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Effects of titanium addition on austenite grain size and mechanical properties of high manganese steel

Ảnh hưởng của titan đến kích thước hạt austenite và cơ tính của thép Mangan cao

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TÓM TẮT

Thép Mangan được ứng dụng rộng rãi trong công nghiệp nhờ vào tính chất chống mài mòn tốt, khả năng hóa bền cơ học cao cùng với độ dai và độ dẻo cao. Nghiên cứu này đã khảo sát ảnh hưởng của biến tính, bao gồm FeTi và Mischmetal, đối với kích thước hạt và cơ tính của thép Mangan cao (13-15 % t.l). Thép hợp kim được biến tính ở các nhiệt độ khác nhau 1500, 1550 và 1600 ℃. Các hợp kim biến tính, sau khi đông đặc, được xử lý nhiệt qua hai bước. Kích thước hạt, thành phần hóa học và sự hình pha của thép sau xử lý nhiệt được phân tích bằng các kĩ thuật hiển vi quang học, nhiễu xạ tia Rơnghen và quang phổ phân tán năng lượng tia Rơnghen. Các cơ tính như độ cứng Brinell, độ bền kéo và độ cứng của thép cũng được đánh giá. Kết quả là, kích thước hạt của các hợp kim sau xử lý nhiệt nhỏ hơn so với hợp kim ban đầu, và đồng thời kích thước hạt càng giảm khi lượng biến tính càng tăng. Việc bổ sung Ti làm giảm lượng C trong pha austenit bằng cách hình thành pha TiC rất bền. Giới hạn bền kéo tối đa 780 MPa đạt được với sự bổ sung của 0,1 % t.l Ti, trong khi độ dai va đập tối đa là 140 J/cm^2 ở 0,05 %t.l Ti.

Từ khóa: *Thép Mangan, biến tính, kích thước hạt, xử lý nhiệt, cơ tính.*

ABSTRACT

Manganese steels have been widely used in industries due to their good wear resistance, high work hardening ability, and high toughness and ductility. This research investigated the effect of modification, i.e., FeTi and Mischmetal, on the grain size and mechanical properties of the high manganese steel (13–15 wt.%). The alloys are modified at different temperatures of 1500, 1550, and 1600 ℃. The modified alloys were heat-treated after solidification by a two-step process. The grain size, chemical composition, and phase formation of the heat-treated steel were characterized by Optical Microscopy, X-ray Diffractometry, and Energy-Dispersive X-ray Spectroscopy. The mechanical properties of the steel, such as Brinell hardness, tensile strength, and toughness, were measured. As a result, the grain size of the heat-treated alloys is smaller compared to that of un-modified alloys and decreases with the increase in modification amount. The addition of Ti reduced C in the austenite phase by forming very stable carbides, TiC. Maximum tensile strength of 780 MPa was achieved with the addition of 0.1 wt.% Ti, while maximum fracture toughness was 140 J/cm^2 at 0.05 wt.% Ti.

Keywords: *Manganese steels, modification, grain size, heat treatment, mechanical properties.*

1. INTRODUCTION

Hadfield manganese steel (HMnS) was discovered by Robert Hadfield in 1882 and contains 12.5% Mn and 1.2% C. HMnS exhibits various properties such as high strength, toughness, and wear resistance, and especially the ability of work-hardening under severe shock-impact conditions during service. Thus, Hadfield manganese steel (HMnS) continues to find extensive use in various practical applications in industries, such as jaw crushers, rail tracks, excavator buckets, wear-resistant components for mining vehicles, and tank chains, etc [1-3]. Recently, HMnS has been considered a good material candidate for future automotive industry applications due to its highly uniform work hardening and excellent energy absorption ability [4-6].

The as-cast high-Mn austenite steels show coarse grains and low thermal conductivity. It may also exhibit intercrystallite fracture, which leads to the premature failure of castings due to hot and cold cracking [1]. To overcome these phenomena, molten high-Mn steels were poured at a low temperature, increasing the cooling rate, and modified using Al or Ti [2]. In the context of steel modification, titanium (Ti) is highly regarded for its impact on the mechanical properties of HMnS. When present, Ti reacts readily with oxygen and carbon, leading to the formation of TiO_2 and TiC, respectively. Therefore, it is crucial to investigate the influence of Ti content on the mechanical properties of HMnS steel to ensure optimal performance in these applications.

