Influence of V and N on Transformation Behavior and Mechanical Properties of Medium Carbon Forging Steels

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Abstract. The influence of vanadium and nitrogen on microstructure and mechanical properties of medium-carbon steels has been studied by means of metallography and mechanical testing. Vanadium addition to the low nitrogen steel suppresses the formation of ferrite-pearlite following the low reheating temperatures and microstructure consists of bainitic sheaves. Increasing nitrogen at the same vanadium level promotes the acicular ferrite formation. For high reheating temperatures, dominantly acicular ferrite structure in both the low nitrogen and the high nitrogen vanadium steels is obtained. The results suggest that vanadium in solid solution promotes the formation of bainite, whereas the effect of nitrogen is related to the precipitation of VN particles in austenite with high potency for intragranular nucleation of acicular ferrite and to the precipitation of V(C,N) particles in ferrite with high potency for precipitation strengthening. Addition of both vanadium and nitrogen considerably increases the strength level, while CVN_{20} impact energy increases on changing the microstructure from bainitic ferrite to the fine ferrite-pearlite and acicular ferrite.

Introduction

The main purpose of vanadium addition to high-strength microalloyed steels is the precipitation strengthening by V(C,N) particles, that precipitates during and/or after austenite-ferrite transformation. Furthermore, a number of authors pointed out that VN particles are among the most potent for intragranular nucleation of acicular ferrite, which could effectively improve toughness of high-strength steels, e.g. [1]. The effect of nitrogen is primarily related to the interaction with vanadium and other alloying elements, such as titanium and niobium.

However, there is some disagreement in literature regarding the effect of vanadium on transformation behavior. While some results suggest that vanadium increases hardenability and suppresses ferrite-pearlite formation [2,3], there are opposite opinions, that vanadium actually decreases hardenability and suppresses formation of bainite [4,5].

The aim of this work was to examine the influence of vanadium and nitrogen contents on microstructure and properties of medium-carbon steels, in attempt to clarify the effect of vanadium on transformation behavior and mechanical properties.

Experimental Procedure

Three medium carbon forging steels with varied content of nitrogen and vanadium (chemical composition is given in Table 1) were vacuum melted, cast into ingots, press forged and hot rolled to 22 mm diameter rods. The 180 mm long test pieces were reheated to different austenitizing temperatures, ranging from 950°C to 1300°C for 30 minutes, and cooled in still air. The still-air cooling rate was estimated to be between 1.15 and 1.35°C/s, depending upon the reheating temperature.

Microstructure was examined using conventional metallographic techniques. The transverse

specimens were polished and etched in a 2% nital.

Room temperature mechanical properties are evaluated from round tensile specimen (l_0=40 mm, d_0=8 mm) and standard Charpy V-notch longitudinal specimens, witch were machined from the center of the bar.

Table 1. Chemical compositions of experimental steels [wt.%].

Steel	C	Si	Mn	P	S	Cr	Ni	Mo	V	Ti	Al	N
High-N	0.26	0.30	1.48	0.0080	0.0080	0.29	0.16	0.03	0.12	0.01	0.02	0.0166
Low-N	0.25	0.34	1.47	0.0060	0.0080	0.29	ND[*]	0.01	0.12	0.01	0.02	0.0057
V-free	0.25	0.32	1.46	0.0070	0.0080	0.28	0.16	0.03	-	0.01	0.02	0.0059

* ND – Not determined

Results

Microstructure. Microstructure of the high-N steel air cooled from 950–1050°C (Figure 1a) consists of polygonal ferrite idiomorphs, nucleated at grain boundaries or within former austenite grains, surrounded by pearlite and some acicular ferrite. With increasing the austenitization temperature to 1150°C–1300°C, the fraction of acicular ferrite increases and becomes dominant morphology, alongside with grain boundary idiomorphs surrounded by some pearlite (Figure 1b).

The low-N steel reheated to 950–1150°C is characterized by bainitic sheaves nucleated at grain boundaries (Figure 2a) and by the absence of primary grain boundary ferrite. For the high austenitizing temperatures (1300°C), microstructure consists of acicular ferrite, grain boundary ferrite and small fraction of pearlite (Figure 2b).

The ferrite-pearlite structure is predominant in the V-free steel after austenitization at 950°C (Figure 3a). Individual plates of intragranulary nucleated Widmanstätten ferrite could also be observed in this microstructure. For the high austenitizing temperature (1250°C) microstructure changes to Widmanstätten ferrite and some acicular ferrite, while former austenite grain boundaries are decorated with allotriomorphs or idiomorphs, surrounded with pearlite (Figure 3b).

