INFLUENCE OF NIOBIUM ON THE MICROSTRUCTURE AND PROPERTIES OF CrMo CAST STEEL FOR LINER PLATE

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Abstract

In this paper the influence of heat-treatment and Nb on the microstructure and properties of a low alloy CrMo wear-resistant steel lining plate were investigated. Based on an appropriate chemical composition design, excellent combinations of hardness and impact toughness have been achieved for the lining plate application. It was found that with a double heat treatment of 920 °C (8 h) + 550 °C (20 h), adding Nb in the range 0.025 to 0.028 wt.% improved the strength and hardness of the low alloy CrMo wear-resistant steel by 13% and 16% respectively, while the impact toughness was slightly reduced. With a heat treatment of 880 °C (8 h) + 550 °C (20 h), adding 0.03 wt.%Nb increased the strength and hardness of the low alloy CrMo wear-resistant steel by 10% and 16% respectively, while the elongation and reduction of area were raised from 2 to 4% and 0.5 to 2% respectively, and the impact toughness was only slightly reduced. Analysis of the microstructure after heat treatment revealed the interlamellar spacing of the pearlitic matrix after the higher temperature processing is smaller than it is after the lower temperature processing.

Introduction

Nb is commonly used as a microalloying element, which can effectively improve the strength and toughness of steel [1]. In recent years, research about the toughening effect of Nb has focused on as-rolled low-C microalloyed steel. The main strengthening mechanisms of Nb are solid solution strengthening, precipitation strengthening by Nb carbonitrides and grain refinement strengthening. Solid solution strengthening and precipitation strengthening tend to reduce the steel toughness, however, grain refinement can simultaneously improve the strength and toughness. Additionally, the Nb carbonitrides can significantly increase the hardness and enhance the abrasion resistance [2]. Research about the effect of Nb in cast steel is not so common, especially in high-carbon wear-resistant steels. Under normal circumstances, wear-resistant steels are mainly treated through appropriate quenching and tempering, or normalizing and tempering processes, to acquire a good combination of strength, hardness and toughness. The maximum hardness of pearlitic wear-resistant low-alloy steels can be up to 400 HBW by a normalizing and tempering treatment. The service life of the pearlitic steel is longer than that of traditional high Mn steel, but lower than for martensitic wear-resistant CrMo steels after tempering at 260 °C, (hardness is in the range 555~601 HBW). Even though the pearlitic wear-resistant steel has the lower hardness, the service life is still higher than that of a martensitic wear-resistant steel liner plate tempered at 480 °C, (hardness is in the range 477~514 HBW) [3].

Experimental Procedure

The influence of Nb on the CrMo steel equilibrium phase diagram has been analysed using Thermo-Calc software. The CrMo steel equilibrium phase diagram was determined at different Nb contents. The chemical compositions are shown in Table I.

Table I. Chemical Compositions used for Thermo-Calc Calculations (wt.%)

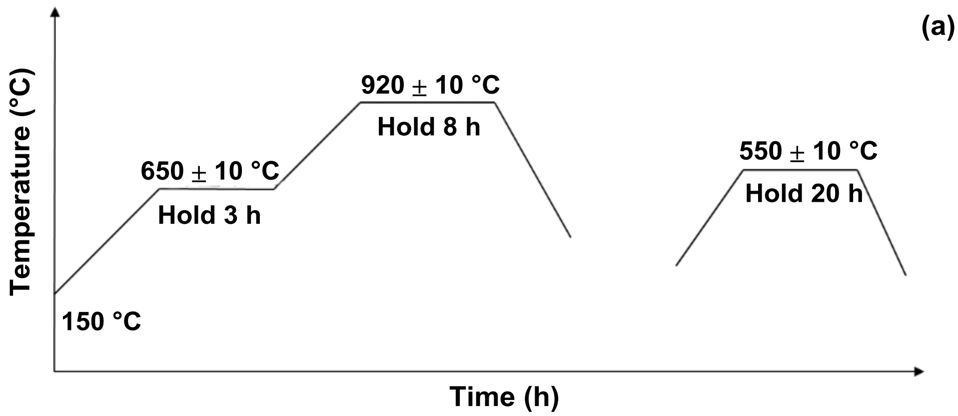
	C	Mn	Si	P	S	Cr	Mo	Ni	Cu	Nb
1#	0.85	0.60	0.60	0.03	0.03	2.50	0.40	0.05	0.20	0.00
2#	0.85	0.60	0.60	0.03	0.03	2.50	0.40	0.05	0.20	0.04
3#	0.85	0.60	0.60	0.03	0.03	2.50	0.40	0.05	0.20	0.05

The compositions of the materials used in the experimental work are shown in Table II. A2# was based on A1# with an addition of 0.028 wt.%Nb; B2# was based on B1# sample with an addition of 0.025 wt.%Nb. The steels were cast into a Y shaped mould. Test samples were then taken from the cast sections. The heat treatment process is shown in Figure 1 and is as follows: firstly, all samples were heated to 650 °C and held for 3 h: A1# and A2# were heated to 880 °C and held for 8 h whereas B1# and B2# were heated to 920 °C and held for 8 h: all samples were then spray cooled to 300 °C after which the specimens were air cooled to room temperature. The tempering process for the specimens was carried out at 550 °C, holding for 20 h, before air-cooling to room temperature.

