Effect of Ultra-Fast Cooling Finish Temperature on Microstructure Transformation and Precipitation Behavior of Nb-V-Ti Microalloyed Steel Postprint

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Abstract

Low-carbon microalloyed steel with combined additions of Nb, V, and Ti was investigated. A thermal simulator was employed to simulate the high-temperature rolling + ultra-fast cooling + slow cooling process, while OM, HRTEM, and microhardness tester were used to study the microstructural transformation and precipitation behavior of experimental steels ultra-fast cooled to different temperatures. The results show that as the final ultra-fast cooling temperature increases, the microstructure transforms from bainite to pearlite and ferrite, the nucleation site of carbides shifts from bainite to ferrite, and the precipitate density in ferrite—greater than that in bainite—reaches a maximum at 620 °C. Precipitates formed at different ultra-fast cooling temperatures are all smaller than 10 nm with aspect ratios approaching 1, indicating a near-spherical morphology, and their size gradually decreases with decreasing final cooling temperature. Using the Orowan mechanism, the precipitation strengthening increment was calculated, demonstrating that the contribution of precipitation strengthening to yield strength is greatest at 620 °C, attaining 25.6%.

Effect of Final Temperature After Ultra-Fast Cooling on Microstructural Evolution and Precipitation Behavior of Nb-V-Ti Bearing Low Alloy Steel

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Abstract

High strength low-alloy (HSLA) steel has been widely used in buildings, bridges, ships and automobiles because of its remarkable strength and formability. Conventional HSLA steels are strengthened through a combination of grain refinement, solid-solution strengthening, and precipitation hardening, with precipitation strengthening traditionally considered to contribute only modestly since alloying elements were added primarily for grain refinement. However, recent research has achieved yield strengths up to 780 MPa in Ti-Mo bearing HSLA sheet steels by producing ferritic matrices with nanometer-sized carbides, with precipitation strengthening estimated at approximately 300 MPa. Thermo-mechanical controlled processing (TMCP) is now widely used for HSLA steels, where the final temperature after ultra-fast cooling (UFC) plays a decisive role in microstructural evolution and precipitation behavior, ultimately determining mechanical properties. This work investigates the effects of final UFC temperature on microstructural evolution, precipitation behavior, and microhardness of Nb-V-Ti bearing low alloy steel using a thermal mechanical simulator, optical microscopy (OM), high-resolution transmission electron microscopy (HRTEM), and microhardness testing. Results show that microstructure and carbide nucleation sites change with final UFC temperature, transitioning from bainite to pearlite and ferrite as temperature increases. The number density of precipitates in ferrite exceeds that in bainite, reaching maximum values at 620 ℃. Carbide sizes remain below 10 nm with aspect ratios close to 1 (near-spherical morphology), becoming smaller with decreasing final cooling temperature. Orowan mechanism calculations reveal that precipitation strengthening contributions to yield strength reach 25.6% at 620 ℃.

KEY WORDS Nb-V-Ti bearing low alloy steel, ultra-fast cooling, hardness, precipitation strengthening

Introduction

Microalloyed high strength low alloy (HSLA) steels are extensively used in construction, bridge building, energy transmission, and automotive industries due to their high strength, toughness, and excellent weldability. These steels employ low-carbon composition design to ensure good welding performance while adding one or more microalloying elements such as Nb, V, Ti, and Mo. Strength is primarily achieved through grain refinement, solid solution strengthening, transformation strengthening, and precipitation strengthening. Historically, researchers believed that microalloying elements mainly contributed to grain refinement with minimal precipitation strengthening effects. However, Funakawa et al. successfully developed a high-strength steel with excellent hole expansion properties based on Ti-Mo microalloyed steel, characterized by numerous carbides approximately 3 nm in size distributed in a ferrite matrix, contributing up to 300 MPa to yield strength. This breakthrough fundamentally changed the understanding of microalloying element functions.

Recent studies have found that thermo-mechanical controlled processing (TMCP) centered on ultra-fast cooling (UFC) can produce nanometer-sized precipitates dispersed in the matrix, with these nanoparticles forming primarily in ferrite and bainite and playing a major role in strengthening. Therefore, controlling the process to obtain nanoscale precipitates in ferrite and bainite is crucial. Researchers have successfully developed experimental steels with uniform microstructures and finely dispersed precipitates using high-temperature rolling + ultra-fast cooling + slow cooling processes. UFC cooling rates typically exceed 100 ℃/s, and rapid cooling from high finishing temperatures to a specific final cooling temperature refines the microstructure while creating immediate supersaturation of trace elements that precipitate during subsequent slow cooling. While lower final cooling temperatures generally promote formation of fine low-temperature microstructures with greater nucleation driving force for precipitation, low temperatures also limit diffusion of microalloying elements, affecting precipitation strengthening. Consequently, systematic investigation of UFC final temperature effects on microstructure and precipitation behavior is necessary to establish optimal rolling processes.

