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Effect of thermomechanical treatment on sliding wear of high-Cr cast iron with large plastic deformation

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ABSTRACT

The effect of thermomechanical treatment on sliding wear of high-Cr cast iron was studied. Due to the inherent embrittlement of high-Cr cast iron, the bimetallic composites, in which the cast iron was cladded by low carbon steel, were prepared to conduct plastic deformation in the temperature range of 950–1150 °C with the strain rate of 0.001 s^{-1}. The wear properties of the as-cast high-Cr cast iron and the bimetallic composites were compared using pin-on-disc type sliding wear tests. Experimental results demonstrated that the brittle cast iron was severely deformed with crack free at high temperatures in the form of bimetallic composites. The thermomechanical treatments not only rotated the carbide orientation with ~90°, but also increased the volume fraction of carbide. Because the long axes of carbide rods were parallel to the worn surface and the higher volume fraction of carbide provided a better protection for the ferrous matrices, the bimetallic composites bonding at 1050 and 1150 °C had a better wear resistance than the as-cast high-Cr cast iron. However, the wear resistance of the bimetallic composite bonding at 950 °C was inferior to the as-cast high-Cr cast iron due to the higher volume fraction of carbide void accelerating the wear rate on both carbide and ferrous matrix.

1. Introduction

Since high-Cr cast irons were patented by Becket in 1917 [1], these alloys have been widely used in industrial applications such as mining, mineral processing, milling and earth moving due to their excellent wear resistance and low production costs. The distinguishing feature of high-Cr cast irons is that a high-volume fraction of Cr-rich carbides in-situ embedded in a ferrous matrix [2–4]. On one hand, these carbides, typically based on M_7C_3 where M includes Cr, Fe and other strong carbide formers, impart high hardness to the alloys which contributes to exceptional wear properties. On the other hand, the same carbides in the form of netlike or rather massive structure result in severe brittleness for high-Cr cast irons because the M_7C_3 type carbides in hexagonal close-packed crystal structure [5,6] have poor formability. This brittleness not only limits the applications of high-Cr cast irons, but also impedes the development of techniques that committed to improving their mechanical properties. Moreover, high hardness combined with brittleness makes that high-Cr cast irons are unweldable [7,8].

Great efforts have been done to improve the properties of high-Cr cast irons while maintaining a relatively high-volume fraction of hard carbides. These studies attempted to modify the characteristics of ferrous matrices and/or carbides including the type, size, morphology and distribution as well as orientation through the methods of heat treatment [2,3,9,10], micro-alloying [11–13] or spray casting [14]. With varying and limited degrees of success, it was found that both a refined microstructure and less interconnected carbides can improve the fracture toughness and wear resistance of high-Cr cast irons [2,3,9–14]. However, few investigations were implemented to produce the fine microstructure by hot working high-Cr cast irons due to their embrittlement.

Recently, the new idea of bonding high-Cr cast irons with mild steels has been proposed to fabricate bimetallic composites [15–24,27,28] in which the cast irons are used for the wear-resistant part while the steels are responsible for ductility and weldability, respectively. The bimetallic components such as bimetal hammer, laminated liner and cladding rolling mill roll have been applied in modern engineering. Sakurai et al. [15] joined high-Cr cast iron to cast steel in air by diffusion bonding at 900–1000 °C. When this bimetal was tested using an impact wear tester, the wear ratio was equal to the raw cast iron. Oh et al. [16] produced duocast materials consisting of high-Cr cast irons and low-Cr steel by a

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duocasting method. Through optimising the amount of Cr and Mo in cast irons, both wear resistance and fracture toughness of the bimetallic composites can be improved. Xiao et al. [17] compared the wear resistance during mineral processing in wet ball mills between an alloyed steel liner and a bimetal liner which composed of high-Cr cast iron and carbon steel making by compound lost foam casting. It was found that the service life of the bimetal liner was three times than that of the alloyed steel liner. This is because the carbon steel provided sufficient fracture toughness for the bimetal, and the high-Cr cast iron has a higher wear resistance than the alloyed steel. In addition, Kurt and Eroglu [18,19], Xiong et al. [20,21], Xie et al. [22,23] and Gao et al. [24,25] also produced bimetallic composites using different bonding techniques to join high-Cr alloys and carbon steels, even though the wear properties of these composites were not investigated.

In the light of previous research [2,3,9–25], this study modified the microstructure of high-Cr cast iron through thermomechanical treatments with large plastic deformation. In order to achieve the deformation on the brittle cast iron without cracks, a sandwich structural bimetal in which the cast iron was cladded by low carbon steel was produced by hot diffusion–compression bonding in the temperature range of 950–1150 °C. The pin-on-disc type sliding wear tests were used to compare the wear resistance of the conventional as-cast high-Cr cast iron and the novel bimetal.

