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Effects of temperature and strain rate on microstructure and mechanical properties of high chromium cast iron/low carbon steel bimetal prepared by hot diffusion-compression bonding

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ABSTRACT

The objective of this study is to develop a hot diffusion-compression bonding process for cladding low carbon steel (LCS) to high chromium cast iron (HCCI) in solid-state. The influence of temperature (950–1150 °C) and strain rate (0.001–1 s^{-1}) on microstructure, hardness and bond strength of the HCCI/LCS bimetal were investigated. The interface microstructure reveals that the unbonded region can only be found for 950 °C due to lack of diffusion, while the intergrowth between the constituent metals occurred at and above 1100 °C. When bonding temperature increases to 1150 °C, a carbide-free zone was observed near the interface on the HCCI layer, and the thickness of the zone decreases with an increase of bonding strain rate. These evolutions indicate that the bond quality was improved by raising temperature and reducing strain rate due to the increase of element diffusion. The hot compression process of the bonding treatment not only changes the carbide orientation of the HCCI, but also increases the volume fraction of Cr–carbide. Based on the microstructural examinations and mechanical tests, the optimum bonding temperature and bonding strain rate are determined to be 1150 °C and 0.001 s^{-1}, respectively.

1. Introduction

High chromium cast irons (HCCIs) with high-volume fraction of hard Cr–carbides and relatively soft ferrous matrix have been widely used in industrial applications, such as mining, mineral processing and cement manufacturing [1–3]. However, inherent embrittlement and poor ductility as well as inferior weld ability are always keeping a lid on their further utilisation [4,5]. Recently, a novel bimetal consisting of high chromium cast iron (HCCI) and low carbon steel (LCS) or medium carbon steel (MCS) has been developed to overcome those shortcomings by absorbing the advantages (i.e. excellent ductility and superior weld ability) of the latter component, while maintaining excellent wear resistance of the former component [6–16]. According to previous research, the HCCI/LCS bimetal can be fabricated by composite casting [6–12], diffusion bonding [13,14] and cast cladding with hot rolling [15,16]. Oh et al. [6] and Kim et al. [7] reported an advanced duocasting method in which the HCCI (~27 wt% Cr) was cast first, and then inserted into the other mould to cast the LCS. The resulting duocast material is mechanically bonded into an appropriate geometrical shape. By exchanging the sequence of casting, Sallam et al. [8] produced bimetal beams using duocasting method via pouring the molten HCCI (19.2 wt% Cr) to clad the solid AISI4140 steel. The mechanical joint was achieved, and the flexural strengths of the bimetal beams can reach up to 790 MPa. Moreover, Cholewa et al. [9] presented a so-called mould cavity preparation method by casting the molten gray cast iron to bond with the solid high chromium steel (18 wt% Cr). The bonding interface was defect-free with a good diffusion connection. Xiong et al. [10,11] compared the liquid–solid casting method with and without electromagnetic

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induction field by casting the HCCI (14.21 wt% Cr) into a sand mould with the pre-set MCS. The results showed that there is a critical volume ratio of HCCI to MCS for realising metallurgical bonding, and the electromagnetic induction field is beneficial to improving bond quality by electromagnetic stirring which cleans the interface and profits the element diffusion. Based on lost foam casting, Xiao et al. [12] proposed a liquid–liquid composing process by pouring HCCI (~22 wt% Cr) and LCS into the same cavity successively to produce bimetallic linear. The combination region between the components was staggered like dog-tooth without mixture of alloys.

On the other hand, a solid-state diffusion bonding process, which joints HCCI (23.8 wt% Cr) and LCS at the temperature range of 1173–1273 K, was carried out by Sakurai et al. [13] in air. When this bimetal was tested using an impact wear tester, the wear ratio was equal to the raw material and it did not separate in the bonded area. Likewise, Eroglu and Kurt [14] investigated the effects of temperature and holding time on the diffusion bonding of HCCI (21.76 wt% Cr) to LCS in an argon atmosphere. It was concluded that a high temperature with a long holding time must be used for enhancing bond strength. Unlike bonding processes without plastic deformation as described above, Xie et al. [15,16] studied the possibilities of implementing hot rolling on HCCI (12.77 wt% Cr) with LCS cladding which was prepared by composite casting. A perfect metallurgical bonding was revealed by the continuous distributions of elements, and the compatible deformation of HCCI together with LCS cladding was observed.

In the light of previous research, a new idea of joining HCCI (23 wt% Cr) and LCS by integrating diffusion and hot forging processes was proposed in this study for the sake of simplifying the bonding process with an improvement of bond quality and mechanical properties. The influence of temperature and strain rate on microstructure and mechanical behaviour of the HCCI/LCS bimetal was evaluated via micro examinations and mechanical tests. The optimum bonding conditions were determined based on the significant investigations.