According to previous research, TiC is stable, has a high melting point, and has a small lattice mismatch degree with austenite (10.61 %). When the lattice mismatch between two phases is less than 12 %, the high melting-point phase can be used as a heterogeneous nucleation agent. Thus, TiC can be used as a heterogeneous nucleation agent for austenite crystallization [3]. In the case of adding rare earth elements to steel, these elements can react with oxygen and sulfur, decreasing their content in steel. The reaction products are oxides, which can act as nucleation agents for steel because of their very high melting temperature, usually above 2500 ℃, and their lattice parameters are not significantly different from austenite [4].

2. Experimental procedure

High-manganese steels were melted in an industrial-scale induction furnace at 1000 kg per charge. Table 1 lists the chemical composition of this steel in percent by weight. After the raw material had been completely melted, ferroalloys were introduced. CaO and CaF_2 compounds were also introduced into the furnace to produce slag, which increases efficiency and reduces heating loss. The melting temperature was raised to 1,500 degrees Celsius and held constant for ten minutes. The slag was then removed from the molten steel, which was transferred to a 300-kg preheated ladle. The bottom of the ladle has been pre-loaded with FeTi and Mismetal compounds. The quantity of Mischmetal per charge is fixed at 0.15 wt%. To examine the effect of Ti content, 0.05, 0.10, and 0.15 wt% of Ti were added to each batch. The steel was then loaded into a Y-shaped mold in accordance with ASTM 439-83 (2004).

Samples were cut in the lower part of the Y-shaped block. The dimension of the optical sample was 15 mm × 15 mm × 10 mm, and I-shaped mechanical test samples were prepared in accordance with ASTM 439-83 (2004). All samples required heat treatment, which consisted of heating at 650 ℃ for 1.5 hours, then heating to 1050 ℃ for 2 hours, and lastly cooling in water. The mechanical properties of steels were determined using the 809 Axial/Torsional Test System. The samples' hardness was measured using the Rockwell and Brinell procedures in accordance with ASTM E10-18. All samples' microstructures were analyzed using a German-made optical microscope, the Axio Observer D1M. A microscope and Matavis Hard software were used to ascertain the grain size.

Table 1. Chemical composition of research steel (wt.%).

C	Si	S	P	Mn	Cr	Ni	V	Mo	RE	Fe
1.30	≤ 0.8	≤0.02	≤ 0.08	13 ÷15	2.0	0.4	0.5	0.15	0.15	bl.

3. RESULTS AND DISCUSSION

3.1. Microstructure

3.1.1. Morphological analysis

Fig. 1 illustrates the as-cast microstructure of high-Mn steels, which indicates the appearance of very small quantities of carbides in the grain boundaries of austenite. After heat treatment, these carbides disappear, the microstructure is only austenite, and there are many inclusions dispersed on the austenite matrix. We considered these inclusions to be carbides (Fig. 2). It can be understood that, in an as-cast sample, carbides in the boundry mostly is $(Fe,Mn)_3C$ [5]. Under heat treatment, these carbides are decomposed to form carbon, and then carbon atoms will be diffused into the austenite matrix. Hence, the carbon content of austenite is increased.

