Effect of liquid-solid volume ratios on the interfacial microstructure and mechanical properties of high chromium cast iron and low carbon steel bimetal

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Abstract

Bimetal casting made of high chromium cast iron (HCCI) and low carbon steel (LCS) was produced by liquid–solid casting technology. The influence of different liquid–solid volume ratios on microstructure and microhardness of the interface was studied. The interface microstructure and the elemental distribution from one side to the other side of the bimetal were analyzed using Energy Dispersive x-ray Spectroscopy (EDX). Wear behavior of the successfully produced bimetal was also investigated in order to emphasize the difference in the mechanical properties between the two bonded alloys. The results showed that a good metallurgical bonding area free of holes could be obtained with increasing the liquid to solid volume ratio to 10:1 and 12:1. By increasing this ratio, diffusion of the elements was accelerated resulting in expanded carbide-free zone and improved bonding of the bimetal. Accordingly, the microhardness decreased at the HCCI side and increased at the LCS part due to the elemental diffusion from the former to the latter through the interface. Sliding wear test on both sides of the bimetal showed that the coefficient of friction was ∼0.79 for HCCI and 0.69 in case of LCS. The transition from the high wear resistant HCCI part to LCS was significantly observed on the worn surface of the interfacial area of the test sample. The wear mechanism involved in the two sides was delimitation and the size of the produced laminates was smaller in case of LCS than in HCCI.

1. Introduction

High chromium cast iron (HCCI) is considered to be one of the most outstanding abrasive resistance materials. It has a wide range of applications, such as mill liners in cement industry and mineral mills as well as mining slurry suction pumps [1–5]. HCCI is the most popular material compared with the others because of its high wear and corrosion resistance in addition to its low production cost. However, the brittleness and low crack resistance as well as poor machinability of HCCI make it limited in these applications [6, 7]. Toughness is an important property of liners and crusher hammer made from HCCI [7, 8]. To solve this problem, bimetal casting technology made from HCCI of excellent wear resistance and low carbon steel (LCS) of sufficient toughness based on liquid–solid technique has been proposed. According to previous work, bimetal can be fabricated by a variety of techniques such as castings [9–15], hot and/or cold rolling [16–18], diffusion bonding [19, 20], extrusion cladding [21], welding [22] and spray deposition [23], etc. The technology of bimetal castings is considered the more economical and effective method than other bimetal fabricated processing techniques [24–26]. Besides its economic advantages it can be compete the other technologies of surfacing by welding and thermally spraying because it does not generate opportunities for the development of cracks in the heat affected zone. These cracks arise as a result of making the layer by using the welding method.

Bimetal castings are based on two fundamental methods containing liquid-liquid and liquid-solid casting techniques. According to the former method, two independent gating systems are made that guarantee two-stages filling of the sand mold cavity. An example for this technology is manufacturing of the hammer [27] or ball...
Table 1. Chemical composition of high chromium cast iron and low carbon steel (wt%).

| Materials | C   | Si  | Mn  | Cr  | Mo | Ni | Cu | S   | P   |
|-----------|-----|-----|-----|-----|----|----|----|-----|-----|
| HCCI      | 2.50| 0.823| 0.80| 16.12| 0.86| 0.62| 1.28| 0.0084| 0.025|
| LCS       | 0.14| 0.182| 1.24| 0.10| 0.022| 0.098| 0.21| 0.0080| 0.019|

mills [7] which are cast in material configurations of the chromium cast iron working layer with a low-carbon cast steel base. Whereas in liquid-solid bimetal casting [9, 13, 14, 24], the element that enriches the surface of the casting is inserted in the mold before the molten metal is poured.

Based on liquid-solid bimetal casting technology, Xiong et al. [13, 14] have demonstrated that the quality of the interface bonding can be determined by the interfacial microstructure which is affected by the volume ratio of high temperature liquid metal to solid metal, i.e. changing the heat energy imported by high temperature liquid metal. They reported also that there is a critical volume ratio of HCCI (liquid metal) to medium carbon steel (solid metal) for obtaining metallurgical bonding which could be improved by using the electromagnetic induction field. T Wrobel [24] reported that to achieve permanent joint between the plate of alloy steel sort X2CrNi 18-9 and unalloyed cast steel, two conditions should be controlled. The conditions are using suitable high pouring temperature of the liquid cast steel and also suitable difference carbon concentration between both joint materials.