2. Experimental procedure

As-cast hypoeutectic HCCI and commercial hot-rolled LCS sheet were selected as the raw materials, which are responsible for excellent wear resistance and superior toughness, respectively. The chemical compositions of the HCCI and the LCS are given in Table 1. In order to simulate hot forging process, a Gleeble 3500 thermomechanical simulator was employed to carry out the bonding experiments by means of hot compression tests. It is recognised that the Gleeble is a fully integrated digital closed loop control thermal and mechanical testing system, which can be used to simulate various processes [17] like continuous casting, hot rolling, forging, extrusion and welding, etc. The cylindrical HCCI samples of 10 mm diameter and 6 mm thickness were wire cut from the same ingot in the same direction, while the LCS discs were prepared with 10 mm diameter and 3 mm thickness. Before joining, all the faying surfaces were polished to 1 μm diamond finish and cleaned by ethanol. Afterwards, HCCI sample was cladded by LCS discs on the 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 hot diffusion-compression bonding in a low vacuum. The test temperature range is 950–1150 °C with an interval of 50 °C and the equivalent strain rates are 0.001, 0.01, 0.1, 1 s^{-1}. Fig. 1 shows the schematic diagram of the assembly and the history of hot diffusion-compression bonding process. In each test, 70% of thickness reduction of the assembly was conducted.

Table 1
Chemical compositions of the HCCI and the LCS (wt%).

Material	C	Si	Mn	P	S	Cr	Ni	Mo	Cu
LCS	0.1	0.15	1.61	0.014	0.002	0.21	/	/	/
HCCI	2.4	1.2	0.9	0.02	0.03	23	0.3	0.5	0.1
LCS	0.1	0.15	1.61	0.014	0.002	0.21	/	/	/

To examine bond quality, all the bimetal specimens were machined across the interface (i.e. *X–Y* plane as shown in Fig. 1(b)), and then mounted and polished to 1 μm diamond finish followed by etching with a solution of 5% ferric chloride, 25% hydrochloric and 70% distilled water. The interfacial microstructure was detected using scanning electron microscope (SEM) equipped with energy dispersive spectroscope (EDS). In addition, the microstructure evolution of the HCCI layer in its transverse section (i.e. *Y–Z* plane as shown in Fig. 1(b)) was analysed by optical microscope (OM), and images were processed with the help of the software "ImagePro" to measure the volume fraction of Cr-carbide. The phase components of the HCCI were determined by X-ray diffractometer (XRD) using monochromated Cu Kα radiation.

Mechanical properties of the bimetal specimens were surveyed according to hardness and shear strength at room temperature. Microhardness profiles across the interface were obtained by a Vickers hardness tester using 25 g load for 10 s, and each hardness value is the average of 5 measurements. The shear test sample was machined with dimensions of 3 mm × 3 mm × 1 mm. A tailor-made testing apparatus was designed to conduct the shear tests on the Gleeble thermomechanical simulator at a tensile speed of 0.5 mm/min. Fig. 2 shows the schematic diagram of the tailor-made apparatus. The bond strength was calculated as Eq. (1), and each strength value is the average of 3 measurements. Moreover, the shear fracture surfaces were examined using SEM.

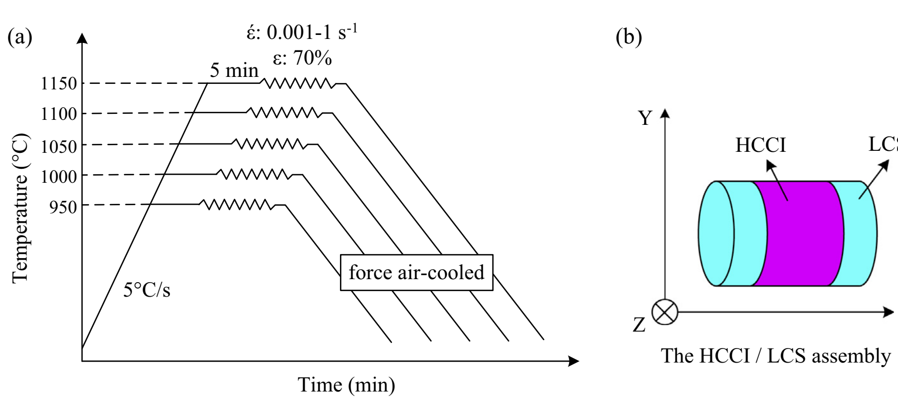

Fig. 1. History of hot diffusion–compression bonding process (a) and schematic diagram of sandwich structural assembly (b).