has an significant impact on transformation process. The transformation duration time decreased from over 142 s to 11 s with increasing cooling rate at 1 °C /s and 5 °C /s, which could be corresponding to bainite and martensite transformation respectively.

1. Introduction

High strength, high toughness, Z direction ductility, and weldability are required for heavy gauge steel for offshore structure, such as 690 MPa grade A517 GrQ steel for heavy-section racks[1-3]. The strength and toughness could only be met by quenching and tempering process, and austenite grain growth plays an important role in the final mechanical properties. Austenite grain growth and grain size distribution during austenitization significantly affect transformations, precipitation, and mechanical properties[4]. Coarse grains and uneven distribution of grain size increase brittleness, and decrease strength and toughness. Therefore, it is necessary to study the grain size evolution and distribution and strictly control the grain growth during austenitization[5]. The austenite grains grow via grain boundary migration[6], austenite nucleation and growth are of importance in steel during austenitization. In-situ observation by CLSM is becoming an effective approach to investigate the phase transformation, grain growth, and precipitation phenomena in steels[7,8], which broke the situation that phase transformation cannot be identified and the grain migration is hard to be monitored.

Cooling rates have obvious effects on the microstructure, especially the bainite transformation and martensite transformation in the quenching of experimental steel[9]. Therefore, determining the microstructure of experimental steel at different cooling rates during continuous cooling and analyzing the phase transformation are essential for obtaining the best microstructure ratio and mechanical properties[10].

The present work was aimed at in-situ observing the process of grain growth and phase transformation. In this paper, the effects of austenitization temperature and holding time on the grain size evolution of experimental steel was investigated, the bainite and martensite transformation were observed, and the grain size distribution was analyzed.

2. Materials and Experiments
The chemical composition of the experimental steel in weight % was: C 0.12-0.16, Si 0.23, Mn 1.05, Ni 2.50, Cr 0.50, Mo 0.50, Al 0.04, B 0.0010, (Nb + V + Ti) < 0.10, Fe balance. The materials used in the study were industrial A517GrQ-Mod steel plate with thickness of 177.8 mm. To observe the austenite grains growth, in-situ observation was carried out on a confocal laser scanning microscope (VL2000DX). The specimens (Φ7mm×3mm) used for in-situ observation were cut from 1/2 thickness of the experimental steel by wire cut electrical discharge machining, mechanically grinding and polishing. The schematic diagram of the in-situ observation is depicted in Fig. 1. The polished specimens were heated to different temperatures (1100, 1150, 1200, 1250 °C) for different holding time (5, 10, 15, 20 min). Then, samples were cooled to room temperature with different cooling rate from 1 °C/s to 5 °C/s. Finally, the samples were etched with 4% nital and then observed by optical microscopy (OM) and scanning electron microscope (SEM).

