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Mechanical and tribological behaviors of copper metal matrix composites for brake pads used in high-speed trains

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A R T I C L E I N F O

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A B S T R A C T

As one of the most important components in high-speed trains, demands are improved on the mechanical and tribological properties of materials for brake pads. In this study, a newly developed copper metal matrix composite (Cu-MMC) for the aforementioned brake pads was fabricated by powder metallurgy route. The microstructure and mechanical properties of Cu-MMC were investigated. Cu-MMC was tribo-evaluated by a full-scale dynamometer, and special attention was paid on the braking performances during emergency stop-braking at initial speeds from 300 to 380 km/h. Examination and analysis of the worn surface and subsurface corroborated the wear mechanism. The results indicate that Cu-MMC exhibits excellent properties and can meet the technical requirements, so it holds great promise for applications in high-speed trains.

1. Introduction

Compared with other forms of transportation, high-speed trains have the characteristics of large capacity, fast running speed, high transport efficiency, low operational cost and high safety coefficient [1,2]. Consequently, a serious interest in this rapidly expanding transport mode has been increasing all over the world. China has successfully developed and commercially operated CRH380 high-speed trains with the maximum speed of 350–380 km/h [3–5].

High speed means more dynamic actions and potential danger. In order to ensure safe operations, braking systems of high-speed trains are required to keep enormous braking forces under control. In braking systems, in addition to the regenerative braking system, the friction braking system is used to guarantee the performances and safety, especially at low speed and in case of emergency or failure [6]. In case of emergency, the friction braking system must be capable of stopping a CRH380 train running at 300 km/h at a maximum acceptable braking distance of 3800 m. Huge kinetic energy would be generated during the emergent braking process, and it is required to be dissipated in brake discs and pads in a short time (up to 19 MJ per disc in less than 2 min). The flash temperature at the disc/pad interface may reach up to 900 °C [7].

In order for high-speed trains to operate safely and comfortably, demands are proposed on the properties of brake pads, such as the predictable friction behavior, satisfactory wear resistance, low aggressivity against the brake disc (e.g., burn marks and thermally initiated cracks), high comfort qualities (i.e. low squeal noise and anti-shudder), and sufficient mechanical characteristics [6,8,9]. Various materials have been developed as candidate for brake pads. Organic brake pads, defined as polymer-based friction materials containing multiple ingredients, have been broadly applied to railroad passenger coaches and locomotives [10,11]. However, poor thermal stability of organic materials, especially the thermal fade, extremely limits applications of organic brake pads, which can only be used at temperatures lower than 300 °C generally [12]. Compared to organic friction materials, metal matrix composites can typically withstand higher temperatures and can be used to temperatures over 1000 °C. Especially, Cu-MMCs are the top choices as brake materials for high-speed trains due to their attractive properties such as high thermal conductivity, excellent tribological properties, and adaptability to working conditions [8,9,13–16].

Considerable attention has been paid to the improvement in properties of Cu-MMCs. Gyimah et al. [14] investigated the wear behavior of a novel Cu-based friction material for train brake pads with a high pressure pad-on-disc braking tester. Su et al. [15] evaluated the

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Nomenclature

P	load during the shear test (N)
L	length of the specimens during the shear test (mm)
B	width of the specimens during the shear test (mm)
F_B	clamping force (namely total nominal contact force) during braking (N)
F_t	total braking force during braking (N)
F_b	total contact force during braking (N)
S_2	braking distance (m)
m_0	weight of the brake pad before the friction tests (g)
m_i	weight of the brake pad after the friction tests (g)
E	braking energy during braking (MJ)

Greek letters

τ	average shear strength during the shear test (MPa)
μ_a	instantaneous coefficient of friction during braking
μ_m	average coefficient of friction during braking
ω	wear rate of the friction material (cm^3/MJ)
ρ	density of the friction material (g/cm^3)

Table 1
Chemical composition of Cu-MMC.