Mechanical properties. Room temperature tensile properties and Charpy V-notch toughness are summarized in Figure 4 alongside with main microstructural features which change with increasing austenitization temperature from 950°C to 1300°C, as described in the previous section.

Starting from the lowest strength level in the V-free steel (59 ppm N) an addition of vanadium to the low-N steel (0.12 %V, 57 ppm N) brings an increase in YS and UTS by approx. 70 MPa (from 407–442 MPa to 478–531 MPa) and 120 MPa (from 690–736 MPa to 818–852 MPa), respectively. In the high-N steel (0.12 %V, 166 ppm N) there is further increase in YS by approximately 100 MPa (to 589–633 MPa) and UTS by approx. 70 MPa (to 888–936 MPa). General effect of increasing the reheating temperature is to slightly enhance the strength level.

The low-N steel has as low CVN_{20} impact energy values as 20 J for austenitization temperatures below 1150°C, while for 1300°C impact energy reaches 42 J. The V-free and high-N steels exhibit an impact energy level of 69–93 J and 78–102 J, respectively, for austenitization temperature of 950°C. With increasing reheating temperature to 1150°C CVN_{20} impact toughness steeply decreases to approx. 40 J for the high-N steel, and to somewhat lower values for the V-free steel. For austenitization temperature of 1300°C high-N steel impact energy drops to 30–38 J, while the V-free steel exhibits an increase to about 50 J.

Discussion

The effect of V on microstructure. Microstructures after reheating at low temperatures (950°C–1150°C) show that vanadium suppresses the formation of ferrite-pearlite. Formation of hard phases such as bainite in the V-containing low-N steel (Fig. 2a), in contrast to predominantly ferrite-pearlite structure in the V-free steel (Fig. 3a), indicates that vanadium increases hardenability. There is a possibility of strong effect of vanadium in solid solution on transformation behavior.
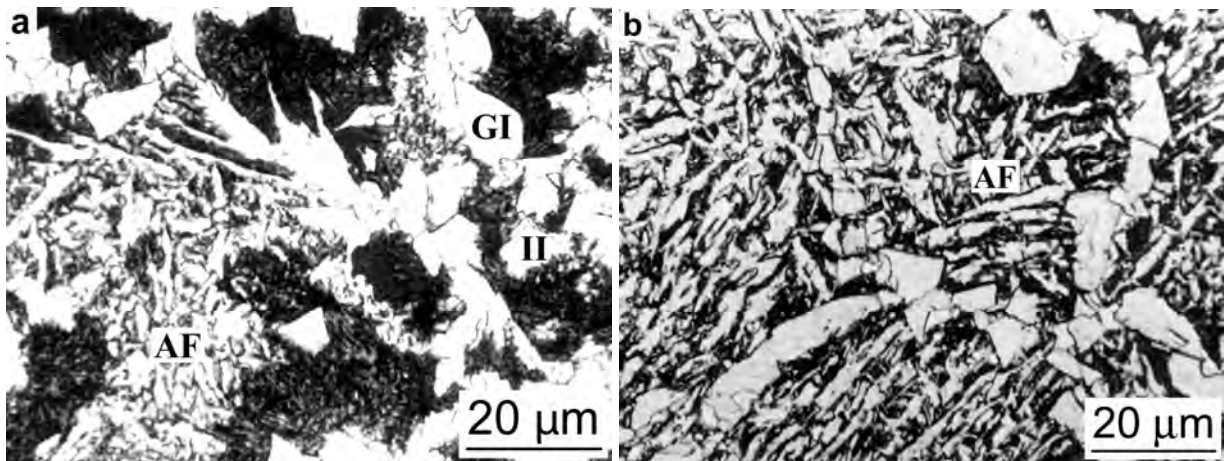
Figure 1. Microstructure of high-N steel air-cooled from austenitization temperature of:
a) 950°C, b) 1300°C (GI – grain boundary ferrite idiomorphs; II – intragranular idiomorphs; AF – acicular ferrite).
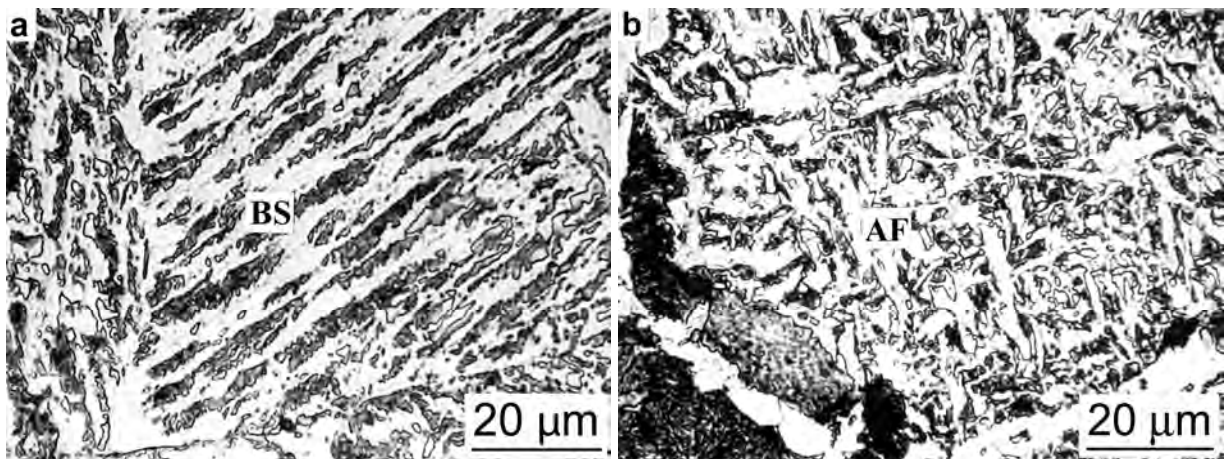

