Microstructure and wear properties of high manganese steel by V-Ti alloying elements

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Abstract: High manganese steel was prepared by adjusting the components of the alloys by adding V-Ti. The investigation was carried out to study the effect of V-Ti elements alloying on the microstructure and wear properties of high manganese steel through metallographic microscope, scanning electron microscopy, mechanical machine and abrasive wear tests. The test results showed that V-Ti alloying improved the properties of high manganese steel. The grains are refined, size of impurities are reduced, the form and distribution of impurities are also ameliorated. In addition, the hardness was increased by 23.7%~84.6% and tensile strength can be increased up to 31.3%.

1. Introduction

In the manufacturing industry, the wear parts and equipment performance requirement are increasing. By ameliorating the wear resistance of the wear parts, which losses could potentially be reduced by 30% within 20 years[1]. High manganese steel as the most commonly wear materials in mining, railway, construction, metallurgy and many other fields[2-3] because of their excellent properties: for instance, low yield stress, excellent uniform elongation and contain abundant deformation twin after plastic deformation. In addition, it can also used in lining plate and hammer. However, we require for wear resistance increasing as the development of industry. The limit of using of high manganese steels in range and life span are caused by their own weakness. Researchers did many experiments for seeking methods to improve high manganese steels’ properties.

Thermal Mechanical Control Processing(TMCP) techniques could improve the wear resistance of steels and are widely used to product of low carbon high manganese steel[4]. However, there are two drawbacks: one is that can not control the amount of pressure and cooling rate; and the other one is that fine crystalization only be limited to a certain range. In addition, another technique is inlaid and cast high chromium iron. In this technique, there will so much net martensitic fiber appear after water toughening treatment, and the strength and hardness of high manganese steel can be improved. However, the technique has not been widely used because it is so complex[5]. Surface deformation strengthening and explosion can improve the wear resistance of high manganese steel, but the hardness of surface distributed uneven.

The wear resistance of high manganese steel can be improved by alloying treatment and conventional to the industry. The high manganese steel has high wear resistance only under large impact load, high contact stress and hard abrasive[6]. Studies have shown that alloying treatment can effectively improve the wear resistance of high manganese steel. Generally, elements such as Cr, V, Ti and Mo are added into traditional high manganese steel[7]. In the traditional composition of high
manganese steel, wear resistant hard particles such as TiC, VC, Al₂O₃ are added into the matrix of high manganese steel, so that V-Ti alloying can refine the grain of high manganese steel[8].

In order to further obtain the excellent wear resistance of high manganese steel in low load, the traditional high manganese steel is toughened with V-Ti alloying according to the design of water toughening process. This study will provide a theoretical basis for improving the wear resistance of high manganese steel and prolonging the life of ball mill lining plate.

2. Material and Methods

The V-Ti alloyed high manganese steel was prepared to research the effect on microstructure and mechanical properties of steels. Each composed specimens was produced by casting in intermediate frequency induction furnace without oxidation, and the steel ingots were hot forged to Φ25*300mm² bar.

The main furnace burden utilized in the process were high-quality carbon steel (or ingot), high-carbon ferromanganese, medium-carbon ferromanganese, high-carbon ferrochrome and high manganese steel, after which the recycled materials were not exceeding 25%. The carbon steel should be smelted firstly, while ferromanganese and other precious alloy material should be smelted for several times, with a small amount for each time. The precious elements should be added at the end to reduce the loss. After the elements are melted completely with the furnace temperature reaching 1580-1600°C, deoxidization, dehydrogenation and denitrification were applied in process. The temperature of casting ladle should be over 400°C before the steel liquid tapping off. The samples were divided into 6 groups, one of which is the control group.

Fig. 1 shows that process of high manganese steel’s water toughening treatment after casting. The castings were heated in a well resistance furnace with the heating rate as 100 °C / h to 550°C and maintained the temperature for 1.5 h, after which they were heated to 650°C and kept for 2 h. Later on, continued to be heated to 1080°C with a keeping for 2 h. Finally, the samples were quenched with water (the inlet water temperature was less than 30°C, and the outlet was less than 60°C).

![Fig. 1 Water toughening treatment process](image)

Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES) was used to measure chemical compositions (wt%), which data are listed in Table 1.
Table 1 Chemical compositions of materials (wt%)

|   | C   | Si  | Mn  | P   | S   | Cr  | V   | Ti  |
|---|-----|-----|-----|-----|-----|-----|-----|-----|
| 1 | 2.3 | 0.66| 11.21| 0.050| 0.0088| 0.74 | 0.15| 0.0044|
| 2 | 2.5 | 0.66| 11.21| 0.054| 0.0081| 0.74 | 0.25| 0.0077|
| 3 | 2.3 | 0.65| 11.20| 0.055| 0.0084| 0.74 | 0.46| 0.0081|
| 4 | 2.4 | 0.68| 11.21| 0.054| 0.0085| 0.74 | 0.47| 0.0045|
| 5 | 2.5 | 0.66| 11.19| 0.054| 0.0084| 0.74 | 0.66| 0.0060|
| 6 | 2.5 | 0.64| 11.21| 0.054| 0.0083| 0.74 |   |   |

The metallographic observation was conducted by using optical microscope and FEI Nova Nano 450FEG field emission scanning electron microscope (SEM). The samples for metallographic observation were prepared by sampling, grinding, polishing and corrosion before observation. The hardness of samples tests were performed by using an HR-150A Rockwell hardness tester, and taking the average of multiple measurements as the hardness value. The tensile tests were prepared with employing a CMT5605 tensile test machine. The tensile samples with Φ10mm and Φ15mm gauge length were machined from lathe in Fig.2 and testing speed was 1mm/min.

