Influence of forging and cooling rate on microstructure and properties of medium carbon microalloy forging steel

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In view of their capacity to develop high strength following limited alloying and ease of processing medium carbon microalloyed (MA) steels are very cost-effective compared to quenched and tempered steels for the production of automotive components. To be able to substitute quenched and tempered steels, MA steels must be processed to similar strength levels and acceptable toughness [1]. The increased use of microalloyed forging steels in production applications should be supplemented with an increased understanding of not only the strengthening mechanisms that occur in these steels, but also the effects of the composition and forging parameters on these mechanisms. The size and percentage distribution of ferrite and pearlite within the microstructure play an important role on the final mechanical properties. Each of the microstructure variables is highly influenced by the composition of the microalloyed steels, the forging parameters utilized, and the post-forging cooling rate [2–4]. The aim of the present study is to investigate the influence of different cooling rates on structure and properties of MA steel processed through forging route.

The chemical compositions of the steels used in this study are shown in Table I. The steels are medium carbon microalloyed steel with different vanadium and aluminum contents. Specimens obtained from steels 1 and 2 were heated at 1100 °C for 30 min and forging operation was carried out. Thirty-six percent deformation was applied by repeated strokes in temperature range of 1000–1100 °C. Then forged steel samples were cooled either in water, air, or sand. Room temperature tensile strength was measured by using an Instron machine at a crosshead speed of 1 mm/min. The pearlite grain size, volume fraction of ferrite, and pearlite were determined by using mean linear intercept (mli) method and point counting. Hardness measurement was also carried out using the Vickers hardness test.

Fig. 1 shows the evaluation of the microstructure for both of the microalloyed steel under various cooling condition. Table II also shows volume fraction of ferrite and pearlite and mli grain sizes of pearlite in as-received, sand-, and air-cooled samples. As can be seen, for both steels, proeutectoid ferrite appears as a thin, continuous network at prior austenite grains and volume fraction of ferrite is increased with increasing cooling rate. These effects are generally associated with the influence of cooling rate on the coalescence and growth rates

TABLE I Chemical composition (wt %)

Steels	C	Si	Mn	P	S	V	Al	N
Steel-1	0.39	0.53	1.27	0.016	0.022	–	0.016	0.0048
Steel-2	0.38	0.52	1.28	0.016	0.027	0.08	0.007	0.0056

TABLE II Volume fraction of ferrite and pearlite and mean linear intercept grain sizes of as-received, sand and air cooled samples

Steels	Ferrite (%) $\pm \sigma$ (SD)	Pearlite (%) $\pm \sigma$ (SD)	Grain size (μm) $\pm \sigma$ (SD)
Steel-1, as-received	30 ± 2.0	70 ± 2.0	13 ± 0.4
Steel-1, sand	19 ± 1.7	81 ± 1.7	15 ± 0.5
Steel-1, air	21 ± 1.8	79 ± 1.8	12 ± 0.4
Steel-2, as-received	35 ± 2.1	65 ± 2.1	10 ± 0.3
Steel-2, sand	30 ± 2.0	70 ± 2.0	8 ± 0.3
Steel-2, air	33 ± 2.1	67 ± 2.1	6 ± 0.2

TABLE III Effect of cooling conditions on the mechanical properties

Steels	Yield strength (MPa, 0.2 %)	Tensile strength (MPa)	Elongation (%)	Hardness (Hv5)
Steel-1, as-received	439	773	17	230
Steel-1, sand	459	794	18	235
Steel-1, air	490	823	17	244
Steel-1, water	1439	1774	7	651
Steel-2, as-received	563	858	17	265
Steel-2, sand	595	890	19	273
Steel-2, air	650	944	19	289
Steel-2, water	1529	1824	4	723

