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Microstructural Evolution and Properties of a High Strength Steel with Different Direct Quenching Processes

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Abstract: A high strength low alloy steel with low carbon equivalent was selected for simulating online direct quenching and coiling (DQ-C) process. The influence of stop quenching temperature on mechanical properties and microstructures was studied and compared with normal direct quenching and tempering (DQ-T) process. The study confirmed that required mechanical properties were obtained for both the processes. Properties of the experimental steel with DQ-C process could reach the same level as that of DQ-T process in general. In the DQ-C process, strength decreased with increase in stop quenching temperature. Martensite was obtained and experienced an aging process at stop quenching temperature below M_f. On fast cooling below M_s, martensite was partially transformed and carbon partitioning occurred during slow cooling. The reduction in solid solution carbon and increased amount of retained austenite led to lower strength compared with the DQ-T process. DQ-C process was more favorable for microalloy carbide precipitation. However, impact toughness under different cooling conditions was adequate because of low carbon equivalent and refined microstructure.

Key words: high strength steel; direct quenching; slow cooling; carbon partitioning; precipitation

In the manufacturing of engineering machinery and structural construction, steels of higher strength are being considered, which are generally subjected to quenching and tempering treatment. With increase in strength, difficulties associated with weldability and toughness become notable. A number of studies have been carried out involving controlled rolling, cooling and heat treatment processes[1-4]. However, the carbon or alloy content was generally high, which resulted in low toughness and poor weldability and higher cost. Thus, low carbon equivalent is required for high performance, which will lead to decrease in hardenability and strength. Studies[5-10] have indicated that controlled rolling and direct quenching process are more favorable for obtaining higher strength than reheated quenching and tempering process. However, steels described in these studies were directly quenched to low temperature and then reheated for tempering. This process is suitable for plate rolling mill production. However, with the development of online fast cooling technology and heavy strip coiling equipment, high strength medium plate can be produced by continuous strip rolling mill. The online fast cooling and coiling process enables steel to be quenched to a certain temperature below M_s followed by subsequent slow cooling. It is unclear if the mechanical properties obtained using this process can approach direct quenched and tempered steels. The effect of parameters such as stop cooling temperature on the properties and microstructure requires elucidation. In the present study, a 960 MPa grade steel with low carbon equivalent was considered to investigate the viability of direct quenching-slow cooling process. The effect of stop quenching temperature on mechanical properties and microstructural evolution was com-

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pared with direct quenching and tempering process.

1 Experimental Procedure

Chemical composition of the experimental steel (in mass%) was C 0.1, Si 0.25, Mn 1.0, Mo 0.2, Al 0.03, B 0.0015, P 0.006, S 0.003, Nb+V+Ti< 0.05, and Fe balance. The carbon equivalent estimated was $C_{EQ}=w_C+w_{Mn}/6+(w_{Cr}+w_{Mo}+w_V)/5+(w_{Ni}+w_{Cu})/15=0.3$. The steel was melted in a 150 kg vacuum induction furnace and cast into ingot. The dynamic continuous cooling transformation (CCT) diagram was obtained using $\phi 8$ mm×15 mm cylinder specimens. The specimens were austenized at 1200 ℃ for 5 min, then compressed to 60% at 900 ℃, and subsequently cooled to room temperature at different rates. Hot rolling and cooling experiments were carried out using a laboratory hot rolling mill. Identical hot deformation process was employed for the experimental steel. Steel blocks were heated to 1200 ℃ and soaked for 1 h. Two-stage controlled rolling process was performed. Start rolling temperatures in the austenite recrystallization zone and non-recrystallization zone were 1100 and 950 ℃, respectively. The finish rolling temperature was about 850 ℃ and the final thickness was 8 mm. Hot rolled steel was subjected to two different cooling processes with fast cooling equipment of the mill, as schematically presented in Fig. 1. The cooling rate was calculated based on decrease in temperature and cooling time and approached 80−100 ℃/s for the experimental plate thickness. In process 1, the steel was directly quenched to room temperature and then reheated for tempering, and is referred as DQ-T process. Tempering temperature was carried out between 250−600 ℃ with holding time of 30 min. In process 2, the steel was fast cooled to different temperatures of 150, 290, 460 and 490 ℃, which were determined by an infrared thermometer, and then the plates were covered by glass fibers for simulating the slow cooling of coiling process, referred as DQ-C process. The results of DQ-C process were analyzed and compared with DQ-T process.

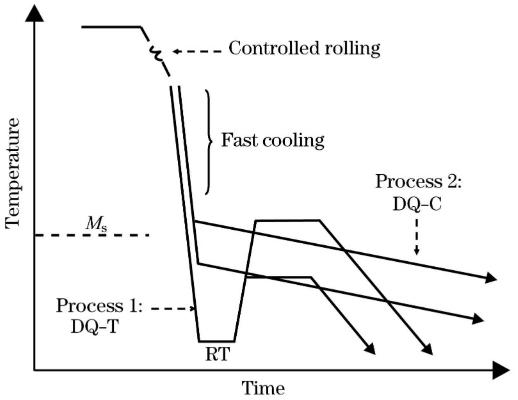

Fig. 1 Schematic diagram of cooling and heat treatment processes

Transverse tensile properties were measured via a WAW-1000 universal testing machine using rectangular specimens of dimensions of 8 mm×15 mm and original gauge length of 60 mm. Longitudinal Charpy impact properties were determined using an Instron 9250 HV drop hammer impact tester using specimens with size of 10 mm×7.5 mm×55 mm at −40 ℃. The average value of three specimens was obtained from the tensile and impact test. The specimens were metallographically polished and etched with 4% nital and observed on a LEICA DMIRM optical microscope. Thin foils for TEM were polished using by jet polishing in 9% perchloric acid alcohol solution (TEM, Tecnai G2 F20). DQ-C process steel samples were electrolytically polished and analyzed by scanning electron microscopy (SEM, FEI Quanta 600) equipped with EBSD (electron backscattered diffraction).

2 Results

2.1 CCT diagram

The CCT diagram and corresponding microstructures of the experimental steel are presented in Figs. 2 and 3. Proeutectoid ferrite, pearlite, and granular bainite were obtained at low cooling rates. During cooling at about 5−40 ℃/s, granular and lath bainite were obtained that became finer with increase in cooling rate. After cooling at 80 ℃/s, lath martensite was obtained. Online fast cooling rate of at least 60−80 ℃/s is required for direct quenching.

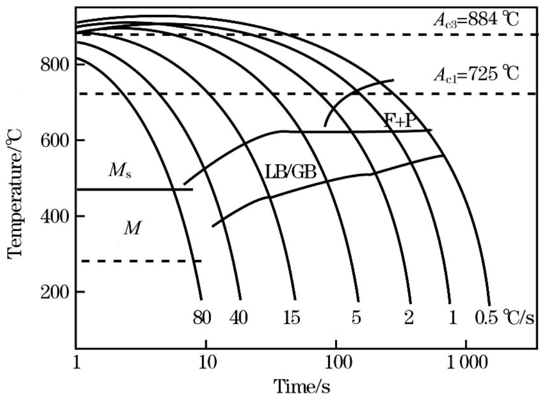

Fig. 2 CCT diagram of experimental steel with 60% austenite deformation at 900 ℃

2.2 Mechanical properties

The influence of cooling and heat treatment pro-