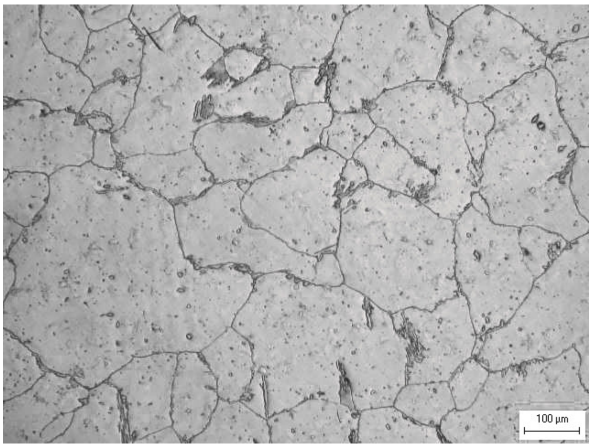

Figure 1. OM images of as-cast steel

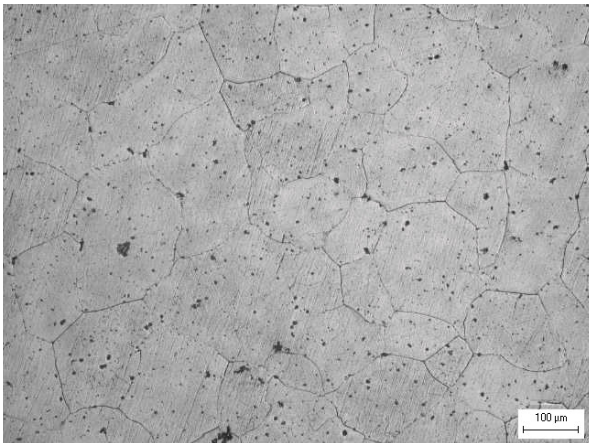

Figure 2. OM images of heat-treated steel

From all of the microstructure after heat treatment, it can be seen that there are a lot of fine inclusions (2–3 mm), which are well dispersed in the metal matrix. To further clarify this observation, the EDS pattern of the heat-treated sample was analyzed, and the results are shown in Figs. 3 and 4.

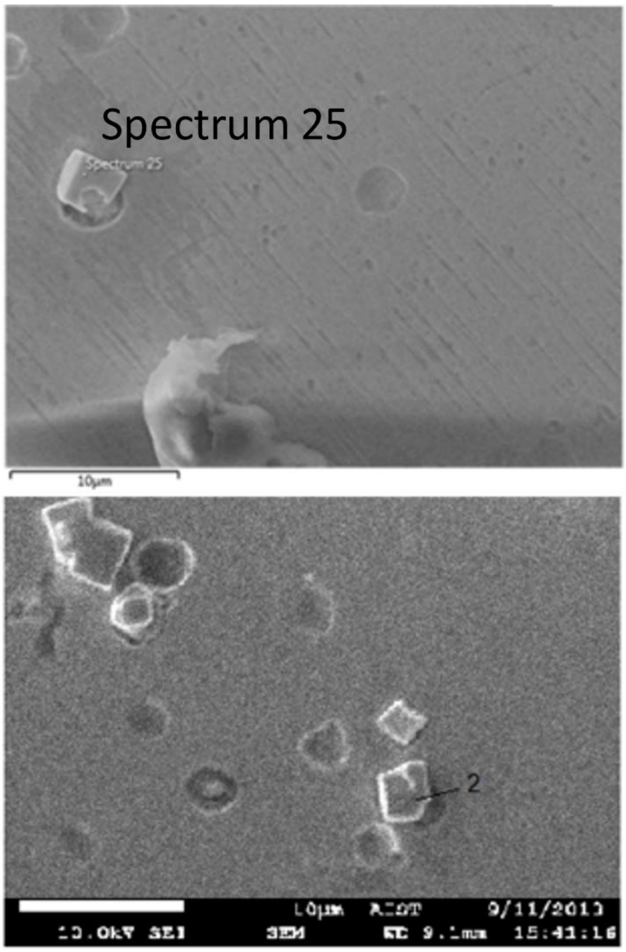

Figure 3. The SEM image of heat-treated sample

EDS analysis reveals that the inclusion is composed of carbon and strong carbide-forming elements such as Ti, Mo, and V. This indicates that the primary components of these inclusions are carbides, such as TiC, VC, and MoC. As a consequence, the modification mechanism and alloying process of high manganese steel are extremely difficult to predict.

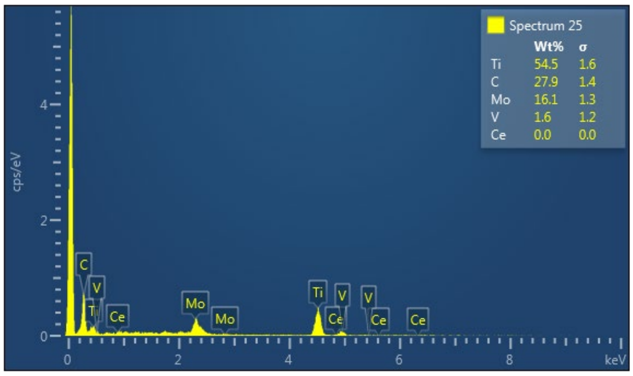

Figure 4. The EDS spectra of inclusion (spect.25, Fig. 3)

3.1.2. Structural analysis

TiO_2 and carbides are selectively formed during the melting process, as shown by XRD analysis (Fig. 5) and the preceding discussion. TiO_2 oxides are exclusive to the degassing procedure. TiC is produced during both solidification and thermal treatment. Ti is therefore not only a modification agent, but also an oxidation agent. These inclusions are uniformly dispersed inside the grains and do not appear at the grain boundary. All inclusions here can act as nucleation agents and refiners for austenite grains.

