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Effect of laser cladding on wear and damage behaviors of heavy-haul wheel/rail materials

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ABSTRACT

The objective of this study is to investigate the effect of laser cladding coating on wear and damage behaviors of heavy-haul wheel/rail materials by means of a laboratory-scale rolling–sliding wear apparatus. The results indicate that the wheel/rail rollers with laser cladding form a uniform and compacted coating without any cracks or stomata. The laser cladding coating markedly improves wear-resistance of wheel/rail rollers. The wear mechanism of wheel/rail rollers undergoing laser cladding is plowing and abrasive wear. However, the wheel/rail rollers without laser cladding exhibit visible adhesion wear and serious spalling damage. Furthermore, there are obvious fatigue cracks in both the surface and subsurface. Excellent wear-resistance of laser cladding coating can effectively alleviate surface damage and prolong wear life of heavy-haul wheel/rail. However, further work should be carried out for clarifying the fatigue characteristic of wheel/rail with laser cladding coating.

1. Introduction

A variety of damages happen on wheel/rail system, which is mainly result from rail side wear (Fig. 1a), surface fatigue crack, corrugation, head check, and wheel spalling (Fig. 1b). Furthermore, these defects may cause the failure of heavy-haul wheel/rail or potential derailment [1–3]. The field investigation indicates that the wears of rail side and wheel flange are important affecting factors on service life of heavy-haul wheel/rail [4]. Increasing strength and hardness of wheel/rail materials would improve wear-resistance. Therefore, rail with excellent wear and rolling contact fatigue resistance (typical composition in wt% (bal. Fe): C: 0.75–0.85%, Mn: 1.10–1.20%, P: 0.005–0.007%, S: 0.003_{max}) is used in North America [5]. In China, new material with higher hardness and strength (PG4 rail with strength of 1300 MPa) has been used in the heavy-haul railway [6]. Garnham [7] studies the growth of rolling contact fatigue crack of pearlitic rail steels in very early stage. The propagation of RCF crack is facilitated running along the pearlite laminae and highly strained regions [8]. In addition, the rail grinding as a treatment technology of rolling contact fatigue problems has been studied and applied widely around the world [9].

The laser cladding is an excellent surface treatment technique for improving the wear and rolling contact fatigue resistance of materials [10,11]. The capabilities of low thermal input and metallurgical bonding of laser cladding allow carrying out several strategies to improve the wear and fatigue resistance [12]. At present, the majority of applications of laser cladding technology focus on steel processing by repairing and cladding with cobalt base alloys for increasing wear-resistance of material.

In this paper, the effects of laser cladding on wear and damage behaviors of heavy-haul wheel/rail materials are investigated using a MMS-2A laboratory-scale rolling–sliding testing apparatus. In particular, the damage mechanism of wheel/rail rollers without or undergoing laser cladding is explored by means of optical microscopy, X-ray diffraction and scanning electronic microscopy.

2. Experimental details

Rolling–sliding wear tests are carried out using a MMS-2A rolling–sliding testing apparatus. The tester is composed of two rollers with a diameter of 40 mm serving as a rail roller (lower specimen) and a wheel roller (upper specimen). The rollers are powered and controlled by a DC motor. The geometric sizes of rollers are determined by means of Hertzian rule [13], shown in Eqs. (1) and (2).

$$(q_0)_{lab} = (q_0)_{field} \tag{1}$$

$$\left(\frac{a}{b}\right)_{lab} = \left(\frac{a}{b}\right)_{field} \tag{2}$$

where, $(q_0)_{lab}$ and $(q_0)_{field}$ are the maximum contact stresses in the laboratory and in the field, respectively; $(a/b)_{lab}$ and $(a/b)_{field}$ are the ratios of semi-major axis to semi-minor axis of the contact ellipses between the wheel and rail in the laboratory and field,

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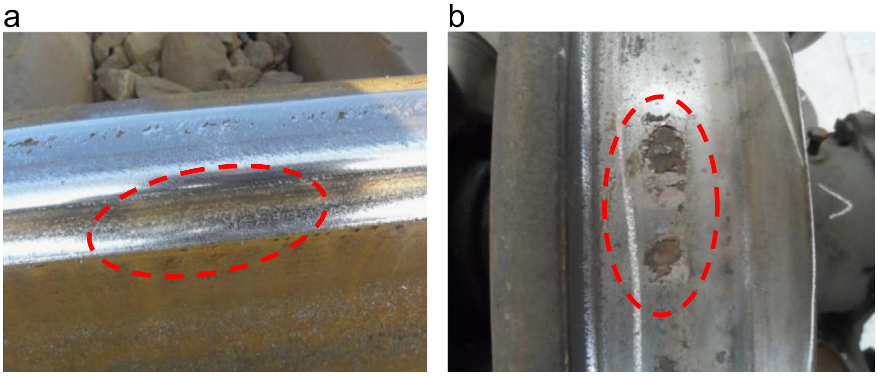

Fig. 1. Typical damages of heavy-haul wheel/rail, (a) rail side wear and (b) wheel spalling.