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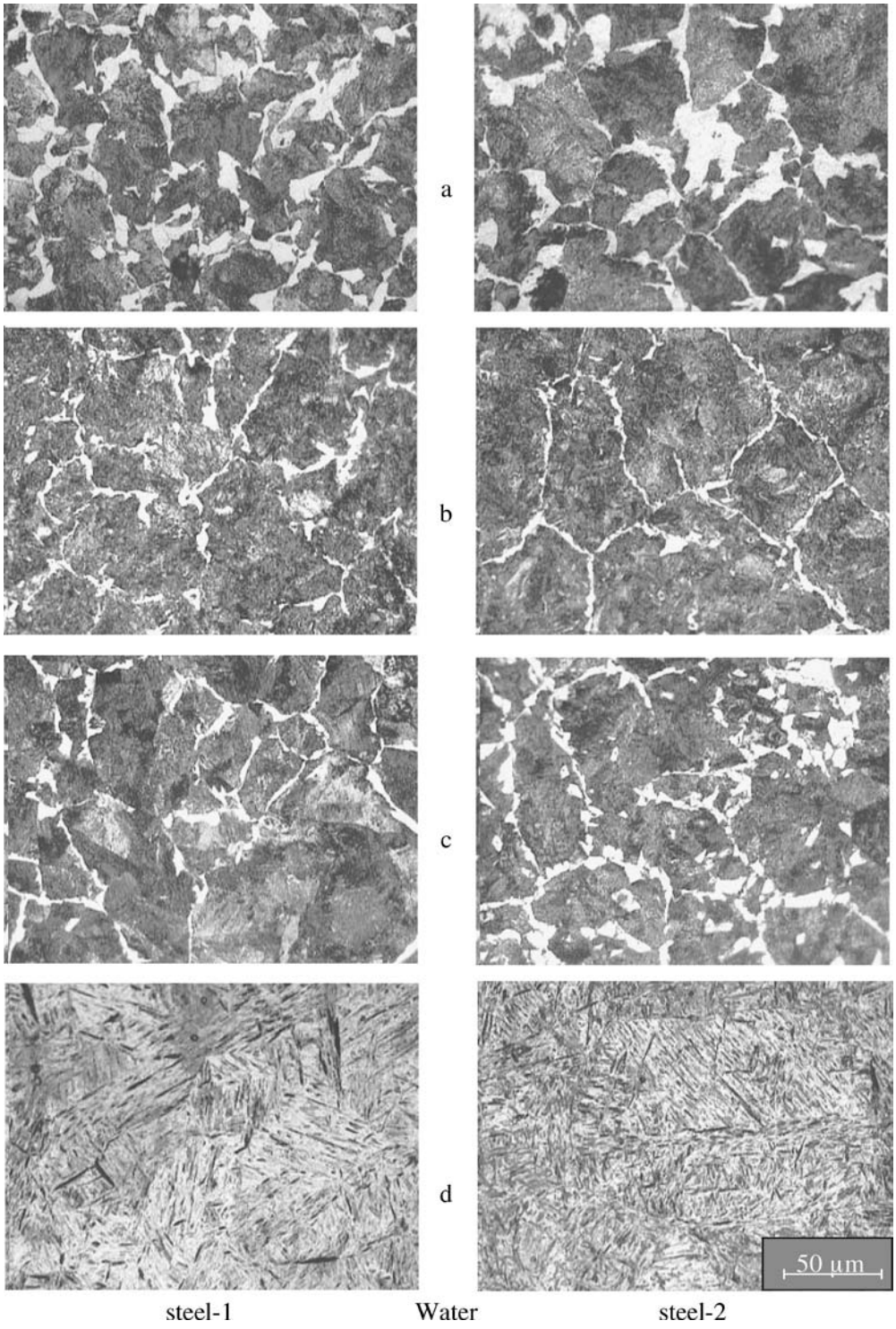

Figure 1 Microstructures of steels under conditions of (a) as-received, (b) sand, (c), air, and (d) water cooled.

of ferrites [5]. An increase in cooling rates lowers transformation temperature and pearlite form at lower temperature resulting in finer pearlite grains [6]. When the samples are continuously cooled in water, the obtained microstructure is martensite, which is not a desired phase due to its detrimental effect in toughness [7].

Tensile properties of forged steels followed by different cooling rates are shown in Table III. As can be seen the yield strength and tensile strength increase with increase in the cooling rates. The elongation tends to improve at lower cooling rates such as air cooling or sand cooling, however increasing the cooling rate has a negative effect on elongation. By increasing the cooling rate during eutectoid reaction, the distance that the atoms are able to diffuse is reduced. Consequently, the lamellae produced during the reaction are finer or more closely spaced. By

TABLE IV Grain size data and structure property analyses of the as-received and heat-treated samples

Sample code	$f^{1/3}$	35+58.5* (%Mn)	mli (μm)	$k_y d^{-1/2}$ (MPa)	$(1-f)^{1/3}$	σ_y test (MPa)	σ_p (MPa)
Steel-1, as-received	0.67	109	13	153	0.89	439	296
Steel-1, sand	0.57	109	15	142	0.93	459	339
Steel-1, air	0.59	109	12	159	0.92	490	360
Steel-2, as-received	0.70	110	10	174	0.87	563	419
Steel-2, sand	0.67	110	8	195	0.89	595	439
Steel-2, air	0.69	110	6	225	0.88	650	476

producing fine pearlite, the strength of the alloy is increased [6].