Table II. Compositions of Experimental Steels (wt.%)

	C	Mn	Si	S	P	Cr	Mo	Nb
A1#	0.84	0.81	0.42	0.038	0.027	2.04	0.26	0.00
A2#	0.84	0.80	0.36	0.028	0.030	2.18	0.30	0.028
B1#	0.86	0.77	0.38	0.032	0.029	2.17	0.29	0.006
B2#	0.85	0.66	0.43	0.024	0.028	2.24	0.30	0.025

Tensile tests were carried out on a WE-100 Hydraulic Universal Testing Machine, according to the national Chinese standard GB/T 228-2002. Round bar specimens were used with a diameter of 10 mm, and a gauge length of 200 mm. Impact tests were performed on a NI500C Charpy impact test machine using standard specimens of dimensions 10 x 10 x 55 mm, which were tested at 20 °C. Metallographic and SEM samples were polished and etched with 4% nital solution. The microstructure was observed and evaluated with a Zeiss microscope and JSM-6700F SEM.



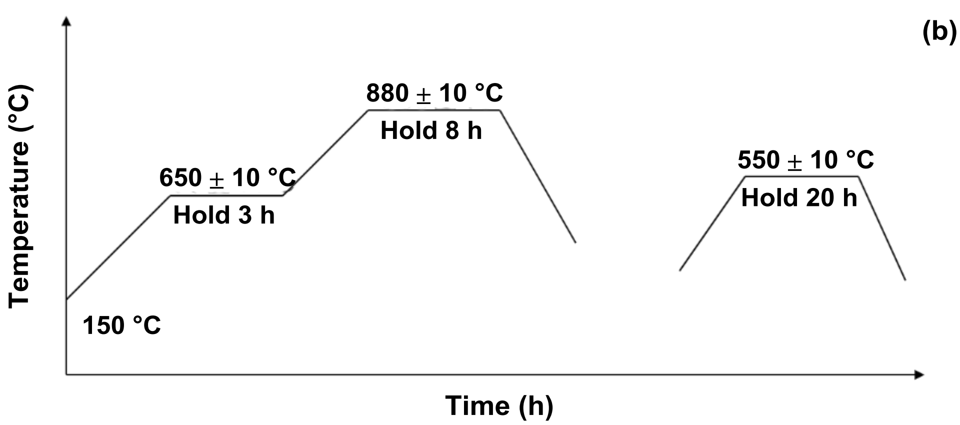


Figure 1. Sample heat treatments; (a) Heat Treatment process for samples B1# and B2#, (b) Heat Treatment process for samples A1# and A2#.

Experimental Results

The Effect of Nb on Mechanical Properties

Figures 2 and 3 show the mechanical properties following different heat treatments. Figure 2 shows data following normalizing and tempering at 880 °C (8 h) + 550 °C (20 h), and Figure 3 shows data following normalizing and tempering at 920 °C (8 h) + 550 °C (20 h). The addition of 0.028 wt.%Nb results in higher tensile strength, elongation and hardness compared to the 0 wt.%Nb steel, as shown in Figure 2. The tensile strength of A2# is 1089 MPa, and the tensile strength of A1# is 997 MPa, which has been given the same heat treatment as A2#. The tensile strength of B2# is 1117 MPa, and the tensile strength of B1# is 1112 MPa, which has been given the same heat treatment as B2#. After the heat treatment 880 °C (8 h) + 550 °C (20 h), the hardness of specimens without Nb or with Nb was 308 HB and 358 HB respectively. After the heat treatment of 920 °C (8 h) + 550 °C (20 h), the hardness of specimens without Nb or with Nb was 306 HB and 354 HB, respectively. However, the impact energy has declined a small amount with the addition of Nb, after either of the two heat treatments. Normalizing and tempering at 880 °C (8 h) + 550 °C (20 h), resulted in impact energies for A1# and A2# of 50 J and 40.5 J, respectively. Normalizing and tempering at 920 °C (8 h) + 550 °C (20 h), produced impact energies for B1# and B2# of 52 J and 47.5 J, respectively. As shown in Figures 3 and 4, the tensile strength and elongation are better following the heat treatment of normalizing and tempering at 920 °C (8 h) + 550 °C (20 h) with similar hardness and impact energy values. The above analysis shows that the mechanical properties of the materials are better with an addition of Nb and normalizing and tempering at 920 °C (8 h) + 550 °C (20 h).