Figure 2. Microstructure of low-N steel air-cooled from austenitization temperature of:
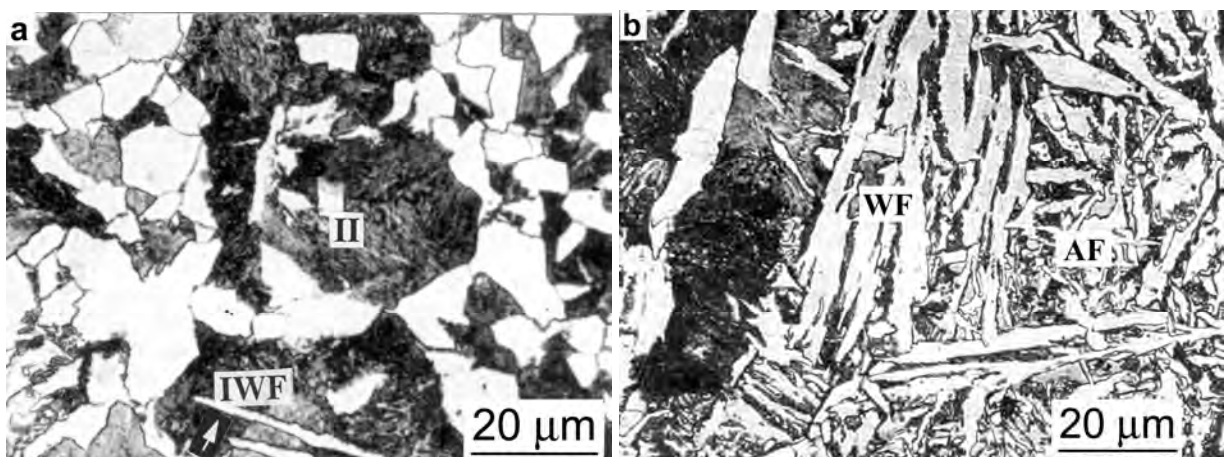a) 1050°C, b) 1300°C (BS - bainitic sheaves; AF - acicular ferrite).