The hardness measurement indicated that water-quenched samples of steel-1 and steel-2 had higher Vickers hardness compared to air- or sand-cooled samples. This is because of the highest free carbon in martensite. It was also found that air-cooled samples had higher hardness than sand-cooled samples due to higher cooling rates. Fast cooling rate was anticipated to give a fine dispersion of small particles in the pro-eutectoid ferrite and pearlitic ferrite which make dislocation movement more difficult and increase hardness. The macro-hardness measurement of the investigated steel also indicated that the hardness of the steel-2 is higher than steel-1 for all cooling conditions. The higher hardness for steel-2 when compared to steel-1, which has the same carbon concentration, is caused probably by increased vanadium content to about 0.08%.

Regression analysis on a wide range of medium to high carbon steels has shown that the yield strength, σ_y, can be related to the compositional and microstructural variables by equations of the form

$$\sigma_\alpha = X \tag{1}$$

$$\sigma_y = f^n \sigma_\alpha + (1 - f^n)\sigma_p \tag{2}$$

where σ_y is the yield strength of the aggregate (MPa), f is the fraction of ferrite, σ_α is the yield strength of the ferrite (MPa) as described by Equation 1, σ_p is the yield strength of the pearlite (MPa), and n is an index describing the nonlinear contributions of the pearlite and ferrite. In the case of yield strength and of tensile strength, the index was $n = 1/3$, indicating that the ferrite fraction contributes more to yield and tensile strength than would be expected on a pro-rata basis. To study the influence of the pearlite content and precipitates on strength of steels it is necessary to calculate the value of σ_p which represents the strength obtained from pearlite and precipitates respectively in the as-received and air-cooled samples tensile tested at room temperature. Therefore the following yield strength, σ_y, has been found to be applicable for ferrite–pearlite steel containing larger pearlite content [8]:

$$\sigma_y = f^{1/3}[35 + 58.5\,(\%\text{Mn}) + 17.4 d^{1/2}] + (1 - f^{1/3})\sigma_p \tag{3}$$

where σ_y is the yield strength (MPa), d is the mli grain size (mm), f is the volume fraction of ferrite, σ_p is the contribution of pearlite and precipitation strengthening on yield strength.

As is noted from Table IV that the as-received, sand-, and air-cooled samples showed differences in grain structure as a consequence of different cooling conditions. Following a structure property analysis, a value for the level of σ_p was derived by subtracting from the experimental yield stress value as illustrated in Table IV. It is proposed that any difference between actual and predicted lower yield strength in the air- and sand-cooled samples consist of a pearlite and precipitation contribution, σ_p, which also includes an unknown contribution for clusters/solid solution strengthening.

A very wide range of values for σ_p was observed in the steel-1 and steel-2. For instance, sample obtained from steel-1 showed lower σ_p compared to the sample from steel-2 for all cooling conditions. This is because the presence of vanadium in steel-2 resulted in fine nucleation of V(CN) particles. The largest use of vanadium in microalloyed steels is a precipitation strengthener [9]. Also, as indicated before, the addition of vanadium reduced the interlamellar spacing of pearlite resulting in an increase in σ_p. Steel-1 having only Al as a microalloying element should not show any measurable precipitation strengthening. Therefore, σ_p up to 296 MPa (or 62% of the total strength) is concluded in the steel without vanadium, which is due to pearlite contribution.

Similar trend was also observed in the air- or sand-cooled sample. For example, sand-cooled samples showed lower σ_p than air-cooled samples for both steel-1 and steel-2, respectively. The reason for this is the differences in cooling rate, precipitate size, and distribution and pearlite structure after forging. For instance, air-cooled samples of the steels 1 and 2 had a higher cooling rate and a finer grain size compared to the sand-cooled samples, faster cooling rates and the lower transformation temperature and refine the pearlite lamellae or precipitate particles which gives an increase in σ_p [10].

Higher strength combined with adequate elongation to fracture can be achieved in steel-1 and steel-2 by forging followed by air cooling. This strength and elongation to fracture obtained is due to finer grain sizes and the larger pearlite and/or precipitation contributions. Steel-2 had higher strength, hardness, and elongation to fracture compared to steel-1 for all cooling conditions due to

an increase in vanadium content to about 0.08%. Vanadium addition raised strength and hardness by precipitation strengthening and by refining the pearlite.

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