In this work, liquid-solid bimetal casting technique was used which consisted of molten metal (HCCI) and solid metal (LCS). The alloying elements in (HCCI) are diffused to (LCS), developing interface layer between the LCS and HCCI. The microstructure of the interface layer can be controlled by modifying the volume ratio of high temperature liquid metal (HCCI) to solid metal (LCS). The objectives of the present work are to investigate the effect of volume ratio of liquid to solid on interfacial microstructure and bonding quality of HCCI and LCS bimetal. The interfacial microstructure, bonding quality and the thickness of the interface layer are the key in the bimetal casting process.

2. Experimental work

High chromium cast iron (HCCI) and low carbon steel (LCS) are characterized by excellent wear resistance and superior toughness, respectively. Therefore, they were both selected in the current investigation to form a bimetal. The chemical compositions of the two selected materials are given in Table 1. Cylindrical LCS desks of constant diameters of 35 mm and thicknesses of 10 mm were grinded with 200 mesh emery papers and inserted into sand moulds without preheating. HCCI was melted in a 100 kg capacity medium frequency induction furnace. Different amounts of molten HCCI were poured into the three rod cylindrical cavities over the solid LCS cylindrical desks with volume ratios of liquid to solid metal (8:1, 10:1 and 12:1), figure 1. After solidification and cooling, the rods were cut transversely through the bond and the interface microstructure was examined using optical and scanning electron microscope after polishing and etching with 2% Nital solution. The composition of the transition region was investigated using energy dispersive spectrometry (EDS). Microhardness measurements were carried out via a microhardness tester using a 100 g load for 15 s.

Since, wear resistance of the two sides is an important property to determine for any processed bimetal as described by Arabi et al. [28], wear test was performed in the current study using a pin-on-disk (T-01M) tribometer. A steel disc (65HRC) was used as counterpart for all the tests and the sample was the pin. A normal load of 100 N was applied and the test speed was 265 rpm. During the test, both of the friction force and the vertical displacement from the sample were continuously recorded and drawn versus the test time. The test was done for each side of the bimetal separately under the same test conditions. A schematic of the test is shown in figure 2.

3. Results and discussions

3.1. Microstructure

Figure 3 presents the optical micrographs of the typical interfacial microstructures with different volume ratios of liquid to solid metal. The left side for each micrograph indicates the HCCI layer and the right side for LCS layer. The microstructure of HCCI layer is characterized by primary austenite dendrites and eutectic mixture of M7C3 carbides and austenite, while the LCS layer consists of banded structure of ferritic-pearlitic matrix. In terms of the interface, figure 4 shows some voids and discontinuity on the bond line only in case of 8:1 liquid to solid volume ratio. On the other hand, the bonded interface is in good condition without any pore by increasing liquid to solid volume ratio (10:1 and 12:1). Since the diffusion is a heat dependent process, the voids and
discontinuity at 8:1 liquid - solid volume ratio can be related to the insufficient heat energy which does not encourage the diffusion of elements.

It can be seen from figures 3(a)–(c) that, the volume fraction of pearlite at the right side near the interface increases by increasing the volume ratios of liquid to solid metal and decreases far from the interface. With increasing the volume ratio of liquid to solid, the imported heat energy to bimetal will be increased, leading to excessive fusion of the solid LCS and advance the diffusion temperature and time of elements. Diffusion processes occur at the boundary between the steel substrate and the molten HCCI alloy \[5, 6, 17\]. Therefore, atoms of C, Cr, Mo, Ni and Cu elements in the HCCI diffuse into the LCS which is in the austenitic condition. Due to the carbon segregation towards the interface on the right side, the transition of austenite to pearlite occurs during cooling. Diffusion of C, Fe and Cr across the interface region is confirmed by EDS map analysis, figure 5. Figure 5(d) revealed that carbon is depleted from the carbide-free zone on the HCCI side and segregated near the interface on the upper side of LCS resulting in transition of austenite to pearlite during cooling.

Figure 3 reveals the carbide-free zone on the left side near the interface of HCCI at all volume ratios of liquid to solid metal. Closer investigation with SEM shows clearly this carbide-free zone, figure 4. The thickness of this zone increases with increasing volume ratio of liquid to solid metal. This is related to the diffusion of C from the higher concentration in HCCI towards LCS side that leads to decrease the melting temperature of the LCS; as a consequence, the molten HCCI partially dissolves the steel substrate. This in its turn causes transfer of Fe from the LCS to the boundary layer of the melt, figure 5(c). The increase in Fe concentration in the melt results in
Figure 3. Typical interfacial microstructure of bimetal containing different volume ratios of liquid: solid (a) 8:1, (b) 10:1 and (c) 12:1.