Figure 3. Microstructure of V-free steel air-cooled from austenitization temperature of:
a) 950°C, b) 1250°C (II-intragranular ferrite idiomorph; IWF- intragranular Widmanstätten ferrite; WF – Widmanstätten ferrite; AF - acicular ferrite).
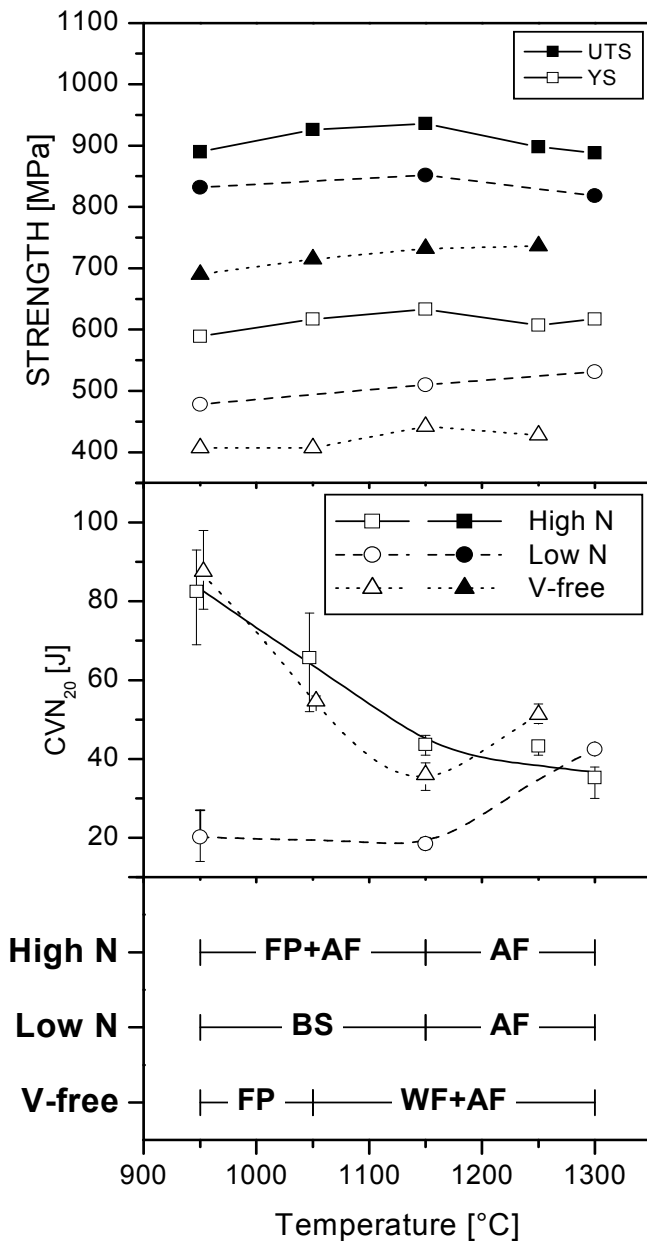
Figure 4. Effect of austenitizing temperature on strength, Charpy V-notch impact energy at 20°C and structure of three experimental steel:
high-N (166 ppm N), low-N (57 ppm N) and V-free steel (FP – ferrite-pearlite; AF – acicular ferrite; BS – bainitic sheaves; WF – Widmanstätten ferrite).

It could be assumed that vanadium segregated toward austenite grain boundaries increasing its surface energy and suppressing formation of grain boundary ferrite that renders grain boundaries inert for bainite nucleation. Similar effect of boron was earlier reported [6]. Segregation of vanadium toward austenite grain boundaries was confirmed in [5]. However, it has been considered by some authors [5,7] that vanadium actually suppresses bainite formation by preventing the nucleation of coarse grain boundary plate structure. Current results do not support that view.

For high reheating temperatures (1250–1300°C) transformation behavior changes in both the V-free and the V-containing (low-N) steel. It could be expected that VN particles are completely dissolved at these temperatures. On the other hand, predominantly acicular ferrite in the low-N vanadium containing steel and the presence of grain boundary ferrite (Figure 2b) imply that the effect of vanadium segregation to grain boundaries is somehow diminished. It can be assumed that at high reheating temperatures due to the thermal dispersion vanadium is more evenly distributed throughout austenite grain interior [8], so it's concentration at grain boundaries is diluted and therefore an inhibiting effect on grain boundary ferrite nucleation is precluded. The V-containing steel yet shows higher retarding effect on transformation than the V-free steel, in which dominates the Widmanstätten ferrite (Figure 3b). If we consider the role of VN particles in intragranular nucleation of acicular ferrite [1,9], it's understandable that acicular ferrite nucleation in the V-free

steel is less probable. In this regard, TiN particles shouldn't be omitted, but it seems that they are less potent as nucleation site, since crystal lattices misfit ratio with ferrite (3.8%) is higher than in the case of VN (1.3%) [6]. This consideration and present results supports earlier findings that VN particles are preferential sites for intragranular nucleation of acicular ferrite. In fact, VN precipitates on the manganese sulfide particles which then act as sites for the intragranular nucleation of acicular ferrite [1,9]. On the other hand, He and Edmonds [5] offer an alternative mechanism for intragranular acicular ferrite nucleation. They suggest that vanadium segregates to austenite grain interiors and form vanadium rich regions or Fe-V clusters that could be energetically favorable sites for acicular ferrite nucleation.