Fig. 2 Tensile Sample

The abrasion samples were measured with using MMW-1 vertical universal friction. All abrasion specimens should be firstly cleaned with dilute nitric acid and alcohol before tested. The abrasion losses of samples in the test were all acquired by the measured mass values.

3. Results

3.1 Microstructure

Fig. 3 demonstrates the microstructures of high manganese steel with different V-Ti contents, in which the metallographic structures of scheme 1°~5° in Fig. 3(a–e) and a control group in Fig.3 (f).
Pearlite appeared in the sample structure of high manganese steel in this heat treatment, and the pearlite of control group is the most. As shown in Fig. 3(a~e), the grain refined with increased of V-Ti, and Fig. 3(e) has the smallest grain size. Fig. 4 shows the microstructure of SEM, and Fig. 4(f) has a lot of bright white inclusions with irregular clusters. However, the amount and size of inclusions could be decreased as the increase of V-Ti alloy (see Fig.4(a~e)), which were shaped with block or granular in the matrix.
3.2 Mechanical Properties

3.2.1 Hardness

Fig. 5 shows that hardness improved by V-Ti alloying treatment. As the content of V-Ti increased, the hardness of steel increased. When V content is moderate, high content Ti has effect of improving hardness. The average hardness of group 3 reached up to 37.3 HRC because of the Ti content is the highest among all.

The averages of hardness for samples with alloying elements can be found an increase by 23.7%~84.6% due to the combination of some kinds of strengthening, fine-grain, solid-solution and diffusion. All samples were alloyed with vanadium and titanium to refine the grain and improve the hardness of the matrix. The alloying elements of vanadium and titanium can significantly affect the structure and properties of high manganese steel[9].

3.2.2 Tensile

All samples were prepared for tensile testing, obtained elastic deformation and uniform plastic deformations. The yield process could improve the strengths of alloyed high manganese steel samples in linear-variation style, result in a clear work hardening phenomenon and maintain a long-term uniform deformation. Once the strength reaches their individual limitations, necking phenomenon would not occur. The room-temperature tensile strength of the high manganese steels are listed in Table 2.

| Scheme | 1<sup>º</sup> | 2<sup>º</sup> | 3<sup>º</sup> | 4<sup>º</sup> | 5<sup>º</sup> | 6<sup>º</sup> |
|--------|-------------|-------------|-------------|-------------|-------------|-------------|
| Tensile Strength/MPa | 444.7 | 463.3 | 486.5 | 575.0 | 647.5 | 494.0 |

Compared with the control group, tensile strength increased with the increased of V-Ti alloy content. However, 1<sup>º</sup> sample existed error as much air hole appeared during the casting. Consequently, the tensile strength of 1<sup>º</sup> is the lowest in all. The strength of 2<sup>º</sup> and 3<sup>º</sup> samples are low because of high content of Ti. Ti combined with C and N to form the second phase precipitation. The precipitation of
the second phase has a negative impact on the tensile strength of steel, and the phase contained angular. As shown in Fig. 3 and Fig. 4, the number of second phase from 1# to 5# is more than control group. Because of the existence of angular, stress concentration problems appeared during tensile deformation, which caused low tensile strength.

As shown in Table 2, the significant effects on the strengths of samples were determined by the V-Ti alloyed elements as these would strengthen the structures of high manganese steels[10]. With alloying of V-Ti, the grain size becomes smaller. Accordingly, in a certain range of alloy content, the content of V-Ti is low, the strengthening effect is poor. And as the high content of V-Ti, the strength is excellent due to the influence of intensity obviously, so the negative effect of the second phase is offset. The addition of vanadium and titanium elements could reduce the size and dispersion of aggregated flocculated inclusions. These inclusions cause stress concentration under loading, resulting in a decrease in tensile strength of the high manganese steel. Thus, individual alloying element contents would affect the tensile strengths of high manganese steels.

