

SELECTED DEVELOPMENTS IN Nb-MICROALLOYED LONG PRODUCTS AND FORGINGS *

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Abstract

Niobium-microalloying technology has been increasingly applied in a wide range of steel applications over the past half-century, to increase strength, control microstructure, enhance properties and enable a variety of applications. To achieve desired performance levels, thermomechanically processed microalloyed steels are widely supplied by the steel industry for high volume applications in hot-rolled plate, sheet and structural steels. However, in steel long products and forgings, the final properties are often generated by downstream users, after heat-treatment, surface hardening, forging or wire drawing. Two examples are presented highlighting advancements associated with Nb-microalloying, to enhance microstructures and properties developed during thermomechanical and/or downstream processing. In the first example, a 0.02 wt. pct. Nb addition was made to a medium-carbon bar steel intended for induction-hardening applications requiring fatigue and fracture resistance in bending and torsion. The Nb addition as well as thermomechanical bar processing led to beneficial refinement of both the pre-induction and post-induction microstructures. In the second example, a 0.01 wt. pct. Nb addition to a high-carbon wire rod was found to refine the pearlite colony size and interlamellar spacing, and increase the hardness.

Keywords: Niobium; Forgings; Induction, Wire Rod, Microalloyed.

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1 INTRODUCTION

Niobium-microalloying technology has been increasingly applied in a wide range of steel applications over the past half-century, to increase strength, control microstructure and enhance different application-specific properties. To achieve desired performance levels, thermomechanically processed microalloyed steels are widely supplied by the steel industry for high volume applications in hot-rolled plate, sheet and structural steels. However, in steel long products and forgings, the final properties are often generated by downstream users, after heat-treatment, surface hardening, forging or wire drawing.

Previous reviews of work in the authors' laboratories on this topic area have provided background on the fundamentals of microalloying in long and forged products, and applications including high strength as-forged components to eliminate heat-treatment, use of Nb for grain refinement of carburized gear steels with improved fatigue performance, microalloyed automotive springs, etc. [1-3]. Nb-containing carbonitrides beneficially suppress grain growth at elevated temperature [4-6], and provide dispersion strengthening in some processing scenarios. Effective use of Nb requires careful consideration of processing details.

Here we review some key highlights of more recent work on microalloyed steels for induction hardened bar applications, and in high strength pearlitic wire.

2 MICROALLOYING OF MEDIUM-CARBON BAR STEELS FOR INDUCTION HARDENING APPLICATIONS

Medium-carbon steels such as grade 1045 are commonly used in induction hardened shafts. Surface hardening increases the performance with respect to bending and

torsion, where stresses are greatest near the surface. The hardness, and thus carbon content of the martensite are typically limited due to fracture considerations, although substructure refinement is considered to offer the potential for enhanced fatigue and fracture performance [7].

To refine the induction hardened microstructure, alloying and processing approaches were considered to modify the microstructure response to the induction hardening process. Microalloying along with thermomechanical processing was thus explored as a means of conditioning the initial microstructure, with the aim of refining the austenite that forms during the rapid induction heating and short austenitizing time prior to quenching [8-11].

Three variants of a 0.45 wt. pct. carbon bar steel were obtained, with variations in microalloy content. The chemical compositions of the three steels are shown in Table 1. The base 1045 composition contained a small (0.021 wt. pct.) aluminum addition that might serve as a grain refiner, in the form of AlN. The two other alloys were modified through an addition of 0.08 wt. pct. vanadium in the 10V45 steel, and a 0.092 wt. pct. vanadium plus 0.020 wt. pct. niobium in the 10V45Nb steel. The steels were industrially melted and rolled, with a controlled variation in the hot-rolling process parameters.

Table 1. Chemical compositions of medium-carbon steels (wt. pct.).

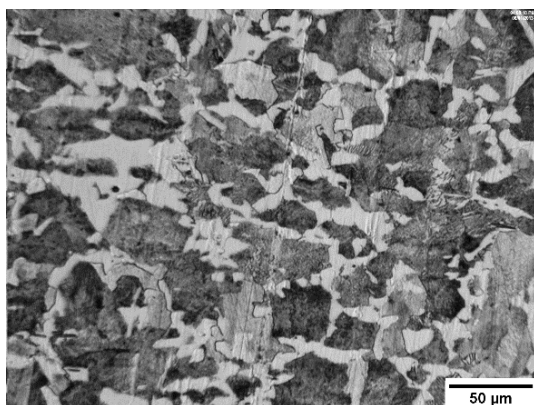
Alloy	C	Mn	Si	Cr	Mo
1045	0.45	0.72	0.24	0.12	0.04
10V45	0.45	0.82	0.28	0.15	0.03
10V45Nb	0.46	0.85	0.27	0.14	0.03

