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Effect of Titanium Alloying on the Microstructure and Properties of High Manganese Steel

Wenwei Zhuang[1,*], Haixu Zhi[1], Handai Liu[1], Daxiang Zhang[1], and Dongmin Shi[1]

[1]East China University of Technology, School of Mechanical and Electronic Engineering,418 Guanglan Street, Changbei District, Nanchang 330013, Jiangxi Province, China.

Abstract. The test used casting process to alloy the traditional high manganese steel with adding Ti. The surface morphology of the high manganese steel sample was observed by the scanning electron microscopy.At the same time, the hardness, the tensile strength and the wear resistance of the sample were tested. Compared with the high manganese steel without alloying, it studied the micro-structure and properties of modified high manganese steel . The results show that the grain of high manganese steel alloyed by titanium alloy is refined, the inclusions is dispersed and their size is reduced. The hardness of high manganese steel is increased by 87 %~263 %, but the tensile strength is reduced. Compared with the sample without added titanium element, the wear resistance of the alloyed high manganese steel is significantly improved.

1 Introduction

As a good wear-resistant material, high manganese steel is widely used in many fields such as machinery, mining, metallurgy, coal, chemical industry railway and many other fields because of its excellent organization and performance [1~2]. During the long-term use process, the traditional high-manganese steel has been found of having defects. For example, under strong impact load the good wear resistance of high manganese steel can be exhibited . A large number of studies have shown that alloying treatment [3] is one of the effective ways to improve the wear resistance of high manganese steel. It usually adds alloying elements such as Cr, V, rare earth, etc. [4~5]. The studies have shown that the addition of more than one alloying elements is more effective than the addition of a single element. Therefore, this test used the controlled variable method. Both different amounts of titanium and the same amount of Chrome element were added to the sample . In order to explore the mechanism of action of Ti in high manganese steel, this paper established a reasonable research method and experimental process. This paper studied the effects of Ti alloying treatment on the micro-structure and properties of high manganese steel, provides important basses to improve the wear resistance of high manganese steel and prolongs the life of the grinding and casting parts.

2 Test Content and Method

2.1 Smelting and Casting

Under normal conditions, the cast high manganese steel is smelted in an electric arc furnace or an intermediate frequency induction furnace. After comparison, the quality of the high manganese steel that smelted by the intermediate frequency furnace is significantly better than that of the high-manganese steel smelted by the electric arc furnace. Therefor, an intermediate frequency furnace is chose in the smelting experiment. The high manganese steel with alloying elements are smelt by the non-oxidation steel-making process in the 10 kg of niobium. The main charge is high-quality carbon steel (or steel ingot), high-carbon ferro-manganese, medium-carbon ferro-manganese, high-carbon ferro-chrome, ferro-titanium alloy and high-manganese steel. And the amount of recycled material is less than 25 %, carried out laboratory sampling from questionable steel, ensured that contents of various elements were not exceeded in steel which required alloys, and the mass fraction can be guaranteed to reach the standard [6]. Firstly, carbon steel is smelted, and various types of ferro-manganese and other precious alloy materials are divided into several times. Each time a small amount is introduced into the furnace, precious elements arre added at the end for reducing the burning loss. After melting, the molten steel is fully boiled [7], at the time of the furnace temperature reaching 1580-1600 °C. It is in the process of deoxidation, dehydrogenation and denitrification. During the tapping process, the Ti-Fe alloy element is used for metamorphism treatment. And it is divided into 5 groups according to different contents, and one of them is a control group without adding titanium element.

Before the molten steel being discharged, the ladle is baked to more than 400 °C, and then cast to obtain the

*Corresponding authorl: 375897526@qq.com

required test sample blank. In the pouring process, it is very important to control the temperature. If the temperature is too high, the high manganese steel structure will have defects such as coarse crystals, column crystals, etc. Therefor the casting temperature should be minimized. However, the temperature should not be too low. It might cause defects as the pores in the casting. The mold and core adopt the magnesia powder as the aggregate coating. The casting system use the open type. When pouring, the casting should be in as low temperature as possible. The casting should be kept in the mold for a long time until it is lower than 200 °C.

Finally, the samples of metallographic test, hardness test, abrasion test and tensile test are obtained by the cast blank of being machined .

2.2 The Titanium alloy test plan

Since more than one alloying elements are added, the improvement of performance is more remarkable than a single element. In this test, different amounts of Ti and an equal amount of Cr were added to every group of samples. The composition of this test sample was analyzed and tested by Jiangxi Analytical Testing Center. The test center used GB/T2015-2006 low-alloy steel multi-element determination inductively coupled plasma optical emission spectrometry. The specific test scheme and alloying element content are shown in Table 1.

