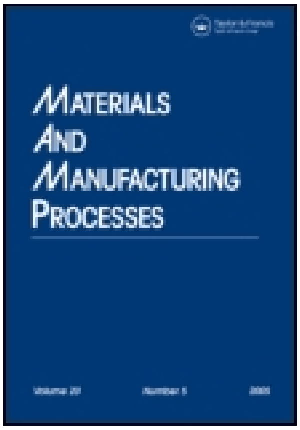

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The Microstructure and Mechanical Properties of Hot Forged Vanadium Microalloyed Steel

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In this article, the effect of hot forging parameters (deformation temperature, strain, and cooling rate) on the microstructure and mechanical properties of commercial vanadium microalloyed forging steel (30MSV6) was investigated. Final, microstructures and mechanical properties were evaluated by optical microscopy, Charpy impact, Brinell hardness, yield, and tensile strength tests. The results show that increasing the cooling rate changes the ferritic-pearlitic microstructure to the acicular ferrite-bainite. It is shown that by increasing post forging cooling rate, both yield and ultimate tensile strength increase, while the impact energy decreases significantly. The specimens with the same cooling rate differ not only in deformation temperature, and the deformation ratio is immaterial in establishing a grain size.

Keywords Characterization; Development; Ferrous; Forming; Hardness; Hot; Optimizations.

Introduction

The aim of the present work was to interpret the effect of processes variables on phase transformation and mechanical properties of vanadium microalloyed forging steel (30MSV6). The use of microalloying in steels is based on the addition of small amounts of vanadium. Fine grained microstructures are as important to achieve a most desirable strength and toughness. This article describes in details the processing, microstructure, and properties of experimental vanadium-containing forging steels.

In recent years, microalloyed (MA) medium carbon forging steels have gained acceptance as a replacement for the conventional quenched and tempered (Q–T) grades in automotive and some other applications. The driving force for the use of MA steels is cost reduction due to elimination of post-forging heat treatment, straightening and stress relieving, and improved machinability [1, 2].

Although microalloyed steels have the same level of strength in comparison with quenched and tempered steels, their toughness is lower. To improve toughness, carbon content of microalloyed steel has been reduced over the years, and the decrease in strength as a consequence of this is compensated by microalloying with vanadium, using its precipitation hardening effect [3]. Further increase of toughness can be achieved by microstructural control during the thermomechanical processing [4].

Microalloyed steels without pearlite have been developed to obtain a good combination of strength and toughness. Acicular ferrite microstructure is produced by a moderate cooling rate after forging, which in turn results in a good combination of strength and toughness [5, 6].

In the present work, the influence of hot forging parameters on the microstructure and mechanical properties of vanadium microalloyed forging steel (30MSV6) has been investigated.

Experimental procedure

The material used in this study was the commercial grade microalloyed steel 30MSV6. The chemical composition of this steel is shown in Table 1. The material was supplied by the Iran Alloy Steels Company located in Yazd city. It had ferritic-pearlitic microstructure.

The steel was supplied in the form of round bar billets of 52 mm diameter and 130 mm in length. The specimens were divided into two groups and solutionized at 1150°C and at 1300°C, respectively, for 2 min in a preheat forging induction furnace.

The steel was supplied in the form of round bar billets of 52 mm diameter and 130 mm in length. The forging tests were designed to perform at temperatures of 1150°C and 1300°C. Therefore, the specimens classified into two groups and solutionized at 1150°C and 1300°C for 2 min in a preheat forging induction furnace. The forging tests were performed at the solutionizing temperature after elapse of the preheat time in a 2500 tons mechanical press by a thickness reduction (30% and 45% strain induced, respectively) at constant strain rate of $0.1\,s^{-1}$ followed by air cooling at the rates of 1.5°C/s and 2.5°C/s. In order to control the cooling rates of specimens precisely and to pursue the homogenous microstructure during cooling, a conveyor device was designed for carrying specimens after exiting of furnace and the cooling rates were calculated by measuring the temperature of specimens after exiting of furnace

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TABLE 1.—Chemical composition of the micro-alloyed steel (wt%).