Alloy	V	Nb	Al	N
1045	0.003	0.001	0.021	0.0097
10V45	0.084	0.001	0.000	0.0127
10V45Nb	0.092	0.020	0.000	0.0124

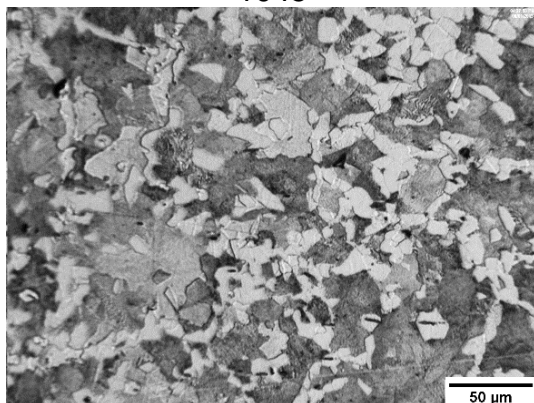
152 mm square billets were reheated to 1150-1200 °C and i) conventionally hot-

rolled with a final rolling temperature of 1000 °C, or ii) thermomechanically rolled with intermediate water cooling prior to finish rolling with a final rolling temperature of 800 °C. For both of these industrial process histories, the 38 mm diameter bars were air cooled after rolling.

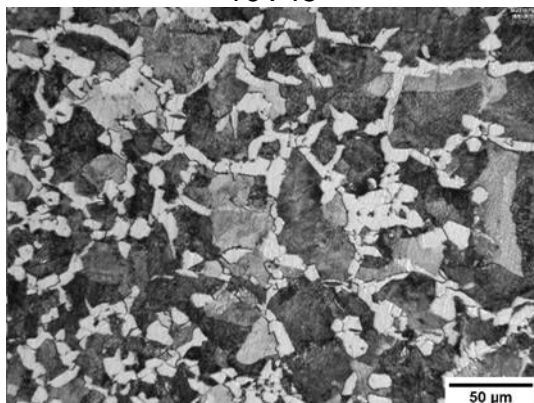
The microstructures of the three hot-rolled steels are shown in Figure 1, and the companion thermomechanically processed



1045



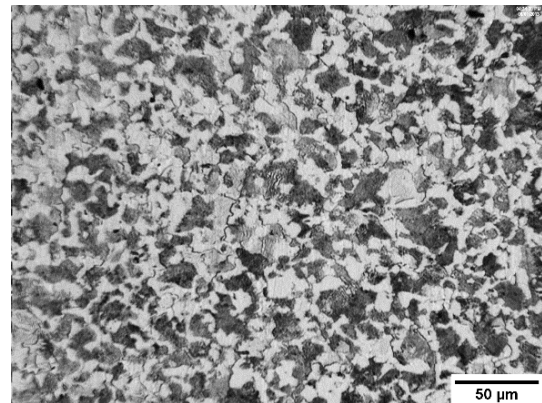
10V45



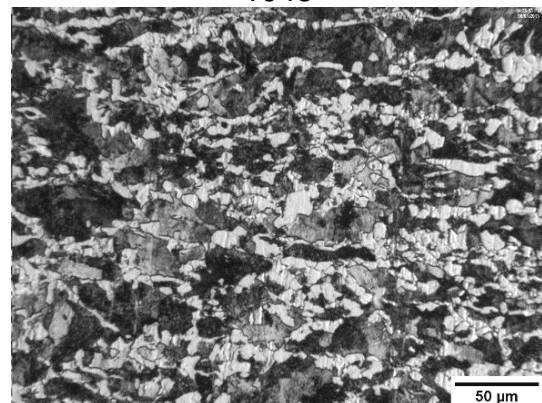
10V45Nb

Figure 1. Light optical micrographs from the near-surface of the three industrially hot-rolled bars after air cooling [8,9]. 2% Nital etch.

