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SELECTED DEVELOPMENTS IN NB-MICROALLOYED FORGINGS FOR INDUCTION HARDENING, AND PEARLITIC WIRE ROD

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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 enhance properties; namely to increase strength, control microstructure, 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 interlamellar spacing, and increase the hardness.
Keywords: Niobium; Forgings; Induction; Wire rod; Microalloyed.

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 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. The behavior of Nb in thermomechanical processing of long products has also been reviewed recently [7].

Here we highlight some key findings of 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 is typically limited due to fracture considerations, although substructure refinement is considered to offer the potential for enhanced fatigue and fracture performance [8].

To refine the induction hardened microstructure, alloying and processing approaches were considered to modify the microstructural response to the induction

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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 [9-12].

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 0.084 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.

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 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, 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.

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	

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

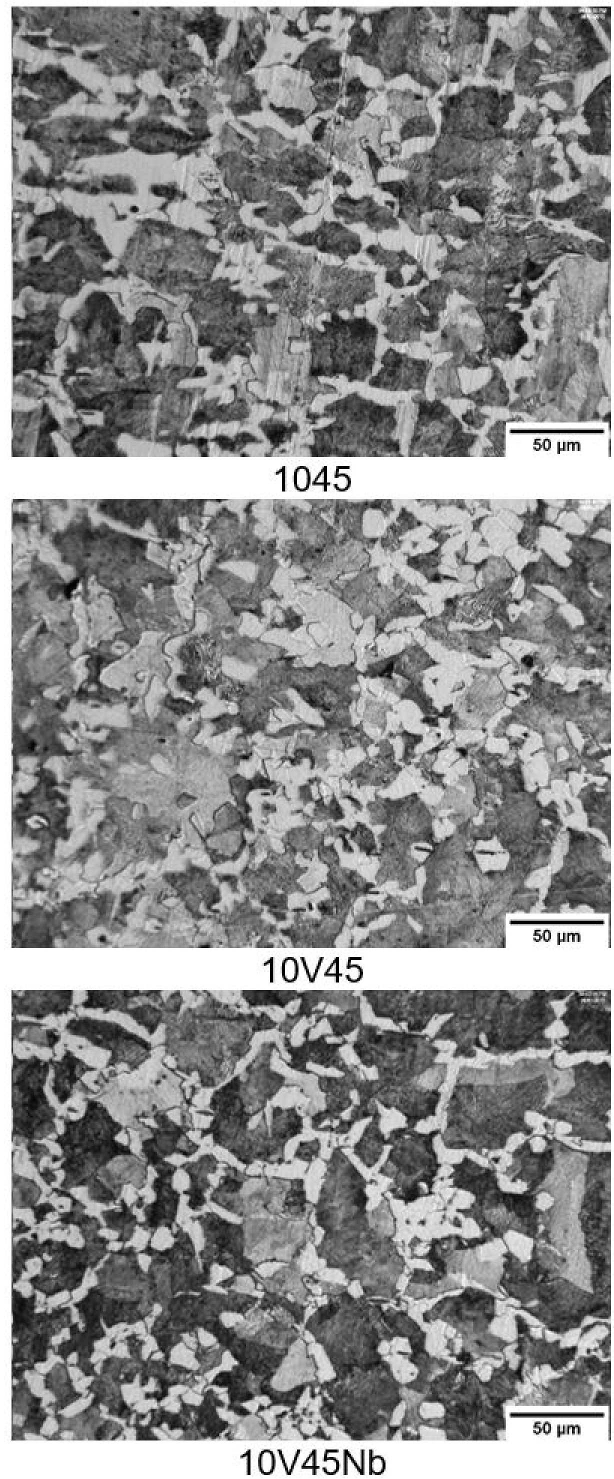

Figure 1. Light optical micrographs from the near-surface of the three industrially hot-rolled bars after air cooling [9,10]. 2% Nital etch.

