Postprint: Strengthening Mechanism of 650 MPa Grade V-N Micro-alloyed Automotive Beam Steel

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Abstract

The microstructures and precipitates of V-microalloyed steel and V-N microalloyed steel were analyzed using OM, SEM, and TEM to investigate the strengthening mechanisms. The results indicate that the microstructures of both V-microalloyed steel and V-N microalloyed steel consist mainly of ferrite with a small amount of pearlite. With increasing coiling temperature, the strength of V-N microalloyed steel exhibits a trend of first increasing and then decreasing, achieving optimal mechanical properties at 600 °C, with yield strength and tensile strength reaching 605 MPa and 687 MPa, respectively, and an elongation of 24.5%. Compared with V-microalloyed steel, V-N microalloyed steel has finer ferrite grains with an average grain size of 4.5 mm, more finely dispersed precipitates ranging from 3 to 50 nm with an average size of 8.0 nm, and a higher dislocation density. Grain refinement, precipitation strengthening, and dislocation strengthening are the primary causes of the high yield strength of V-N microalloyed steel, among which fine grain strengthening is the dominant mechanism, accounting for 43.05% of the total yield strength, while precipitation strengthening and dislocation strengthening contribute up to 34.44% to the yield strength.

Full Text

Preamble

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Study on Strengthening Mechanism of 650 MPa Grade V-N Microalloyed Automobile Beam Steel*

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Abstract

High-strength automobile beam steel represents a major development trend in the automotive industry. With the advancement of heavy-duty vehicles, there is an urgent need to develop low-cost automobile beam steels possessing both high strength and high toughness. The V-N microalloying method combined with thermomechanical controlled processing exhibits significant grain refinement effects. Therefore, the relationship between different nitrogen contents and processing parameters requires detailed investigation. In this work, the microstructure and precipitates of V-microalloyed and V-N microalloyed steels were analyzed using optical microscopy (OM), scanning electron microscopy (SEM), and transmission electron microscopy (TEM), and their strengthening mechanisms were studied. The results show that both steels primarily consist of ferrite with a small amount of pearlite. As the coiling temperature increases, the strength of V-N microalloyed steel first increases and then decreases, with optimal mechanical properties obtained at 600 ℃, achieving a yield strength of 605 MPa, tensile strength of 687 MPa, and elongation of 24.5%. Compared with V-microalloyed steel, V-N microalloyed steel exhibits finer ferrite grains with an average size of 4.5 mm, more finely dispersed precipitates ranging from 3–50 nm with an average size of 8.0 nm, and higher dislocation density. Grain refinement strengthening, precipitation strengthening, and dislocation strengthening are the main reasons for the high yield strength of V-N microalloyed steel, among which fine grain strengthening is the most dominant mechanism, accounting for 43.05% of the total yield strength, while precipitation strengthening and dislocation strengthening contribute up to 34.44%.

Keywords: V-N microalloying, automobile beam steel, strengthening mechanism, coiling temperature

Introduction

The development of high-strength automobile beam steel is a major trend in the automotive industry. Research has shown that reducing steel sheet thickness by

0.05 mm, 0.10 mm, and 0.15 mm can decrease vehicle weight by 6%, 12%, and 18%, respectively. Since vehicle fuel consumption can be reduced by 6–8% for every 10% reduction in total mass, lightweight vehicle bodies can significantly improve fuel efficiency and driving range while maintaining overall strength and reliability. Automobile beam steel is primarily used for manufacturing structural components such as cross members and longitudinal beams in various vehicle frames. Currently, medium and heavy-duty trucks in China mainly adopt a double-beam structure using 510 MPa steel plates with thicknesses of 4.0–8.0 mm. Some cargo trucks also use 8 mm thick 590 MPa steel for main beams and 5 mm thick 510 MPa steel for reinforcing beams. With the development of heavy-duty vehicles, higher strength levels of beam steel plates are needed.