Element	Cu	Fe	Graphite	MoS_2	ZrO_2	FeCr	Others
Content (wt. %)	40–55	10–12	17–19	2–3	6–8	6–8	4–10

tribological properties of copper-based friction materials with exogenous copper powder third body by a pin-on-disc tribometer. Goo et al. [9] developed three Cu-MMCs for brake pads, and found that the friction coefficients of the developed materials were higher than those of materials in service during pin-on-disc experiments. Chung et al. [16] examined the brake performances of sintered friction materials developed for high-speed trains on a 1/5 scale dynamometer, and claimed that the improvement in tribological properties of the newly developed friction materials was attributed to the high graphite content. Kim [17] reported a full-scale dynamometer that was designed to simulate the brake characteristics of high-speed trains, and gave a brief description of the braking performance evaluation on brake pads. For practical applications, it is essential to assess the safety of brake pads by verifying their braking performances on full-scale dynamometers. Nevertheless, reports concerning the braking performances of Cu-MMCs for brake pads tested on full-scale dynamometers are limited, especially at speeds over 300 km/h.

In addition, for brake pads in service, there are still unsolved problems concerning the low mechanical strength of the friction materials, as well as the insufficient bonding strength between the friction materials and the metal backing plate, frequently resulting in spallation of the friction materials and detachment of the friction material from its backing plate [18]. Thereby, improving mechanical properties is also an important concern on brake pads.

The current work aims to present a newly developed powder metallurgy processed Cu-MMC for high-speed trains, and introduce the preparation, mechanical properties and full-scale dynamometer test results of this material.

2. Experimental procedures

2.1. Materials preparation

In this study, the chemical composition of Cu-MMC is shown in Table 1. The commercial-grade powders of electrolytic Cu (99.7% purity, <74 μm), reduced Fe (98% purity, <74 μm), graphite (97% purity, 150–600 μm), MoS_2 (96% purity, <6.5 μm), ZrO_2 (92% purity, 100–250 μm), and FeCr intermetallic compound (92% purity, <74 μm, hereafter referred to simply as “FeCr”) were used as the main raw materials.

As illustrated in Fig. 1, the powder metallurgy route for manufacturing Cu-MMC involves the following sequential steps. The powders listed in Table 1 were accurately weighed out in amounts corresponding to the desired proportions, and thoroughly mixed in a V-cone blender for 8 h. After the blending process, the mixed powders were consolidated into compacts via cold die compaction, under a pressure of 650 MPa at room temperature. Subsequently, the green compacts were sintered directly to the steel backing plates under a pressure of 2.5 MPa, in a protection atmosphere of H_2 or cracked ammonia, at a temperature of 970 °C for 180 min. After sintering, the samples were cooled down to room temperature in the furnace.

2.2. Experimental apparatus

A part of Cu-MMC was cold mounted for the metallographic examination. The micro-images were taken using an optical microscope (Leica DM4500P, Germany). The bulk density of Cu-MMC was measured by the Archmedes' method at room temperature. The surface hardness of Cu-MMC was evaluated via a Brinell hardness tester (310 HBS-3000, China) using a standard 10 mm diameter tungsten carbide ball indenter, at a normal load of 250 kgf and a dwelling time of 30 s.

The schematic illustrations of the shear strength testing apparatus are given in Fig. 2. The shear tests were conducted in a universal testing machine (Instron 3369, USA) at a cross-head rate of 1 mm/min, using specimens of approximate dimensions 15 × 15 mm^2 cut from Cu-MMC. The shear planes of the specimens were parallel to the friction surfaces of Cu-MMC. The load and displacements were monitored continuously until failures of the specimens, the load (P) registered at debonding was converted into an average shear strength (τ) by

$$\tau = \frac{P}{L \times b} \tag{1}$$

where L is the length, and b is the width.

According to TJ/CL 307–2014C.4 test programme issued by China Railway Corp. [19], the friction and wear tests of Cu-MMC, simulating the

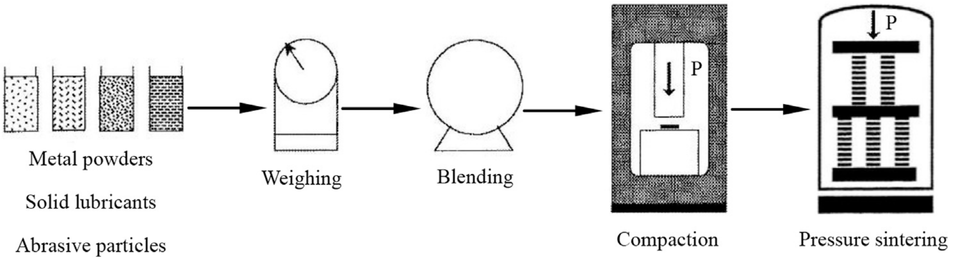

Fig. 1. Processing steps for Cu-MMC.