Figure 4. SEM interfacial microstructure of bimetal containing different volume ratios of liquid: solid (a) 8:1, (b) 10:1 and (c) 12:1.
formation of an austenite layer upon solidification which is increased in thickness with increasing the liquid to solid volume ratio. Another way to confirm this mechanism is EDS point analysis which was used to show the elemental distribution in the interface zone between high chromium cast iron and low carbon steel, figure 6. It is apparent from figures 5(b) and 6 that the carbide-free zone near the interface is still rich in Cr and consequently the highly alloy content of the austenite suppressed its martensitic transformation to below room temperature.

Diffusion phenomenon is also seen in the EDX-linear microanalysis of Cr and Fe carried out in the interface region between both materials, figure 7. Due to the carbon and chromium depletion, a layer of carbide-free zone is formed and this process will continue until diffusion of these elements from the HCCI into the LCS is stopped. The results of the linear microanalysis in the joint area are summarized in figure 8 which shows the influence of liquid to solid volume ratio on the diffusion of Cr across the interface. As expected, Cr diffused from the HCCI to the LCS more actively at the highest liquid to solid volume ratio (12:1). This is attributed to the highest heat energy imported by high temperature liquid metal (HCCI) which is also consistent with the findings of Xiong et al [13]. Figures 5–8 confirmed that the depletion of Cr near the interface in the HCCI layer resulted in the formation of the carbide-free zone, which is expected to improve the bonding of the bimetal. Similar carbide-free zone in the bimetal casting materials was also obtained in the previous literatures by Gao et al [5], Oh et al [10] and Kim et al [11].

### 3.2. Hardness

The microhardness as a function of the distance from interface is plotted in figure 9. The microhardness of bimetal near the interface was measured from the HCCI (left side) to the LCS (right side). As shown in figure 9, the microhardness is gradually decreased from the HCCI to the LCS, and it lies in between the HCCI to the LCS at the bonding interface. It is obvious from figure 9 that at same distance from interface, the lower microhardness in HCCI was obtained at the highest volume ratio of liquid to solid metal (12:1) while the higher microhardness was recorded for LCS. The main important factor affecting the microhardness is the C content, where high C content will contribute to the improvement of microhardness. Therefore, according to the map analysis of C element in figure 5(d), the C content gets debasing from the carbide-free zone near the interface on
the HCCI layer to LCS, resulting in decreasing of microhardness near the interface on HCCI and increased at distance of 50 μm on LCS side. As previously mentioned in this work, the diffusion process is accelerated by increasing the imported heat energy (increasing liquid to solid volume ratio). Therefore, at the same distance from interface, with the increase of liquid–solid volume ratio, the microhardness degrades in HCCI but increases in LCS. This result was also obtained in previous literature by Xie et al [17].

3.3. Wear
3.3.1. Dry sliding wear resistance
Wear process is a complex process in which several parameters such as the environment (wet or dry), the mode of loading, the speed and the materials properties are interfering together. In the current wear tests, the
experimental conditions and the environment were almost the same and a counter disc made of steel (65 HRC) was used in all the experiments. The only variable here is the material being tested. Since one side of the bimetal is low carbon steel (∼250 HV) and the other one is high Cr cast iron (∼600 HV), so significant differences in the wear resistance is expected. This is because of the strong relationship reported in several works between hardness and wear resistance for iron alloys [28–30]. The wear rate of the two samples (at the highest volume ratio of liquid to solid metal) explained in (μm/Km/N) as calculated by the tribometer software was 8.7 and 1.9 for the LCS and HCCI respectively. Accordingly, the weight loss of the steel is much higher than that of the WCI. This emphasizes the benefit of casting the LCS as a bimetal with HCCI which has excellent wear resistance. During the test, the material removed from the sample due to friction was continuously plotted as (vertical displacement) against the test time. Figure 10 compares the trend lines for displacement vrs. time of the LCS and HCCI samples. Taking into consideration that the running in stage of the test was not plotted in these curves.

