NIOBIUM-BASED ALLOY DESIGN FOR STRUCTURAL APPLICATIONS: PROCESSING-STRUCTURE-PROPERTY PARADIGM

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Abstract

The use of niobium as a microalloying element in high strength steels is now well-known and widely adopted. However, with recent advances in thermo-mechanical processing, inclusive of ultrafast cooling technology, and modifications in alloy design, niobium continues to provide significant mechanical property and processing benefits. With this in perspective, we describe here the footprint of niobium in the new generation of high strength microalloyed steels that involve low carbon-based alloy design approach. In this regard, we underscore the effectiveness of niobium in low carbon-Nb (or low C-Nb-Ti) microalloyed steels in terms of obtaining superior mechanical properties and cost-effectiveness, using recent experiences in the processing of microalloyed steels. Also, elucidated are precipitation and microstructural characteristics when niobium is used as a standalone microalloying element or in conjunction with titanium and molybdenum.

Introduction

Niobium-microalloyed steels containing small percentage of niobium (0.02-0.1%) significantly impact mechanical properties and is a cost-effective approach to achieve a balance combination of mechanical properties. The addition of niobium to steel results in the precipitation of niobium carbide and niobium nitride within the structure of the steel. These components refine grain size, retard recrystallization, and provide precipitation strengthening, the consequence of which is high strength-toughness combination, formability, and weldability of microalloyed steels. The grain refining effect of Nb is primarily associated with the delay in recrystallization. Furthermore, by lowering austenite-to-ferrite transformation temperature, Nb simultaneously enhances ferrite nucleation rate and reduces grain growth rate. The combined effect leads to a fine-grained transformation structure that simultaneously increases strength, toughness, and ductility.

A number of structural steels (linepipe, automotive, construction) with yield strength greater than ~350 MPa and above contain niobium to obtain the right balance of strength, toughness and weldability. The selection of Nb as a microalloying element compared to aluminum, titanium, and vanadium is because of the combined benefits of precipitation hardening and refinement of microstructure that gives the best combination of high yield strength and toughness. Discussed below are two instances that illustrate the footprint and profound impact of Nb microalloying.

Niobium Microalloying in Structural Beams

In recent years, the significant advantages of niobium microalloying were extended to beams that have traditionally been C-Mn steels. The room temperature tensile properties of Nb-microalloyed steels were: yield strength 57-65 ksi (393-448 MPa), tensile strength 72-75 ksi (496-517 MPa) and % elongation of 23-25. During processing of structural beams, a wide range of toughness were obtained with change in cooling rate without compromising strength (Figure 1) [1].

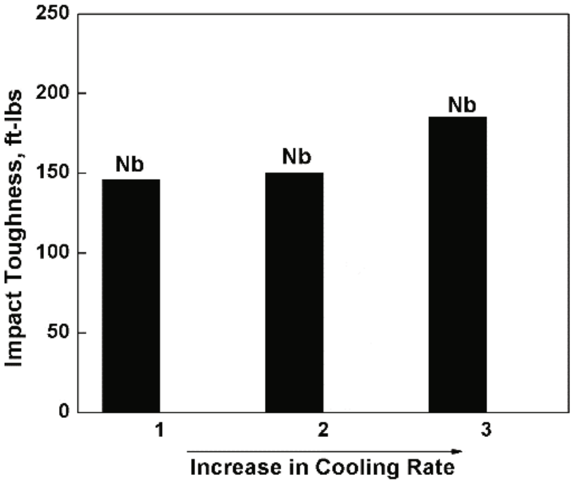


Figure 1. Room temperature Charpy v-notch impact toughness of Nb-microalloyed steels [1].

The variation in impact toughness as a function of cooling rate was related to the microstructure (Figure 2) [1]. The primary microstructure at low cooling rate was polygonal ferrite and pearlite. At intermediate cooling rate, the microstructure consisted of lath-type/bainitic ferrite together with degenerate pearlite, while at high cooling rate it was predominantly bainite. The average grain size of the steels processed at different cooling rates was similar and in the range of ~ 10-12 μm. The different type of ferrite morphologies were formed by different mechanisms and are discussed elsewhere [1]. With increase in cooling rate the cementite morphology in pearlite changed from lamellar pearlite to degenerate pearlite and finally to small cementite particles. Degenerate pearlite is formed by nucleation of cementite at ferrite/austenite interface followed by carbide-free ferrite layers enclosing the cementite particles in the transformation temperature range between pearlite and upper bainite [2]. Similar to lamellar pearlite, degenerate pearlite is also formed by the diffusion process and considering its morphology, the difference is attributed to the insufficient carbon diffusion to develop continuous lamellae [3]. Degenerated pearlite promotes toughness [4].