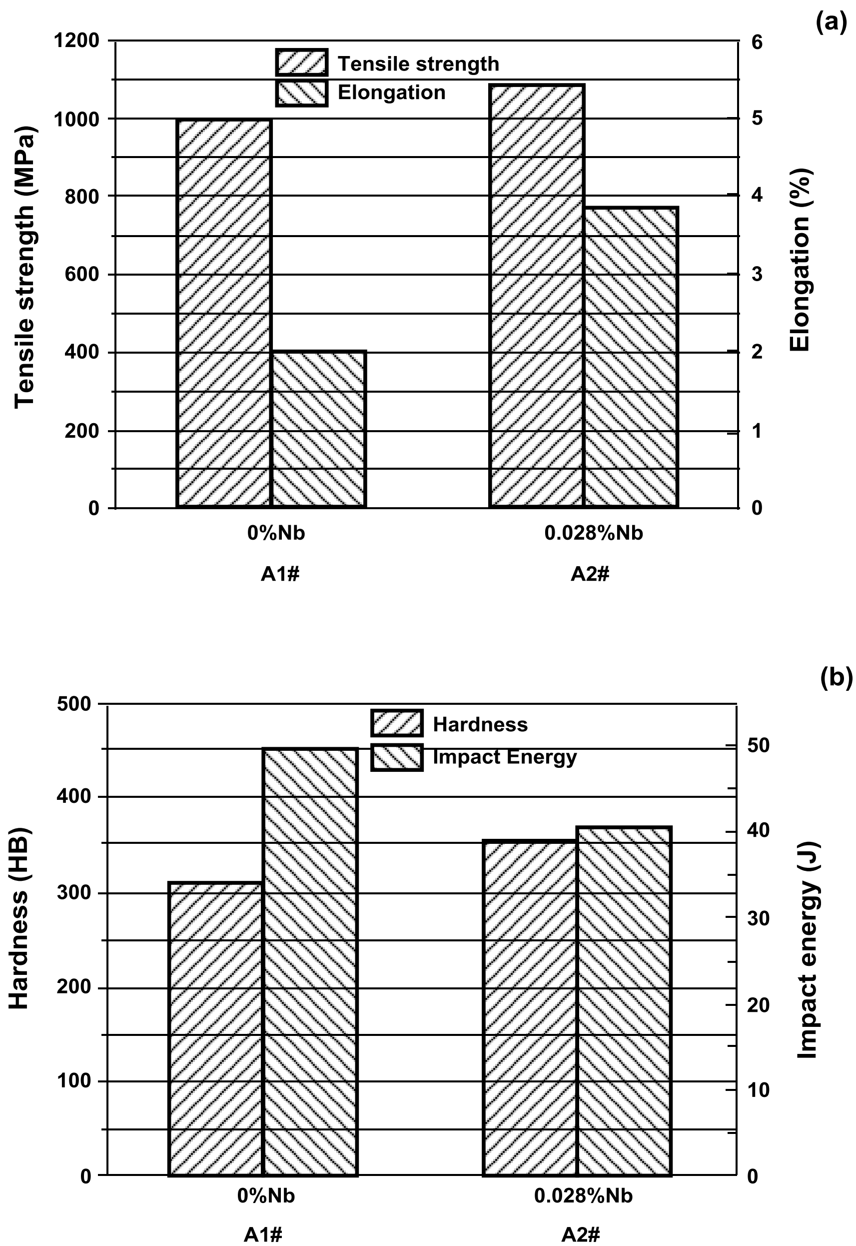
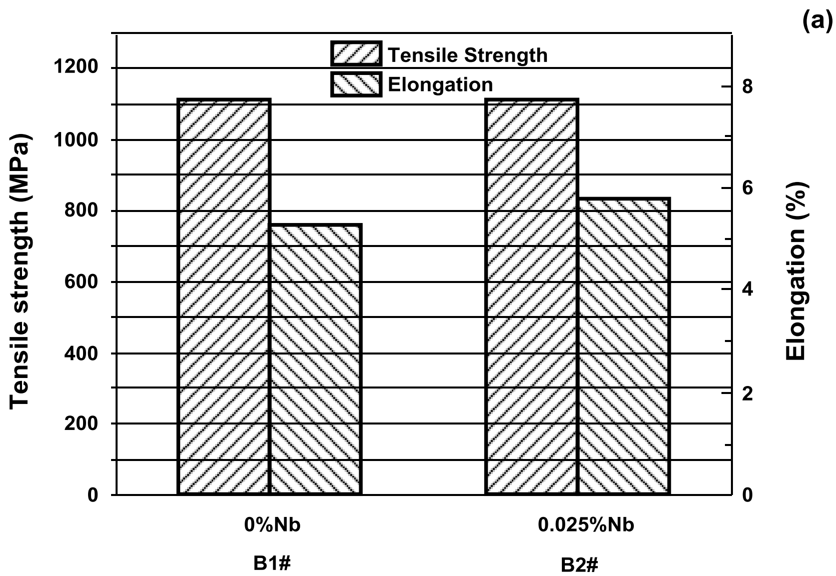


Figure 2. The mechanical properties of steels A1# and A2# after normalizing and tempering at 880 °C (8 h) + 550 °C (20 h).