Automobile beam steels with strength above 600 MPa both domestically and internationally adopt low-carbon composition design with additions of one or more microalloying elements such as Nb, V, and Ti. Their strength no longer relies on interstitial solid solution strengthening by carbon but is achieved through fine grain strengthening, solid solution strengthening, transformation strengthening, precipitation strengthening, and dislocation strengthening. However, most research has focused on microalloying systems such as Nb, V, Nb-V, Nb-Ti, and Nb-V-Ti, with limited reports on V-N microalloyed beam steels. Compared with Nb and Ti microalloyed steels, V-microalloyed steel offers distinct technical advantages: (1) high solubility of V, which easily dissolves in steel at conventional heating temperatures; (2) easy precipitation of V carbonitrides, which can precipitate not only in the high-temperature austenite region to inhibit austenite grain growth and increase ferrite nucleation sites but also in the low-temperature ferrite region to provide intragranular ferrite nucleation cores and refine ferrite grains; (3) strong affinity between V and N, promoting V(C,N) precipitation and converting dissolved V into precipitated V, thereby significantly increasing steel strength; (4) suitability for production on conventional rolling mills without special process requirements, breaking through the traditional unrecrystallized zone controlled rolling required for Nb-microalloyed steels; and (5) economic efficiency, as V microalloying does not require nitrogen removal, transforming nitrogen from a harmful impurity into a useful and inexpensive alloying element—a unique feature of V microalloying. Due to these advantages, V-microalloyed steels with high-temperature recrystallization controlled rolling have been rapidly developed and applied worldwide in recent years, though research has mainly focused on medium-carbon non-quenched and tempered steels and H-beam steels. Studies on VN or V(C,N) precipitation in austenite and its effect on microstructure in V-N microalloyed low-carbon hot-rolled strips remain limited.

Building on previous research, this work added appropriate amounts of V and N elements to C-Mn steel to maximize alloy savings and reduce costs while ensuring comprehensive properties. Using OM, SEM, and TEM analyses, we investigated the effects of different nitrogen contents and coiling processes on the microstructure and properties of V-N microalloyed high-strength hot-rolled strips. A 650 MPa grade high-strength beam steel with composition 0.09%C-

1.5%Mn-0.1%V-0.028%N (mass fraction) was successfully developed, and its strengthening mechanism was analyzed.

1 Experimental Methods

In alloy design, to promote VN precipitation in austenite and refine austenite grains, the steel must contain relatively high V and N contents. The chemical compositions after melting are shown in Table 1 . The N content in V-microalloyed steel is 0.0055%, representing conventional control levels in steel plants, while the N content in V-N microalloyed steel is 0.0280%, designed according to the stoichiometric ratio based on the atomic weights of V and N.

For rolling process design, the relatively low dissolution temperature of V(C,N) in V-N microalloyed steel allows for low-temperature heating. Therefore, the heating temperature should be as low as possible to obtain fine and uniform austenite structure while ensuring sufficient dissolution of microalloying elements. Assuming no vacancies in carbides and nitrides and ideal stoichiometry, the complete dissolution temperature can be calculated using the following formula [16]:

$$6.72 - 9500/3.63 - 8700/AS = 1$$

where wV, wC, and wN are the mass fractions of V, C, and N in steel, respectively, and T_{AS} is the complete dissolution temperature of the experimental steel. Substituting the chemical compositions of V-microalloyed and V-N microalloyed steels from Table 1 yields dissolution temperatures of 995 ℃ and 1135 ℃, respectively. Thus, heating temperatures of 1000 ℃ and 1150 ℃ are appropriate for V-microalloyed and V-N microalloyed steels, respectively.

The thermomechanical controlled processing (TMCP) was designed as follows: after holding at the heating temperature for 120 min, rolling commenced with a finishing temperature of 870 ℃ in two stages. To obtain a uniform microstructure, sparse front-end cooling was applied after exiting the finishing mill. The coiling temperature for V-microalloyed steel was set at 600 ℃, while V-N microalloyed steel was coiled at 560 ℃, 600 ℃, and 660 ℃.