The effect of N on microstructure. Comparing microstructures of the high-N and the low-N steels for lower reheating temperatures (950–1150°C), it seems that higher nitrogen content suppresses the formation of bainite (Figure 1a). In the high-N steel great deal of vanadium is in VN at 950°C (temperature for complete dissolution of VN is at 1077°C, see below), which means that less vanadium could segregate to grain boundaries, grain boundary ferrite formation is not suppressed and intragranular nucleation of acicular ferrite is promoted (Figures 1a,b). In the low-N steel all of the vanadium is available to segregate to grain boundaries ($T_{VN} = 933°C$) and reduce its potential for grain boundary ferrite nucleation, promoting bainite formation (Figure 2a). The presence of acicular ferrite in the high-N steel microstructure (Figure 1a), in contrast to bainitic structure in the low-N steel (Figure 2a), indicates an effect of nitrogen. High nitrogen creates the more favorable condition for VN precipitation on MnS inclusions which then serve as the preferred sites for acicular ferrite nucleation [1].

For high austenitization temperatures (1150–1300°C), microstructures of the high-N and low-N steels are practically the same – they consist predominantly of acicular ferrite structure with grain boundary ferrite (Figures 1b and 2b). Temperature for complete dissolution of VN, according to the equation [10]:

$$\log[V][N] = -7840/T_{VN} + 3.02, \tag{1}$$

is as follows. For the high-N steel: $T_{VN} = 1077°C$ and for the low-N steel: $T_{VN} = 933°C$, so at temperatures at and above 1150°C the total amount of vanadium is in solid solution for both steels. The fact that the microstructures of both the high-N and the low-N steels are similar indicates that 27 ppm of N in low-N steel is sufficient to promote the precipitation of VN on MnS particles, which then serve as the nucleation sites for the formation of acicular ferrite.

Strength. The profound strength increase with increasing vanadium and nitrogen contents, shown in Figure 4, is principally due to precipitation strengthening by V-carbonitride second phase particles [3,11]. As the nitrogen contents is increased the precipitation of V(C,N) in basically acicular ferrite and bainitic structure is enhanced and particles become more dispersed [3]. The strength is therefore highest for the high-N and lowest for the V-free steel. The effect of microstructure on the strength level seems to be small what reflect the small sensitivity of strength to structure. However, the contribution of the microstructural refinement to the strength on reheating to low temperatures (notably 950°C) can not be excluded.

There is a relatively high increase in strength level in the low-N vanadium containing steel in respect to the V-free steel, in particular for samples reheated to low temperatures. The temperature for complete dissolution of VN particles in the low-N steel is 933°C, so that all of the vanadium and nitrogen are in solid solution at 950°C. This imply a possibility for significant precipitation of V(C,N) particles in ferrite to occur, which would eventually explain pronounced strength increase at low reheating temperatures in the low-N steel.

Toughness. Toughness is known as a strong structure sensitive property. Therefore, the change of CVN_{20} energy in Fig.4 reflects microstructural changes. The lowest toughness exhibits the low-N steel with bainitic structure. In this type of structure CVN_{20} energy values would depend mainly on size distribution of relatively coarse carbides, serving as a fracture initiation sites [12]. Once

critical-sized microcrack is formed by fracturing of particle, crack readily advances through sheaves of bainite plates with similar crystalographic orientation. Marked toughness increase in the low-N steel after high reheating temperatures coincides with microstructural change from bainite to acicular ferrite. Fine interlocking acicular ferrite plates/needles without crystallographic parallelism increase energy required for crack propagation through matrix/matrix boundaries [13].

The highest toughness exhibits the fine ferrite-pearlite structure present alongside with acicular ferrite in the high-N and ferrite-pearlite structure in the V-free steels reheated in the low temperature range. CVN_{20} energy decrease with increasing reheating temperature follows the decrease of fraction of ferrite-pearlite in microstructure in favor of acicular ferrite in the high-N steel, or Widmanstätten ferrite in the V-free steel. It should be emphasized, however, that these two steels exhibit a highly different strength level and that the high reheating temperature is more relevant to the hot forging process. So a combination of UTS of about 900 MPa and CVN_{20} of about 40 J after reheating at 1300°C in the high-N steel with acicular ferrite structure seems to be very promising.

Conclusions

1. Vanadium addition suppresses the formation of ferrite-pearlite and promotes the formation of bainite following low reheating temperatures (950–1150°C).
2. Increasing nitrogen contents creates the more favorable condition for VN precipitation on MnS inclusions, which then serve as the preferred sites for acicular ferrite nucleation.
3. After reheating at high temperatures (1250–1300°C) acicular ferrite becomes dominant in structure of both the low nitrogen and the high nitrogen steel.
4. Strength increases with addition of vanadium and nitrogen due to precipitation strengthening effect of V(C,N) particles. The highest strength exhibits the high nitrogen vanadium containing steel.
5. Impact toughness increases as microstructures change in the following sequence: bainite sheaves, acicular ferrite, and fine ferrite-pearlite.

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