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# Effect of volume ratio of liquid to solid on the interfacial microstructure and mechanical properties of high chromium cast iron and medium carbon steel bimetal

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## ABSTRACT

The high chromium cast iron and medium carbon steel bimetal was fabricated by liquid–solid casting technology. The effect of volume ratios of liquid to solid (6:1, 10:1 and 12:1) on the interfacial microstructure and mechanical properties of bimetal was investigated. The interfacial microstructure was analyzed using scanning electron microscope (SEM) and transmission electron microscope (TEM). The shear strength and microhardness in as-cast condition were studied at room temperature. The results show that the volume ratios of liquid to solid affect significantly the interfacial microstructure. When liquid–solid volume ratio was 6:1, the unbonded region was detected in interface region because the imported heat energy cannot support effectively the diffusion of element, whereas, when liquid–solid volume ratios reach 10:1 and 12:1, a sound interfacial microstructure was achieved by the diffusion of C, Cr, Mo, Cu and Mn, and metallurgical bonding without unbonded region, void and hole, etc. was detected. With the increase of liquid–solid volume ratio, the elemental diffusion activity improves, resulting in the increase of width of interface transition region. At the same distance from interface, with the increase of liquid–solid volume ratio, the microhardness is degraded in HCCI, but increased in MCS. The shear strength is also improved with the increase of liquid–solid volume ratio.

## 1. Introduction

Bimetallic material has been extensively employed as an advanced functional material in many fields because of its unique physical and mechanical properties [1–3], which can be fabricated by bonding, similar and dissimilar materials [4]. According to the application, the physical and mechanical properties of constituent metals should be considered for choosing sound metals [5]. The wettability, reactivity, phase transformation, melting temperature, thermal conductivity and thermal expansion of constituent metals must be suitable to bond each other. In the current study, the bimetal will be used in wear-resistance and impact-resistance for mineral processing. In view of the above mentioned factors, the bimetal comprises high chromium cast iron (HCCI) and medium carbon steel (MCS). The HCCI was chosen for its high wear-resistance and hardness, whereas the MCS for high strength property to resist impacting. Currently, there are several fabrication methods of bimetal, such as casting [5], diffusion bonding [6,7], rolling [8], extrusion [9], cladding [10,11] and powder metallurgy technology [12]. The casting as a simple, economical and effective method for fabricating bimetal has been confirmed [5], as well as was used in the current study.

The interfacial microstructure between two metals plays a crucial role in determining mechanical properties of bimetal [13], and the interface is formed by the contact of liquid–solid state. The interfacial microstructure can be controlled by modifying the volume ratio of high temperature liquid metal (HCCI) to solid metal (MCS) [14,15], as well as changing the heat energy imported by high temperature liquid metal. The objectives of the present study are to investigate the effect of volume ratio of liquid to solid on interfacial microstructure and mechanical properties of HCCI and MCS bimetal fabricated by sand mould casting, and to achieve the significant information for controlling the interfacial microstructure and improving mechanical properties.

## 2. Experimental procedure

The high chromium cast iron and medium carbon steel were selected as raw materials to fabricate bimetal by liquid–solid casting technology. The chemical compositions of HCCI and MCS are given in Table 1. The MCS was cut into 20 mm × 20 mm × 50 mm, and each surface was processed by grinding from 320

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**Table 1**
Chemical compositions of high chromium cast iron and medium carbon steel (wt.%).

| Materials | C | Cr | Mo | Mn | Si | Cu | Ti | P | S | Fe |
|---|---|---|---|---|---|---|---|---|---|---|
| High chromium cast iron | 2.31 | 14.21 | 1.40 | 0.60 | 0.65 | 0.72 | 0.15 | 0.01 | 0.01 | Bal. |
| Medium carbon steel | 0.42 | – | – | 0.92 | 0.51 | – | – | 0.01 | 0.01 | Bal. |

to 1200 grit paper and polished with 1 μm alumina, subsequently ultrasonically cleaned in alcohol. The HCCI was weighed according to the volume ratios of liquid to solid metal (6:1, 10:1 and 12:1, respectively), and melt in induction furnace. When the temperature of furnace was raised to 1500 °C and held for 30 min, the molten metal was poured into a sand mould. Prior to pouring, the processed MCS was preheated about 1600 s to 600 °C, and placed into the sand mould. The bimetal was cooled to the room temperature in the sand mould.

The microstructure characterization specimens were cut transversely through the bond, prepared by grinding from 320 to 1200 grit paper and metallographically polished with 1 μm alumina, subsequently ultrasonically cleaned and etched using a reagent of 4% picric acid. The microstructures have been examined using a MeF-3 optical microscope and a JSMT-200 scanning electron microscope. The composition in the transition region was investigated using energy dispersive spectrometry (EDS).