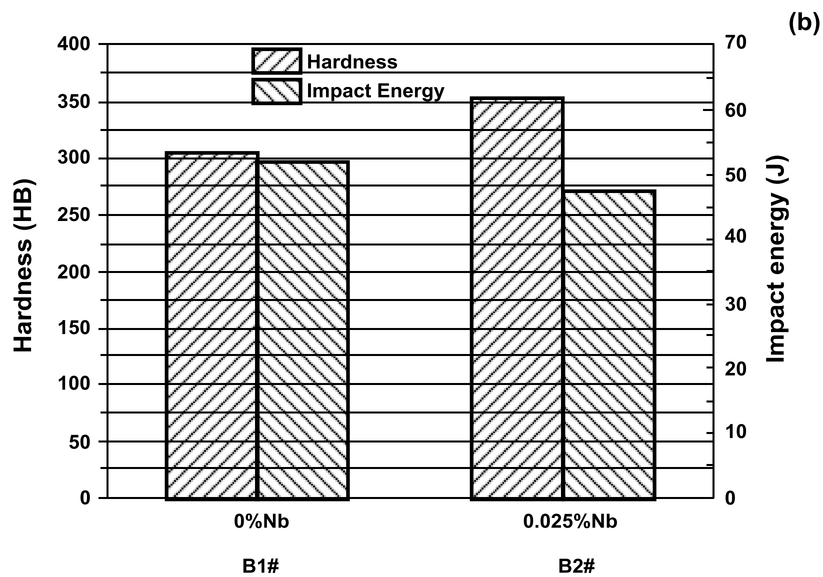


Figure 3. The mechanical properties of steels B1# and B2# after normalizing and tempering at 920 °C (8 h) + 550 °C (20 h).

The Effect of Nb on Grain Refinement

Figures 4(a) and (b) show micrographs revealing austenite grain boundaries in the 0 wt.%Nb and 0.028 wt.%Nb alloy, respectively, after normalizing and tempering at 880 °C (8 h) + 550 °C (20 h). It is evident that the austenite grain size of the sample with 0.028 wt.%Nb is much smaller than the sample with 0 wt.%Nb. Figure 5 shows the austenite grain boundaries in the steels with 0%Nb and 0.028 wt.%Nb after normalizing and tempering at 920 °C (8 h) + 550 °C (20 h). The austenite grains of the steel with 0.028 wt.%Nb are smaller than in the Nb-free sample. In addition, it can also be seen that for similar amounts of Nb, although the normalizing temperature has increased, the size of the austenite grains did not change significantly. This is due to NbC particles pinning the austenite grain boundaries and inhibiting grain growth during austenitization [4].

The Effect of Nb on Microstructure

Figures 6 and 7 show the optical microstructure and SEM micrographs of the samples with and without Nb after normalizing and tempering at 880 °C (8 h) + 550 °C (20 h). The heat treatment process of normalizing is carried out in order to obtain a homogeneous pearlitic microstructure in the final product. Considering the heat treatment process, the microstructure of the samples should be pearlitic. Generally, the pearlite interlamellar spacing is too fine to be observed optically, although occasional colonies can be resolved. Figure 6 shows grey and bright white areas which are colonies with smaller interlamellar spacing. The difference, however, is clear from SEM examination, Figure 7. Figures 8 and 9 show the equivalent observations after the 920 °C (8 h) + 550 °C (20 h) heat treatment.

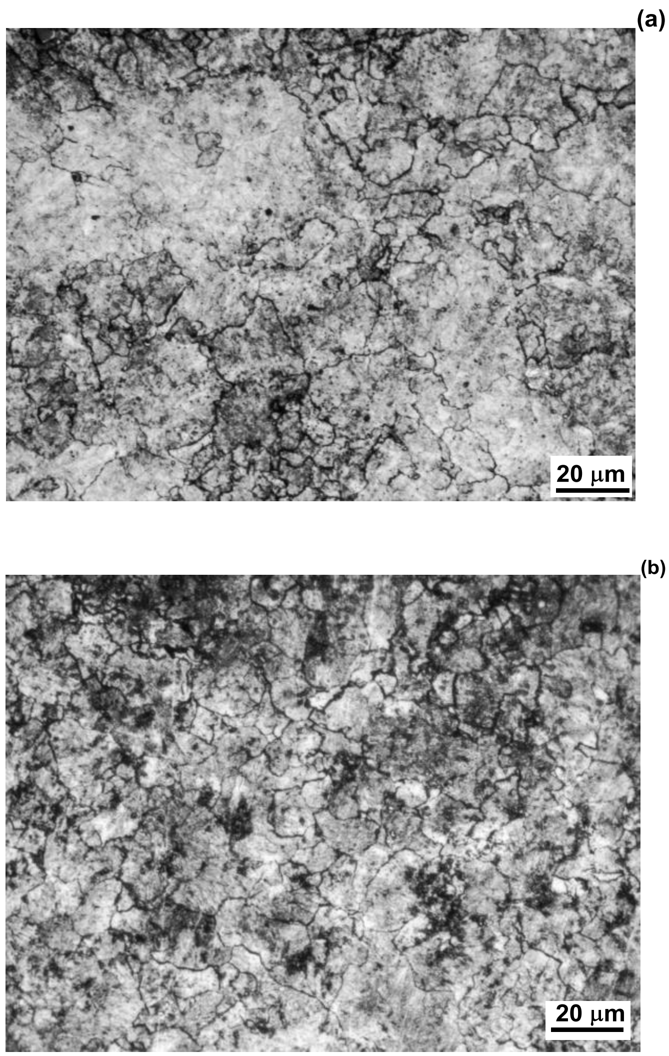


Figure 4. The austenite grain structure after normalizing and tempering at 880 °C (8 h) + 550 °C (20 h); (a) 0 wt.%Nb, (b) 0.028 wt.%Nb.

