

Application research of ferrous matrix composites in roller ring used in high-speed wire/bar rolling mill

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ABSTRACT

Tungsten carbide particle (WC_p) reinforced ferrous matrix composites roller rings were fabricated by centrifugal casting. The microstructures, properties and application effect of the composites roller rings were investigated by SEM, TEM and various property testers. The experimental results show that the WC_p were uniformly distributed in outer reinforced-layer (working-layer) of 20–50 mm in thickness and their volume fraction reached 60–80 vol.%; there was a good interface bonding between WC_p and Fe–C alloy without any reaction products; hardness attained to HRA80–85 in working-layer, and HRA73–76 in inner ferrous matrix where the toughness was over 8 J/cm²; the wear resistance of the composites roller rings excels that of high-speed steel; service life of the composites parts approached to that of the WC hard alloy roll when the same WC_p -volume-fraction in working-layer were obtained for both of them, but the production cost of the WC_p /Fe–C composites roller ring decreased by 50%.

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1. Introduction

Currently, WC hard alloy rolls produced by powder metallurgy have been used in high-speed hot rolling mill so as to meet the requirement of higher wear resistance. Besides, high-speed steel (HSS) whose carbon concentration excels 1.6 wt% has also been used to fabricate hot rolls and has been successfully applied to the hot rolling mills, due to its good red-hardness, wear resistance and toughness. Nevertheless, these rolls are monolithic materials with a high cost (¥ 500–600 per kg WC powder in China, and complicated process of HSS) and restricted shape and size, and thus have a low utilization rate of material, which has caused severe waste of raw material. Therefore, it is necessary for us to develop a new type of substitute material for the WC carbide rolls in order to cut the production cost and to reduce the waste of material. As introduced in our previous work [1–3], WC_p reinforced ferrous matrix composites roller rings were fabricated by centrifugal casting method. Under the action of centrifugal force, the added WC_p in the Fe–C melt moved towards the outer region due to its relatively high density, leading to the formation of the outer reinforced-layer (working-layer) and the inner unreinforced-layer (core matrix) during the casting. This new type of composites roller ring, if used in the high-speed wire/bar rolling mill, can be expected to reduce the production cost to the fullest extent possible.

Metal matrix composites are an attractive choice for aerospace and automotive applications because of their high specific stiffness [4,5]. Composites with aluminum and magnesium matrices have been investigated extensively [6–8], while less work has been carried out on iron matrix composites. In the present study, the microstructures and properties of WC_p /Fe–C composites roller rings fabricated by centrifugal casting were studied. On this basis, an assessment was then made on the application effect of the new parts in high-speed wire/bar rolling mill.

2. Experimental procedures

The ferrous matrix alloy was placed in a 50-KG medium frequency induction furnace and superheated to 50–60 °C above its liquidus temperature. The chemical composition (expressed in weight) of the ferrous matrix alloy was as follows: 3.0–3.8% C, 1.8–2.6% Si, 0.2–0.5% Cr, 3.0–5.0% Ni, Mn < 0.3%, S and P ≤ 0.03%, and balance Fe. The reinforcements of the composites, i.e. tungsten carbide particles (WC_p), were commercially provided. The sizes of WC_p are 100–150 μm, the hardness of the WC particle is HRA93–93.7, the density is 16.5 g/cm³, and the fusion temperature is 2525 °C. At up to 1500 °C, the mixture of the Fe–C melt and the preheated WC_p was directly poured into a horizontal centrifugal mold rotating at 1000–1400 rpm. The density of WC_p is higher than that of liquid Fe–C alloy, so WC_p dispersed in the melt will move towards the outer region under the condition of centrifugal casting. The dimensions of the centrifugally cast composites roller rings in this study are as follows: 245–450 mm in outer diameter, 110–200 mm in inner diameter, and 78–150 mm in length.

