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INFLUENCE OF Cr, Mn AND Mo ON STRUCTURE AND PROPERTIES OF V MICROALLOYED MEDIUM CARBON FORGING STEELS

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Abstract

The influence of Cr, Mo and Mn on microstructure and mechanical properties of V-microalloyed medium-carbon steels has been studied by means of metallography and mechanical testing. Cr, Mn and Mo addition promotes the formation of bainitic sheaves suppressing the formation of ferrite-pearlite and acicular ferrite. The influence of Mn is somewhat masked by a low content of nitrogen. In a low nitrogen steel VN particles are not present and the nucleation of acicular ferrite is suppressed. The yield strength of Cr, Mo and Mn alloyed steels with bainite structures is lower in comparison to the base steel due to less pronounced precipitation strengthening effect. The presence of bainitic sheaves decreases the CVN₂₀ impact energy in comparison to ferrite-pearlite and acicular ferrite microstructures.

Key words: Medium-carbon steels, Cr, Mo, Mn, bainite, acicular ferrite

Introduction

The main alloying element in microalloyed medium carbon forging steels is V which promotes strengthening by precipitation of V(C,N) particles which precipitate during and/or after austenite-ferrite transformation. At the same time, an increase in toughness is provided by intragranular nucleation of acicular ferrite, dominantly on VN particles [1-3]. In order to suppress the grain growth at high temperature, small amount of titanium is usually added [4].

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Some of the alloying elements, primarily Cr and Mo are not originally added to the V-microalloyed medium carbon forging steels. However, the effect of these elements, including Mn, on the formation of tough acicular ferrite structure may be of the particular interest.

Influence of Mn, Cr and Mo on hardenability is well known [5]. These elements promote the formation of hard phases such as bainite and martensite [5]. On the other hand, in the medium carbon V-microalloyed steel bainites and/or acicular ferrites are frequently encountered structures [1-4]. Both microstructures are formed in the same temperature range; the only difference being the nucleation sites, i.e. while bainites nucleates at the austenite grain boundaries (intergranularly), acicular ferrite nucleates on the particles within the grains (intragranularly) [6]. The influence of V and nitrogen is reported in numerous papers [1,2,7], while the results reporting the influence of Cr, Mo and Mn are limited [8-10]. Therefore, the aim of this work was to study the influence of Cr, Mo and Mn on the formation of bainites and/or acicular ferrite during continuous cooling of medium-carbon steels and respective mechanical properties.

Experimental procedure

Four medium carbon forging steels with varied content of Cr, Mo and Mn (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 min, 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, which were machined from the center of the bar.

Table 1. Chemical compositions of experimental steels (wt.%).

Steel	Base-steel	L-7 Cr	L-9 Mo	L-22 Mn
C	0,26	0,26	0,27	0,26
Si	0,3	0,32	0,32	0,31
Mn	1,48	1,57	1,58	1,75
P	0,008	0,008	0,008	0,01
S	0,008	0,005	0,006	0,01
Cr	0,29	0,57	0,29	0,37
Ni	0,16	0,16	0,17	0,18
Mo	0,03	0,03	0,21	0,04
V	0,12	0,12	0,1	0,17
Ti	0,01	0,01	0,01	0,01
Al	0,02	0,03	0,02	0,03
N	0,0166	0,0159	0,0138	0,0021

Results

Microstructure

Microstructure of the base-steel (with highest amount of nitrogen) 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).

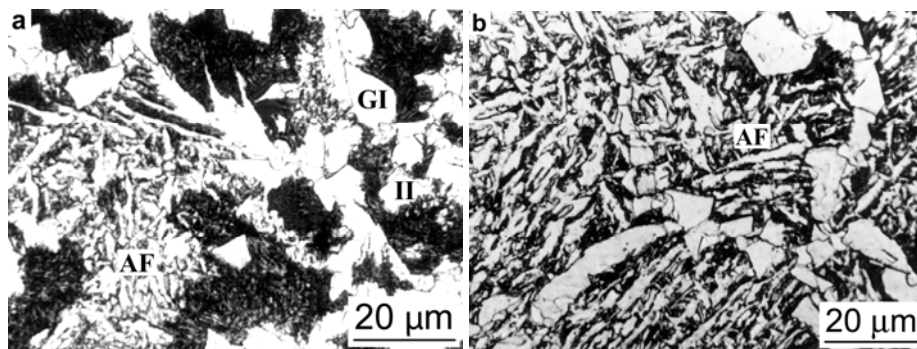


Figure 1. Microstructure of high-N steel air-cooled from austenitization temperature of: a) 950°C, b) 1300°C (GI – grain boundary ferrite idiomorphs; II – intragranular idiomorphs; AF – acicular ferrite).