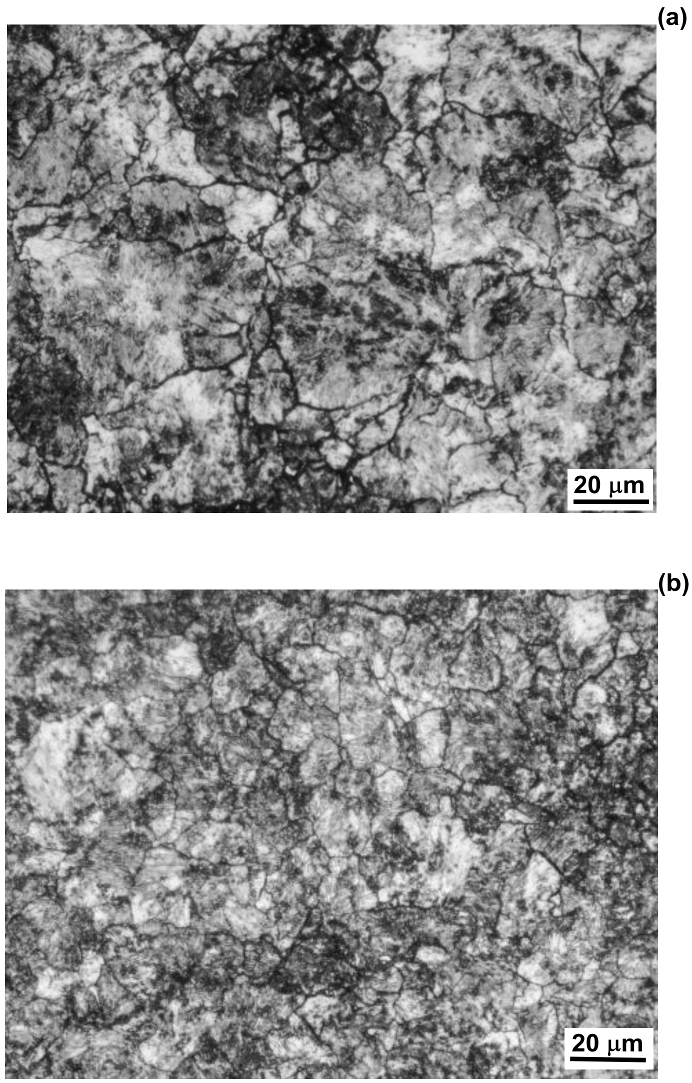


Figure 5. The austenite grain structure after normalizing and tempering at 920 °C (8 h) + 550 °C (20 h); (a) 0 wt.%Nb, (b) 0.025 wt.%Nb.

Comparing the SEM images in Figures 7 and 9, it is possible to observe that the samples with Nb contain pearlite with smaller interlamellar spacing than the sample without Nb. The smaller the interlamellar spacing of the pearlite, the higher the strength and hardness and the better the ductility [3]. However, the decrease of the interlamellar spacing will cause a deterioration in impact toughness [5]. This refinement of the interlamellar spacing is the main reason that tensile strength, hardness and elongation of the samples containing Nb are better than the Nb-free sample, and the impact energy is lower.

(a)

(b)