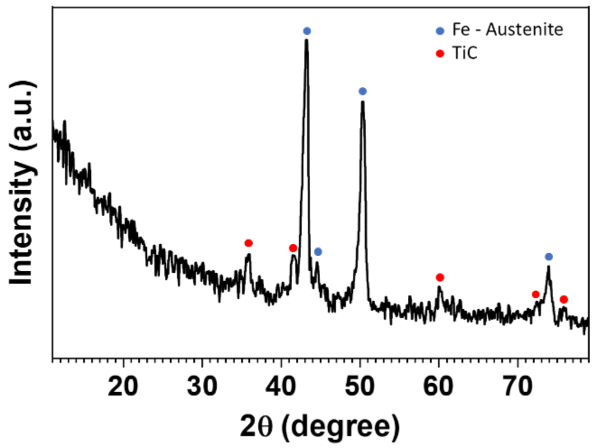

Figure 5. XRD pattern of the heat-treated steel

Comparing the microstructures of as-cast and heat-treated high manganese steels (Fig. 1 and 2) reveals that in addition to $(FeMn)_3C$ at the grain boundary, certain types of carbides are also present within austenite grains. Following thermal treatment, the boundary carbides have completely decomposed, and the amount of carbide grains has significantly increased.

According to the conventional theory of high manganese steels, the mechanism of strain hardening is the transformation of austenite to martensite as a result of impact energy; therefore, the appearance of carbide was unexpected. In some instances, however, this has not been the case. No martensite is detected, for instance, when as-cast Mn13-steels are subjected to intense impact stresses. It indicates that the high strength and abrasion of the steel are due not only to martensite transformation but also to other factors, such as dislocation, flaws, and siblings. Consequently, the alloying and modification mechanisms of Mn13-steel have changed substantially. It is not the reason why the modified steel has high strength and excellent wear resistance. Figure 6 depicts this phenomenon. During melting and modification, Cr, Ti, and V react with C to form carbides (M_xC) within austenite crystals (Figure 1).

Moreover, secondary carbides were formed and refined during the retention period at 650–700 °C [5]. Consequently, after thermal treatment, the amount of carbide increased. At 1050 °C, the Ellingham diagram indicates that the free energy of carbide-forming reactions increases in an orderly fashion: TiC → Cr_7C_3 → VC → Mn_3C. This indicates that Mn_3C can be readily decomposed into carbon atoms and then diffused into austenite grains. Carbon atoms combine with dissolved atoms (Cr, V) to form carbides, thereby increasing the amount of carbides in solid solutions. These carbides inhibit dislocation motion, which contributes to the work hardening of Mn13-steels.

3.2. Modification and grain size

From the Fe -Ti phase diagram [7], it can be seen that the dissolution of Ti in Fe is very low. At room temperature, Ti almost does not dissolve in Fe, even at high temperature, e.g., only 0.12 wt.% Ti was dissolved in Fe at 1350 °C. The addition of Ti in the Mn13 steel will lead to the formation of TiC.

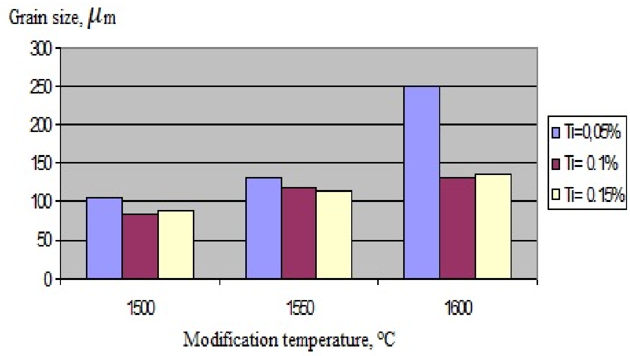

Figure 6. Grain sizes of austenite at different modified temperature with different Ti

In general, the grain sizes of austenite in the Mn13 steels increase with the modified temperatures, which are in the range of 80 to 160 μm. That average grain size is significantly smaller than that of the previous report [5]. At the same modified temperature, the grain size of austenite slightly varies with the amount of Ti.