Table 1. Titanium alloy test plan

Element sample	The control group	1#	2#	3#	4#
Si	0.98	0.98	0.98	0.98	0.98
Mn	11.21	11.21	11.21	11.21	11.21
P	0.058	0.058	0.058	0.058	0.058
S	0.009	0.009	0.009	0.009	0.009
Cr	1.31	1.31	1.31	1.31	1.31
Ti	0	0.0045	0.0073	0.016	0.017

Analyzed the metallographic structure of the high manganese steel before and after the alloying treatment , and observed the changes of the metallographic structure of the sample before and after the modification. The metallographic analysis samples are polished with sandpaper, then etch with a 4 % nitric acid solution, rinse with an alcohol solution, blown dry, and the as-cast microstructure is observed using a scanning electron microscope.

In this test, the hardness of the test material is the HR-150A Rockwell hardness tester. Three tests were performed on each sample.And the obtained data were averaged.

It used MM-W1 vertical universal friction and wear testing machine to test the wear resistance of the high manganese steel before and after the alloying treatment. The heat-treated mold steel is used as the small test ring to the top piece. After comparison, the test speed is 300 r/min, the applied force is 200 N, during 30 minutes. At the end of the test, the sample is washed with 95 % absolute ethanol to remove the grinding. After the cleaning, the quality of the wear is calculated by weighing with a one-tenth of a photoelectric balance. The weight loss is calculated after weighing.

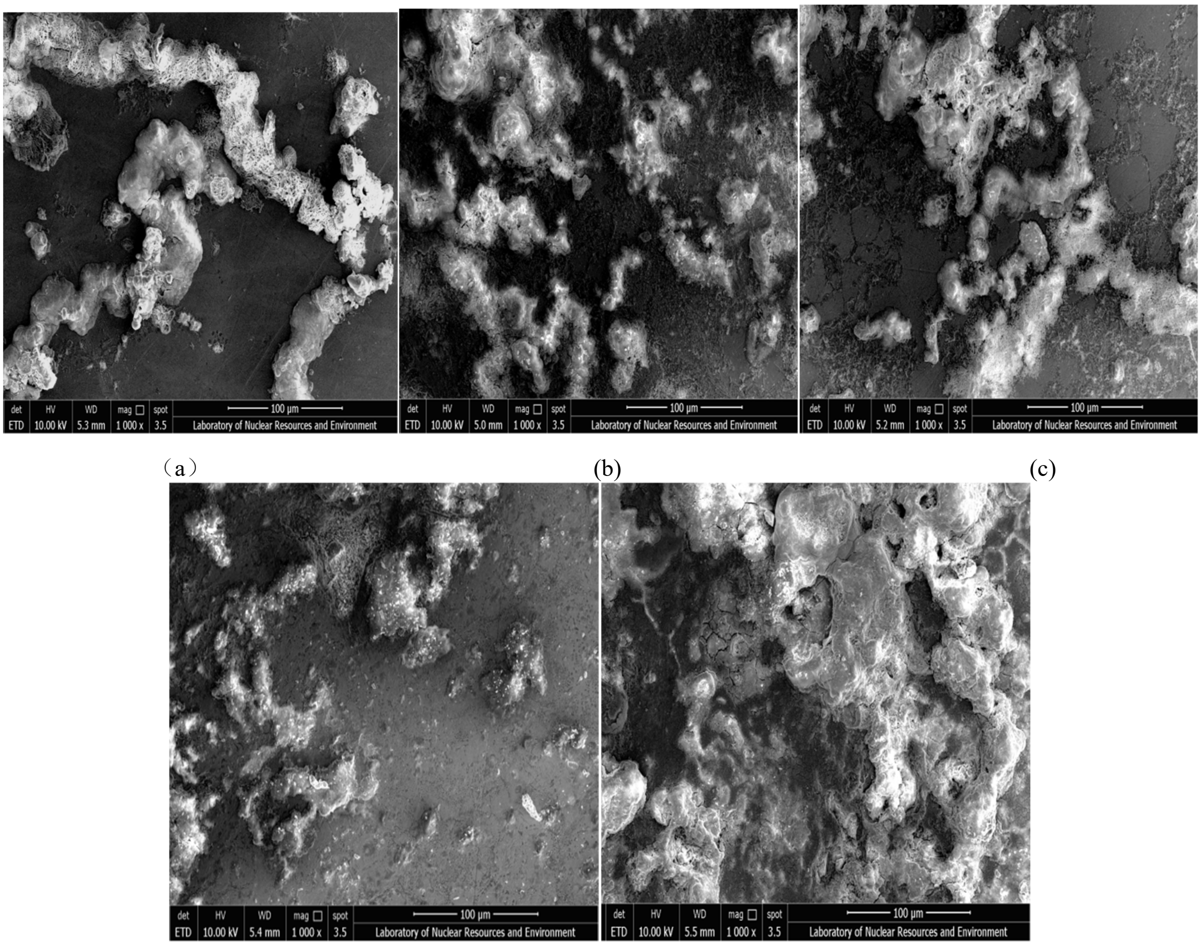
It used CMT5605 electronic universal testing machine to test the tensile of the high manganese steel before and after the modification treatment. Tensile specimens were prepared according to the GB/T1348-1988 standard and the displacement speed is 1 mm/min at room temperature 25 °C.

