International Journal of Natural and Engineering Sciences
Uluslararası Doğa ve Mühendislik Bilimleri Dergisi
E-ISSN: 2146-0086, 11 (2): 05-09, 2017. www.nobel.gen.tr

The effect of accelerated air cooling on microstructures and mechanical properties of microalloyed steel

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Received: May 05, 2017
Accepted: July 25, 2017

Abstract

The microstructures and mechanical properties of the 38MnVS6 microalloyed steel under accerelated air cooling conditions were investigated. Compared to conventional cooling, accelerated air cooling (AAC) makes it possible to significantly increase strength properties without lowering impact toughness. The microstructure consisted of ferrite which formed at prior austenite grain boundaries and large amounts of pearlite. The cooling rates had an important effect on impact energy. The microstructure was characterized by optical microscopy and SEM analysis; the mechanical behavior was studied by hardness, tensile and instrumented Charpy V-notch impact tests carried out at 50°C, room temperature and -18°C. The observed microstructure was consistent with the continuous cooling transformation diagram. Continuous cooling transformation (CCT) diagrams, phase fractions and particle sizes have been calculated by means of JMATPro which is the best-practice tool for the calculation of temperature-dependent materials properties for a variety of technical alloys.

Keywords: 38MnVS6, microalloy, JmatPro, hot forging, accelerated air cooling

INTRODUCTION

Hot forging is a well-known industrial process and responds for millions of steel components manufactured per year. To obtain a good combination of toughness and strength forgings have to present a refined grain microstructure which depends on the initial grain size, on the forging temperature, and finally on the control of the cooling rate after forging. [1,2]

Kaynar et all [3] stated out that 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. Also, various cooling strategies have been applied to modify the microstructure and mechanical properties of the microalloyed steels. [4,5,6]

Among these parameters, cooling rate after finish forging is a more controllable parameter by producer due to limitations by suppliers or customers. However, it is generally disregarded in convectional production way. Higher cooling rates lead to a decrease of ferrite grain size formation of high strength, hardness, dislocation density, and phases because it suppresses the atomic diffusion. In contrast for lower cooling rates where, slow cooling rates lead to transformation into soft, coarse, and less dislocated phases like polygonal ferrite [7].

The present study aimed to the determination of thermomechanical and thermo-metallurgical properties of 38MnVS6 microalloyed steel by experimental methods. On the other hand, in many cases, trial-and-error procedure is neither optimal nor cost effective in terms of achieving the desired properties in the finished product. Data collection from experiments with traditional way is expensive, and furthermore, these properties can be sensitive to microstructure and alloy composition. Saunders et al.and Guo et al. reported that a computer program, Java-based materials properties (JMatPro), has developed an extensive database for the calculation of physical and thermo-physical properties such as molar volume, tensile strength, elastic modulus, fraction liquid, density and Poisson's ratio. [8,9,10,11]

Estimation of physical, metallurgical and/or mechanical properties of steels produced by various different parameters by numerical analyses can be beneficial when developing the appropriate forging procedure or pre and/or post treatments due to advantages e.g. cost and time savings, over real-time experiments. Hence, in this paper, experimental studies will supported or checked by JMatPro simulations.

MATERIALS and METHODS

38MnVS6 microalloy steel is used in this study. The chemical composition of used steel is listed in Table 1. As-received industrially hot rolled steel bars were cut 22x250 mm for hot forging application. Specimens were heated in an induction furnace and soaked at 800°C for 60 seconds before forging. The forging were performed outside the furnace, using tool faces lubricated with Molykote® HTP in order to reduce frictional effects. Temperature before and after forging process was measured by using an infrared laser temperature measuring instrument. The forging were performed with a 1.6 tonne forging hammer with 5 m/s at 800°C. Then forged steel samples were cooled in the air at 0.75°C/s and 1,5 °C/s. The cooling rates was carefully monitored during air cooling by a pyrometer. Hot forging performance was carried out in real working conditions in a hot forging factory.