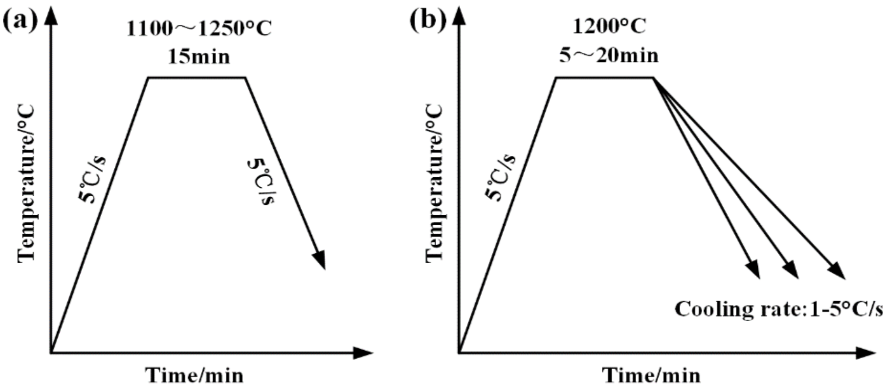

Figure 1. Schematic diagram of the in-situ observation in experiment

3. Results and Discussion

3.1. Influence of Temperature on Grain Growth
Fig. 2 exhibits the in-situ morphology of experimental steel subjected to different austenitization temperature (1100, 1150, 1200, 1250 °C) for 15 min. The average grain size and grain morphologies have significant changes with the increase of temperature. As the temperature increases from 1100 °C to 1250 °C, the average grain size is 32.7, 39.5, 72.2 and 137.9 μm, respectively. The austenite grain size is 30-40μm and uniformly distributed (Fig. 2a, 2b) at 1100 °C and 1150 °C, which is obviously different from the grain size at higher temperatures. From Fig. 2c and 2d, it can be seen that austenite grain grows rapidly and even grows abnormally (Fig. 2d). The larger the austenite grain, the lower the strength of the experimental steel according to Eq. (1)[11]. At the same time, the size of the austenite grain will affect the grain size of the rolled product according to the genetic influence of steel[12], which will affect the product performance. Coase austenite grains are unfavorable for the strength and toughness of steel.

$$\sigma = \sigma_0 + k_y d^{-1/2} \tag{1}$$

where σ is the yield strength, σ_0 is a materials constant for the starting strength, k_y is the strengthening coefficient (a constant specific to each material), and d is the average grain diameter

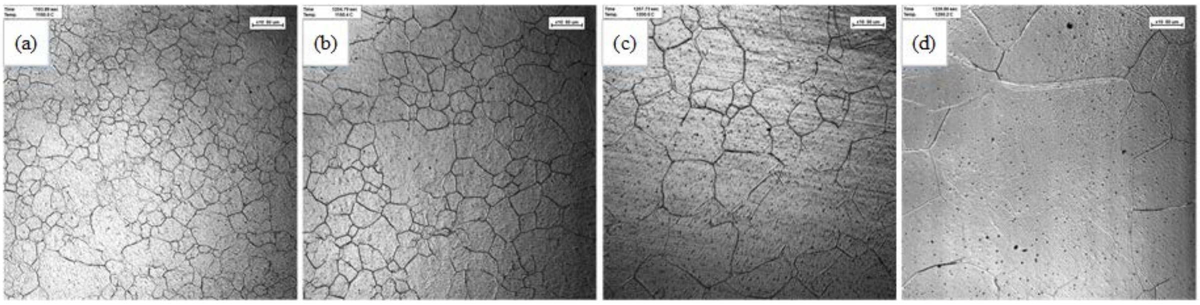

Figure 2. Micrographs of different austenitization temperature for 15 min
(a) 1100 °C; (b) 1150 °C; (c) 1200 °C; (d) 1250 °C

3.2. Influence of Holding Time on Grain Growth

Fig. 3 exhibits the in-situ morphology of experimental steel subjected to different holding time (5, 10, 15, 20 min) at 1200 °C. As the holding time increases from 5 to 20 min, the average grain size is 70.2, 71.6, 75.2 and 84.8 μm, respectively. The austenite grain boundary on the surface of the experimental steel was not obvious when holding for 5 min, few austenite grain boundaries appeared. After holding for 10 min, the austenite grain boundary was observed obviously (Fig. 3b). When the holding time was extended to 15 min and 20 min (Fig. 3c and 3d), austenite grain boundaries were observed to be significantly coarsened, which indicated that the austenite grains continued to grow during this process. In-situ observation of high temperature austenite at different holding times shows that as the holding time increases, the austenite grain boundaries become more and more clear, and the grain size of austenite changes accordingly.