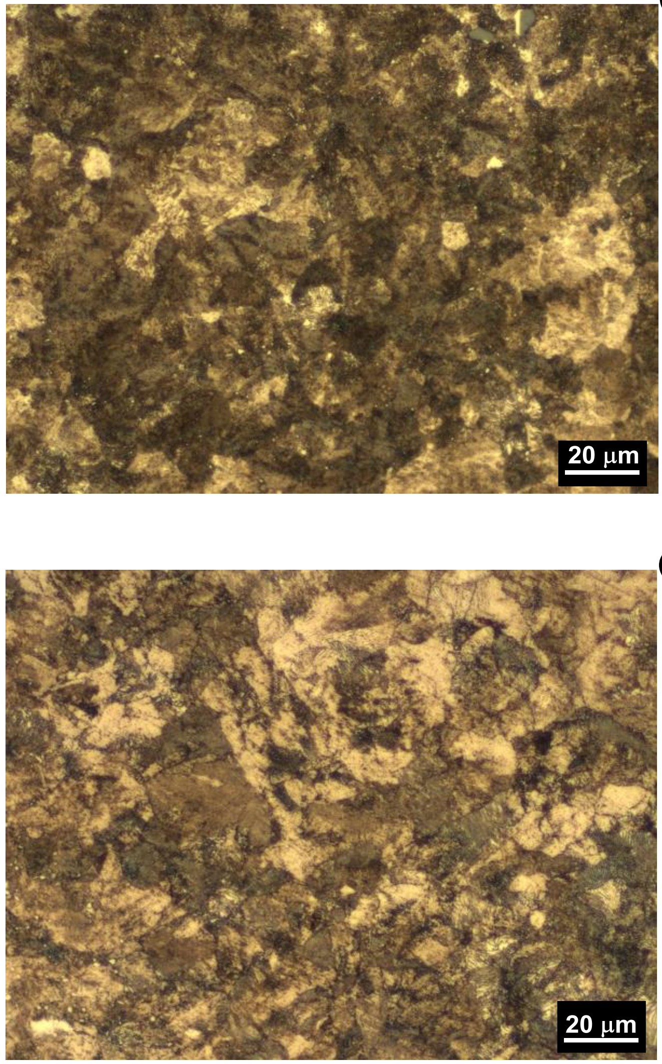


Figure 6. Microstructure after normalizing and tempering at 880 °C (8 h) + 550 °C (20 h); (a) 0 wt.%Nb, (b) 0.028 wt.%Nb.

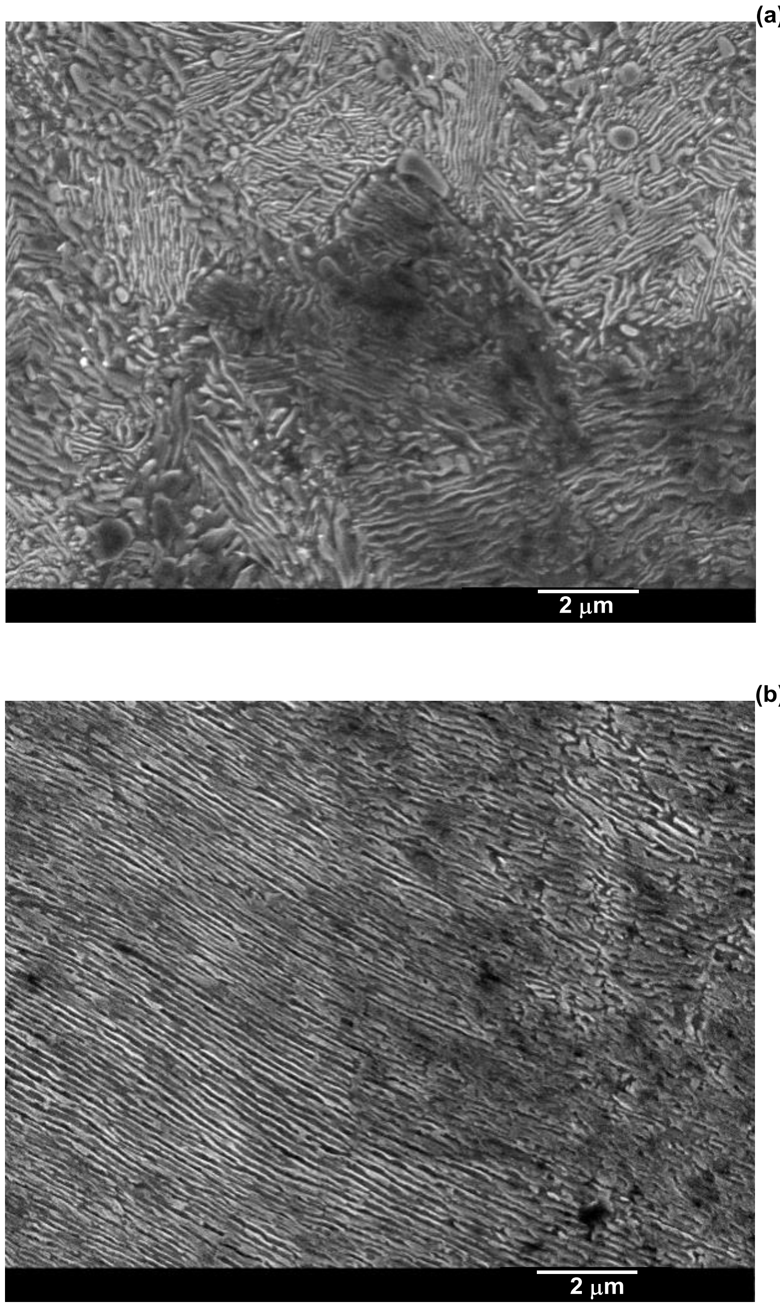


Figure 7. SEM micrographs after normalizing and tempering at 880 °C (8 h) + 550 °C (20 h); (a) 0 wt.%Nb, (b) 0.028 wt.%Nb.