Mechanical properties of as-cast specimens were surveyed according to the shear properties and hardness at room temperature. The bimetal sample was machined for preparing shear test sample with 8 mm × 8 mm × 10 mm. An Instron tensile testing machine was used for the shear tests at a speed of 0.5 mm/min. Microhardness measurements were carried out on a microhardness tester using a 100 g load for 15 s.

## 3. Results and discussion

### 3.1. Interfacial microstructure

The typical interfacial microstructures of as-cast samples are shown in Fig. 1. The low magnification of interfacial microstructure in bimetal containing volume ratio of 6:1 is presented in Fig. 1(a), and high magnification is indicated in Fig. 1(b). It is obvious from Fig. 1(a) that the long unbonded regions at the interface of that were found, and short unbonded region also was detected as shown in Fig. 1(b). It is illustrated that the interface cannot form desired metallurgical bonding, whereas, the interfacial microstructures with

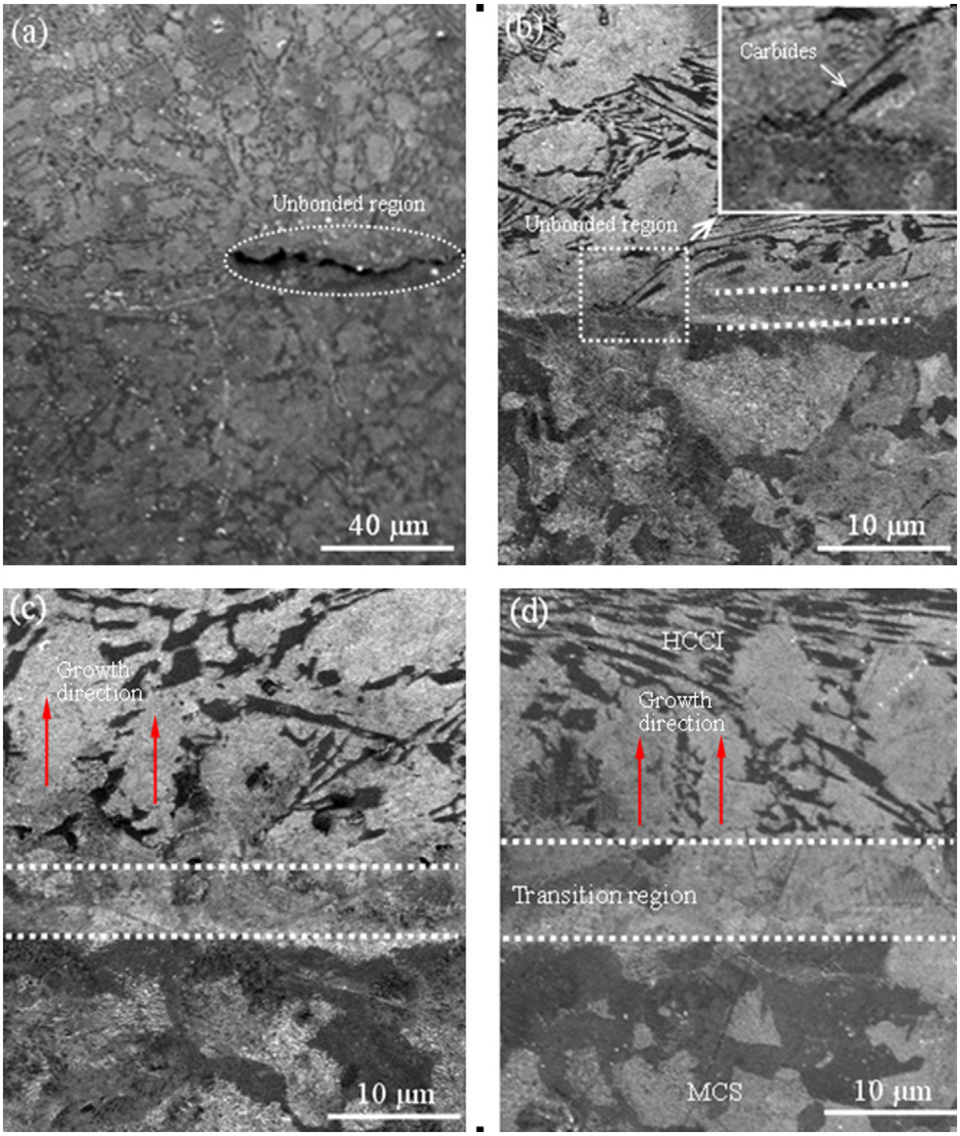

**Fig. 1.** Typical interfacial microstructures of as-cast samples: (a) low magnification of interfacial microstructure in bimetal containing volume ratio of 6:1, (b) high magnification of interfacial microstructure in bimetal containing volume ratio of 6:1, (c) 10:1 and (d) 12:1.