The fine precipitates were MC type cubic niobium carbides and the precipitates exhibited [100]α//[110]NbC Baker-Nutting orientation relationship with the ferrite matrix. Strain-induced precipitation of NbC at dislocations and fine-scale precipitation contributed to strengthening.

The microstructural parameters that influenced toughness were ferrite grain size, degenerate pearlite, and bainitic ferrite. The finer cementite in degenerate pearlite as compared to the lamellar pearlite contributed to the yield strength and toughness combination because coarse pearlite deforms inhomogeneously with strain localized in narrow slip bands, whereas fine degenerate pearlite exhibits uniform strain distribution during deformation [5]. Thus, the significant increase in toughness with cooling rate of Nb-microalloyed steels was related to toughening, through the presence of the phases of degenerate pearlite and bainite.

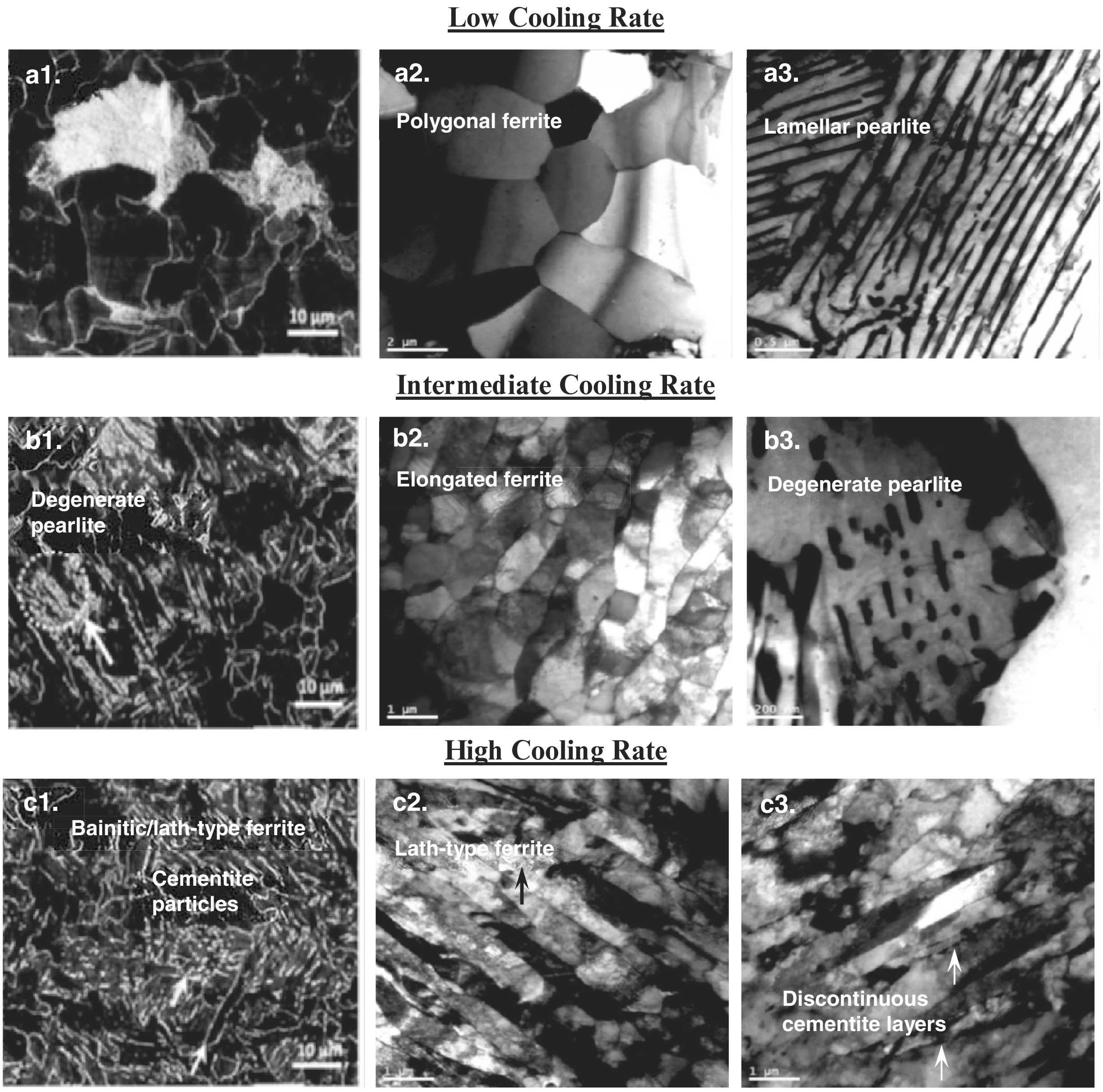


Figure 2. Representative scanning (a1, b1, c1) and transmission electron (a2, b2, c2, a3, b3, c3) micrographs of Nb-microalloyed steels processed at different cooling rates (a) low, (b) intermediate, and (c) high cooling rates [1].