Metallographic samples were cut from the hot-rolled plates, ground and polished along the rolling direction, and electrolytically polished to remove surface oxides. After etching with 4% HNO_3 + 96% C_2H_5OH solution for 15 s, microstructural observation was conducted using a LEO-1450 SEM. Tensile specimens were machined along the rolling direction according to GB/T 228-2002 and tested at room temperature using an MTS810 universal testing machine at a strain rate of 2 mm/min.

Carbon extraction replicas were prepared by polishing samples and etching with 4% HNO_3 + 96% C_2H_5OH. A carbon film was then deposited using a spray coater, cut into 3 mm × 3 mm grids, and separated in 10% HNO_3 + 90%

C_2H_5OH solution before retrieval with copper grids. Thin foil specimens were mechanically thinned to 60 m, punched into 3 mm diameter discs, and electropolished to perforation using 5% HCl + 95% C_2H_5OH electrolyte at 35–45 V. Fine microstructures and precipitates were examined using a JEM-2000FX TEM and a JEM-2010 high-resolution TEM (HRTEM).

2 Results and Discussion

2.1 Mechanical Properties

Table 2 presents the mechanical properties of V-microalloyed and V-N microalloyed steels. The mechanical properties of V-microalloyed steel are significantly lower than those of V-N microalloyed steel at different coiling temperatures. At a finishing temperature (T_f) of 870 ℃ and coiling temperature (T_c) of 600 ℃, V-microalloyed steel exhibits a yield strength (σ_s) of only 475 MPa, tensile strength (σ_b) of 546 MPa, and elongation (δ) of 33.5%. For V-N microalloyed steel with constant T_f, mechanical properties vary considerably with T_c. At T_c = 570 ℃, σ_s and σ_b are 568 MPa and 649 MPa, respectively, with $\delta = 25.0\%$. When T_c increases to 600 ℃, both σ_s and σ_b increase substantially to 605 MPa and 687 MPa—improvements of 37 MPa and 38 MPa compared to 570 ℃ coiling, and increases of 130 MPa and 141 MPa compared to V-microalloyed steel under the same process—while δ reaches 24.5%. Further increasing T_c to 660 ℃ causes a significant strength decrease, with σ_s and σ_b dropping to 491 MPa and 577 MPa, respectively, though δ increases to 31.4%, slightly better than V-microalloyed steel at 600 ℃. Both steels exhibit relatively low yield ratios (0.86–0.88). These results demonstrate that V-N microalloyed steel possesses superior mechanical properties, with optimal performance achieved at T_f = 870 ℃ and T_c = 600 ℃.

2.2 Microstructure

Figure 1 [Figure 1: see original paper] shows SEM images of V-microalloyed and V-N microalloyed steels under different hot rolling conditions. Both steels consist of ferrite with a small amount of pearlite, where the gray phase is ferrite and the bright white phase distributed at ferrite grain boundaries is pearlite. Under identical processing conditions (T_f = 870 ℃, T_c = 600 ℃), V-microalloyed steel exhibits an average ferrite grain size of approximately 8.5 mm with irregular grain shapes—ferrite boundaries are not as smooth and straight as those of polygonal ferrite—and local regions contain some fine ferrite grains, indicating poor microstructural uniformity. In contrast, V-N microalloyed steel shows more uniform ferrite grains with an average size of about 4.5 mm and increased pearlite content (Figures 1a and 1c). This demonstrates that increased N content significantly refines ferrite grains and promotes pearlite formation. For V-N microalloyed steel at constant T_f = 870 ℃, the average ferrite grain size is about 6.5 mm at T_c = 570 ℃ (Figure 1b), decreases to approximately 4.5 mm at T_c = 600 ℃ (Figure 1c), but coarsens dramatically to about 12.5 mm at T_c = 660 ℃, with concurrent pearlite colony coarsening (Figure 1d). Thus, ferrite grain size does not simply increase with T_c; an optimal parameter exists for grain refinement, primarily related to VN or V(C,N) precipitation behavior in austenite.