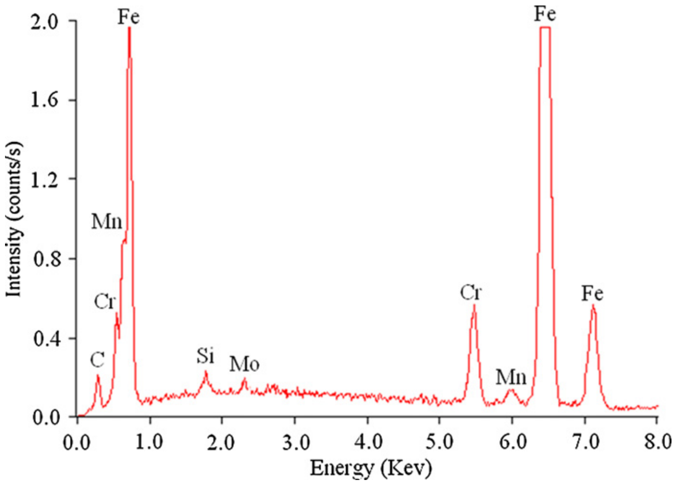

**Fig. 2.** EDS pattern in interface region in sample containing volume ratio of 10:1.

high quality are exhibited in Fig. 1(c) and (d), because of the absence of any defects such as unbonded region, void and hole along the interface between. It is declared that the good bonding of bimetal was fabricated according to the volume ratios of 10:1 and 12:1, respectively. Liu et al. [14] studied on the interface of bimetal fabricated by liquid–solid casting process. They found that the quality of interfacial bonding depends on imported heat energy of liquid metal. It is possible to obtain effective interface bonding in liquid–solid volume ratio of 8:1. Wu et al. [15] worked on the calculation of liquid–solid volume ratio to instruct the fabrication of bimetal by liquid–solid casting process. It is indicated that increase of liquid–solid volume ratio is favorable to form desirable interface bonding at the interface. In the present study, when volume ratio of liquid to solid is 6:1, the imported heat energy of liquid metal is not enough to melt the surface of solid metal or reach effective diffusion temperature, resulting in the appearance of bad interface bond, while liquid–solid volume ratios reach 10:1 and 12:1, the imported heat energy is sufficient for achieving good metallurgical interface bonding.