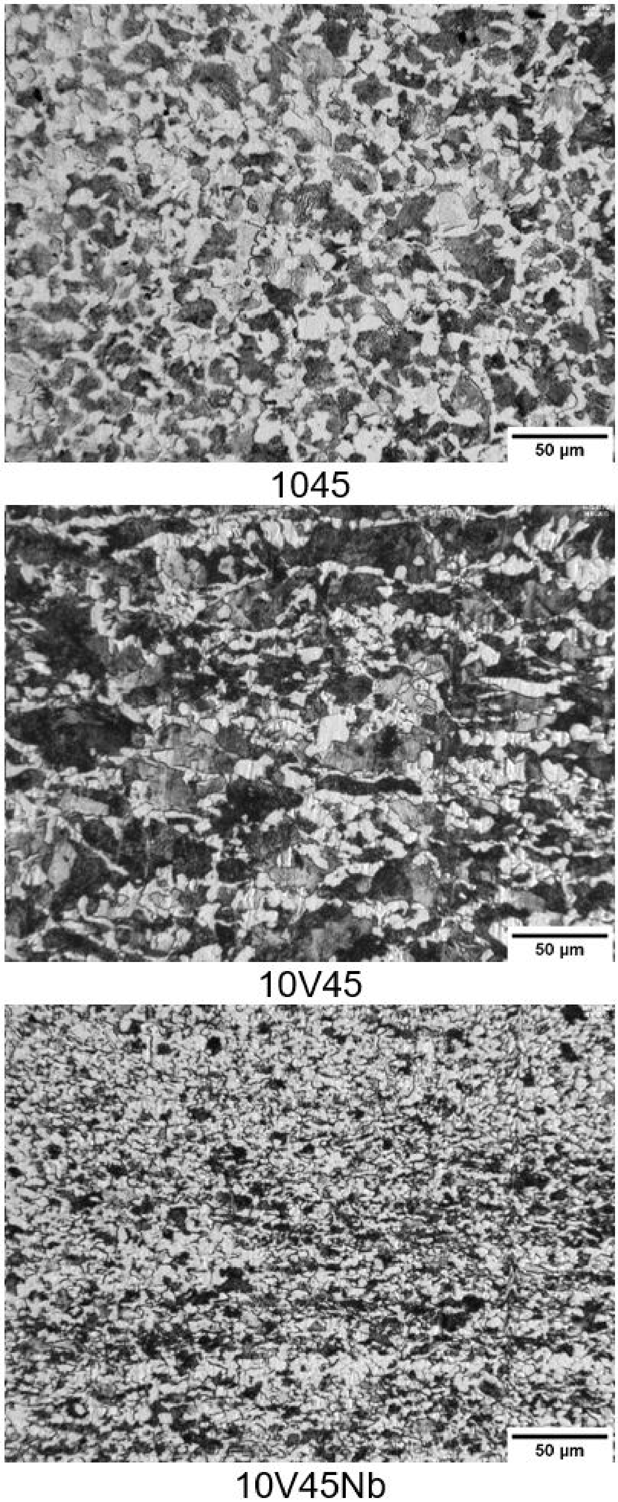

Figure 2. Near-surface microstructures of the three industrially thermomechanically rolled bars after air cooling [9,10]. 2% Nital etch.

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

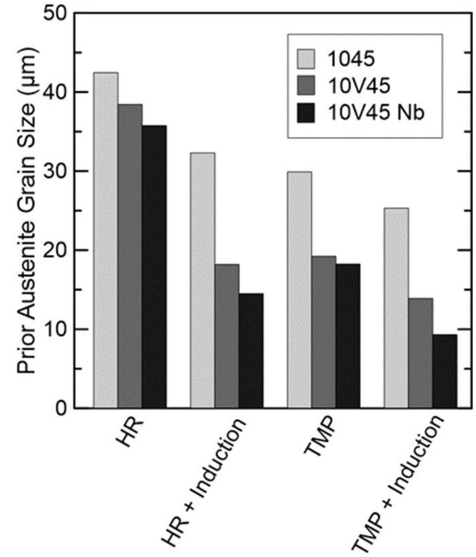

Figure 3. Average prior-austenite grain size (PAGS) after hot-rolling or thermomechanical rolling of three 1045 steel variants, and the associated PAGS after simulated induction hardening.

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 [9].

The PAGS results in Figure 3 for the simulated induction austenitizing conditions show 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 [8,9,13].

3 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

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

Alloy	C	Mn	Si	Cr	V	Nb	Al	N
1080V	0.8	0.5	0.2	0.2	0.079	0	0.005	0.006
1080V+Nb	0.8	0.4	0.2	0.2	0.079	0.01	0.004	0.0126

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

interlamellar spacing (ILS), 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 [14,15]. The reduced solubility of NbC at high carbon levels has also been questioned recently, and this remains an issue for further clarification [16].

In the work reviewed here, microstructure evolution was investigated in eutectoid steels with and without niobium, having the chemical compositions shown in Table 2 [17-23].

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 [19,22].

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 [21]). 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) [18], although the effects were less clear in the patented microstructures [20]. 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 [18]. 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 CONCLUSIONS

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 microstructural refinement was carried through the rapid austenitizing treatment associated with induction hardening, resulting in refinined final austenite structures, 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 interlamellar spacing after transformation, and increase the hardness.

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REFERENCES

1 Matlock DK, Speer JG. Microalloying concepts and application in long products. Materials Science and Technology. 2009;25(9):1118-1125.

2 Matlock DK, Alogab KA, Richards MD, Speer JG. Surface processing to improve the fatigue resistance of advanced bar steels for automotive applications. Materials Research. 2005;8(4):453-459.

3 Matlock DK, Krauss G, Speer JG. New microalloyed steel applications for the automotive sector. Materials Science Forum. 2005;500-501:87-96. http://dx.doi.org/10.4028/www.scientific.net/MSF.500-501.87.