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The specimens of the composites for metallographic, mechanical properties and wear tests were cut off by line cutting method. The mechanical properties were measured by JB294/147A impact tester, and HR150D hardness tester. Dry sliding wear experiments are performed at room temperature. Wear properties of the composites have been investigated using a MMS-1G high-speed wear testing machine which employed a steel ring rotating against the test pin on which a load was applied by a lever mechanism. The weight loss of the test pin is determined by a scale with an accuracy of 10^{-4} g at definite time intervals. Wear surface temperature were measured under different loads by nickel–chromium/nickel–silicon thermocouple which was inserted to a temperature measuring hole 1.5 mm far from wear surface of the pin sample. The steel ring is made of 3Cr2W8V die steel, which is hardened to HRC51 and has a diameter of 160 mm. The size of the test pin is $\varnothing 14 \times 40$. The microstructures and interface structure of the composites ring samples were analysed by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The thin foil for TEM are cut to 0.2 mm thickness foil from the above pin sample, and normally ground to about 50 μ m, then a ion milling is used to reduce thickness of the TEM film specimen until it is thin enough to be studied in the TEM.

3. Results and discussion

3.1. Mechanical properties

Table 1 presents the mechanical properties of the WC_p/Fe–C composites roller ring, the WC hard alloy roll, and the high-speed steel rolls.

As shown in Table 1, the impact toughness both in outer working-layer and inner matrix of the WC_p/Fe–C composites roller rings excel those of the WC hard alloy rolls and HSS, and the hardness in the WC_p/Fe–C composites working-layer are almost the same as those of the WC hard alloy and HSS rolls. Therefore, this new type of WC_p/Fe–C composites roller rings can be expected to meet the requirements of roller rings used in high-speed rolling mill due to their high hardness in working-layer and excellent impact toughness in inner matrix.

3.2. Microstructures

Fig. 1 shows the WC_p-distribution in working-layer and the inner matrix microstructures of the WC_p/Fe–C composites roller ring. It can be seen from Fig. 1 that the WC_p are evenly distributed in the working-layer, and their volume fraction reaches up to 70 vol.%. The joint face between the working-layer and inner Fe–C matrix is clear without any defect and displays curved shape. The microstructure of inner Fe–C alloy matrix consists of bainite, graphite and small amounts of carbides.

In order to study the interfacial structure between the reinforcing phases (WC_p) and Fe–C alloy matrix in the composites layer, TEM was used to observe and analyse the microstructure mor-

Table 1

Mechanical properties of different roll materials.

Roll materials	Impact toughness a_k (J/cm ²)	Hardness (HRA)
WC _p /Fe–C composites working-layer	3.8–5.0	80–85
Inner Fe–C matrix	8.2–11.5	73–76
WC hard alloy rolls	2.5–3.5	81–87
High-speed steel rolls (HSS)	6.1–6.2	80–82

phologies and interfacial structures of the composites. The TEM images and electron diffraction analyses of the reinforcing phases, Fe–C alloy matrix near to the reinforcing phases and their interface are shown in Fig. 2. It can be found from Fig. 2(a) that the interface between reinforcing phases and Fe–C alloy matrix is clear, the reinforcing phases is WC (Fig. 2(c)), and the matrix near to the reinforcing phases is bainite, i.e. α Fe + Fe₃C (Fig. 2(b)). There is not third phases in the interface layer except the reinforcing phases (WC_p) and bainite matrix (Fig. 2(d)). Thus, the interfaces reaction between WC_p and bainite matrix didn't occur in the manufacturing process of the composites, and the interfacial bonding between WC_p and the matrix belongs to metallurgical bonding.

3.3. Wear property

The wear resistance comparison of the WC_p/Fe–C composites and the high-speed steel at room temperature are shown in Fig. 3 under loads of 100 and 200 N. It can be observed from Fig. 3 that under a fixed sliding speed of 60 m/s and wear time of 2 min, the wear resistances of the WC_p/Fe–C composites containing about 70 vol.% WC_p reached 23.64 at the load of 100 N. When the load increases up to 200 N, the wear resistances of the composites reduces to 7.96. Compared with the high-speed steel, the wear resistance of the composites under loads of 100 and 200 N raise over 20 times, respectively. It is thus clear that the composites has much higher wear resistance than that of the high-speed steel.