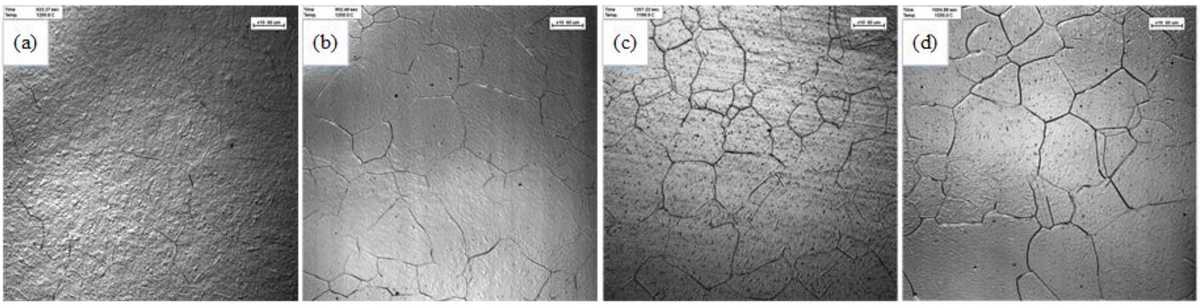

Figure 3. Micrographs of different holding time at 1200 °C
(a) 5 min; (b) 10 min; (c) 15 min; (d) 20 min

3.3. Grain Size Distribution

With the increase of austenitization temperature and holding time, the grain size distributions also gradually changed. Fig. 4 shows the grain size frequency distribution of experimental steel different austenitization temperature (1100, 1150, 1200, 1250 °C) for 15 min. Fig. 5 shows the grain size frequency distribution of experimental steel subjected to different holding time (5, 10, 15, 20 min) at 1200 °C. The grain size distributions under different conditions all obey lognormal function. The height of bars represents probability density (relative frequency). Dotted lines are the fitted results by lognormal function. From Fig. 4 and Fig. 5, it can be found that excessive austenitizing temperature leads to the coarsened grain. However, the grain coarsening effect is not significant at 1200 °C for different holding time.

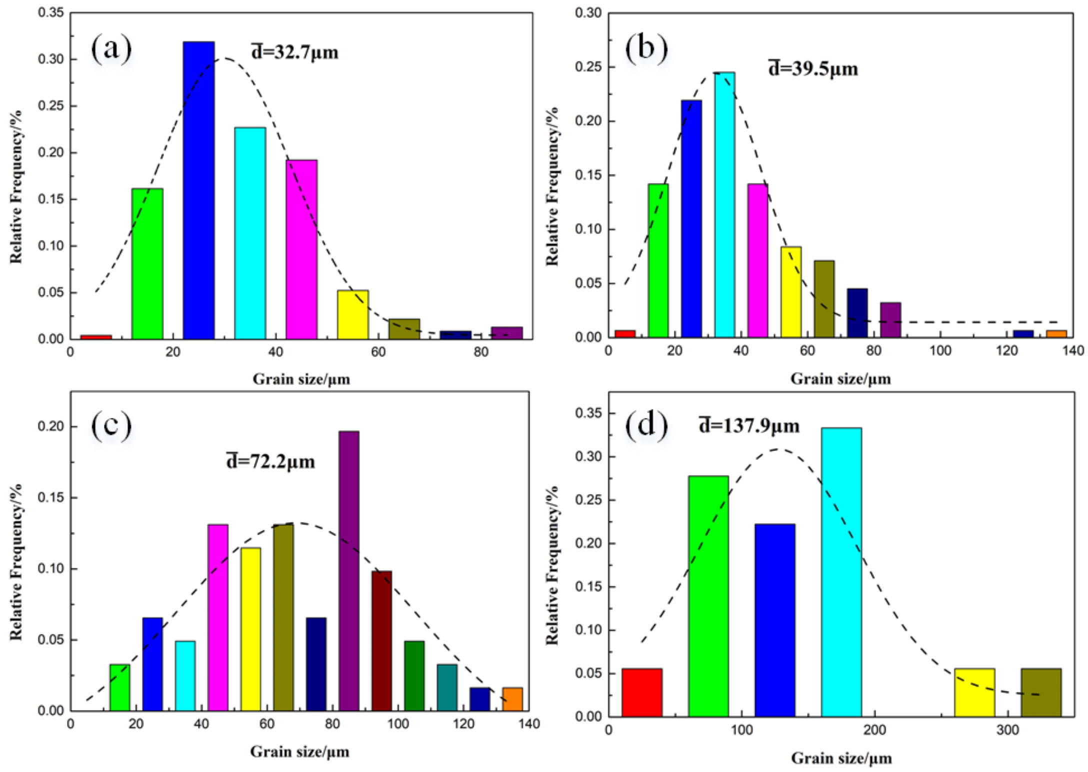

Figure 4. Grain size distribution of different austenitization temperature holding for 15 min (a) 1100 °C; (b) 1150 °C; (c) 1200 °C; (d) 1250 °C