Microstructure of the L-7 (Cr steel) air cooled from 950–1050°C (Figure 2a) consists of intragranularly nucleated polygonal and plate like ferrite, grain boundary idiomorphs and allotriomorphs. With increasing austenitization temperature to 1150°C–1300°C, the acicular ferrite becomes dominant morphology, alongside with grain boundary idiomorphs and bainite (Figure 2b).

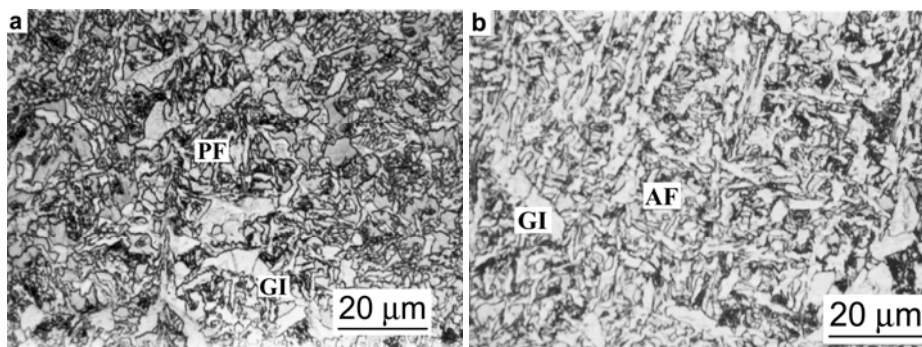


Figure 2. Microstructure of Cr steel air-cooled from austenitization temperature of: a) 1050°C, b) 1300°C (PF - polygonal ferrite, GI - grain boundary idiomorphs; AF - acicular ferrite).

The Mo-steel reheated to 950–1150°C is characterized by bainitic sheaves and some acicular ferrite (Figure 3a), and by the absence of primary grain boundary ferrite. For the high austenitizing temperatures (1250°C), microstructure consists of bainitic sheaves and some acicular ferrite (Figure 3b).

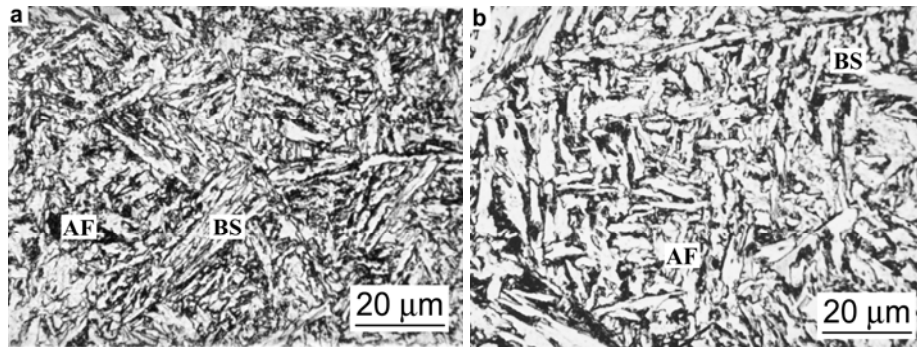


Figure 3. Microstructure of Mo steel air-cooled from austenitization temperature of: a) 1150°C, b) 1250°C (BS – Bainitic Sheaves, II-intragranular ferrite idiomorph; AF – acicular ferrite).

Fully bainitic sheaves microstructure free of grain boundary ferrites is obtained in the Mn steel after air cooling from both the low austenitization temperature (950°C - Figure 4a) and the high austenitization temperature (1300°C) (Figure 4b). The only difference seems to be the size of sheaves, i.e. larger sheaves were obtained on cooling from higher austenitization temperature.

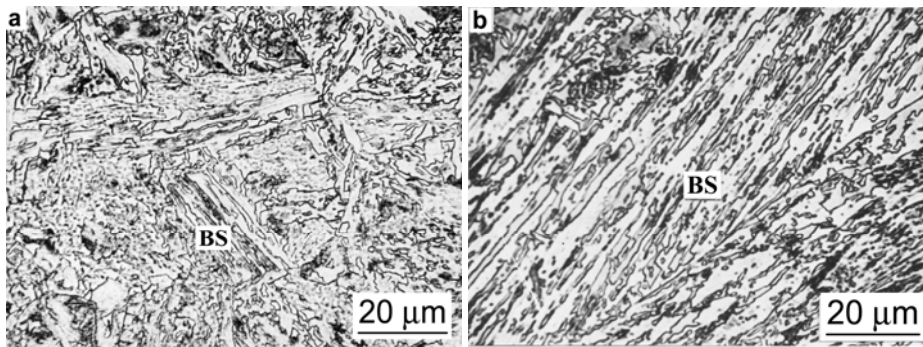


Figure 4. Microstructure of Mn steel air-cooled from austenitization temperature of: a) 950°C, b) 1300°C (BS – Bainitic Sheaves).