Element	C	Si	Mn	Ni	Cr	Mo	V	Cu	Ti	P	S	Fe
Wt%	0.30	0.56	1.49	0.08	0.22	0.01	0.11	0.19	0.017	0.013	0.078	Balance

and after exiting conveyor using a calibrated pyrometer. The temperature of the billets during deformation was also recorded by the same pyrometer. Table 2 shows 12 different thermomechanical states used for investigation of the effects of forging parameters.

The specimens were polished for microstructure observations. Mechanical properties were measured using tensile, Charpy impact test, and Brinell hardness tests. Figure 1 shows schematic of samples for tensile and Charpy impact test.

In order to control the cooling rate of specimens precisely and to pursue the homogenous microstructure during cooling, a twin conveyor device was designed and built. The cooling rates were calculated by measuring the temperature of specimens after exiting of furnace and after exiting conveyor using a calibrated pyrometer. The temperature of the billets during deformation was also recorded by the same pyrometer.

Table 2 shows 12 different thermomechanical states used for investigation of the effects of forging parameters.

TABLE 2.—Twelve different thermomechanical states used for investigation on the effects of forging parameters.

Experiment status	Preheat temperature (°C)	Strain (%)	Cooling rate (°C/Sec)
A1	1150	0	1.5
A2	1150	30	1.5
A3	1150	45	1.5
B1	1150	0	2.5
B2	1150	30	2.5
B3	1150	45	2.5
C1	1300	0	1.5
C2	1300	30	1.5
C3	1300	45	1.5
D1	1300	0	2.5
D2	1300	30	2.5
D3	1300	45	2.5

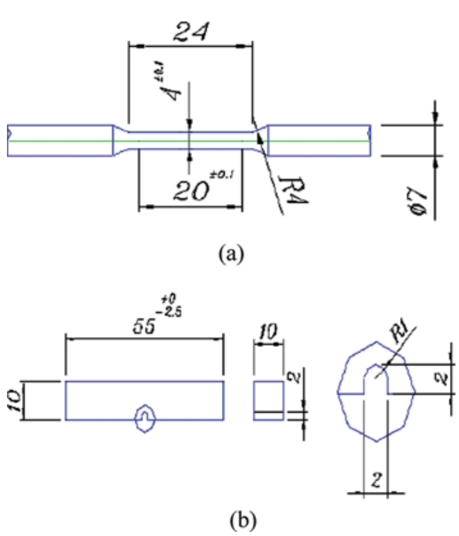

FIGURE 1.—A schematic of test specimens: (a) tensile testing specimen and (b) Charpy testing sample. Dimensions in mm (color figure available online).

RESULTS AND DISCUSSION

We investigate the properties of a number of specimens that were subjected to various thermomechanical treatments (Table 2). The microstructures of samples deformed at 1150°C and 1300°C followed by air cooling at 1.5 and 2.5°C/s rates with various degrees of upset are shown in Fig. 2. It is observed that depending on the different thermomechanical conditions, a variety of microstructures may be obtained. According to the metallographic observations, in two out of four states (where the cooling rate is 1.5°C/s) the microstructure consists of 20–40 vol% grain boundary ferrite and 60–80 vol% pearlite. In the other two, the microstructure consists of bainite, grain boundary ferrite, and pearlite.