2. Experimental procedure

As-cast hypoeutectic high-Cr cast iron and commercial hot-rolled low carbon steel sheet were selected as the raw materials, which were used for the wear-resistant part and the ductile part, respectively. The chemical compositions of the cast iron and the steel are given in Table 1. In order to simulate hot forging process, a Gleeble 3500 thermomechanical simulator was employed to carry out the bonding and hot working by means of hot compression tests. It is recognised that the Gleeble 3500 is a fully integrated digital closed-loop control thermal and mechanical testing system, which can be used to simulate various processes [26] like continuous casting, hot rolling, forging, extrusion and welding, etc. The cylindrical cast iron samples of 10 mm diameter and 6 mm thickness were wire cut from the same ingot in the same direction, while the steel discs were prepared with 10 mm diameter and 3 mm thickness. Before joining, all the bonding surfaces were polished to 1 μm diamond finish and cleaned by ethanol. Afterwards, the cast iron sample was cladded by the steel discs on both sides to form a sandwich structural assembly. The assembly was placed in the testing chamber and fixed between the anvils, and then subjected to thermomechanical treatments in a low vacuum. Fig. 1 shows the schematic diagram of the bimetallic assembly and the history of thermomechanical treatments. The test temperatures were 950, 1050 and 1150 °C, while the strain rate was 0.001 s^{-1}. In each test, 70% of thickness reduction of the assembly was conducted.

Table 1
Chemical compositions of high-Cr cast iron and low carbon steel (wt%).

Material	C	Si	Mn	P	S	Cr	Ni	Mo	Cu
High-Cr cast iron	2.4	1.2	0.9	0.02	0.03	23	0.3	0.5	0.1
Low carbon steel	0.1	0.15	1.61	0.014	0.002	0.21	–	–	–

The pin-on-disc configuration, which has the advantage of having a simple set-up and low testing cost [27], was used to measure the friction and sliding wear properties of the as-cast high-Cr cast iron and the bimetallic composites. For each bimetallic composite, the wear test was performed on the wear-resistant part. Thus, the bimetal specimens for wear tests were prepared by machining the composites to reveal the fresh surface of the cast iron layer. According to the requirement of CETR UMT pin-on-disc apparatus, the test specimens were mounted in polyester resin in a stainless steel stud with 50 mm diameter, and then played the role of disc part. Spherical pin of 6.35 mm diameter which is made of cemented carbide (6 wt% Co) with hardness of ~92 HRA was used in the test. Fig. 2(a) and (b) shows schematic diagram of the pin-on-disc apparatus and photograph of one test specimen, respectively. Dry sliding wear tests were carried out at room temperature and room humidity. The test methodology followed the guidelines presented in ASTM G99-05 standard [28].

The surface of disc part was polished to a roughness level of 1 μm and cleaned up with ethanol before testing. A constant load of 40N was applied to press the pin wear against the rotating disc plate for a period of 30 min. The angular velocity and the diameter of wear track were 400 rpm and 4 mm, respectively, responding to a total linear sliding distance of 150 m. In order to verify the results, three specimens of each metallurgical condition were tested. During each test, variations of the friction coefficient were recorded as a function of the sliding distance.

The microstructure of the test specimens was examined by an optical microscope (OM) after etching with a solution of 5 vol% ferric chloride, 25 vol% hydrochloric and 70 vol% distilled water. The phase components of the high-Cr cast iron with and without thermomechanical treatment were determined by an X-ray diffractometer (XRD) using monochromated Cu Kα radiation. To evaluate the wear resistance, wear weight loss was measured in an analytical scale with an accuracy of ±0.0001g and wear track was observed using a Keyence VHX-1000 digital microscope (DM). The wear mechanism was revealed by analysing the worn surface with a scanning electron microscope (SEM). Microhardness of the primary M_7C_3 type carbide as well as the ferrous matrix with and without sliding wear of the test

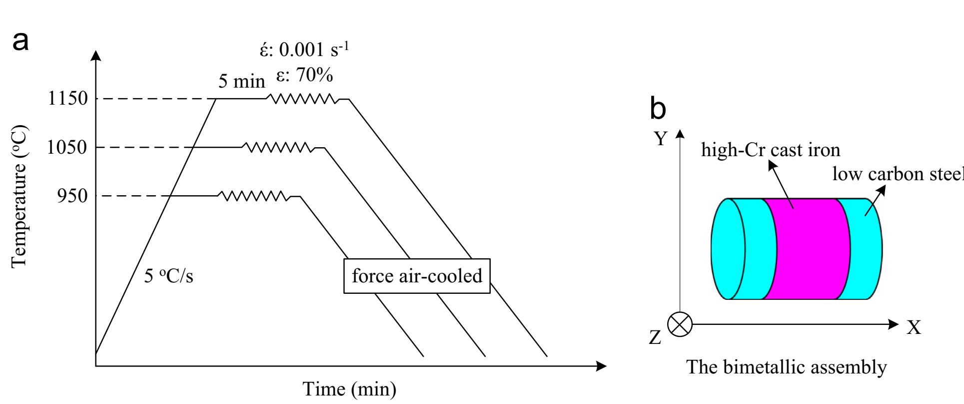

Fig. 1. (a) History of thermomechanical treatments and (b) schematic diagram of sandwich structural assembly.