3 Result and Analysis

3.1 The Effect of Different Contents of Titanium on Metallographic Structure of High Manganese Steel

In order to obtain further influences of titanium alloying on the microstructure and properties of high manganese steel alloying, there are five groups of high-manganese steel metallographic samples are polished, etched with 4% nitric acid solution, washed with alcohol solution and dried. It obtains the surface morphology of the high manganese steel sample with different titanium content according to a scanning electron microscope. As shown in Figure 1.

Among them, a, b, c, and d in Fig. 1 are the surface topographys of the high manganese steel samples that have been obtained by adding different contents of titanium elements. While e is the surface morphology of the control sample without adding titanium element. It can be clearly observed from the figure that the control sample without added vanadium and titanium elements has many inclusions and is distributed in a large number of irregular flocs. While the number of inclusions in the 1#~4# sample with vanadium-titanium alloy treatment reduce. The sizes are significantly reduced, and dispersed in a matrix, chain or granular form in the matrix.



（a） (b) (c)

(d) (e)

Fig. 1. Surface morphology of high manganese steel samples treated by different titanium contents

After be alloyed by titanium, high manganese steel can refine the crystal structure and eliminate the columnar crystal [8]. The lattice type of titanium is dense-hexagonal crystal, and the atomic radius is 1.468× 10^{-10} m. It can form stable compounds with nitrogen, oxygen and carbon [9]. According to the heterogeneous nucleation theory proposed by Tumbell and Vonnegut [10], when the mismatch of two phases is less than 12 %, the high melting point phase can be used as a heterogeneous nucleation core. Because that titanium carbide and titanium nitride are stable, and the melting poins are high. The mismatch degree with γ-Fe is 12.53 % and 10.61 %, respectively. Thus they can be used as a heterogeneous nucleation core of austenite crystallization. The carbon and nitrogen compounds formed by Ti and C and N act as heterogeneous nucleation cores, which can promote the nucleation of molten steel [12]. Thereby they inhibit the further growth of grains and inclusions, and significantly reducing the size of inclusions. The block or granules are dispersed in the matrix. So the alloying treatment can improve the size, shape and distribution of the inclusions.

3.2 The Effect of Hardness of High Manganese Steel with Different Contents of Titanium

In this test, the hardness of the test material of the HR-150A Rockwell hardness tester was used. Three tests were performed on each sample, and the obtained data were averaged. Table 2 shows the hardness distribution of different contents of titanium element high manganese steels.

Table 2. Hardness distribution (hardness, HRC) of different content of titanium high manganese steel

Group No.	Sample No.	A	B	C	Average for the common sample	Average for the common group
Control Group	Sample1	13	12.5	10.5	12.0	14.6
	Sample2	26.5	21	17	21.5	
	Sample3	8.5	14	11.5	11.3	
	Sample4	12	11	18	13.7	
1#	Sample1	31.5	33.5	24.5	29.8	27.3
	Sample2	21	21.5	25	22.5	
	Sample3	21	25	21.5	22.5	

	Sample4	33	35	35	34.3	
2#	Sample1	22	22.5	24.5	23.0	26.0
	Sample2	21.5	25	34.5	27.0	
	Sample3	29.5	26.5	28	28.0	
	Sample4	24	24	30	26.0	
3#	Sample1	53	55	55	54.3	51.5
	Sample2	53.5	54	54	53.8	
	Sample3	50.5	43	46.5	46.7	
	Sample4	50	52	52	51.3	
4#	Sample1	50	30.5	55.5	45.3	53.0
	Sample2	56	56	56	56.0	
	Sample3	52.5	58	55.5	55.3	
	Sample4	54	56	56.5	55.5	