In hot rolled steel strip, the microstructure and mechanical properties are greatly affected by the process parameters, such as rolling ratio, rolling temperature, cooling pattern, cooling rate and the coiling temperature. Among them, the influence of coiling temperature is considered to be significant [6, 7]. Undoubtedly, controlling the coiling temperature is economical and efficient way to improve the properties of microalloyed steels. Moreover, the coiling temperature is associated with the precipitation of microalloying elements [8-12], which is expected to play a strengthening role via nanoscale precipitation.

At coiling temperature of 579°C, the yield strength was in the range of 701-728 MPa, tensile strength was 996-997 MPa, and elongation was 21-23% (Figure 3a) [13]. When the coiling temperature was 621°C, yield strength, tensile strength, and elongation were in the range of 749-821 MPa, 821-876 MPa, and 19-25%, respectively (Figure 3a) [13].

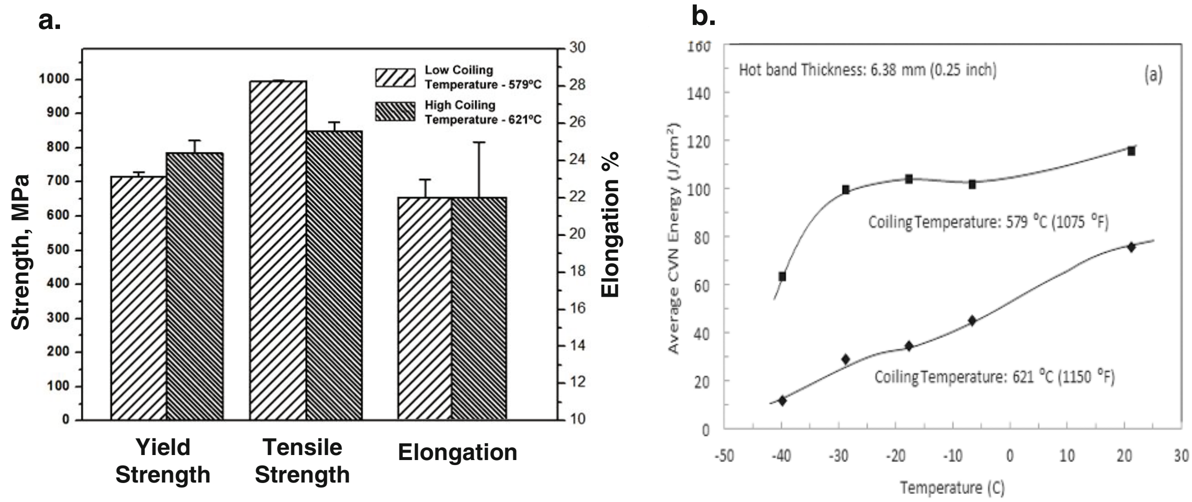


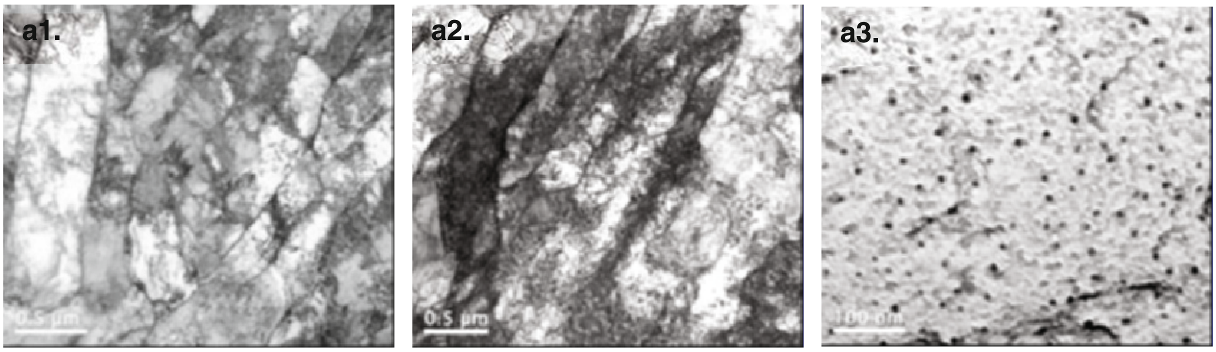
Figure 3. (a) Average yield strength, tensile strength, and elongation and (b) impact toughness (constant gage thickness of 6.38 mm) of Nb-microalloyed steels coiled at 579°C and 621°C [13].