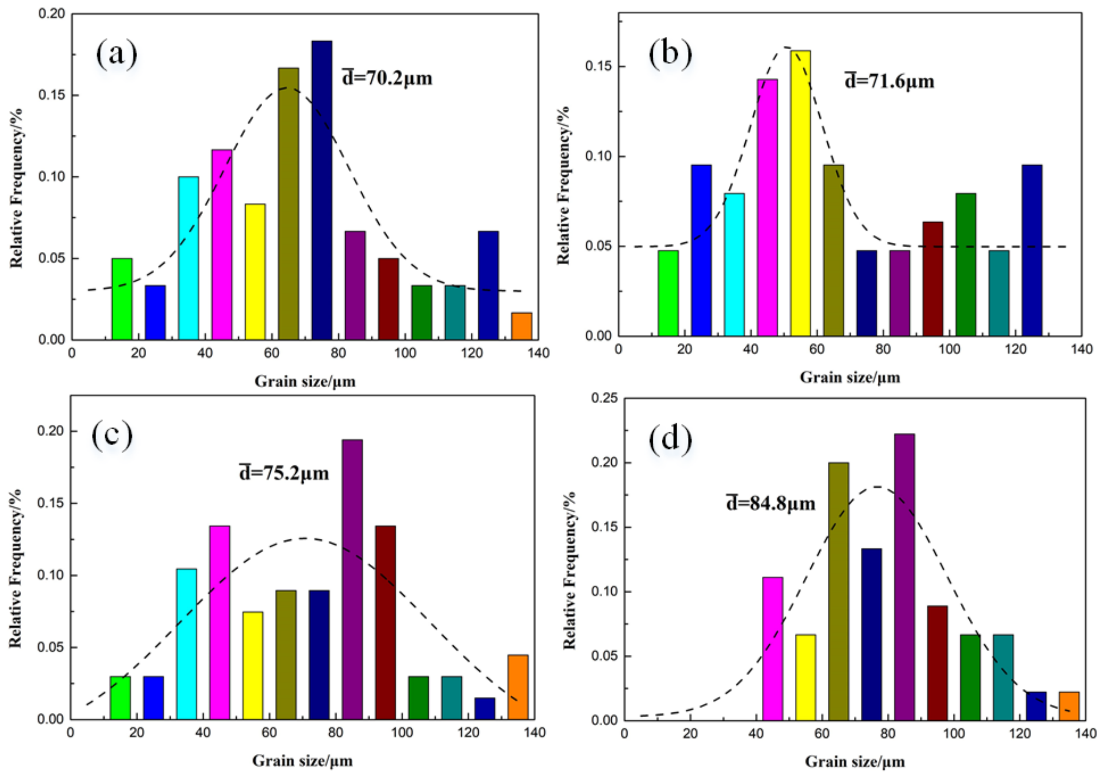

Figure 5. Grain size distribution of different holding time at 1200°C (a) 5 min; (b) 10 min; (c) 15 min; (d) 20 min

3.4. Effect of Cooling Rate on Phase Transformation

Fig. 6a-6d and Fig.6e-6h showed the in-situ morphology of 1 °C/s and 5 °C/s during continuous cooling after austenitization at 1200 °C for 15 min, respectively. The transformation duration time decreased from over 142 s to 11 s with increasing cooling rate at 1 °C /s and 5 °C /s, which could be corresponding to bainite and martensite transformation respectively. The Bs and Ms is ~ 460 °C and ~ 395°C, respectively.

As the temperature decreases, the bainite transformation of the experimental steel first nucleated at the austenite grain boundary, gradually grew and traverses the grain. The crystal nucleus formed by transgranulation continue to grow and new nucleation formed at other grain boundary locations (zone A in Fig. 6a-6d). In addition to nucleation on the austenite grain boundaries, bainite can also be nucleated on bainite lath already formed in the crystal (zone B in Fig. 6a-6d).