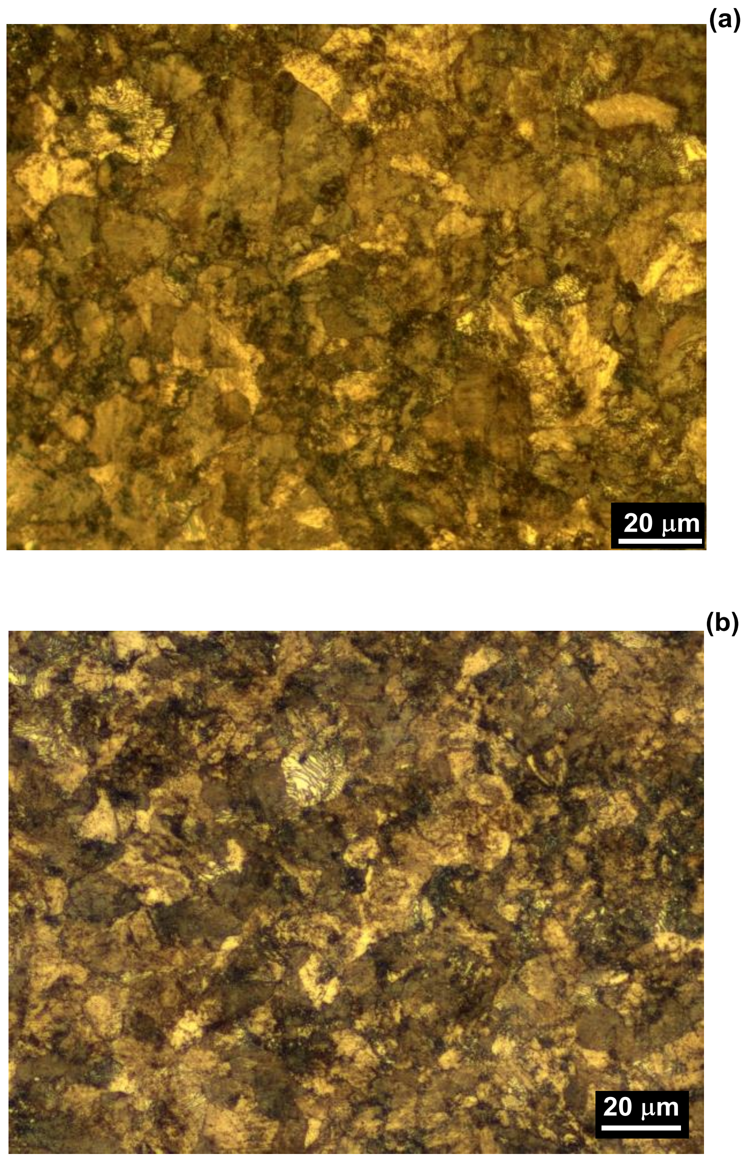
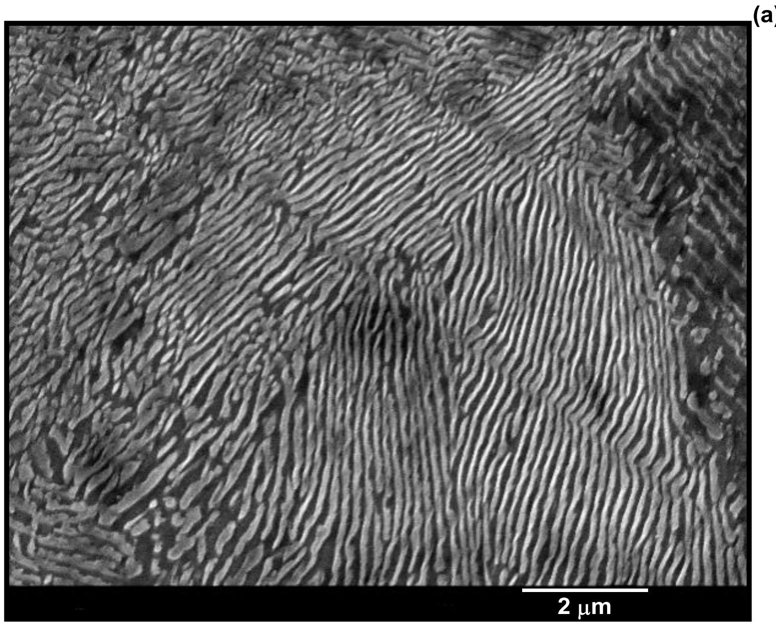


Figure 8. Microstructure after normalizing and tempering at 920 °C (8 h) + 550 °C (20 h); (a) 0 wt.%Nb, (b) 0.025 wt.%Nb.