2.3 V(C,N) Precipitate Characteristics

TEM images of precipitate distributions in V-microalloyed and V-N microalloyed steels at T_f = 870 ℃ and T_c = 600 ℃ are shown in Figure 2 [Figure 2: see original paper]. In both steels, second-phase particles precipitate dispersedly within ferrite grains, at grain boundaries, and along dislocation lines, indicating three precipitation modes: homogeneous nucleation, grain boundary nucleation, and dislocation line nucleation. In V-microalloyed steel, precipitates are primarily intragranular, relatively large, and few in number, with fewer grain boundary precipitates (Figure 2a). V-N microalloyed steel contains numerous precipitates distributed throughout grains, grain boundaries, and dislocation lines (Figure 2b). According to Yong Qilong [16], although grain boundary nucleation of V(C,N) is fastest, it is not dominant because V atoms do not easily segregate to grain boundaries. Once V(C,N) forms at a grain boundary, it creates a V-depleted zone, and further precipitation requires bulk diffusion of dissolved V atoms to the boundary, which involves a large energy barrier. Consequently, once V(C,N) forms at a grain boundary, it loses continued nucleation capability, and dislocation line nucleation becomes predominant [17]. V(C,N) precipitation along dislocation lines pins dislocations, increasing resistance to dislocation motion and requiring greater external stress for plastic deformation, thereby enhancing strength through precipitation strengthening. V(C,N) precipitation along austenite/ferrite boundaries not only inhibits austenite grain growth but also refines ferrite grains, simultaneously providing fine grain and precipitation strengthening. As is well known, V(C,N) precipitation in austenite is limited, with most precipitation occurring in ferrite, providing stronger precipitation strengthening than Nb and Ti. Increasing N content and applying deformation can promote V(C,N) precipitation in austenite for fine grain strengthening and toughness improvement, while the remaining V precipitates in ferrite for strengthening [18].

TEM images of precipitates in both steels are shown in Figure 3 [Figure 3: see original paper]. At the same coiling temperature (600 ℃), V-microalloyed steel contains fewer V(C,N) precipitates ranging from 5–45 nm, primarily spherical and ellipsoidal (Figure 3a). V-N microalloyed steel contains more numerous V(C,N) precipitates with near-cubic, spherical, and ellipsoidal morphologies. The cubic V(C,N) particles are larger (50 nm), while spherical and ellipsoidal precipitates range from 3–50 nm, with approximately 60% being smaller than 10 nm (Figure 3c). At constant N content, T_c significantly affects precipitate quantity and size. At T_c = 570 ℃, numerous V(C,N) precipitates form, primarily 10–40 nm in size (Figure 3b). At T_c = 660 ℃, significant coarsening occurs, with sizes mainly 35–50 nm (Figure 3d). Since smaller, more dispersed precipitates provide stronger strengthening, V-N microalloyed steel exhibits maximum precipitation strengthening at $T_c = 600$ ℃.

2.4 Intragranular Ferrite Nucleation

Figure 4 [Figure 4: see original paper] shows OM and SEM images of intragranular ferrite (IGF) in V-N microalloyed steel, along with EDS analysis of precipitates and a nucleation schematic. The OM image (Figure 4a) reveals numerous IGF nuclei (indicated by arrows). Literature [19] indicates that extensive V(C,N) precipitation in austenite facilitates ferrite nucleation within austenite grains, providing favorable conditions for IGF formation. The IGF nucleation mode shown in Figure 4a is typical of nucleation on V(C,N) precipitates. The SEM image (Figure 4b) clearly shows IGF morphology, with bright white V(C,N) precipitates (EDS shown in Figure 4c) and dark IGF nucleated on these precipitates. The nucleation schematic (Figure 4d) illustrates that IGF does not nucleate randomly within austenite grains but rather forms layer-by-layer along the ferrite side of austenite/ferrite boundaries, extending into the grain interior. Two necessary conditions for high IGF nucleation rates are the presence of established ferrite interfaces and numerous finely dispersed V(C,N) precipitates in the matrix.