Tensile strength was measured on a Schimadzu tensile-testing machine at a crosshead speed of 2 mm/min at room temperature. The Charpy V-notched specimens with a cross section of 10 mm x 10 mm, length of 55 mm, notch angle of 45° and notch depth of 2 mm were prepared for Charpy tests. The tests were carried out at 50°C, room temperature and -18°C to measure the impact fracture toughness. Hardness measurements were also carried out using the Rockwell hardness test. A minimum of 10 hardness measurements was made on each specimen to obtain satisfactory statistical reliability.

The metallographic examinations were carried out using NIKON Ecilipse LV100 optical microscope supported by CLEMEX digital camera. The average pearlite and ferrite volume fractions were measured by CLEMEX professional edition analysis program.

The phase transformations during solidification of the 38MnVS6 microalloy steel was controlled by differential thermal analysis (DTA) method. For this examination DTG-60H detector was used with a high temperature cell in nitrogen atmosphere. Complete dilatometric curve corresponding to a heating up to 1500°C and subsequent cooling down to room temperature showing the transformation temperatures for Ac1 and Ac3.

JMatPro (Sente Software Ltd., Guildford, UK) software [8,13] software was used the determine the continuous cooling transformation (CCT) diagrams of 38MnVS6 steel. This software was also used to monitor the evolution of potential phases as a function of cooling rates.

Table 1. Chemical composition of the investigated steel (wt.%).

C	Si	Mn	S	P	Cr	Ni	V	Cu	Al	N	Ti	Nb
0,4	0,75	1,43	0.028	0,015	0,29	0,038	0,13	0,047	0,012	0,007	0,02	0,003

RESULTS and DISCUSSION

Fig. 1 illustrates the result of the DTA measurement at a rate of 10°C/min obtained from a sample to determine the phase transition temperatures. A broad endothermic peak with a peak temperature of 793,98°C was observed during heating, which corresponds to γ→ α transformation (Ac3). Austenite is decomposed to ferrite, which is important to selecting austenisation temperature. The lower (Ac1) transformation temperatures was 716,33°C. The CCT diagram of the investigated steel, as calculated by JMatPro, is presented in Fig. 2. It is seen that Ac3 was 783.9 °C and Ac1 was 731.9 °C. JMatPro predicts the grain size of 11.1 ASTM number after the austenitization at 800 C for 60sec. Hence, the calculated temperature of the α to γ transformation is in reasonable agreement with the DTA results.

The micrographs obtained after air cooling at 0,75°C/s and accelarated air cooling at 1,5 °C/s are presented in Fig. 3. It can be observed that air cooling gave rise to the proeutectoid ferrite and pearlite. Notice that the structure is comprised of about ~40% ferrite and ~60% pearlite, in this case. Hence, these steels are often referred to as pearlite-ferrite steels [14]. The volume fraction measurement of retained austenite from optical microstructure was nearly impossible. Hence, the presence of negligible amount of austenite which remained untransformed during cooling from 800°C was ignored. Accelarated air cooling presented the lower ferrite fraction and the higher pearlite fraction (Table 2).

Quantitative analyses of the fraction of different microstructural constituents both calculated by JmatPro and experimental are presented in Table 2. As pointed out above, thermodynamic calculations also show that as cooling rate increase, ferrite amount decrease. Predicted volume fraction of the phases was lower than experimental.

The grain size of ferrite was measured as both widht and length (Fig.4). It lies within 2,62–6,57 µm. It is evident from these micrographs (Fig.3) that the prior-austenite grain boundaries are occupied by ferrite. Austenite to ferrite being a diffusive transformation, growth of ferrite took place during post-deformation cooling. It is noticeable that higher cooling rate decreases the amount of pro-eutectoid ferrite that can form during transformation because of suppression of growth rate of ferrite [15].