3.3.2. Friction behavior
The force generated during the test as a result of friction was calculated automatically and plotted against the test time as shown in figure 11. The friction force (F_{fr}) in case of LCS was fluctuating between ∼40 and 80 N. On the other hand, HCCI showed higher force of friction which was varying between ∼60 to 100 N. This implies that, the coefficient of friction (μ_f) will be different for the two materials. The coefficient of friction was reported to be

![Figure 8](image-url)  
*Figure 8. Variation of Cr content as a function of distance from interface at different volume ratios of liquid to solid metal.*

![Figure 9](image-url)  
*Figure 9. Microhardness as a function of the distance from interface.*
equal to \((F_f/F_N)\) where \(F_N\) is the applied force \([31]\). Consequently, \((\mu_f)\) is about 0.65 for LCS and 0.79 for HCCI. Here the running of values of \(F_f\) were not considered since the sample (pin) and the steel disc takes time in the self-mating stage to reach the required intimate contact with clear interfacial area. The value of \((\mu_f)\) in case of HCCI was higher than that of LCS which is mainly attributed to the higher hardness of the HCCI (\(\sim 600\) HV) which is expected to decrease the contact area with the counter disc and accordingly less energy is required to shear the junctions during sliding as explained by Arabi et al \([28]\).

### 3.3.3. Wear mechanisms

In order to understand the wear mechanisms of the current HCCI/LCS bimetal, Stereoscope macrographs and SEM micrographs of the samples worn surface were investigated. The wear debris was also analyzed using back scattered electron (BSE) image. Figures 12 and 13 present the macrographs of the counter disc and the test samples respectively. Comparing the wear tracks of the two samples, narrow grooves were observed in case of LCS while HCCI sample showed wider ones. The track morphology at the interface, figure 13(b), was a mixture of the two types.

Figure 14 shows the SEM micrographs of the worn surface morphology and the corresponding 3D images of the two samples at higher magnification. The light area here presents the removed material from the sample. The micrographs of the wear debris and their BSE analysis of the LCS and HCCI samples are shown in figures 15 and 16 respectively.

These figures show that the metallic debris removed from HCCI is larger compared to that of LCS sample. This reflects the smooth surface observed in LCS shown in figure 14(a) compared to the worn surface of the HCCI, figure 14(b). The shape of the debris suggests that the wear mechanism is delamination. The size of the produced laminates was smaller in case of LCS than in HCCI due to its higher ductility compared to HCCI.
Figure 12. Macrographs of the disc after ~35,000 cycles on (a) LCS and (b) HCCI.

Figure 13. Macrographs of the wear track of the samples at the side of LCS, interface and HCCI respectively from the left side.

Figure 14. SEM micrographs and their 3D images of the worn surface after ~35,000 cycles of (a), (c) LCS and (b), (d) HCCI.
Figure 15. Electron back scattered image of the wear debris taken from the LCS sample and its 3D morphology and elemental analysis.

Figure 16. Electron back scattered image of the wear debris taken from the HCCI sample and its 3D morphology and elemental analysis.
4. Conclusions

Bimetal consists of HCCI and LCS was prepared by liquid - solid casting technique. The effect of different volume ratios of liquid to solid on the interfacial microstructures and hardness was investigated. The following conclusions could be summarized as follows:

1. The bonding between the two metals of HCCI and LCS at interfacial zone is highly affected by the volume ratio of liquid to solid. Where some micro voids and holes on the interface are detected only in case of 8:1 liquid to solid volume ratio while sound metallurgical bond is achieved in both cases of the higher volume ratios 10:1 and 12:1.

2. As the liquid to solid volume ratio increased the thickness of carbide-free zone near the interface on the HCCI layer is increased and the percent of pearlite near the interface on the LCS layer is also increased. This is attributed to enhance the diffusion activity of elements especially C and Cr which may be improved the bonding quality between the two metals by increasing liquid to solid volume ratio.

3. The microhardness is affected by diffusion process, where the diffusion of C and Cr from the HCCI to LCS will enhance the microhardness in the LCS side while decrease at the HCCI side at the same distance from the interface.

4. The wear resistance is enhanced with the increase in hardness, where the wear rate was 8.7 and 1.9 for the LCS and HCCI respectively.

5. The shape of the wear debris suggested that the wear mechanism involved was delimitation. The size of the produced laminates was smaller in case of LCS than in HCCI due to its higher ductility compared to HCCI.

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