The impact toughness as a function of temperature for the two coiling temperatures are presented in Figure 3b [13]. It can be seen that toughness increases with increase in temperature for both the coiling temperatures. However, the impact toughness was superior for the low coiling temperature as compared to the high coiling temperature. For instance, at -40°C the toughness was 70 J/cm^2 for the coiling temperature of 579°C and 38 J/cm^2 for the coiling temperature of 621°C [13]. These results imply that the impact toughness is strongly influenced by the coiling temperature.

The microstructure of steels with different coiling temperatures were characterized by a dual-phase microstructure consisting of lath bainite with sub-boundaries and polygonal ferrite (Figure 4) [13]. However, lower coiling temperature was predominantly bainitic, compared to the higher coiling temperature which comprised of significant fraction of polygonal ferrite. From the CCT and TTT diagrams of the experimental steel [13], bainite transformation was expected to occur at

606°C. Thus, steel coiled at a lower temperature of 579°C, the polygonal ferrite grains were formed during the pre-coiling process, while for the steel coiled at higher temperature of 621°C, the ferrite grains were nucleated during the coiling process, when the ferrite transformation occurred, such that the ferrite grain size was relatively large. With some degree of approximation, it can be said that when the coiling temperature was 579°C, coiling occurred close to bainite transformation (Bs ~ 606°C), while in the other case, coiling occurred at a temperature greater than Bs.

Coiling Temperature: 579ºC



Coiling Temperature: 621ºC

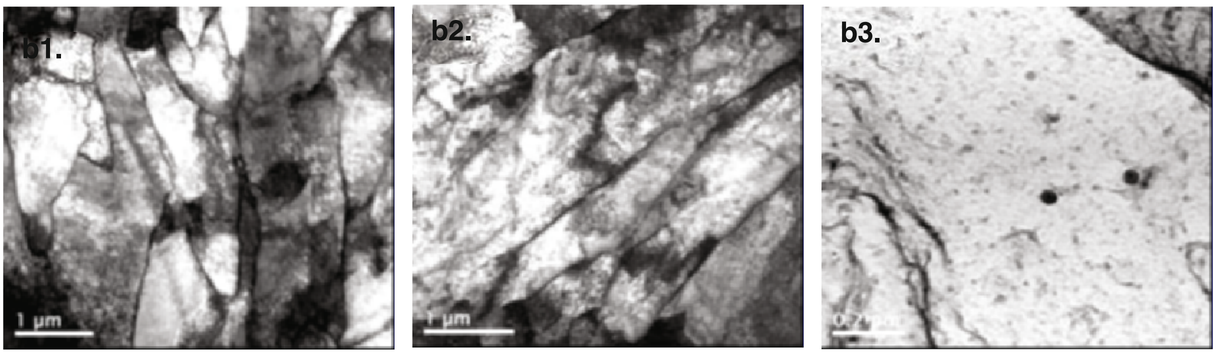


Figure 4. Representative transmission electron (a1, b1, a2, b2, a3, b3) micrographs of Nb-microalloyed steels processed at different coiling temperatures (a) 579ºC, and (b) 621ºC [13].

Steel processed via thin slab casting, Nb and Ti, contributed to (NbC, Ti(Nb)C) grain refinement and precipitation strengthening. The (Ti,Nb)C is not surprising because according to solubility calculations, microalloying elements, Ti and Nb, are interchangeable in the precipitate lattice in view of similarity in the crystal structure (NaCl-type) and lattice parameter [14]. The nanoscale carbides had a lattice parameter of 0.438 nm [15]. If we compare the precipitation behavior at different coiling temperatures, the NbC precipitates formed at 579°C were relatively fine, and uniformly dispersed in comparison to the coiling temperature of 621°C. This difference in behavior is attributed to the application of lower coiling temperature. Additionally, bainite transformation produced a high density of dislocations, providing nucleation sites for carbides to precipitate.

In summary, coiling in the bainite temperature range (low coiling temperature) led to higher volume fraction of bainite (hard phase) and low fraction of polygonal ferrite, such that the higher volume fraction of bainite was favorable for high tensile strength. As regards the low yield strength of low coiling temperature steel, the dislocation accumulation (just before yielding) in the ferrite phase is envisaged to be higher because of lower content of ferrite phase than in the higher coiling temperature steel, such that it yields first. Furthermore, the finer lath microstructure and dual-phase microstructure of bainite and ferrite was favorable for toughness. The bainite constituent improves the toughness significantly by preventing crack propagation at packet and lath boundaries [16]. The uniform distribution of precipitates was also favorable for enhancing toughness. Thus, near uniform dispersion of precipitates and high volume fraction of bainite were the underlying reasons for the best combination of strength and toughness.

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