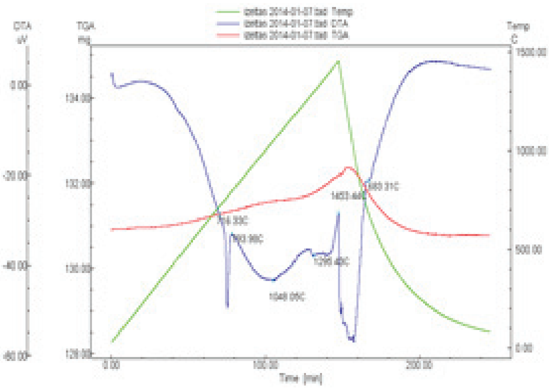


Figure 1. DTA curves of the analysed alloy (10°C/min)

Table 2. Phase analyses results both by calculated by JmatPro and by experimental

Cooling Rate, C/s	Calculated by JmatPro				Experimental results	
	ASTM austenite grain size	Austenite grain size, Micron	Ferrite, %	Pearlite, %	Ferrite, %	Pearlite, %
0,75	11,1	8,5	21,01	78,99	39,18	60,82
1,5	11,1	8,5	18,31	81,69	32,83	67,17

In microalloyed steels, strength is affected not only the pearlite or ferrite volume fraction but also precipitation strengthening of the ferrite matrix as controlled with microalloy additions (e.g., Ti, Nb, or Al for grain size control and V for precipitation strengthening) [16,17].

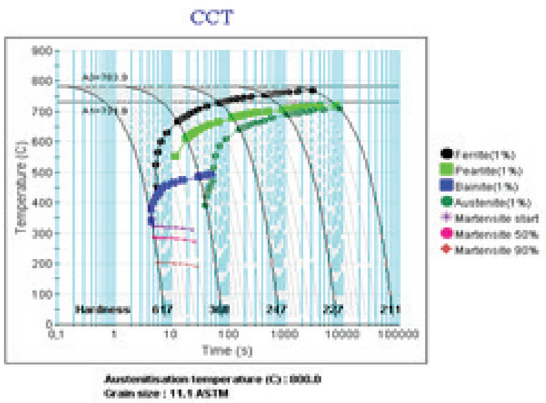
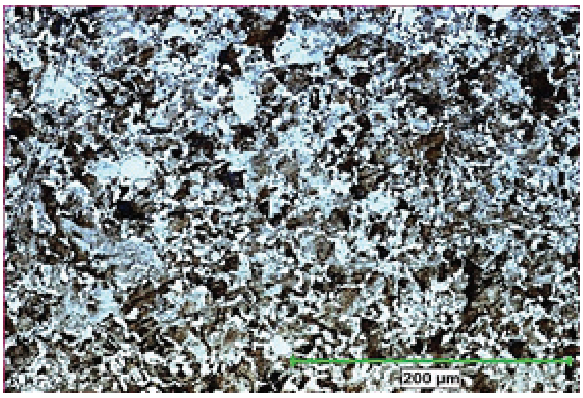


Figure 2. CCT diagram for 38MnVS6 steel by JMatPro

Interphase precipitation of Ti,V (C) and Ti,V(C,N) during austenite-to-ferrite transformation under slow cooling of Ti and V-microalloyed steel is a well-known phenomenon [18,19,20]. In this study, it was determined Ti,V(C) intermetallics at both air cooled and accelarated air cooled samples. The presence of fine Ti,V(C)precipitates were also confirmed by Energy Dispersive Spectroscopy (EDS) (Fig. 5). The morphology and distribution of the microalloy precipitate have been found to be similar in both samples. It was seen that accelarated air cooling reduced the precipitate sizes (Fig 5 a-b). The volume fraction measurement of the precipitates from scanning electron microstructure was nearly impossible due to low volume percentage. JmatPro is able to determine the precipitate volume percentage and their particle size without considering cooling rate. As it is seen in Fig.6, M3C and M(C,N) correspond sementite in the pearlite and Ti,V(C)precipitates, respectively. Ti,V(C) has too low volume percentage and tiny particle size. It is known that slow cooling is favorable for interphase precipitation. Increase in cooling rate can suppress the precipitate growth by restricting the diffusion of Ti and V [20,21].