Experiments 1 and 2 are associated with low cooling rate and the transformation $\gamma \rightarrow \alpha + P$ is the predominant activity, while experiments 3 and 4 are associated with the high cooling rate and the transformation $\gamma \rightarrow \alpha + P + B$ is the governing activity [7]. Therefore, at a constant cooling rate (one of the above mentioned groups) both preheat temperature and strain value

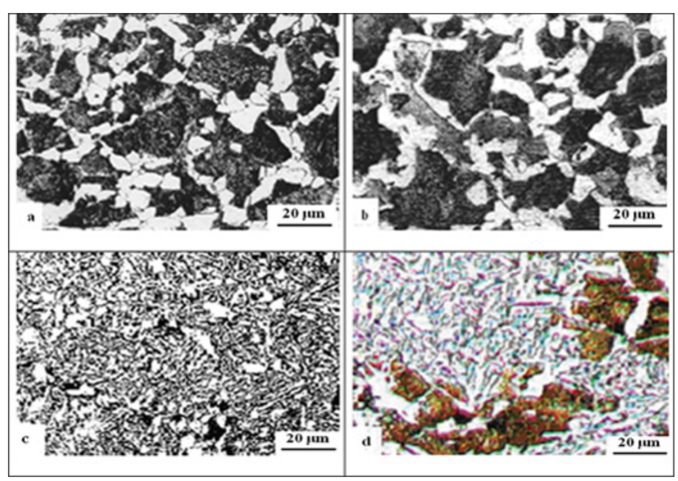

FIGURE 2.—Microstructures of specimens at deformation condition of (a) 1150°C, 1.5°C/s, 0% upset, (b) 1300°C, 1.5°C/s, 45% upset, (c) 1150°C, 2.5°C/s, 30% upset, and (d) 1300°C, 2.5°C/s, 45% upset (color figure available online).

determine volume fraction of ferrite and pearlite in the microstructure [8].

Figure 3 depicts hardness (a), yield stress (b), ultimate tensile strength (UTS) (c), and impact energy (d), as a function of strain, forging temperature, and cooling rate. With increasing strain at a constant deformation temperature and cooling rate, hardness increased. Hence, higher preheat temperature at constant cooling rate indicates higher hardness.

The hardness of samples at high cooling rate (2.5°C/s) are higher than those of samples at lower cooling rate (1.5°C/s). The samples deformed at 1150°C consist of acicular ferrite and grain boundary ferrite. In fact, by increasing the deformation temperature, the amount of grain boundary fracture (GBF) is increased [9]. Also, at low deformation temperature the acicular ferrite microstructure is refined and ferrite plate size is decreased [10–12]. Comparing the microstructure of samples with the same cooling rates shows that by increasing the deformation temperature the final austenite grain size increases. Also, the microstructures of samples deformed at 1300°C are coarser than those deformed at 1150°C. Another difference is the presence of grain boundary ferrite at specimens deformed at lower temperature and presence of pearlite and bainite at higher deformation temperature. Also, decrease in the deformation temperature decreases the primary austenite grain size and shift the continuous cooling transformation (CCT) diagram to lower temperatures and longer times and results in a large volume fraction of ferrite [13]. More dissolution of vanadium carbonitrides at higher temperatures increases hardenability of steels. On the other hand, increasing deformation temperature from 1150°C to 1300°C more V(C, N) is dissolved in ferrite. This effect leads to improvement in mechanical properties such as hardness of microalloyed forging steels [14].

Figures 3(b,c) show yield stress and ultimate tensile stress versus strain values at different deformation temperatures and cooling rates. With increasing strain at a constant deformation temperature and cooling rate, yield stress and ultimate tensile stress increased. Hence, higher preheat temperature corresponds to higher yield and ultimate tensile stress.

Figure 3(b) shows that the yield stress of samples cooled at high rate (2.5°C/s) is more than that of those cooled at lower cooling rate (1.5°C/s). The ultimate tensile strength was highly influenced by the pearlite interlamellar spacing and was also related to the ratio of ferrite to pearlite, cooling rate, and the pearlite colony size.

