Effect of cooling rate on microstructural formation and hardness of 30CrNi3Mo steel

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Abstract The variation of microstructural formation and the hardness of the 30CrNi3Mo steel were systematically explored as a function of applied cooling rates in the range of 1–500°C/min. According to the measured Rockwell hardness results, four characteristic stages could be separated as different ranges of cooling rates, which corresponds well with the microstructural evolution observed. With the applied cooling rate increasing, the transformed structure evolves from granular bainite, lower bainite, self-tempered martensite, to finally martensite without self-tempering. Among them, the self-tempered martensite, obtained in the transformed specimens cooled with rates of 25–80°C/min, exhibits the highest hardness values due to the precipitation of fine carbides within it.

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1 Introduction

The 30CrNi3Mo, a medium-carbon low alloy super-high strength steel developed from the AISI 4340 alloy in recent years, is used as an armor plate material for providing protection in military and non-military vehicles [1–5]. This steel exhibits quite good hardenability due to its relatively high content of Ni component, and thus martensite structures can be completely obtained in air cooling conditions. Generally, quenching and tempering are well-established means to strengthen steels due to the precipitation of fine and disperse alloy carbides during tempering [6]. Therefore, in practical production, the steel was generally air cooled after controlled rolling and then tempered at low temperature. Hardness is one of the most important mechanical properties for armor steels, and it has been based on for predicting ballistic performance of armor steels and as a design specification [7, 8]. Current specifications for military applications recommend a minimum hardness range of 540–600 BHN or 55–60 HRC [9]. It is well known that the cooling rate of super-cooled austenite has significant effects on the ultimate microstructure and mechanical properties of steels [10, 11]. However, up to now there has been no systematic study related to influence of the applied cooling rates from the austenitizing temperature on microstructure and mechanical properties of the 30CrNi3Mo steel.

The present study focuses on the relationship between the microstructural formation of the 30CrNi3Mo super high-strength steel with the applied cooling rate of 1–500°C/min and the hardness of transformed products from super-cooled austenite, aiming to provide some guidance for further development in the selection of cooling or heat-treatment controlling parameters after receiving the hot-rolling plate.

2 Experimental materials and procedures

The chemical composition of the experimental 30CrNi3Mo steel is as follows (in weight percent): 0.3 C, 0.26 Si, 0.45 Mn, 3.1 Ni, 0.47 Mo, 0.94 Cr, 0.003 S, and 0.009 P. Dilatometry samples with dimensions of ∅6 × 10 mm were
spark-cut from a 30-mm-thick hot-rolled steel plate having been uniformly heat-treated.

Dilatometric tests were performed on a high-resolution differential dilatometer. Dilatometry samples were first austenitized at 900°C for 10 min, then continuously cooled from the austenite region down to room temperature at different rates of 1, 3, 5, 8, 10, 12, 15, 18, 20, 25, 40, 50, 80, 100, 200, 300, and 500°C/min, respectively. In these heat-treatment processes, the corresponding dilatometric curves between length changes and temperatures of the explored steel samples were obtained.

An HR-150A Rockwell hardness tester was used to determine the hardness of the transformed samples. Five indentations were made for each sample, and the average value was finally obtained as the Rockwell hardness value.

An optical microscope (OLYMPUS), scanning electron microscope (X-650) and a transmission electron microscope (JEM-100CX II) were used in microstructural observations. Specimens for optical and scanning electron microscopy were cut from dilatometric samples subjected to different cooling rates. Foils for transmission electron microscopy (TEM) were prepared by cutting thin wafers from dilatometric samples, and grinding them to about 100 μm in thickness. Three-millimeter discs were punched from the wafers and electropolished using an electrolyte of 10% perchloric acid and 90% ethanol.

3 Results and discussion

In order to investigate the influence of applied cooling rate on the microstructure formation and the mechanical performance, 15 cooling rates in the range of 1–500°C/min were adopted to cool the explored 30CrNi3Mo steel samples from the austenite region down to room temperature. Figure 1 shows the measured average Rockwell hardness values of the investigated 30CrNi3Mo samples cooled down to room temperature at different rates in the range of 1–500°C/min after being austenitized at 900°C for 10 min. It was found that the measured Rockwell hardness values of the experimental steel do not increase linearly with the increasing applied cooling rate. In detail, the curve in Fig. 1 can be divided into four separated stages (as indicated in the figure): (I) hardness increasing rapidly with the cooling rate of 1–10 °C/min; (II) reaching a plateau stage between 10 and 20°C/min; (III) leaping on another plateau stage when cooling rate exceeds 25°C/min; (IV) hardness decreasing slightly with the increasing cooling rate when the cooling rates are larger than 100°C/min.

The variation of the measured Rockwell hardness should be correlated with the transformed microstructures. Figure 2 illustrates the typical optical microstructures of the experimental steel cooled at various rates in the range of 1–500°C/min. It was shown that morphologies of the transformed 30CrNi3Mo steel samples were greatly influenced by the applied cooling rate, which strongly suggests that the observed variation of the hardness with respect to applied cooling rate in Fig. 1 is to be explained by the microstructural observations in Fig. 2.

As shown in Figs. 2(a) and 2(b), all transformed products obtained at slow-cooling conditions (1–5°C/min) exhibit granular structures, that is, a lot of particles distributed in the matrix of polygonal ferrite. All particles in the granular structures tend to be irregular and inhomogeneous. Some of them are relatively large and look like lots of dots. Part of them are sparsely-distributed, while others are so dense that it is difficult to distinguish them under optical microscope and they look black nodular (as indicated by arrows). Figure 2(c) represents an enlarged image of the granular structures in the 30CrNi3Mo specimen cooled at 3°C/min from the austenite region.

The onset and end transformation temperatures of the experimental 30CrNi3Mo steel with slow cooling rates (1, 3, and 5°C/min) can also be determined from the measured dilatometric curves, as shown in Fig. 3. As seen from it, the highest onset temperature is about 470°C, and the lowest end temperature is about 300°C. It is obvious that the experienced phase transformations of the explored steel samples under the above slow cooling conditions occurred in the moderate temperature range [12], and hence the above granular structures should be determined as bainite, instead of pearlitic. This was further verified that a small amount of austenite was retained in all the three slowly-cooled specimens according to the X-ray diffraction results. It is generally believed that the austenite will never be retained after the termination of pearlitic transformation. Granular bainite

![Fig. 1 Measured Rockwell hardness values of the explored 30CrNi3Mo steel cooled down to room temperature from the austenite region at different cooling rates in the range of 1–500°C/min](image-url)