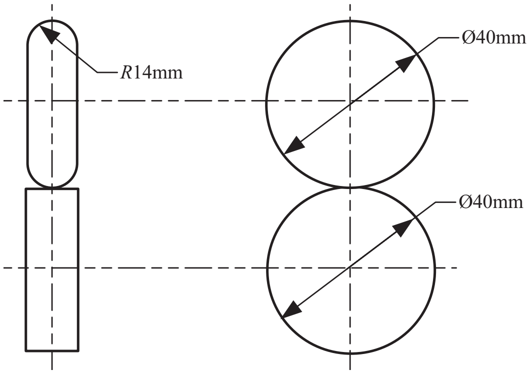

Fig. 2. Scheme of the wheel and rail rollers.

Table 1
Chemical composition of wheel/rail materials (%wt).

Specimen	C	Mn	Si	S	P
Wheel	0.55–0.65	0.58–0.80	0.17–0.37	≤ 0.045	≤ 0.04
Rail	0.62–0.77	1.35–1.65	0.15–0.37	≤ 0.050	≤ 0.04

Table 2
Chemical composition of Co-based alloy powder (%wt).

Composition	C	Si	Fe	Cr	Ni	W	Co
Content	1.1	1.0	1.5	28.5	1.5	4.4	Bal.

respectively. The scheme of geometric sizes calculated by above equation is shown in Fig. 2.

The normal force is determined according to above Eqs. (1) and (2). The normal forces of 170 N, 220 N and 250 N in the laboratory simulate the axle loads of 25 t, 32 t and 35 t in the field, respectively. The rotating speeds of the upper roller (wheel specimen) and the lower roller (rail specimen) are 180 rpm and 200 rpm, respectively. Therefore, the slippage ratio between the wheel and rail rollers is 10% for accelerating the wear of wheel/rail materials. The number of cycles of rail roller is 4.8×10^5.

The real heavy-haul wheel/rail materials from the field were used to make wheel/rail rollers. The chemical compositions of wheel/rail specimens in weight percentage are given in Table 1. In this study, the surfaces of wheel/rail rollers are cladded with common Co-based alloy powders using a multimode cross flow CO_2 laser (TR-3000). The granularity of Co-based alloy powders is about 45–105 μm. The chemical compositions in weight percentage are given in Table 2. During the laser cladding process, the diameter of laser beam is 4 mm and the power is 2 KW. The scanning speed is 0.2 m/min and the flow rate of alloy powder is about 15 g/min.

All tests are performed under the same ambient condition (temperature: 18–23 °C and relative humidity: 20–50%). The wheel/rail rollers are cleaned in acetone and weighed using an electronic balance (TG328A) before and after testing. The wear loss of wheel/rail rollers is determined by mass loss. The wear and damage behaviors of wheel/rail rollers are investigated by means of examining the hardness and wear scar using microhardness tester (MVK-H21, Japan), optical microscopy (OLYMPUS BX60M, Japan), X-ray diffraction (XRD) (D8, Germany) and scanning electronic microscopy (SEM) (QUANTA200, FEI, England).

3. Results

3.1. The microstructure of laser cladding coating

The results from Fig. 3 indicate that the microstructures of laser cladding coating of wheel/rail rollers are uniform and compact. No cracks or stomata were found on the laser cladding coating. XRD spectrums in Fig. 4 (copper target, voltage: 40 KV, diffraction angle: 20–90°, Step: 0.02°) indicate that the cladding coatings are composed of γ-Co phase and carbide $Cr_{23}C_6$. During the laser cladding process, Cr element with high content in Co-based alloy powders and C element form the carbide $Cr_{23}C_6$ by means of chemical reaction at high temperature.

3.2. The hardness and weight loss from wear of wheel/rail rollers

It is noted from Fig. 5 that the surface hardness of wheel and rail rollers undergoing laser cladding are higher than that of wheel/rail rollers without treatment. The increased ratios of surface hardness of wheel and rail rollers are 41.9% and 43.1%, respectively. In addition, the surface hardness of the rail roller is larger than that of the wheel roller before and after laser cladding. The hardness changes of the laser cladding coatings along with depth direction shown in Fig. 5b indicate that there is different hardness on the cladding layer, transition layer and substrate zone. With an increase of depth, the hardness of the cladding coatings decreases gradually and is close to the substrate hardness of wheel/rail rollers. In addition, it is concluded that the thickness of the cladding layer is about 0.8–1.2 mm. Furthermore, the depth of maximum hardness of the cladding coatings is about 0.2 mm. Therefore, the wheel/rail rollers undergoing laser cladding obtain high hardness compared to original heavy-haul wheel/rail materials.

The laser cladding coatings markedly decrease weight loss from wear of wheel/rail rollers (Fig. 6). The decrease rates of weight loss of wheel and rail rollers are 78.8% and 78.5% before and after laser