This study examines Nb-V-Ti bearing low-carbon microalloyed steel, investigating the influence of different final cooling temperatures on microstructural transformation, precipitation behavior, and microhardness using a thermal mechanical simulator. High-resolution TEM observations characterize the size, quantity, morphology, and distribution of nanoscale precipitates in ferrite and bainite regions, while analyzing the contribution of precipitation strengthening to yield strength at different UFC temperatures to establish optimal TMCP parameters.

Experimental Procedures

The experimental Nb-V-Ti microalloyed steel had a chemical composition (mass fraction, %) of: C 0.09, Mn 1.05, Si 0.25, N 0.0037, Ti 0.011, V 0.03, Nb 0.025, Fe balance. A 150 kg ZGIL0.01-50-4K vacuum melting furnace was used for smelting with Ar gas protection to prevent oxidation. The molten steel was cast into 50 kg ingots, which were then cropped to remove shrinkage cavities and forged into 100 mm × 100 mm billets. The billets were reheated to 1200 ℃ for 2 h for homogenization, then rolled in 7 passes on a two-reversible hot rolling mill with 450 mm diameter rolls to a final thickness of approximately 12 mm. The 12 mm thick plates were placed in a K010 box resistance furnace at 1200 ℃ for 72 h to dissolve carbides completely into the matrix, followed by quenching to room temperature. Thermal simulation specimens measuring 8 mm in diameter and 15 mm in length were cut along the rolling direction.

Heat treatment and dynamic continuous cooling transformation (CCT) curve determination were performed on an MMS-300 thermal mechanical simulator. The heat treatment process involved heating specimens at 10 ℃/s to 1200 ℃, holding for 3 min, cooling at 10 ℃/s to 900 ℃, applying 60% deformation, then cooling at 80 ℃/s to 540, 580, 620, and 660 ℃ respectively, followed by slow cooling at 0.1 ℃/s to room temperature to simulate the slow cooling process after UFC. CCT curve determination followed a similar heating and deformation schedule, but with continuous cooling at rates of 0.5, 1, 2, 5, 10, 15, 20, 25, 30, and 40 ℃/s to room temperature. The dynamic CCT curve was plotted using dilatometry data combined with metallographic analysis [Figure 1: see original paper].

Thermal simulation specimens were sectioned approximately 1 mm below the thermocouple, mechanically ground and polished, then etched with 4% (volume fraction) nitric acid alcohol solution for approximately 15 s. Microstructures were observed using a LEICA DMIRM optical microscope (OM), and local microhardness was measured with an HV-50 Vickers microhardness tester at 25 g load for 10 s, with 20 measurements averaged per specimen. To investigate precipitation behavior after UFC to different temperatures, 300 m thick discs were cut from heat-treated specimens, mechanically ground with SiC paper to below 50 m, then thinned using a Tenu-Pol-5 twin-jet electropolisher with 9% (volume fraction) perchloric acid alcohol electrolyte at 30-35 V and -20 ℃. Precipitate size, quantity, morphology, and distribution were examined using a TECNAI G2 F20 field emission transmission electron microscope (TEM).

Results and Discussion

2.1 Microstructure

Figure 2 shows optical micrographs of the experimental steel after UFC to different temperatures. When cooled to 540 and 580 ℃, the microstructure consisted primarily of bainite (Figs. 2a and b). At 620 and 660 ℃, the microstructure was mainly polygonal ferrite, acicular ferrite, and minor pearlite (Figs. 2c and d). During transformation, polygonal ferrite nucleated first at prior austenite grain boundaries, followed by pearlite formation due to carbon diffusion, with the remaining austenite transforming to acicular ferrite in the intermediate temperature range.

