Microstructure and Performance of a High Manganese Steel Matrix Composite Reinforced by (Fe,Cr)7C3 Particle Beams

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ABSTRACT

A high manganese steel matrix composite with reinforced (Fe, Cr)\textsubscript{7}C\textsubscript{3} particle beam was fabricated via melt compositing and in-situ formation method. The microstructure of the composite was analyzed by scanning electron microscopy and energy dispersive X-ray spectroscopy. The reinforced phase of the composite mainly include column and fine short rod or globular carbide (Fe, Cr)\textsubscript{7}C\textsubscript{3}, and the former is primary. To investigate the wear resistant properties of the composite, wear tests at different loadings (5N, 10N, 15N and 20N) were carried on the wear machine. For comparison, the wear tests of a high manganese steel were also conducted with the same conditions. The results show that the abrasive wear resistance is strengthened significantly due to the formation of (Fe, Cr)\textsubscript{7}C\textsubscript{3} particle beam, which were created through the chemical reaction of alloy powders. According to the impact fracture experiments of the composite, it is found that the fracture of particle beams in the composite belongs to a brittle fracture.

INTRODUCTION

As a traditional wear-resistant material, high manganese steel has broad applications in metallurgy, mining, building materials and other industries due to its excellent work hardening ability by water quenching. When facing impact loading, a strong hardening surface layer would be generated and high toughness still remains in the interior. Such remarkable characteristics are denoted as the abrasive wear resistance. Generally speaking, higher-impact energy could readily trigger the formation of hardening layer. In other words, no hardening layer would be formed with the low-impact case with significant abrasion loss. Although various attempts have been carried out to overcome this shortcoming, the improvement of the wear...
resistance is still not satisfied [1-4]. Recently, many attentions are paid on the high manganese steel matrix composites [5-9].

In this paper, we present a novel technique to synthesize the \((\text{Fe, Cr})_7\text{C}_3\) particle beams reinforced the high manganese steel matrix composite. The main idea is first to insert the core wire as the inclusion into the matrix. Then \((\text{Fe, Cr})_7\text{C}_3\) particle beams are formed in the in-situ process. The present work also highlights the microstructural and abrasive wear resistance characteristics of the composite.

**MATERIALS AND EXPERIMENTAL PROCEDURES.**

High carbon ferrochrome powder (50-100μm in diameter), low carbon steel strip (0.25 mm in thickness, 15mm in width) and high manganese steel (Mn13) are the main components. The chemical composition of Mn13 steel and high carbon ferrochrome powder are listed in Table 1.

| TABLE 1. THE CHEMICAL COMPOSITIONS OF HIGH MANGANESE STEEL AND HIGH CARBON FERROCHROME POWDER (WT %). |
|---|
| Powder | W_Cr | W_C | W_Mn | W_Si | W_S | W_P | W_No | W_Ni | W_Cu | W_Fe |   |
| Mn13 steel | 0.284 | 1.156 | 12.2 | 0.429 | 0.013 | 0.049 | 0.054 | 0.04 | 0.05 | 8 | Rem/|

The \((\text{Fe, Cr})_7\text{C}_3\) particle beams reinforced high manganese steel matrix composite was prepared as following procedures (seen Fig. 1). Firstly, the core wires, which parcelled the high carbon ferrochrome powders using the low carbon steel strip, were fabricated by rolling and drawing with 3.2 mm in outer diameter and about 56% filling powder rate, as shown in Fig. 1(a). And then, the core wires were cut into sections with 120 mm in height and were welded to a steel plate arranging 10 mm in spacing, to form the core wire framework part (see Fig. 1(b)). Thirdly, the framework part was pressed into liquid high manganese steel matrix in sand mould at 1400-1450°C. Finally, the composite was taken out of the mould and heated at 1050°C for 120 min, and then quenched into water. Lastly, a high manganese steel matrix composite with reinforced \((\text{Fe, Cr})_7\text{C}_3\) particle beams was created.

![Figure 1. Schematic diagram of manufacturing of the high manganese steel matrix composite.](image)

Composite specimens were polished according to the standard metallographic technique and etched with 4% nitric acid alcohol solution. The representative microstructure of the composite was observed utilizing scanning electron
microscopy (SEM) (JSM-6390A, Japan) equipped with energy-dispersive spectroscopy (EDS).

For abrasive wear resistance tests, the cylindrical pin specimens with a diameter of 6 mm and a length of 15 mm were sectioned, cleaned in ultrasonic cleaners and dried. Two-body abrasive wear tests were performed on a ML-100 wear test machine. Both the Mn13 steel and the composite pin specimens were loaded against a rotating disc (25 rpm) covered with a 360 mesh alumina abrasive paper at the load of 5 N, 10 N, 15 N and 20N, respectively. To ensure fresh supply of abrasive particles to the pin specimens, the worn alumina abrasive paper was replaced with new one for every sliding distance of 20 m. The wear resistance tests were at least repeated three times for each samples, and the weight losses of all the specimens were measured in an electronic balance with an accuracy of 0.0001 g. The weight losses $\Delta G$ is equal to initial weight minus the worn weight. The wear morphology was examined with scanning electron microscopy (JSM-6700F, Japan).