In fact, the large difference in hardness and yield stress observed in Fig. 3 is due to the changing in transformation from $\gamma \rightarrow \alpha + P$ to $\gamma \rightarrow \alpha + P + B$ when the cooling rate increased from 1.5°C/s to 2.5°C/s. Increasing the cooling rate after completion of forging at 1150°C leads to finer ferrite grain sizes and also increased ferrite volume fraction. These effects are generally associated with the influence of cooling rate on the coalescence of ferrite.

Figure 3(d) shows the influence of the deformation temperature and the amount of strain on the impact energy of microalloyed steels. Impact energy tends to improve with decreasing deformation temperature. Also, impact energy tends to decrease slightly with increase in the strain values. The elongation and impact toughness are both influenced by the percentage of ferrite and the interlamellar spacing of pearlite. They both increase with the ferrite/pearlite ratio [15].

Generally, an increase in the deformation temperature leads to an increase in austenite grain size and decrease in nucleation sites for ferrite at grain boundaries [16]. As a result, the elongation and impact energy decreased due to decreasing the amount of ferrite. The relatively large scale plates of ferrite can be responsible for the lower toughness. Another influencing factor on the toughness could be the presence of GBF after deformation at low temperatures which improves the ductility [17].

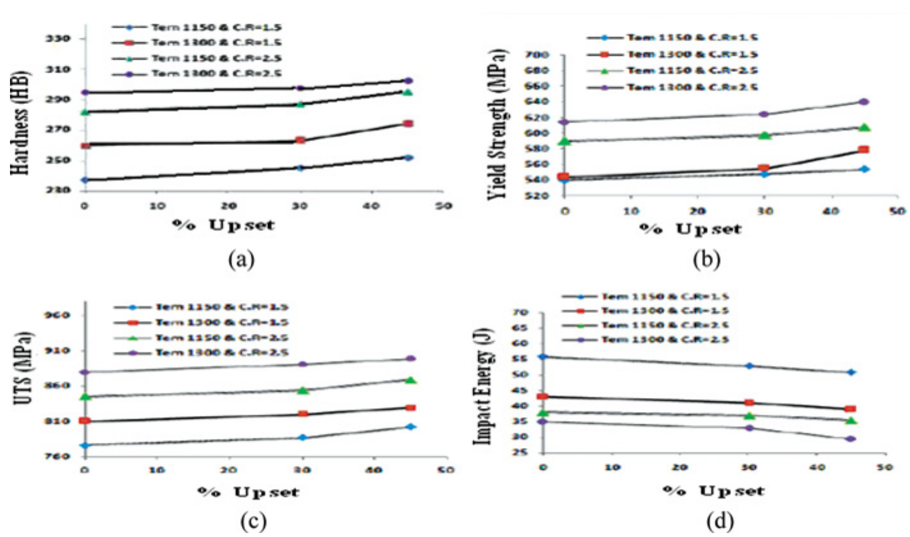

Figure 3.—(a) Effect of forging parameters on the hardness, (b) effective yield strength, (c) effective UTS, (d) impact energy (color figure available online).

Increasing the primary austenite grain size also increased the volume percent of acicular ferrite and reduced pearlite content in the microstructure even for very low post-forging cooling rates [18]. Increasing the cooling rate from 1.5 to 2.5°C/s increased the acicular ferrite content and led to increasing elongation and impact energy of samples.