4 Alogab KA, Matlock DK, Speer JG, Kleebe HJ. The influence of niobium microalloying on austenite grain coarsening behavior of Ti-modified SAE 8620 steel. ISIJ International. 2007;47(2):307-316.

5 Enloe CM, Findley KO, Speer JG. Austenite grain growth and precipitate evolution in a carburizing steel with combined niobium and molybdenum additions. Metallurgical and Materials Transactions A, Physical Metallurgy and Materials Science. 2015;46(11):5308-5328.

6 Thompson RE, Matlock DK, Speer JG. The fatigue performance of high temperature vacuum carburized Nb modified 8620 steel. SAE Transactions. 2007;116:392-407.

7 López B, Pereda B, Bastos F, Rebellato M, Rodriguez-Ibabe JM. Challenges of Nb application in thermomechanical processes of steels for long products. Materials Science Forum. 2018;941:386-393.

8 Hayashi T, Kurosawa N, Yamada K. Method of prior austenite grain refining using induction hardening. Japan: JFE Steel Corporation; 2010. p. 4-9. (JFE Technical Report; no. 15) [cited 2020 May 4]. Available at: www.jfe-steel.co.jp/en/research/report/015/pdf/015-03-2.pdf

9 Whitley B. Thermomechanical processing of microalloyed bar steels for induction hardened components [thesis]. Golden: Colorado School of Mines; 2017.

10 Whitley BM, Easter CT, Cryderman RL, Speer JG. Thermomechanical simulation and microstructural analysis of microalloyed medium carbon bar steels. In: Proceedings of the International Symposium on Advances in Metallurgy of Long and Forged Products; 2015; Vail, Colorado. Warrendale: AIST;2015. p. 48-58.

11 Whitley BM, Speer JG, Cryderman RL, Goldstein RC, Findley KO, Matlock DK. Effects of microalloy additions and thermomechanical processing on austenite grain size control in induction-hardenable medium carbon steel bar rolling. Materials Science Forum. 2016;879:2094-2099.

12 Cryderman R, Whitley B, Speer J. Microstructural evolution in microalloyed steels with high-speed thermomechanical bar and rod rolling. In: Proceedings of 23rd IFHTSE Congress; 2016; Savannah, USA. Materials Park: ASM International; 2016. p. 181-187.

13 Cryderman RL, Speer JG. Microstructure and notched fracture resistance of 0.56% C steels simulated induction hardening. In: Proceedings of the 29th Heat Treating Society Conference; 2017; Columbus, Ohio. Materials Park: ASM International; 2017. p. 226-233.

14 Jansto SG. MicroNiobium alloy approach in medium and high carbon steel bar, plate and sheet products. Metallurgical and Materials Transactions. B, Process Metallurgy and Materials Processing Science. 2014;45:438-444.

15 Jansto SG. Niobium-bearing construction steels and global application trends. In: Proceedings of the Value-Added Niobium Microalloyed Construction Steels Symposium; 2015; Singapore. Warrendale: CBMM, TMS; 2015. p. 91-113.

16 Mi YF, Cao JC, Zhang ZY, Qi HQ, Zhou XL, Yong QL. Effect of carbon content on the solubility of niobium carbide in austenite. Iron and Steel. 2012;47(3):84-88.

17 Miller S. Effect of microalloying on the strength of high carbon wire steels [thesis]. Golden: Colorado School of Mines; 2012.

18 Miller S. Effect of microalloying on pearlite transformation of high carbon wire steels [thesis]. Golden: Colorado School of Mines; 2015.

19 De Moor E, Miller SL, Van Raemdonck W. Microalloyed high carbon wire steels. In: Proceedings of the TMS 2014: 143rd Annual Meeting & Exhibition; 2014; San Diego, California. Cham: Springer; 2014. p. 935-942.

20 Miller SL, De Moor E. Influence of Nb additions on microstructural evolution of a V-microalloyed high-carbon wire steel during patenting. Journal of The Minerals, Metals & Materials Society. 2014;66(8):1471-1478.

21 Miller SL, De Moor E, Eavenson G. Thermomechanical processing simulation of mill deformation of high carbon wire rod. In: AISTech 2014 Proceedings; 2014; Indianapolis. Warrendale: AIST; 2014. p. 2735-2742.

22 De Moor E, Miller SL. Effects of niobium additions to a vanadium microalloyed high carbon wire steel. Wire Journal International. 2014;47:69-72.

23 Miller SL, De Moor E. Vanadium and niobium microalloying to increase strength of high-carbon wire steels. In: Proceedings of the 83rd Annual Convention of the Wire Association International Interwire Trade Exposition; 2013 Apr 22-25; Atlanta, Georgia. Guilford: WAI; 2013. p. 1-13.

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