Mechanical properties

The room temperature tensile properties and the Charpy V-notch toughness are summarized in Fig. 5 together with the main microstructural features which change with increasing austenitization temperature from 950°C to 1300°C, as described in the previous section.

Strength. The base steel exhibits the yield strength (YS) in the range 589–633 MPa and the ultimate tensile strength (UTS) of 888–936 MPa. Addition of Cr, Mn and Mo leads to decrease in YS approximately by 100 MPa, while UTS increases about 50 MPa only with Cr addition. General effect of increased austenitization temperature is to slightly enhance the yield strength level.

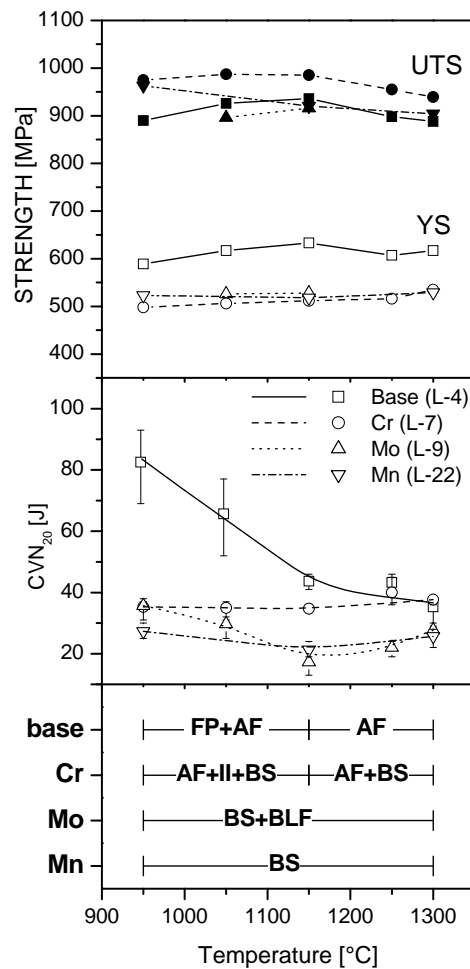


Figure 5. Effect of austenitization temperature on strength, Charpy V-notch impact energy at 20°C and structure of four experimental steels: (FP – ferrite-pearlite; AF – acicular ferrite; BS – bainitic sheaves; II – intragranular idiomorphs, GI – grain boundary idiomorphs).

Charpy toughness. The base steel exhibits very strong influence of austenitization temperature on toughness. With increasing austenitization temperature to 1150°C, CVN₂₀ impact toughness steeply decreases to approximately 45 J, whereas at

austenitization temperature of 1300°C base-steel impact energy drops to 30–38 J. Steel with Cr addition exhibits very slight increase of the impact toughness in the range 31–39 J with increasing austenitization temperature. On the other side, steels with Mo and Mn additions have lower toughness in comparison to the base- and Cr-steels and show a similar behavior. An increase of austenitization temperature up to 1150°C leads to decrease of impact toughness from 36 J to 18 J and from 27 J to 21 J for Mo and Mn steels, respectively. Further increase in reheating temperature slightly increases the toughness to 28 J to 27 J for the Mo and Mn steels, respectively.

Discussion

Microstructure

The formation of bainites or acicular ferrite plays a dominant role in the transformation behaviour of the continuously cooled medium carbon V-microalloyed steels. In order to describe the influence of alloying elements on the transformation behavior, temperatures for start of acicular ferrite formation – Ar_3 and for start of bainitic formation – B_s are predicted applying the equations 1 [11] and 2 [12], using chemical compositions (wt. %) given in Table 1. The results are given in Table 2.

$$Ar_3(^{\circ}C) = 910 - 310(\%C) - 80(\%Mn) - 20(\%Cu) - 15(\%Cr) - 55(\%Ni) - 80(\%Mo) + 0.35(t - 8) \quad (1)$$

$$B_s(^{\circ}C) = 830 - 270(\%C) - 90(\%Mn) - 70(\%Cr) - 37(\%Ni) - 83(\%Mo) \quad (2)$$

Table 2. Calculated Ar_3 and B_s temperatures

Steel	Ar_3 , °C	B_s , °C
Base-steel	695	598
Cr-steel	684	570
Mo-steel	670	571
Mn-steel	671	566

The equilibrium temperatures for complete dissolution of VN was calculated according to the equation (3) [13] and the corresponding results are given in Table 3. Due to preferable formation of TiN at high temperatures, the total nitrogen content for calculation of temperature of dissolution is reduced for 29ppm.

$$\log[V][N] = -7840/T_{VN} + 3.02, \quad (3)$$

Table 3. Calculated temperature for complete dissolution of VN

Steel	TVN dissol, °C
Base steel	1078
Cr Steel	1072
Mo steel	1037
Mn Steel	*

*All nitrogen in Mn steel is bonded in TiN and no nitrogen is available for the formation of VN.