The worn surface temperatures of the high-speed steel and the WC_p/Fe–C composites pins under the load of 100 N and velocity of 60 m/s are measured to be 657 °C. Under the conditions, the relatively thinner oxide films generated on the worn surface of composites pin are due to the fact that metal-to-metal contact is prevented by the hard WC_p in the composites pin as the sliding friction is performing. The less metal-to-metal contact will also reduce the weight loss of the material being removed from the pin. Thus, the more WC_p distributed in the composites pin, the better the wear resistance of the composites pin. In this case, the wear on WC_p is relatively low, but eventually they will make the WC_p worn down, fractured or removed away together with the oxide around them and form stripped pit. Under the same sliding speed, the larger load applies, the higher wear rate is (Fig. 3). When the applied load reaches 200 N, the worn surface temperature rises to 810 °C. At a higher load (200 N) the stress on the oxide film becomes an influential factor of the wear resistance. The relatively high wear surface temperature can not only reduce the strength of Fe–C alloy matrix and accelerate the oxidation of them, but also increase ther-

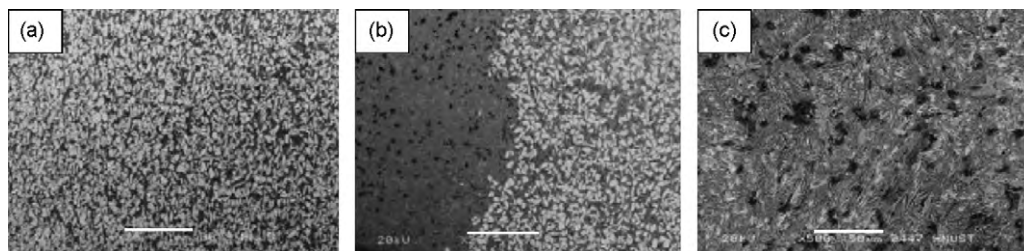


Fig. 1. SEM images showing microstructures of the composites roller ring: (a) WC_p-distribution in working-layer; (b) joint face between the working-layer and inner matrix; (c) inner matrix.