Impact toughness samples without gap are 10mm in width $\times$10mm in highness $\times$ 55 mm in length. The composite impact samples contain a particle beam. For the impact toughness test, a pendulum with 380 j energy was selected. The impact toughness $a_k$ is calculating by the formula as follow:

$$a_k = A_k / F$$

Here, $a_k$—Impact toughness (J/cm$^2$), $A_k$—Impact energy (J), $F$—The cross sectional area of specimen (cm$^2$).

RESULTS AND DISCUSSION

Powder Composition Analysis

The alloy powders are consisted of a high carbon ferrochrome powder (<200μm of particle size), ferrous powder (<200μm of particle size) and carbon powder (<50μm of particle size) according to proportion, as showed Fig.2. The iron powder formed many small granules, which is pointed by the letter A in Fig.2(a). The high carbon ferrochrome powder consisted of many particles with irregular shape, namely, are pointed by the letter B in Fig.2(a). The chemical compositions of above both powders are showed in Figs.2(c) and (d). The carbon powders uniformly exist in the gap between the high carbon ferrochrome and iron powders because grain size of carbon powder is small, as shown in Fig.2(a) the arrows indicated by the letter C. In order to verify a existence of the above particle phase, the alloy powder was analyzed using XRD method, it can be seen from the results of the analysis that the primary components of the alloy powder is consisted of Fe, Cr$_7$C$_3$ and C phase, as shown in Fig.2(b).
Figure 2. The morphology and composition of the alloy powders (a) morphology of the alloy powders; (b) analysis result of the alloy powders by XRD. (c) chemical compositions of the high carbon ferrochrome and iron powders of A point. (d) chemical compositions of the high carbon ferrochrome and iron powders of B point.

Microstructure of the Composite.

Fig. 3(a) shows the macro morphology of the composite in cross section. Apparently, the particle beams with spacing about 8-10 mm were uniformly distributed in alignment, and the diameter of each particles beam was almost the same. The macrostructure of single particle beam in the cross section is illustrated in Fig. 3(b). The internal generating products of the core wires were not diffused outward. In Fig. 3(c), the EDS results indicate that the product are (Fe, Cr)\(_7\)C\(_3\) particles. Columnar-like structure is observed since these particles distributed along a longitudinal section, see Fig. 3 (d). We name this distribution of hard inserter as ‘hard particle beam’ visually. In addition, blowholes and inclusions were not be detected in the product, which can guarantee the continuity of the whole composite.
Figure 3. The macrostructure of the composite: (a) the macroscopic photograph in the cross section, (b) the microstructure of one hard particle beam in the cross section, (c) the component analysis result of on hard particle beams by EDS, (d) the microstructure of one hard particle beam in a longitudinal section.

Fig. 4 is the microstructure of in-situ hard particle beams reinforced high manganese steel matrix composite, i.e., zoom-in image of the red circle area in Fig. 3(b). It can be concluded from Fig. 4(b) that columnar carbide enhancement phase is distributed along the austenitic grain boundary. Intragranular white short rod and globose fine carbide particles shown in Fig. 4(c) are separated out and appear in the grain internal. In order to confirm the role of each reinforcement phase in the composite, energy-dispersive spectroscopy analyses for 001 surface area in Fig. 4(b) and 002 point area in Fig. 4(c) were performed. Through atomic ratio calculating, both the columnar and the short rod fine carbide are \((\text{Fe, Cr})_7\text{C}_3\), as shown in Fig. 4(d). The \((\text{Fe, Cr})_7\text{C}_3\) is formed when chrome atoms dissolve into unstable carbide \(\text{Fe}_7\text{C}_3\), which has six square lattice structure with the lattice constants \(a=6.882, c = 4.540\). And each carbon atom (atomic radius 0.24) close contacts with six adjacent iron atoms (atomic radius 0.12) in that structure. Because Fe and Cr atoms are close in size and their arrangements of atoms in \(\text{Fe}_7\text{C}_3\) and \(\text{Cr}_7\text{C}_3\), which belongs to orthorhombic system, respectively. This makes that the Cr atom more easily replace the Fe atom with large number in forming process of \((\text{Fe, Cr})_7\text{C}_3\). In addition, Cr atom can reduce the chemical potential of carbon atoms in iron that makes \((\text{Fe, Cr})_7\text{C}_3\) to become a more stable compound. The carbide \((\text{Fe, Cr})_7\text{C}_3\) has a quite special close-packed hexagonal lattice structure, which is formed with the growth step provided by the screw dislocation in smooth solid-liquid interface. The most of the forming crystal is six square prism shapes. This is just because the crystal lattice in the C axis orientation grows faster than others. And due to the rapid cooling direction to roughly parallel to the orientation of C axis crystal, so the side of the prism-like crystal is flat and not formed lateral branch[10]. It can be demonstrated by
the showing morphology in the Fig. 4(b). Fig. 4(e) shows the interface of the composite arriving at the metallurgical bonding, which can be seen from the boundary characteristic between reinforced particles beams and the Mn13 matrix.