Figure 3 depicts hardness (a), yield stress (b), UTS (c), and impact energy (d), as a function of strain, forging temperature, and cooling rate. With increasing strain at a constant deformation temperature and cooling rate, hardness increased. Hence, higher preheat temperature at constant cooling rate indicates higher hardness. This is attributed to the mean length of ferrite plate size of acicular ferrite. The measurements by a computerized image analyzer (Quantimet 520, Cambridge Instruments) showed that the mean length of ferrite plate size of specimens deformed at 925°C is about 7 μm while in the case of deformation at 1150°C is 11 μm. This difference in the size of ferrite plates is related to the mechanism of the acicular ferrite nucleation and the role grain boundary ferrite formation at the grain boundaries of austenite before the transformation to ferrite. Generally, decrease in the deformation temperature leads to a decrease of the austenite grain size and increase of the degree of pan-caking before transformation to ferrite [18]. At these conditions, the transformation of austenite to ferrite or pearlite is promoted due to the increase in nucleation sites at grain boundaries. Therefore, the ferrite + pearlite transformation range is displaced to higher cooling rates due to the decrease of hardenability of the steel. The hardness of samples at high cooling rate (2.5°C/s) are higher than those of samples at lower cooling rate (1.5°C/s). Generally, an increase in the deformation temperature leads to an increase in austenite grain size and decrease in nucleation sites for ferrite at grain boundaries [16]. As a result, the elongation and impact energy decreased due to decreasing the amount of ferrite.

As can be seen in Fig. 3 (b), the yield stress of samples cooled at high rate (2.5°C/s) is more than that of those cooled at lower cooling rate (1.5°C/s). The ultimate tensile strength was highly influenced by the pearlite interlamellar spacing and was also related to the ratio of ferrite to pearlite, cooling rate, and the pearlite colony size.

In fact, the large difference in hardness and yield stress observed in Fig, 3 is due to the changing in transformation from $\gamma \rightarrow \alpha + P$ to $\gamma \rightarrow \alpha + P + B$ when the cooling rate increased from 1.5°C/s to 2.5°C/s. Increasing the cooling rate after completion of forging at 1150°C leads to finer ferrite grain sizes and also increased ferrite volume fraction. These effects are generally associated with the influence of cooling rate on the coalescence of ferrite.

Impact energy tends to improve with decreasing deformation temperature. By decreasing the deformation temperature the final austenite grain size decreases. Decreasing the austenite grain size is responsible for higher impact energy [13].

From Fig. 3(d) it can be inferred that impact energy tends to decrease slightly with increase in the strain values (upset). The elongation and impact toughness are both influenced by the percentage of ferrite and the interlamellar spacing of pearlite. They both increase with the ferrite/pearlite ratio [15].

Increasing the primary austenite grain size also increased the volume percent of acicular ferrite and reduced pearlite content in the microstructure even for very low post-forging cooling rates [18]. Increasing the cooling rate from 1.5 to 2.5°C/s increased the acicular ferrite content and led to increasing elongation and impact energy of samples.

By increasing the cooling rate after hot deformation and keeping all other conditions the same, the effective yield strength, UTS, and the hardness increased in all cases. However, the elongation significantly decreased by increasing the cooling rate. Variation of the mechanical properties of specimens deformed at different temperatures cooled at the same rate show that the effective yield strength, ultimate strength, and the hardness increased by increasing the deformation temperature. This is attributed to the mean length of ferrite plate size of acicular ferrite. By decreasing the austenite grain size, the probability of formation of bainite instead of acicular ferrite increases.

It can be inferred that a good combination of strength and toughness can be obtained under the condition of deformation at 1150°C and air cooling at 2.5°C/s.

Conclusions

1. By increasing the cooling rate after hot deformation, the effective yield strength, UTS, and hardness are increased. However, the effective impact energy is significantly decreased by increasing the cooling rate.
2. The microstructure of samples deformed at 1300°C are coarser than those samples deformed at 1150°C.
3. Large difference in hardness and yield stress is due to the changing in transformation from $\gamma \rightarrow \alpha + P$ to $\gamma \rightarrow \alpha + P + B$ when the cooling rate increased from 1.5°C/s to 2.5°C/s.
4. By increasing the deformation temperature, the final austenite grain size increases.
5. Grain boundary ferrite appears in specimens deformed at lower temperature, while pearlite and bainite become the predominant phase at higher deformation temperatures. Hence, higher preheat temperature corresponds to higher yield and ultimate tensile stress.
6. With increasing strain at a constant deformation temperature and cooling rate, hardness and effective yield strength increased.

Acknowledgments

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