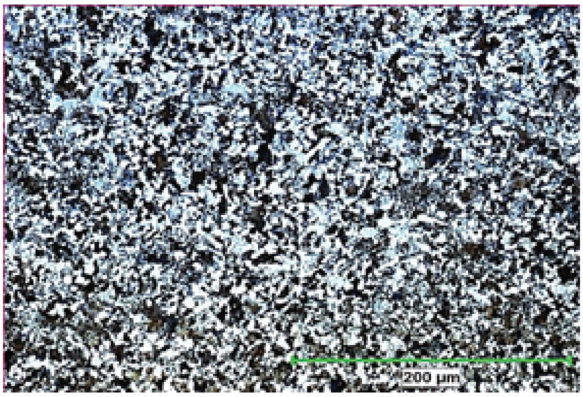


Figure 3. a) The micrographs obtained after air cooling at 0,75°C/s; b)accelareted air cooling at 1,5°C/s

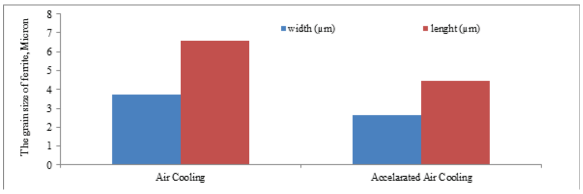


Figure 4. The grain size of the ferrite phase

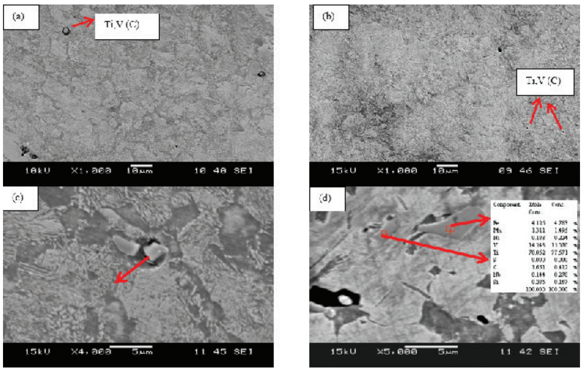


Figure 5. SEM micrographs of typical precipitates in air-cooled sample (a)(c); accelarated air cooled sample (b)(d)

Fig.7 shows mechanical properties obtained experimental methods. It was found that when the air cooling was changed to accelarated air cooling, it has no considerable effect on hardness, YS and UTS, but it significantly decreased the impact energy due to decrement of ferrite content. Generally, an increase in either the cooling rate or the forging temperature leads to a loss in toughness [22].

The accelerated air cooling has a detrimental effect on the steels toughness, indeed the impact energy values are reduced by quarter in respect with the still air cooling condition. Fig. 7-b exhibits the Charpy absorbed energy of the steels developed as a function of temperature. The results revealed that the air cooling offer superior impact properties (i.e., greater Charphy absorbed energy), compared with the accelarated air cooling not only room temperature but also higher and subzero temperatures.

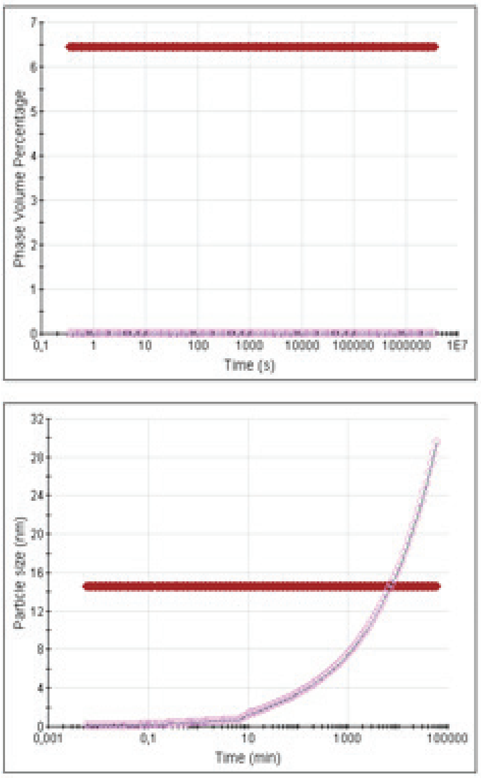


Figure 6. The precipitate volume percentage and their particle size by JMatPro simulations without considering cooling rate