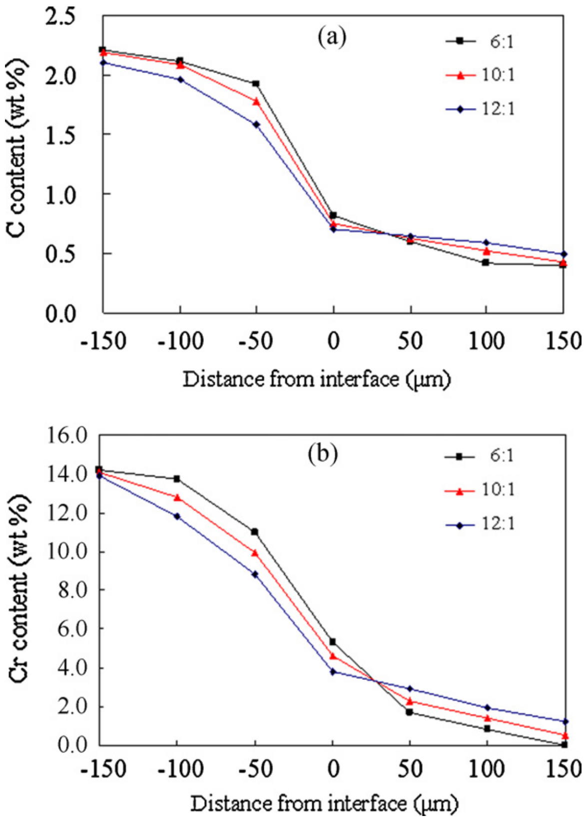

**Fig. 3.** Results of element diffusion distance: (a) C and (b) Cr.

The width of transition in interface region is obviously different from that shown in Fig. 1. With the increase of volume ratio of liquid to solid, the width of transition region obviously increases. This phenomenon may be explained by the diffusion of elements. Previous literatures [5] have reported that the diffusion of element takes place at interface according to chemical potential and forms transition region. Because the higher C, Cr, Mo, Cu content and lower Mn content are present in HCCI than MCS, the diffusion of elements must occur. In order to further analyze the element diffusion, the energy dispersive spectrum was executed at the interface in sample containing volume ratio of 10:1, and the EDS pattern is shown in Fig. 2. It is consistent with the above mentioned viewpoint of element diffusion. However, the EDS result cannot reveal the diffusion distance of elements, which is important to analyze the diffusion of elements due to the content difference. The variation of C and Cr elements from HCCI to MCS is displayed in Fig. 3. At the same distance from interface, the diffusion content of elements increases, with the increase of liquid–solid volume ratio. At the distance −50 μm from interface, the content of C and Cr in volume ratio of 12:1 was decreased by 21.6% and 24.7% comparing to volume ratio of 6:1, respectively The diffusion temperature and time have obvious effect on the interfacial microstructure of bimetal [16]. With the increase of liquid–solid volume ratio, the more heat energy can be imported to bimetal, leading to the improvement of diffusion temperature and time of elements. Therefore, the elemental diffusion activity is improved and the diffusion velocity of C, Cr, Mo, and Cu atoms gets rapider from HCCI to MCS, as well as Mn diffusion but in opposite direction. Furthermore, because plenty of C element has been diffused at interface from HCCI to MCS, the residual C elements can effectively dissolve in Fe matrix at HCCI side, and only little C elements can react with Fe and Cr elements to form (Fe, Cr)$_7$C$_3$ phase [17]. The transition region is obviously displayed in microstructure image of bimetal in Fig. 1, because of the appearance of diffusion and carbide phase difference. Therefore, based on the above analysis, with the increase of liquid–solid volume ratio, the width of transition region increases obviously, but the interfacial phases in transition region are not change obviously, and the representative transition region microstructures are identified as in Fig. 4. Moreover, due to the appearance of unbonded

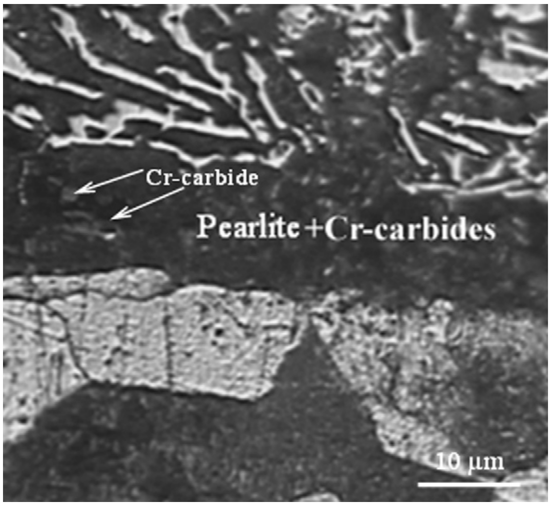

**Fig. 4.** Representative transition region microstructures.

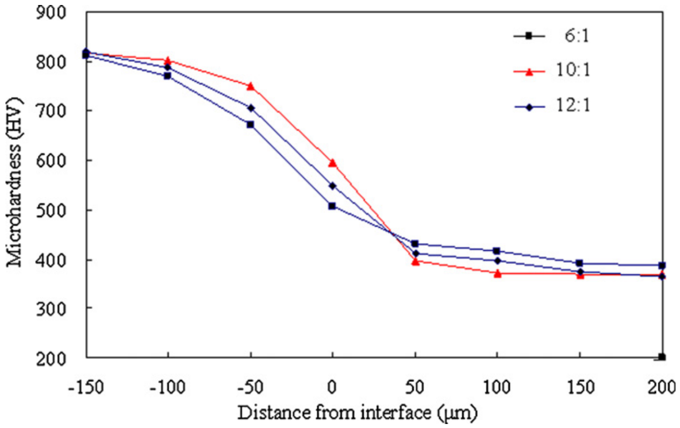

**Fig. 5.** Microhardness as a function of the distance from interface.

region in Fig. 1(b), the diffusion channels of elements were hindered. Therefore, the big carbide lamellas were found nearby the unbonded region as in Fig. 1(b).

The phenomena that grain is directional grow along heat transfer direction in HCCI nearby interface was detected obviously in Fig. 1(c) and (d) but not found in Fig. 1(b). With the increase of liquid–solid volume ratio, the directional growth of grain gets more obvious. This result is in agreement with the viewpoints obtained by Liu et al. [14].