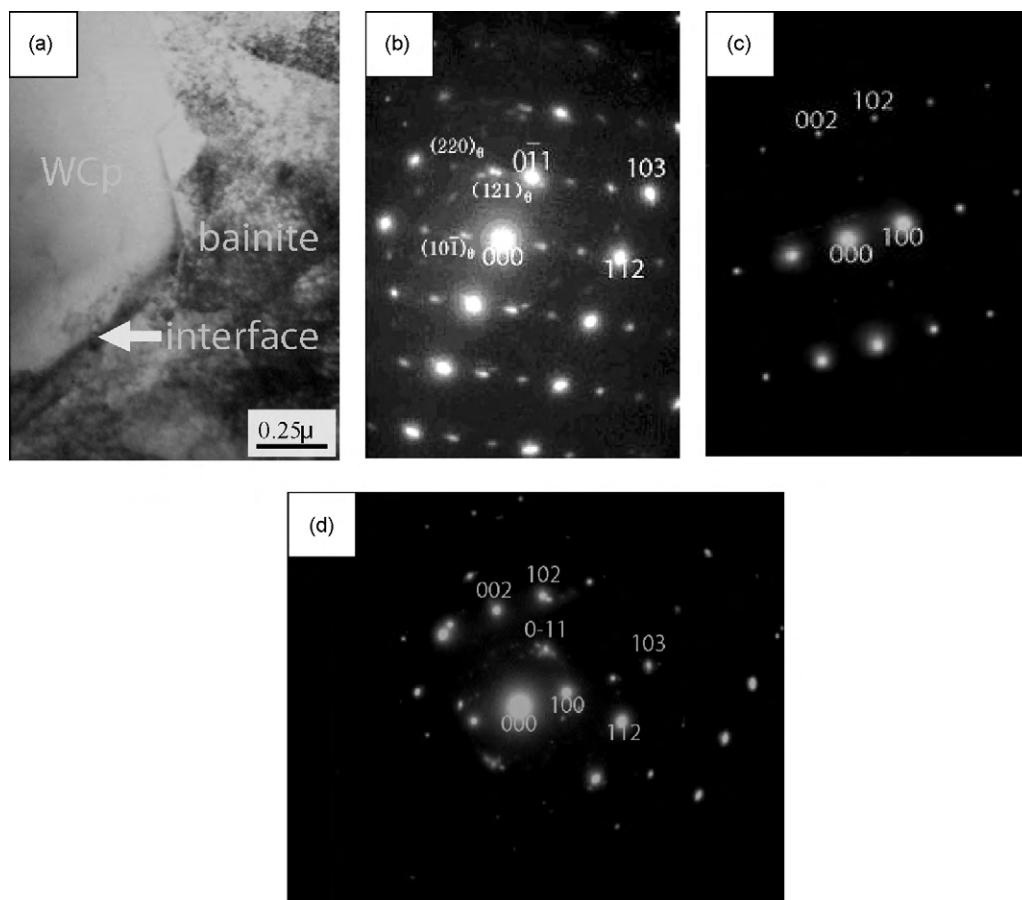


Fig. 2. TEM images and electron diffraction patterns of the WC_p/Fe–C composites: (a) TEM images of interfacial morphology; electron diffraction patterns of (b) Fe–C alloy matrix near to WC_p, (c) WC_p, and (d) interface between WC_p and Fe–C alloy.

mal shock at the metal–oxide boundary and sub-surface fatigue cracking. This pressure caused by high load results in yielding of the iron matrix, which will make the WC_p pushed down the wearing surface. Metal–metal contact, however, leads to oxidation which grows rapidly, and the oxide films are fractured under the action of sliding load. Rapid wear has occurred between the sample and the counter face. So the wear rate is increased. The less carbide in the high-speed steel cannot efficiently prevent metal-to-metal contact. The thicker oxide films are generated on the worn surface of the high-speed steel pin, which is more easily removed from the pin, leading to the lower wear resistance. In addition, the high-

speed steel under the same testing conditions cannot resist this pressure of the load and plastic deformation has occurred (Fig. 4). Thus, it has lower wear resistance than that of WC_p/Fe–C composites. The worn surface morphologies of the WC_p/Fe–C composites and the high-speed steel pins run under the loads of 100 and 200 N are shown in Fig. 5.

3.4. Application

According to product drawings offered by the supplier, the WC_p/Fe–C composites roller rings (outer diameter 285–325 mm,

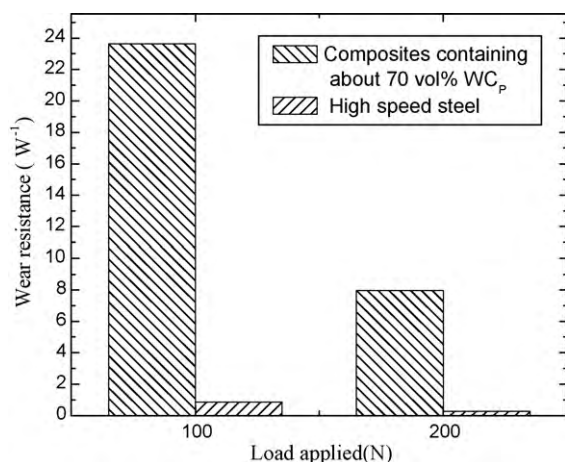


Fig. 3. Wear resistance of different materials.

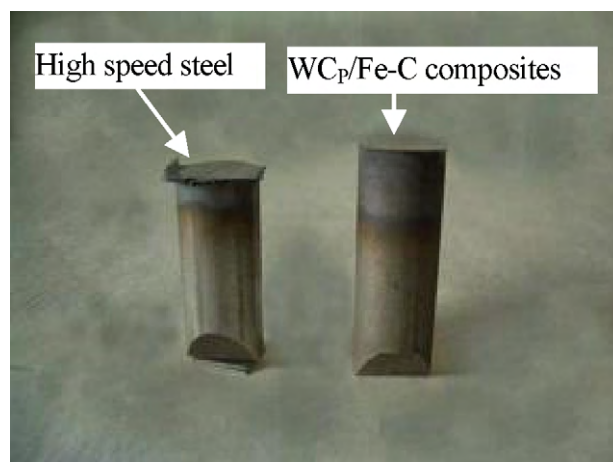


Fig. 4. Samples after sliding wear under testing condition.