2.5 Strengthening Mechanisms

The above analysis shows that increasing N content leads to increased σ_s and σ_b. This is primarily attributed to N promoting V precipitation. On one hand, V(C,N) precipitation in austenite refines austenite grains and promotes IGF formation, thereby refining ferrite grains. On the other hand, increased precipitate quantity enhances precipitation strengthening. The combined effects of fine grain and precipitation strengthening result in significantly higher strength in V-N microalloyed steel compared to V-microalloyed steel. At constant N content, both σ_s and σ_b first increase then decrease with increasing T_c, achieving optimal properties at 600 ℃. At low T_c, rapid cooling after finishing prevents nitrogen from precipitating, leaving it in solid solution, while slow diffusion of V and N atoms during coiling results in limited V(C,N) precipitation and weak strengthening. As T_c increases, dissolved nitrogen decreases and more V(C,N) precipitates form, increasing precipitation strengthening and promoting ferrite grain refinement, leading to substantial strength improvement. At $T_c = 660$ ℃, although most nitrogen precipitates, high temperature accelerates atomic diffusion, causing significant V(C,N) coarsening that weakens precipitation strengthening, while ferrite grains also coarsen, reducing fine grain strengthening and decreasing overall strength.

For ferrite-pearlite steel, yield strength can be predicted using the extended Hall-Petch formula [20]:

$$\sigma_y = \sigma_0 + \Delta\sigma_{ss} + \Delta\sigma_{grain} + \Delta\sigma_{dis} + \Delta\sigma_{Orowan}$$

where σ_y is yield strength, σ_0 is matrix lattice resistance (P-N force), and $\Delta\sigma_{ss}$, $\Delta\sigma_{grain}$, $\Delta\sigma_{dis}$, and $\Delta\sigma_{Orowan}$ are yield strength increments from solid solution strengthening, fine grain strengthening, dislocation strengthening, and precipitation strengthening, respectively. Analyzing the contributions of each strengthening mechanism reveals the primary strengthening mechanisms and the roles of microalloying elements V and N.

Strength calculations were performed for both steels processed under identical conditions. The contributions from each strengthening mechanism are as follows:

Matrix lattice resistance (P-N force) [21]: $\sigma_0 = 54$ MPa.

Solid solution strengthening contribution [22]: $\Delta\sigma_{ss} = 475w_C + 375w_{Si} + 37w_{Mn} + 84w_{Si} + 555w_P + 3450w_N$, where w_M is the mass fraction of solute M (C, N, Si, Mn) dissolved in the ferrite matrix. Si and Mn are ferrite-forming elements present entirely in ferrite at 0.18% and 1.50%, respectively. C and N contents are affected by V(C,N) precipitation. Assuming precipitates have the stoichiometry $VC_xN_{(1-x)}$, the dissolved amounts can be calculated using solubility product formulas for VC and VN in austenite [16]:

$$w[V] \cdot w[C]^x = 10^{6.72-9500/T}$$

$$w[V] \cdot w[N]^{(1-x)} = 10^{3.63-8700/T}$$

$$w[V] = wV - 50.94 \cdot f$$

$$w[C] = wC - 12x \cdot f$$

$$w[N] = wN - 14(1-x) \cdot f$$

where wV, wC, and wN are total mass fractions, $w[V]$, $w[C]$, and $w[N]$ are dissolved mass fractions, x is the effective activity of VC in $VC_xN_{(1-x)}$, T is temperature, and f is the volume fraction of precipitates. At the finishing temperature of 870 ℃, the dissolved V, C, and N in austenite are 0.078%, 0.089%, and 0.0010% for V-microalloyed steel, and 0.016%, 0.089%, and 0.0062% for V-N microalloyed steel. After rapid cooling to 600 ℃, assuming minimal precipitation during cooling and that $VC_xN_{(1-x)}$ precipitates in ferrite after pearlite transformation (with matrix C content of 0.0218%), the solubility products in ferrite [16] give:

$$w[V] \cdot w[C]^x = 10^{2.72-6080/T}$$

$$w[V] \cdot w[N]^{(1-x)} = 10^{2.45-7830/T}$$

Solving these equations yields dissolved V, C, and N in ferrite of 0.0086%, 0.0063%, and 0.000002% for V-microalloyed steel, and 0.0009%, 0.0216%, and 0.0021% for V-N microalloyed steel. The calculated solid solution strengthening contributions are 74 MPa and 82 MPa, respectively.