### 3.2. Mechanical properties

The microhardness of bimetal was measured across the interface form HCCI to MCS. Each microhardness value is the average of five measurements. The microhardness as a function of the distance from interface is plotted in Fig. 5. From HCCI to MCS, the microhardness gets reduced as shown in Fig. 5. The microhardness in bimetal containing volume ratio of 12:1 was decreased by 13.8% at the distance of −50 μm from interface but increased by 16.2% at the distance of 50 μm comparing to volume ratio of 6:1. The high C content will contribute to the improvement of microhardness. Therefore, according to the analysis of C element diffusion distance in Fig. 3, the C content gets debasing from HCCI to MCS, resulting in the decrease of microhardness. This result was also obtained in the previous literature by Xie et al. [17]. Under different liquid–solid volume ratios, the microhardness is proportion to the C content at the same distance from interface

The interface shear strength as a function of the liquid–solid volume ratio is given in Fig. 6. It is obvious from Fig. 6 that the shear strength improves with the increase of liquid–solid volume ratio. When liquid–solid volume ratio is 6:1, the interface shear strength is very low (133.2 MPa), whereas, when liquid–solid volume ratios reach 10:1 and 12:1, the shear strength increases abruptly to 236.5 and 248.2 MPa, respectively. The lowest interface shear strength of bimetal containing liquid–solid volume ratio of 6:1, is related mainly to two factors: (1) The unbonded regions were detected at interface from Fig. 1(a) and (b), which will yield very low interface mechanical properties. (2) The brittle carbide lamella was present in interface regions from Fig. 1(b). Previous literature [18] has illuminated that the appearance of brittle carbide lamella will decrease the shear strength of bimetal sample due to change in the shear behavior of the interface. When liquid–solid volume ratio is 6:1, the time and temperature of C element diffusion are the lowest than others, resulting in the C element cannot diffuse adequately from HCCI to MCS. Therefore, the plentiful C element still was reserved in HCCI and brittle carbides were formed. This result is supported by the C element diffusion analysis in Fig. 3. Similarly, because the C element diffusion temperature and time are lower in bimetal containing liquid–solid volume ratio of 10:1 than 12:1, the residual C element is more and formed brittle carbide is also much. Therefore, the interface shear strength improves, with the increase of liquid–solid volume ratio.

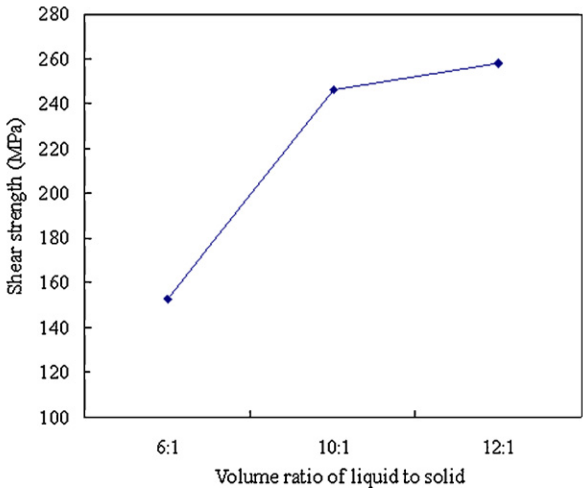

**Fig. 6.** Interface shear strength as a function of the liquid–solid volume ratio.

## 4. Conclusions

The high chromium cast iron and medium carbon steel bimetal were fabricated by liquid–solid casting technology. The effect of volume ratio of liquid to solid on the interfacial microstructure and mechanical properties was investigated. The results obtained are summarized as follows:

1. The volume ratio of liquid to solid affects significantly the interfacial microstructure. When liquid–solid volume ratio is 6:1, because imported heat energy cannot support effectively the diffusion of element, the unbonded region was detected in interface region, whereas, when liquid–solid volume ratios reach 10:1 and 12:1, a sound interfacial microstructure was achieved by the diffusion of elements, and metallurgical bonding without unbonded region, void and hole, etc. was detected.
2. With the increase of liquid–solid volume ratio, the elemental diffusion activity improves, resulting in the increase of width of interface transition region.
3. The microhardness is proportional to the C content, since the high C content will contribute to the improvement of microhardness. Therefore, at the same distance from interface, with the increase of liquid–solid volume ratio, the microhardness degrades in HCCI, but increases in MCS.
4. The shear strength improves with the increase of liquid–solid volume ratio. The shear strength of bimetal with liquid–solid volume ratio of 6:1 is the lowest because of the appearance of unbonded region and brittle carbides, while the other bimetals have excellent shear property.

## Acknowledgements

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