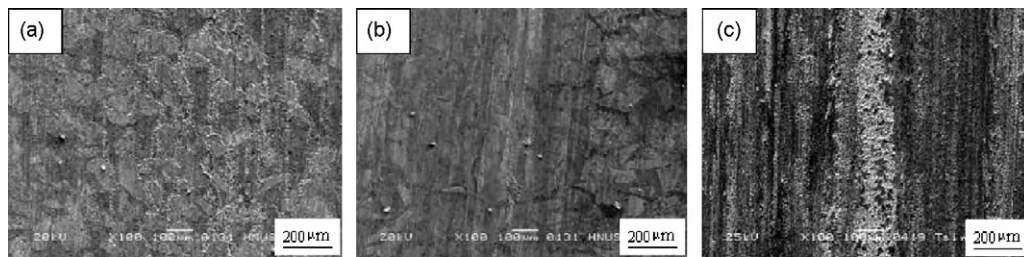


Fig. 5. Worn surface morphologies (SEM) of the WC_p/Fe–C composites and the high-speed steel pins at sliding speed of 60 m/s. Composites containing 70 vol.% WC_p at the loads of 200 N (a) and 100 N (b); (c) high-speed steel at load of 200 N.

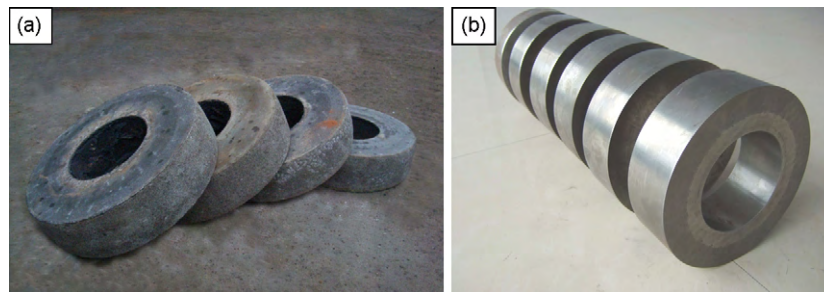


Fig. 6. Photos of the composites roller rings: (a) rough casts and (b) products after finish machining.

inner diameter 160–200 mm, length 95–135 mm) are fabricated by centrifugal casting method at 800–1000 rpm. After heat treatment, PCBN tools are used for rough machining of the roller ring roughs, and then the diamond grinding wheel is used for finish machining. The composites roll rings before and after machining are shown in Fig. 6.

It can be found from Fig. 6 that the radial thickness of the composites working-layer for the roller ring reaches 30–33 mm (Fig. 6(b)), exceeding the required radial work layer thickness (15–20 mm) of the high-speed wire/bar mill roller rings. The new composites roller rings are installed in K2 mill housing of high-speed bar mill (15.6 m/s) for rolling $\Phi 18$ rod and bar, the service life of the new composites roll rings is 72 h, and the rolling quantity for the bar on one groove pass reach 7100t. When rolling $\Phi 5$ wire rod in pre-finishing stands for high-speed wire mill (60 m/s), it can work 96 h continuously, and the rolling quantity for the wire rod exceed 4000t, and reach or exceed the rolling quantities of the WC hard alloy roller rings which are about 2500–5500t in same service condition [9–12], being about 9 times more than the rolling quantities of high-speed steel roll ring [13].

It can be concluded that the new types of composite roll rings combine the high hardness and wear resistance in the working-layer with the excellent impact toughness in inner matrix. Under the same service conditions, the service life of the new roller rings reach or exceed that of the tungsten carbide hard alloy when they are both of the same WC_p-volume-fractions in working-layer, but the production cost of the WC_p/Fe–C roller ring decreases by 50%.

4. Conclusions

- (1) In the present work, WC_p/Fe–C composites roller rings with different sizes are fabricated by centrifugal casting method, and

the thickness of the outer composite working-layer can be controlled within 20–45 mm according to the need.

- (2) The WC_p are uniformly distributed in outer working-layer and their volume fraction attains 60–80 vol.%, there is a good interface bonding between WC_p and Fe–C alloy matrix without any reaction products. The hardness of the roll ring attained to HRA80–85 in the working-layer and HRA73–76 in the inner ferrous matrix where the toughness value was over 8 J/cm².
- (3) The wear resistance of the composites working-layer for the roller rings is 20 times more than that of the high-speed steel under same wear condition.
- (4) Service life of the composites roll rings reach or exceed that of the tungsten carbide hard alloy roll when they are both of the same WC_p-volume-fraction in working-layer, is about 9 times more than the rolling quantities of high-speed steel roll ring, but the manufacturing cost of the composites roller ring decrease by 50%.

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