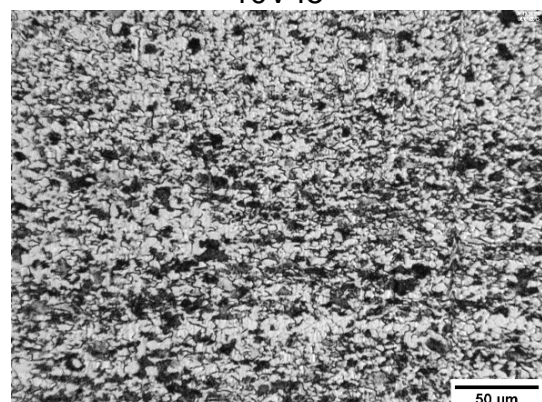
steels in Figure 2. Ferrite-pearlite microstructures were obtained in all instances. The grain-boundary proeutectoid ferrite allotriomorphs in the hot rolled steels are suggestive of the austenite size and morphology prior to transformation. Substantial differences between the three hot-rolled steels are not apparent, and transformation occurred from equiaxed,



1045



10V45



10V45Nb

Figure 2. Near-surface microstructures of the three industrially thermomechanically rolled bars after air cooling [8,9]. 2% Nital etch.

recrystallized austenite. In contrast, in the thermomechanically-processed steels, the overall microstructure is somewhat refined in the 1045 and 10V45 steels, reflecting austenite conditioning effects.

In the 10V45Nb steel, thermomechanical processing of the austenite resulted in substantial refinement of the final microstructure, reflecting “pancaking” of the austenite during finish rolling at temperatures below the “recrystallization-stop” temperature. These effects of Nb are well known in flat-rolled steel products. While less common in long-products, new bar production technologies with water cooling boxes and precision sizing blocks should enable increased use of thermomechanically processed Nb-microalloyed steels.

Laboratory investigations were conducted using the same three steels to examine the evolution of austenite, where rapid cooling enables characterization of the “prior” austenite grain size (PAGS) and morphology at room temperature after transformation. Gleeble[®] simulation was employed to model the thermal and deformation conditions associated with multi-stand industrial bar rolling with hot-rolling (HR) or thermomechanical (TMP) rolling schedules, as well as subsequent induction hardening.

Evolution of the austenite grain size is illustrated via the PAGS results in Figure 3. The refinement in the simulated as-rolled conditions (HR and TMP) associated with microalloy additions and reduced finish rolling temperatures are consistent with the discussion of the industrially produced microstructures (Figures 1 and 2), as expected. Induction hardening simulation in the Gleeble[®] was enabled by its rapid resistance heating capability. The simulation was designed to match the thermal history expected 0.5 mm below the surface, for a 2 mm case depth [8]. The PAGS results in Figure 3 for the simulated

induction austenitizing conditions shows that additional austenite grain refinement results from rapid heating. More importantly, the microstructural refinement in the as-rolled conditions, associated with microalloying and thermomechanical rolling is carried through the induction hardening process. Finer ferrite plus pearlite microstructures provide a greater number of austenite nucleation sites, leading to finer austenite. Microalloy precipitation developed in the as-rolled microstructures may also contribute to the refinement observed after simulated induction hardening, through their retarding effects on grain growth after austenite formation. The finest microstructures are obtained after thermomechanical rolling, in the steel containing additions of both vanadium and niobium. The austenite refinement achieved by microalloying and thermomechanical processing is considered to provide potential for enhanced fracture resistance of induction hardened components [7,8,12].

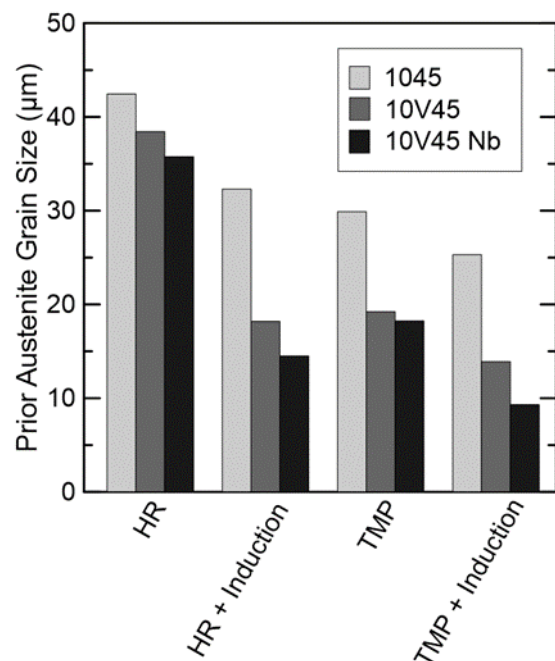


Figure 3. Average prior-austenite grain size (PAGS) after hot-rolling or thermomechanical rolling of three 1045 steel variants, and the associated PAGS after simulated induction hardening.