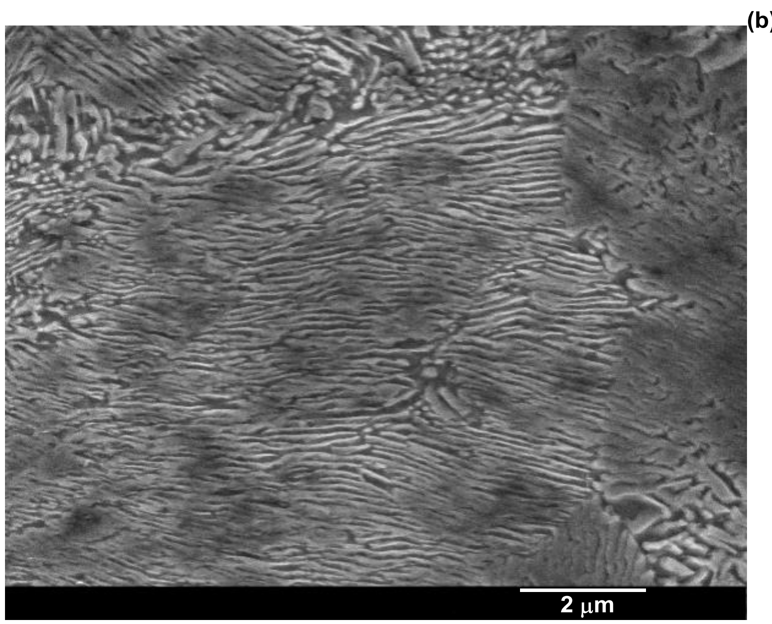


Figure 9. SEM micrographs of microstructure after normalizing and tempering at 920 °C (8 h) + 550 °C (20 h); (a) 0 wt.%Nb, (b) 0.025 wt.%Nb.

Discussion

In the production process of pearlitic wear-resistant steels, the grain size of the original austenite and the spacing and thickness of the pearlite lamellae determine the wear-resistance. Yang Chaofei et al. [6] found that the addition of small amounts of Nb in high-carbon steel refined the pearlite lamellar spacing significantly. The authors inferred that the addition of Nb, under continuous cooling conditions, lowers the transformation temperature of the pearlite, at the end of the incubation period, by interacting with carbon. This results in the Continuous Cooling Transformation (CCT) curve moving to the bottom right, ie lower temperature and longer time, which increases the transformation undercooling, ΔT, of pearlite. According to the Zener [7] semi-empirical formula: $S=\sigma VmTc/\Delta H\Delta T$ (S: the pearlite lamellar spacing, σ: specific Interfacial Energy, Vm: molar volume, Tc: the transition temperature of pearlite, ΔH: molar latent heat of phase transition, ΔT: undercooling degree), the pearlite lamellar spacing is inversely proportional to the level of undercooling and so the pearlite lamellar spacing becomes smaller with the addition of Nb.

Elwazri et al. [8] and Gladman [9] suggest that pearlite lamellar spacing is the most important factor in determining the strength of pearlite; the smaller the lamellar spacing, the higher the strength of the steel. Additionally, in the austenitizing process, the austenite grain size of the sample with Nb was smaller than observed in the Nb-free sample because of the niobium hindering austenite grain boundary migration. Finer austenite grains, leading to finer pearlite colonies and reduced lamellar spacing, are the main reasons that steel containing Nb is superior to the steel without Nb.

Under the two normalizing temperatures used, impact energies of the samples with Nb were lower than for the Nb-free samples. As described previously, the addition of Nb moves the eutectoid point to the left (lower carbon content), so for a given carbon content the amount of cementite at room temperature will increase, which can lead to an increase of hardness and the decreasing of the impact toughness. Because of the higher normalizing temperature, steel B2# should have more dissolved niobium during austenitization than steel A2#, meaning that the dissolution of Nb at higher temperatures is a bit more than that at low temperature. However, the solubility will still be rather low even at 920 °C [3]. Even so, it is evident that there is still sufficient niobium in solution to play a role in controlling austenite grain refinement and pearlite formation.

As reported previously, the austenite grain size has not increased with the increasing of the normalizing temperature. With the same grain size, sample B2# has a little added precipitation strengthening and has the better mechanical properties through the combined influence of grain refinement strengthening and precipitation strengthening.

Conclusions

Different heat treatments have been used to process a CrMo steel with and without Nb. Mechanical properties and microstructure of the wear-resistant steels after heat treatment were studied and the following conclusions are drawn from this work:

1. After both of the heat treatment cycles, A2# and B2#, which both contain Nb, have the better mechanical properties. B2#, containing 0.025 wt.%Nb, and austenitized at the higher temperature, has the best elongation and impact energy while having the same tensile strength and hardness as A2# which contains 0.028 wt.%Nb and was austenitized at the lower temperature.

2. The addition of Nb reduces the pearlite transformation temperature, resulting in the pearlite forming at a larger degree of undercooling, and consequently a finer interlamellar spacing is evident in the Nb containing steels.

3. Additionally, Nb precipitation was instrumental in hindering austenite grain growth during normalizing. The dissolution of Nb in the austenite at the higher (920 °C) normalizing temperature was a bit more than at that at the lower temperature (880 °C), which reduced the size of the precipitates, and the fine second phase precipitated during the cooling process.

4. The steel microalloyed with Nb and normalized at 920 °C (8 h) and tempered at 550 ºC (20 h) has the better mechanical properties due to the combined action of grain refinement strengthening, pearlite refinement and precipitation strengthening.

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