2.2 Precipitation Behavior

Figure 3 presents precipitation morphologies in the experimental steel after UFC to different temperatures, with bainitic region precipitates shown in Figs. 3a and b and ferritic region precipitates in Figs. 3c and d. Rapid cooling through the $\gamma \rightarrow \alpha$ transformation zone suppresses interphase precipitation of microalloy carbides to some extent; during subsequent slow cooling, carbides precipitate primarily through homogeneous nucleation in ferrite and bainite matrices. The number density of precipitates in ferrite is significantly higher than in bainite because the chemical driving force for carbon rejection is greater in ferrite. In bainite, precipitate number density increases with increasing final UFC temperature, while the opposite trend occurs in ferrite. This behavior is determined by the interplay between nucleation driving force from precipitation thermodynamics and diffusion kinetics of microalloying elements. Bainite transformation occurs at relatively low temperatures that hinder precipitation, and although decreasing final temperature increases nucleation driving force, this cannot compensate for the substantial reduction in diffusion rates, resulting in fewer precipitates at lower temperatures. In ferrite, however, the increased nucleation driving force at lower temperatures can offset the slight decrease in diffusion rates.

Overall, precipitate density increases then decreases with rising final UFC temperature. Figure 4 shows HRTEM images of nanometer-sized carbides after UFC to different temperatures. Carbide size increases continuously with final UFC temperature. The aspect ratios measured as 1.09, 1.08, 1.15, and 1.02 in Figs. 4a-d are all close to 1, indicating near-spherical morphology. Averaging 20 carbide measurements yields diameters of 3.6, 5.0, 6.4, and 9.7 nm respectively. Clear Moiré fringes are visible in Figs. 4a and c due to the large size difference between carbides and matrix thickness, creating secondary diffraction effects that produce Moiré fringe contrast patterns, which allow accurate carbide size measurement. No Moiré fringes appear in Figs. 4b and d because carbide sizes are comparable to matrix thickness, preventing secondary diffraction effects. However, the sharp phase interfaces between similarly-sized carbides and matrix enable direct and accurate size measurement.

2.3 Microhardness

Microhardness measurements were performed in the centers of relatively large ferrite and bainite grains to minimize grain boundary effects. Figure 5 shows the microhardness of the matrix after UFC to different temperatures. Microhardness initially increases slightly then decreases with rising final temperature. Since measurements were taken within individual grains, excluding grain boundary strengthening, the hardness variations primarily result from carbide precipitation. Bainite matrix hardness exceeds that of ferrite, and the overall microhardness trend reflects the competing effects of microstructure type and precipitation density.

2.4 Precipitation Strengthening Calculation

In the precipitation strengthening mechanism, the interaction between carbides and dislocations follows the Orowan mechanism, where gliding dislocations encounter carbides, bend around them under increasing stress, and eventually bypass the particles leaving dislocation loops. The strength increment can be calculated as:

$$\Delta\sigma_{pre} = \frac{Gb}{L}$$

where $\Delta\sigma_{pre}$ is the precipitation strengthening contribution to yield strength, G is the matrix shear modulus, b is the magnitude of the Burgers vector, and L is the interparticle spacing.

Calculations yield precipitation strengthening increments of 28.2, 46.7, 142.3, and 90.6 MPa for final UFC temperatures of 540, 580, 620, and 660 ℃ respectively, with the maximum increment at 620 ℃. Converting the measured matrix microhardness values of 245, 249, 228, and 208 HV to yield strengths gives 583.5, 601.5, 556.2, and 506.5 MPa respectively. The calculated contributions of precipitation strengthening are 4.8%, 7.8%, 25.6%, and 18.0% respectively, as shown in Figure 6. Precipitation strengthening is more pronounced in ferrite than in bainite, with the most significant contribution occurring at 620 ℃.

Conclusions

(1) When UFC to 540 and 580 ℃, the microstructure consists primarily of bainite; at 620 and 660 ℃, the microstructure is mainly polygonal ferrite, acicular ferrite, and minor pearlite. (2) The final UFC temperature determines carbide nucleation sites, occurring primarily in bainite at 540 and 580 ℃ and in ferrite at 620 and 660 ℃. Carbide density in ferrite significantly exceeds that in bainite, reaching maximum nanometer-sized carbide density at 620 ℃. Carbide sizes remain below 10 nm at all temperatures with aspect ratios near 1 (near-spherical morphology), decreasing with lower final temperatures. (3) Microhardness initially increases slightly

then decreases with rising final UFC temperature. Orowan mechanism calculations demonstrate maximum precipitation strengthening contribution to yield strength (25.6%) at 620 ℃.

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