Base-steel. In the lower austenitization temperature range (950–1050°C - Figure 1a) the great deal of V is present as VN since its complete dissolution occurs at higher temperatures (Table 3). Therefore, less V is available to segregate to grain boundaries; grain boundary ferrite formation is favoured in respect to the grain boundary bainite while intragranular nucleation of acicular ferrite is promoted (Figures 1a). For high austenitization temperatures (1150–1300°C), the microstructures of the base steel consists predominantly of acicular ferrite with some grain boundary ferrite (Figures 1b). It is usually assumed that a coarse austenite grain size promotes the formation of acicular ferrite [6,9,10]. According to Table 3 and results of Roberts *et al.* [13] all amount of V is in the solid solution. However, due to the thermal dispersion V is more evenly distributed within the austenite grains [14], causing a dilution of its concentration at grain boundaries and an inhibiting effect on grain boundary ferrite nucleation is precluded. Therefore, acicular ferrite nucleates following the formation of the grain boundary ferrites [4].

Steels with Cr, Mo and Mn additions. The addition of Cr, Mo and Mn in quenched and tempered steels suppresses formation of the allotriomorphic ferrites and pearlite, enhancing formation of martensites and/or bainites [5]. The only element that increases hardenability more effectively than Cr, Mo and Mn is boron [5]. The data of Table 2 indicate that the addition of Mn, Cr and Mo suppresses the Bs temperature in medium carbon V microalloyed steels. The acicular ferrite formation start temperature (base steel) is apparently higher than the bainite ferrite transformation start temperature (Mn, Cr, Mo added steels). The assumption that both microstructures are formed in the same temperature range [6] does not seem to be strictly valid.

Strength

In all four steels, the pronounced yield point was not observed. Since the bainites are characterized with high density of mobile dislocations [15], only 0.2% offset stress was possible to measure. A higher YS of the base steel in comparison to the Mn, Cr and Mo added steels is principally due to precipitation strengthening by VCN second phase particles [16,17]. This behavior is attributed to introduction of bainitic sheaves in the microstructure and less effective precipitation of VCN in bainite which forms at a lower temperature when diffusivity is reduced [18].

The strain hardening rate of bainitic sheaves is very high [19] in comparison to the ferritic/pearlitic microstructure, resulting in a higher UTS. In the Mn, Cr and Mo steels, this effect, leads to a larger difference between YS and UTS in comparison to the base steel. This effect is most pronounced in steel with Cr addition..

Toughness

The change of CVN₂₀ energy in Fig. 5 reflects microstructural changes, confirming a strong structure sensitivity of toughness. The highest toughness exhibits the fine ferrite-pearlite structure present alongside with acicular ferrite in base steel reheated in the low temperature range. CVN₂₀ energy decreases with increasing austenitization temperature reflecting a decrease of fraction of ferrite-pearlite in microstructure in favor of acicular ferrite.

The lowest toughness exhibit Mo and Mn steels with dominant bainitic structure. In this type of structure CVN₂₀ energy values would depend mainly on size distribution of relatively coarse carbides, serving as a fracture initiation sites [20]. Once the critical-sized microcrack is formed by fracturing of particle, crack readily advances through sheaves of bainite plates with similar crystallographic orientation.

Fine interlocking acicular ferrite plates/needles without crystallographic parallelism increase the energy required for crack propagation through the matrix/matrix boundaries [21].

Conclusions

1. Addition of Cr, Mo and Mn suppresses the formation of polygonal ferrite - pearlite and acicular ferrite and promotes the formation of bainite in V microalloyed medium carbon forging steels.

2. A lower yield stress of the Mn, Cr and Mo alloyed steels in comparison to the base-steel is principally due to less effective precipitation strengthening by VCN second phase particles.

3. Due to very high strain hardening rate of bainites, all three steels exhibits the more pronounced strain hardening effect than the base steel. The strongest hardening is in the Cr-steel.

4. Impact toughness increases as microstructures change in the following sequence: bainite sheaves, acicular ferrite, and fine ferrite-pearlite.

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