2 MICROALLOYING OF HIGH CARBON PEARLITIC WIRE ROD

Cold-drawn pearlite is ubiquitous in many high strength wire applications. Very high strengths are achieved by heat treatment to obtain very fine pearlite with small pearlite interlamellar spacing, along with strain hardening associated with cold-drawing. Alloying to control the austenite-to-pearlite transformation kinetics is common, and vanadium is often used for precipitation strengthening. Niobium has been less commonly added in higher carbon steels, in part due to the more limited solubility of NbC under industrially relevant processing conditions, but recent studies have suggested that small Nb additions may be beneficial; some refinement of pearlite interlamellar spacing has also been reported [13,14]. Microstructure evolution was consequently investigated in eutectoid steels with and without niobium, having the chemical compositions shown in Table 2 [15-21].

Table 2. Chemical compositions of microalloyed pearlitic steels (wt. pct.).

Alloy	C	Mn	Si	Cr
1080V	0.8	0.5	0.2	0.2
1080V+Nb	0.8	0.4	0.2	0.2

Alloy	V	Nb	Al	N
1080V	0.079	0	0.005	0.006
1080V+Nb	0.079	0.01	0.004	0.0126

The steels were processed by laboratory hot-rolling from a reheating temperature of 1200 °C, followed by air cooling. Subsequent Gleeble[®] heat treatment involved austenitizing at 1093 °C, and continuous cooling at various rates. Vickers hardness was assessed, and the apparent pearlite interlamellar spacing was measured on high resolution scanning electron micrographs recorded from etched metallographic cross-sections, based on an average of nine measurements from four different fields of view. Results are shown in Tables 3 and 4, for cooling rates of 2.5 and 5.0 °C/s, respectively [17,20].

Table 3. Hardness of pearlite after continuous cooling at 2.5 °C/s.

Steel	Vickers Hardness (1 kg)	Pearlite Interlamellar Spacing (nm)
1080V	348 ± 6	177.3 ± 4.8
1080V+Nb	393 ± 2	158.2 ± 4.7

Table 4. Hardness of pearlite after continuous cooling at 5.0 °C/s.

Steel	Vickers Hardness (1 kg)	Pearlite Interlamellar Spacing (nm)
1080V	377 ± 10	168.0 ± 4.0
1080V+Nb	406 ± 3	138.1 ± 5.7

Comparison of Tables 3 and 4 indicates that the hardness increases and the pearlite interlamellar spacing is reduced when transforming to pearlite at a greater cooling rate, as expected. Notably, both Tables indicate that the steel with a 0.01 Nb (wt. pct.) microalloy addition exhibits increased hardness and reduced interlamellar spacing relative to the steel with only a V microalloy addition. These results support earlier studies suggesting that Nb can refine the pearlite interlamellar spacing.

It should be noted that the ILS results were obtained as part of a larger study examining a wider range of thermal processing than described here (including “patenting” with different austenitizing and isothermal transformation temperatures, as well as full hot-torsion simulations of multipass bar rolling and Stelmor[®] cooling [19]). Finer pearlite interlamellar spacing associated with the Nb addition was also found in the full thermomechanical simulations of wire rod production (with a 1093 °C reheat prior to rolling) [16], although the effects were less clear in the patented microstructures [18]. In these studies, Nb was also found to refine the austenite microstructure, decrease the pearlite colony size, and suppress the transformation of austenite. Atom probe tomography studies to identify solute Nb effects on transformation behavior (*i.e.* “solute-drag”) were attempted, but were

not conclusive due to the very small concentrations of Nb in solution at the processing temperatures employed in wire processing [16]. Nonetheless, it appears that Nb microalloying additions can provide beneficial pearlite refinement in high-carbon wire rod products, and additional studies are warranted to confirm the effects in industrially produced materials, and to further clarify the controlling mechanisms.

4 CONCLUSION

The results of two studies are highlighted, exploring the influence of niobium additions in long products.

In the first example, Nb microalloying was beneficially employed in medium-carbon bar steel intended for induction-hardening applications requiring fatigue and fracture resistance in bending and torsion. Refinement of the pre-induction microstructure resulted from both the Nb addition as well as thermomechanical processing to condition the austenite prior to transformation. The pre-induction microstructure refinement was carried through the rapid austenitizing treatment associated with induction hardening, refining the austenite structure, and thus providing the opportunity for enhanced performance.

In the second example, Nb microalloying was beneficially employed in high carbon steels intended for high strength wire rod production. Nb was found to refine the pearlite colony size and interlamellar spacing after transformation, and increase the hardness.

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