Figure 4. The microstructure and EDS analyses results of the composite (a) the amplification microstructure in red circle area; (b) the columnar carbide particles, (c) the short rod and the globose fine carbide particles, (d) the component analysis result of 001 area and 002 point by EDS, (e) the interface of the composite.

Abrasive Wear Characteristics of the Composite.

The wear loss responding to different applied loads (5N, 10N, 15N and 20N) for Mn13 steel and the composite is shown in Fig. 5. Clearly, more wear loss is found in Mn13 steel compared to the composite, and both losses increase with the stronger loading. The loss ratio between the Mn13 steel and composite is basically the same in these applied loadings, which is about 1.6. In brief, the composite shows good wear resistance compared to pure Mn13 steel.
Now we turn our attention on the role of enhanced phase during the abrasive wear process. Wear morphology of the composite sample under 120 meshes SiO$_2$ abrasive paper and load of 20N was inspected by SEM, and the results are shown in Fig. 6. It is observed from Fig. 6(a) that the cutting groove morphology is obviously interrupted to arrive into those hard particles, and the particles itself are intact and without shattering. Such performance is mainly a good combination of the hardness of (Fe, Cr)$_7$C$_3$ and a superior plasticity of the matrix. So, the wear of the composite can be reduced effectively. Fig. 6 (b) shows the embrittlement of the hard particles under the normal force.

Impact Toughness of the Composite

The impact toughness of the (Fe, Cr)$_7$C$_3$ particle beam reinforced high manganese steel matrix composite and the high manganese steel is seen in Table 2. The $a_k$ value in table 2 is the average of three times in the test. It can be seen that the impact toughness of the composites is obviously lower than the high manganese steel. One reason may be the exists of porosities and defects inside the particle beams.

|          | $a_k$ (J/cm$^2$) |
|----------|------------------|
| The composite | 49               |
| High Mn steel  | 121              |

**Figure 5.** Weight losses of Mn13 and the composite under different loads.

**Figure 6.** The wear morphology of the composite under 120 mesh SiO$_2$ abrasive paper and the load of 20N (a) the cutting groove morphology, (b) the embrittlement of the hard particles.
Fig. 7 shows the fracture morphology of the particle beams in an impact sample of the composite. Fig. 7(a) shows the fracture morphology close to the edge of the steel strip inside a particle beam. It can be seen that the fracture is a kind of mixed crystal morphology with cleavage – intergranular, namely, the morphology includes an obvious characteristics of cleavage at steel band and an intergranular fracture characteristics at the particle beam close to the steel strip. And several cracks exist. The place marked by letter A has a crack source. The crack was expanded to B starting through the surrounding grain, and was extended along the three different parts marked as letters C, D and E, respectively. The amplification microstructure in a circle in Fig. 7(a) is shown in Fig. 7(b). It can be observed that the fracture morphology is consisted of many prisms along different direction, which obviously signed intergranular fracture. Fig. 7(c) shows the fracture morphology in the middle of the particle beam. It presents the granular crystal morphology with a smooth surface and some cavities which were formed maybe to relate to the filling rate of the alloy powders. The amplification microstructure circled by rectangles and ovals are shown in Fig. 7 (d) and Fig. 7 (e), respectively. Fig. 7 (d) presents the fracture microstructure of hard reinforced phase. Here, the microstructure on the both sides reveals the embrittlement and the cataclasm of columnar (Fe, Cr)\(_7\)C\(_3\) hard carbides under larger impact energy, and the microstructure in the middle of the picture shows that the secondary carbide particles liked short rods were fell off. Fig. 7(e) shows the regular arrangement of the hard particles in the fracture. Generally, the fracture of particle beam in the composite is a brittle fracture.

**Figure 7.** The fracture morphology of the particle beams in impact samples of the composite (a) the fracture morphology close to the edge of the steel strip inside a particle beam, (b) the amplification microstructure in a circle, (c) the fracture morphology in the middle of the particle beam, (d) the amplification microstructures circled by rectangle, (e) the amplification microstructures.
CONCLUSIONS

In this paper, a high manganese steel matrix composite with reinforced (Fe, Cr)$_7$C$_3$ particle beams has been synthesized using melting compositing and in-situ reacting method. Microstructure and performance of the composite were analyzed. And the following conclusions can be arrived according to the experimental results.

1. The method can be also used to produce the composites of other matrix, in which the filled alloy powders are also allowed to be replaced with others powders if only the carbide with a high strength can be formed in the process of the reacting.

2. The reinforced phase of the high manganese steel matrix composite with reinforced (Fe, Cr)$_7$C$_3$ particle beams is mainly including a column and a fine short rod or a globular carbide (Fe, Cr)$_7$C$_3$, and the former is the primary.

3. Abrasive wear performance of the high manganese steel matrix composite with reinforced (Fe, Cr)$_7$C$_3$ particle beams is significantly improved due to the dominated column inclusion, which is caused by the strong metallurgical bonding between the particles and matrix.

4. According to the analysis of impact fracture for the high manganese steel matrix composite with reinforced (Fe, Cr)$_7$C$_3$ particle beams, the fracture of particle beams in the composite belongs to a brittle fracture.

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