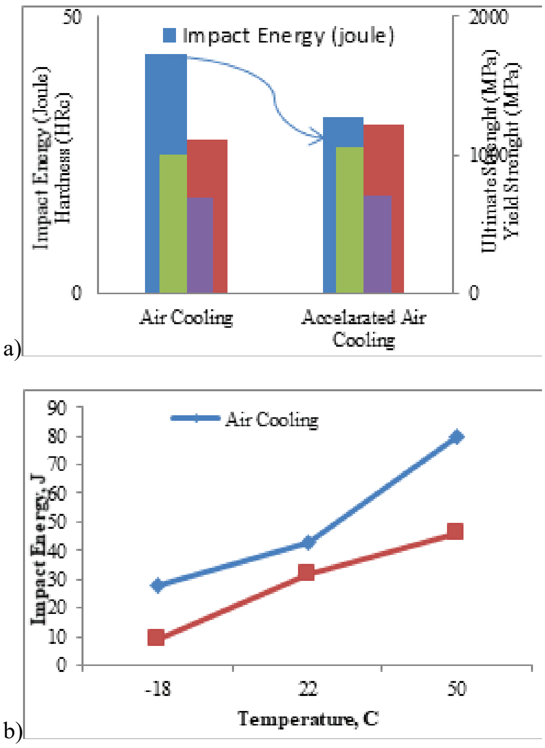


Figure 7. Mechanical properties obtained after air cooling (a); accelareted air cooling (b).

It is known that as cooling rate increases, lamellar spacing of pearlite gets shorter and precipitates occurs more smaller [21]. In fact, the lamellae density and precipitate size have significant effects on the impact toughness, which will be investigated in detail in the future [23].

CONCLUSION

The relationships between the microstructures and the mechanical properties of 38MnVS6 microalloyed steel have been examined after forging in 800 0C temperature followed by air cooling at 0,75°C/s or accelarated aircooling 1,5°C/s. The forging schedules were performed in a forging factory. The influence of accelareted air cooling vs air cooling on the microstructure and, consequently, on the hardness, tensile behavior and impact toughness at room, sub-zero and elevated temperatures of 38MnVS6 microalloyed steel were ingestigated. CCT diagrams and phase fractions were determined using dilatometry methods, experimental methods and the JMatPro computer simulations. Major conclusions derived from this study are listed below:

- Increase in cooling rate reduced the ferrite grain size and ferrite volume fraction, suppressed the austenite-to-ferrite transformation start temperature, and increased the fraction of pearlite which is harder microstructural constituents.
- Increase in cooling rate did not caused considerable effect on hardness, YS and UTS, but it significantly decreased the impact energy due to decrement of ferrite content. While impact energy was 43,33 J for air cooling, it was 31,66 J for accelarated air cooling.
- It is well-known that pearlite lamellae density has significant effects on mechanical properties as much pearlite volume fraction as. Precipitation hardening also plays an important role in microalloyed steel. These effects will be discussed considering the cooling rate after austenization in the future.
- Phase fractions according to different production parameters can be calculated by JMatPro simulations. In this study, predicted volume fraction of the phases was lower than experimental. It will be detailed analysed in the next studies.
- CCT or TTT diagrams and the precipitate volume percentage and their particle size were estimated by JMatPro simulations. JMatPro give us an easy key when data collection from experiments with traditional way is difficult, expensive and time-consuming.

ACKNOWLEDGEMENTS

The authors would like to thank Celal Bayar University (Project Code: 2016-008) for providing financial support. The authors are thankful to IZELTAS A.S. for providing samples and hot forging trials.

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