Compared to bainite transformation, martensite transformation is more faster. During martensite transformation, martensite first nucleated at the grain boundary and grew rapidly through the grain. The nucleation at the grain boundary was simultaneously at the same angle, and at a 60 degree angle with first formed martensite lath (zone C in Fig. 6e-6h). Bainite transformation is a transitional phase transformation, which is difficult to distinguish from martensite transformation[13]. A more intuitive in-situ observation of bainite transformation and martensite transformation can be observed by CLSM.

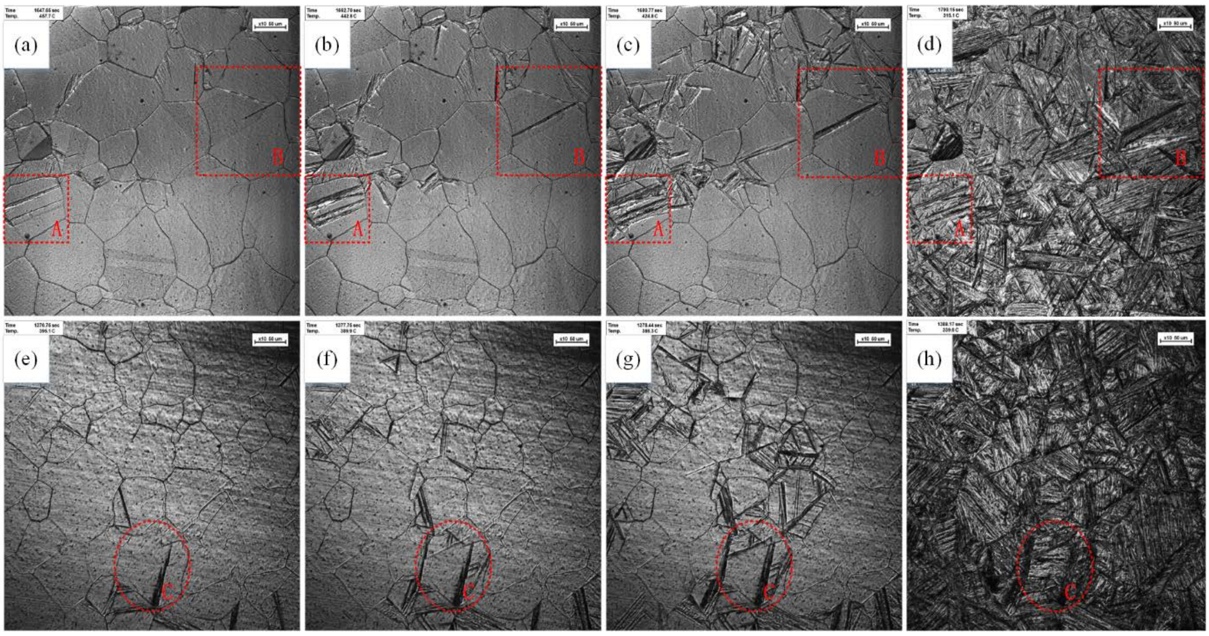

Figure 6. In-situ morphology of different cooling rate during continuous cooling
(a) ~ (d)1 °C/s; (a)458 °C,1648 s; (b)443 °C,1663 s; (c)425 °C,1681 s; (d)315 °C,1790 s
(e) ~ (h)5 °C/s; (e)395 °C,1377 s; (f)390 °C,1378 s; (g)386 °C,1378 s; (h)339 °C,1388 s

4. Conclusions

In this article, the in-situ morphologies and bainite and martensite transformation of experimental steel were observed, the grain size distribution of different austenitization temperature and holding time were analyzed. All of the conclusions are shown as follows:

(1) The austenitization temperature and holding time have significant effects on the average grain size evolution and grain size distribution.

(2) The average grain size grows slowly with increasing holding time at 1200°C, and the average grain size grows rapidly with increasing austenitization temperature. The grains grow abnormally at 1250 °C for 15min.

(3) The transformation duration time decreased from over 142 s to 11 s with increasing cooling rate at 1 °C /s and 5 °C /s, which could be corresponding to bainite and martensite transformation respectively.

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