The formation of very fine TiC grains in the Mn13 steel results in the formation of nucleation, refining the austenite grain and preventing the movement of dislocations, which lead to an increase in strength and hardness of the steel, as shown in Fig. 7.

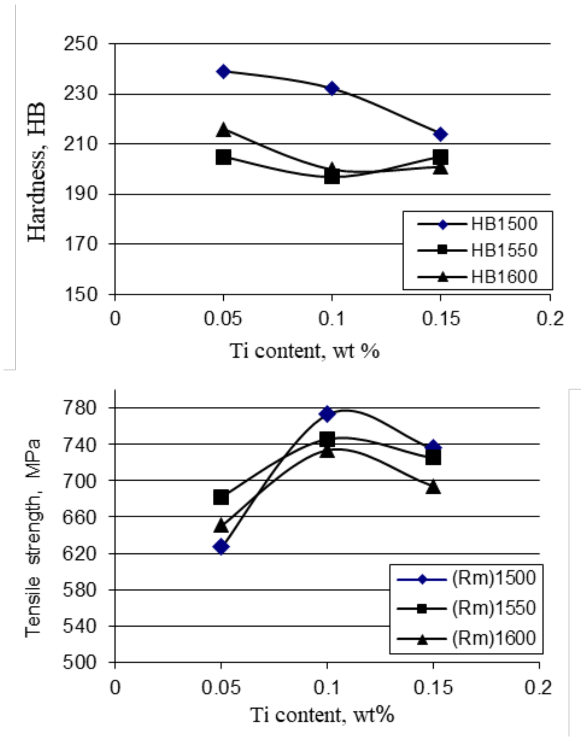

Figure 7. The hardness and tensile strength of modified Mn13 steels with different amount of Ti.

The hardness of Mn13 steels decreases with the increase in modified temperatures. For the same modified temperature, the hardness decreases when increasing Ti, as seen in Fig. 8. This can be explained by the decrease in C content.

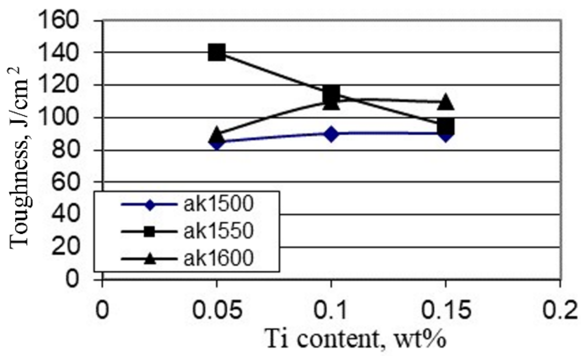

Figure 8. Effect of Ti content to the toughness of Mn13 steel at different modified temperature.

When adding Ti, C diffuses out of the austenite phase and reacts with Ti to form TiC, as presented in Fig. 9. Thus, the loss of C led to a decrease in the hardness of Mn13 steels. The toughness of Mn13 steels decreases with the increase in Ti. A maximum toughness of 140 J was achieved for Mn13 with the addition of 0.05 wt.% Ti at 1500 ℃.

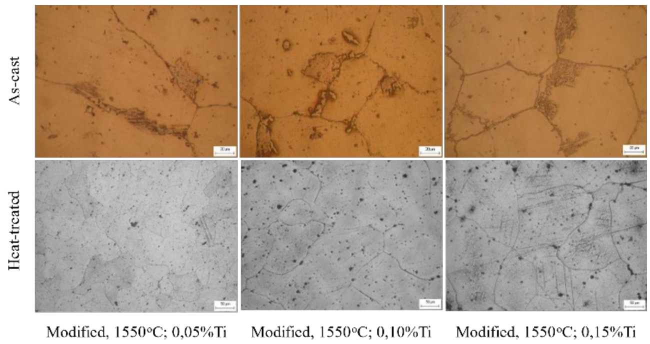

Figure 9. Micostructure of as-cast and heat-treated steel

4. CONCLUSION

The mechanical properties of Mn13 steels are significantly enhanced with the addition of Ti in the range of 0.05–0.15 wt.%. The grain sizes of the heat-treated Mn13 steels were smaller compared to those of cast alloys and decreased with the increase of Ti. TiC was precipitated after modification and heat-treatment. Maximum hardness and fracture toughness of heat-treated Mn13 steels are 240 HB and 140 J/cm^2, respectively, at 0.05 wt.% Ti.

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