It can be seen from the table that when the titanium content is 0.0073 %, the average hardness value of high manganese steel is 26.0 HRC. And when the titanium content is 0.017 %, the average hardness value of high manganese steel is about 53.0 HRC. Compared with the control samples, the average hardness has been greatly improved from 87 % to 263 %. Owing to amounts of second phase particles with high hardness in the metal matrix, which could better the wear resistance of material, the hardness of high manganese steel could reflect its wear resistance.

The studies show that TiC, a steady substance with high melting point, which is formed by titanium and coal in the steel, can act as a crystalline core to refine grains. Meanwhile, these carbides can be dispersed and distributed in the matrix to act as a dispersion strengthening effect. Titanium has a strong affinity with the nitrogen in the high manganese steel. After adding titanium to high manganese steel, it can form stable TiN particles inside the material. The melting point of these particles is higher than the temperature of molten steel. During the crystallization of steel, TiN becomes the core of austenite non-spontaneous crystallization, thereby refining the grains. Titanium can be incorporated into the γ and α phases to form a solid solution that distorts the crystal lattice. The combination of fine-grain strengthening, solid solution strengthening and dispersion strengthening enhances the hardness of the body [13].

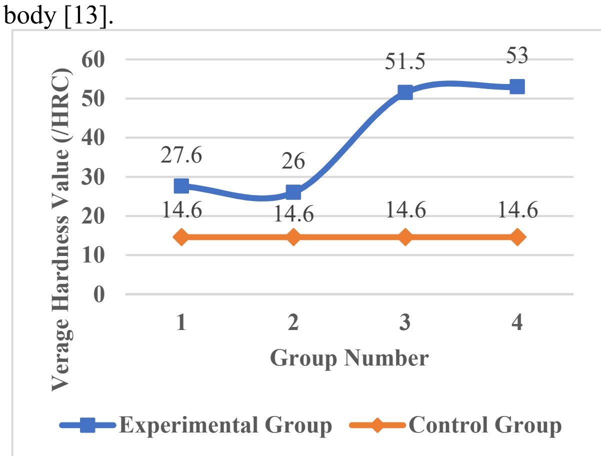


Fig. 2. Hardness of alloyed high manganese steel with different content of titanium

In order to visually reflect the biggest effect of titanium contents on the hardness of high manganese steel, the writer uses a line graph to represent the hardness value of high manganese steel . Figure 2 shows the hardness values of alloyed high manganese steel with different contents of titanium. It can be seen intuitively from the figure that Scheme 3,the hardness value of the modified high manganese steel with the content of titanium content of 0.017 % is the highest.

3.3 The Effect of Tensile Strength of High Manganese Steel with Different Contents of Titanium

In this test, the CMT5605 electronic universal testing machine was used to carry out the tensile test on the high manganese steel before and after the alloying treatment. When the high manganese steel with different titanium content is stretched, there are two stages of elastic deformation and uniform plastic deformation. When the modified high manganese cast steel yields, the strength would continue to rise. Because of the deformation process that Granular dislocations and constant changes in twins in the matrix, high manganese steel will still undergo significant work hardening phenomenon [14]. And they can maintain uniform deformation for a long time. When the highest strength is reached, the modified high manganese steel will immediately fail. Without necking.

Table 3. Tensile strength of high manganese steel alloyed by titanium alloy with different contents

Scheme	Control Group	1#	2#	3#	4#
Tensile Strength (MPa)	494	458	—	418.7	270.5

According to the results of the test, the tensile strength of the high manganese steel sample of the control group without the addition of Ti element was 494 MPa on average. And the tensile strength of the test rod to which the titanium element being added is decreased. As far as the test results are concerned, the addition of titanium reduces the tensile strength of high manganese steel. The possible reason is that the content of titanium was not controlled in a suitable range. In addition, although the addition of titanium enables the aggregated floc inclusions to be dispersed, most of these inclusions have sharp edges and corners, which tend to cause stress concentration under load. That resulted in a decrease in tensile strength of high manganese steel.

3.4 The Effect of Wear Resistance of High Manganese Steel with Different Contents of Titanium

The wear resistance test of high manganese steel before and after alloying treatment was carried out with MM-W1 vertical universal friction and wear tester. The difference in material properties is obtained by the results of abrasion resistance test. Table 4 shows the data obtained by the abrasion test of high manganese steel with different contents of titanium.