3.2.3 Abrasive

The rig MMW-1 was utilized for abrasive wear test, and results are shown in Table 3. Drawing curve in Fig. 6 so that reflect the effect of V-Ti alloying treatment on high manganese steel directly. The percentages of abrasion for high manganese steels after the V-Ti treatment were lower than the one without treatment. Meanwhile, the mass of abrasion in group 2 was the lowest with a percentage of 0.2%. Hence, the abrasion of group 2 should be the best, which means the addition of V-Ti elements can significantly increase the abrasive resistance of high manganese steel.

| Group | Mass before test /g | Mass after test /g | Weight of abrasion /g | Abrasion Percentage |
|-------|---------------------|--------------------|----------------------|---------------------|
| 1#    | 4.8844              | 4.8725             | 0.0119               | 0.24%               |
| 2#    | 5.0000              | 4.9898             | 0.0102               | 0.20%               |
| 3#    | 4.9561              | 4.9417             | 0.0144               | 0.29%               |
| 4#    | 4.9039              | 4.8868             | 0.0171               | 0.35%               |
| 5#    | 3.2833              | 3.2718             | 0.0115               | 0.35%               |
| 6#    | 4.9280              | 4.9105             | 0.0175               | 0.36%               |

Fig. 6 Comparison chart for wear amounts of high manganese steel samples

On the one hand, the matrix improved by solid solution of alloying elements in high manganese steel, and wear resistance also ameliorated. On the other hand, alloying treatment was refined the grain, besides some dispersion particles could be generated in the matrix via alloying treatment[11]. The grain boundary and particles largely hinder the dislocation, increasing the density of dislocation,
generating the cellular and snarling sub-structure[12], strengthening the working hardness ability of high manganese steel and thus, the surface hardness had improved. In addition, the V-Ti alloying treatment improved the shape and distribution of inclusions, preventing the inclusions from stress concentration during the process of deformation, improving the impact toughness, which was conducive to inhibiting the generation and expansion of cracks, and reduced the damage of the inclusions on the substrate fatigue and spall abrasion.

4. Discussion
As shown in Fig. 3 and Fig. 4, the grains refined with an increased alloy elements. The number of white inclusions $1^\circ-5^\circ$ is less than $6^\circ$, and Cai[13] found that the main element of inclusions were O, S, Al, Mn in high manganese steel. SUITO H et al[14] proved nucleation theory when the mismatch degree of the two phases is less than 12%, and high-melting point phase can be used as the heterogeneous nucleation core. Owing to the stability and high melting point of titanium carbide and titanium nitride, meanwhile, the mismatch degrees with $\gamma$-Fe are 12.53% and 10.61% respectively. Therefore, it can be used as the heterotypic core of austenite crystallization. Vanadium has similar properties, can combine with carbon to form stable $V_{2}C_{3}$ and $VC$ with a high melting point. At the same time, the binding capacity of vanadium and nitrogen is also so strong that form steady properties to VN. Vanadium carbide, which is usually a fine particle, is insoluble in austenite. Thus, it could prevent the movement of grain boundary and inhibit the grain growth. Vanadium carbide, vanadium nitride and vanadium oxide can also be used as the crystal core in the process of crystallization to refine the casting structure of high-manganese steel. In terms of the effects of alloying elements on the inclusions, ($V$,Ti) and ($C$,N)combined high melting point of compounds. ($V$,Ti) and ($C$,N) compounds are preferred to hinder inclusions growth because of the mismatch degrees with $\gamma$-Fe is low. Consequently, the size of inclusion obviously decreased.

As shown in Fig. 5, increase the Ti improves the hardness significantly. The grain refined strengthened deformation hardening capacity, and nearly all Ti combined with C, N to form high melting point, strong hardness and good stability second phase. Some V and rarely Ti dissolved into the matrix causes strong distortion of the austenite lattice and generated Korotkoff gas masses. Consequently, three aspects considered comprehensive strengthening of high manganese steels.

With the increase of V-Ti content, the grain size has a certain influence on the yield strength. The grain of the sample is obviously refined, and the strength of high manganese steel is enhanced by fine grain strengthening. The grain size effect is determined by following the Hall-Petch analysis[15]:

$$\sigma_s = \sigma_0 + Kd^{-1/2}$$

$\sigma_s$ is the yield stress, $\sigma_0$ is the friction stress, d is grain size in micrometers and K is the Hall-Petch coefficient. If the size of the grain, d is small, the yield stress $\sigma_s$ will be larger. In a word, the effect of grain refinement on grain-boundary strengthening in high manganese steel is significant. The amount of alloy is proportional to the strength.

5. Conclusions
1. High manganese steel was alloyed by V-Ti elements, and the dissolution of some V and Ti in matrix inhibited the growth of grain. The other V and Ti combined with C and N to form a large number of high melting point compounds. Those compounds have low mismatches with austenite, so a large number of heterogeneous nucleation cores can be formed to achieve the effect of grain refinement. With increasing the V-Ti, the grains size refined obviously. V and Ti elements can significantly better the size, shape and distribution of inclusion.

2. Because of Ti with C, N formed the second phase, which hindered the dislocation movement. When dislocation line through hard points, the energy increased so that hardness improved. Under the combined effects of fine-grain strengthening, solid solution strengthening and dispersion strengthening, V-Ti alloying treatment significantly improves the hardness of high-manganese steel, which can be increased to 84.6%. In addition, tensile strength(647.5MPa) improved because grains refined.
wear resistance also improved and the second group only 0.2% abrasion loss.

3. The strengthening effect of alloying process enhances the work hardening ability of high manganese steel. The hardness of grinding surface, the shape and distribution of inclusions are improved. The wear resistance of high manganese steel increases with the decrease of harmful impurities. In summary, V-Ti alloying high manganese steel ameliorated by water toughening treatment under low loading.

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