Fine grain strengthening contribution [23]: $\Delta\sigma_{grain} = k \cdot d_F^{-1/2}$, where $k = 17.40\ \mathrm{MPa} \cdot \mathrm{mm}^{1/2}$ [23] and d_F is the average ferrite grain size (equivalent diameter). The average ferrite grain sizes are 8.5 mm and 4.5 mm for V-microalloyed and V-N microalloyed steels, respectively, giving fine grain strengthening contributions of 188 MPa and 260 MPa.

Dislocation strengthening contribution [24,25]: $\Delta\sigma_{dis} = \alpha G b \rho^{1/2}$, where $\alpha = 0.435$ (a crystallography-dependent factor), $G = 8.3 \times 10^4$ MPa (shear modulus), $b = 0.248 \times 10^{-7}$ cm (Burgers vector magnitude), and ρ is dislocation density (cm^{-2}). For ferrite-pearlite steel, dislocation density is not as high as in bainite or martensite. TEM observations of thin foil samples estimate dislocation densities of $1.20 \times 10^{10}\ \mathrm{cm}^{-2}$ and $2.47 \times 10^{10}\ \mathrm{cm}^{-2}$ for V-microalloyed and V-N microalloyed steels, respectively, yielding dislocation strengthening increments of 98 MPa and 141 MPa.

Precipitation strengthening contribution [26,27]: $\Delta\sigma_{Orowan} = 8.995 \times 10^3 \cdot f^{1/2} \cdot d^{-1} \cdot \ln(2.417d)$, where f is the volume fraction of precipitates and d is the average precipitate diameter. Statistical analysis of Figure 3 gives average precipitate diameters of 13.5 nm and 8.0 nm for V-microalloyed and V-N microalloyed steels, respectively. Based on dissolved V content in ferrite, the volume fractions are 0.192% and 0.210%, respectively, yielding precipitation strengthening increments of 102 MPa and 153 MPa.

Table 3 summarizes the yield strength components for both steels. Key conclusions are: (1) The calculated yield strengths are 458 MPa and 604 MPa, closely matching measured values; (2) Fine grain strengthening is the dominant mechanism in both steels, contributing 41–44% of total strength; (3) The combined contribution of precipitation and dislocation strengthening ranks second, reaching 31–35%. The high dislocation density, precipitation strengthening, and fine grain strengthening in V-N microalloyed steel result in significantly higher yield strength than V-microalloyed steel, with strengthening mechanisms ranked as: fine grain strengthening > precipitation strengthening > dislocation strengthening > solid solution strengthening > matrix strengthening.

Conclusions

(1) The microstructure of both V-microalloyed and V-N microalloyed steels consists primarily of ferrite with small amounts of pearlite. Under identical finishing and coiling temperatures, V-microalloyed steel with lower

yield strength has an average ferrite grain size of 8.5 mm, while V-N microalloyed steel with higher yield strength has a grain size of 4.5 mm. Fine grain strengthening is the primary strengthening mechanism in both steels, accounting for 41–44% of yield strength.

(2) At constant finishing temperature, the yield and tensile strengths of V-N microalloyed steel first increase then decrease with increasing coiling temperature, achieving optimal comprehensive mechanical properties at 600 ℃ coiling, with yield strength of 605 MPa, tensile strength of 687 MPa, and elongation of 24.5%.

(3) Under identical finishing and coiling temperatures, V-N microalloyed steel contains finer, more dispersed precipitates than V-microalloyed steel, with sizes mainly 3–50 nm (approximately 60% smaller than 10 nm) and an average size of 8.0 nm, along with higher dislocation density. The combined contribution of precipitation and dislocation strengthening to yield strength reaches 34.44%.

(4) Nitrogen promotes vanadium precipitation. V(C,N) precipitation in austenite facilitates intragranular ferrite nucleation, ultimately promoting ferrite grain refinement.

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Note: Figure translations are in progress. See original paper for figures.