It can be seen from Table 4 that the wear rate of the high manganese steel to which titanium is added is much lower than that of the unadded wear rate. So it is clearly that the addition of titanium element significantly improves the wear resistance of the high manganese steel.

In order to visually reflect the biggest effect of titanium contents on the hardness of high manganese steel, the writer uses a line graph to represent the hardness value of high manganese steel . The variation of the wear amount of high manganese steel in each group is shown by a line graph. As shown in Figure 3.

Table 4. The results of the abrasion loss of high manganese steels with different titanium contents

Number	Weight before test/g	Weight after test/g	Loss Amount/g	Loss Rate
1	3.456	3.4499	0.0061	0.18%
2	4.8349	4.8268	0.0081	0.17%
3	4.9912	4.9823	0.0089	0.18%
4	5.1592	5.1478	0.0114	0.22%
Average	4.610325	4.6017	0.008625	0.19%
No added	5.1966	5.1636	0.033	0.64%

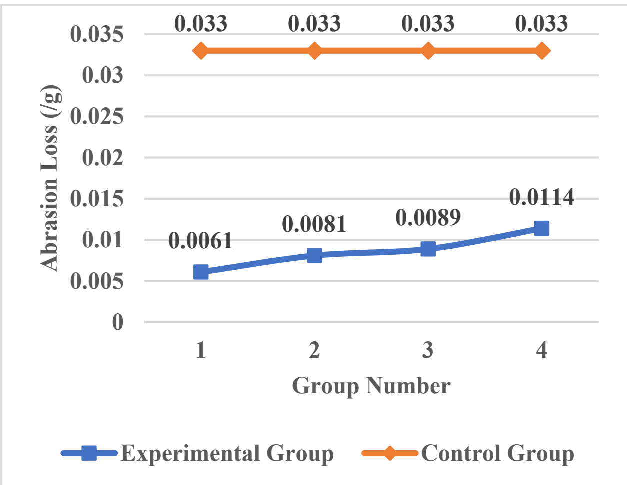


Fig. 3. The abrasion loss of high manganese steels with different titanium contents

It can be seen from the above figure that the addition of different contents of titanium improves the wear resistance of high manganese steel. The wear resistance of high manganese steel can directly reflect the use value of high manganese steel. Increasing the wear resistance of high manganese steel can directly and effectively reduce the wear and tear of high manganese steel, and directly improve the utilization rate of high manganese steel. At the same time, the above figure reflects the scheme 1# that when the added titanium content reaches 0.0045%, the high manganese steel has the smallest wear and the lowest wear rate. The experiment shows that the high manganese steel has the best wear resistance.

High manganese steel can improve the wear resistance after titanium alloying. Mainly because the alloying treatment makes titanium form titanium carbide and titanium nitride in high manganese steel, which not only refines the grain, but also diffusely distribute these particles are in the matrix [15]. These diffuse particles strongly hinder the movement of dislocations, which increases the dislocation density. And the dislocations are intertwined into dislocation cells or dislocation walls, which enhances the work hardening ability of high manganese steel [16]. Thereby, the hardness of the grinding surface is improved; in addition, the addition of titanium changes the distribution mode of the inclusions, and reduces the damage of the aggregate inclusions to the fatigue peeling of the matrix.

4 Conclusion

1. After alloying with titanium in high manganese steel, titanium forms a large number of stable, high melting point compounds in austenitic manganese steel, such as TiC, TiN, which can be used as a crystal core. Thus making high manganese steel grains and inclusions. The size of the object is reduced , the shape and distribution of the inclusions can be improved.

2. The crystal structure of the high-manganese steel treated by titanium alloying is obviously improved. the grain is refined and the crystal quality thereof is strengthened. Under the action of solid solution strengthening and dispersion strengthening of the titanium-containing compound, the hardness of the modified high manganese steel is significantly improved, while the tensile strength is decreased. That compares with the high-manganese steel without titanium element.

3. The high-manganese steel is treated with titanium alloying, which not only refines the grain, but forms inclusions, and a lot of dispersed particles. That enhances the work hardening ability of the high-manganese steel, thereby improving the hardness of the grinding surface. These high hardness second phase particles in the matrix during wear can improve the wear resistance of the material. The wear rate of high manganese steel alloyed by titanium is significantly smaller than that of high manganese steel which is not treated with titanium.

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