Wear Behavior of a Modified Low Alloy as Cast Hardening White Iron

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This work analyses the wear behavior of a modified white cast iron (MWCI) with moderate chemical composition using 1.77Ni, 1.42Cr, 0.26Mo and 1.59Cu in comparison to a conventional white cast iron (CWCI). The wear test has been carried out for alloys in the as cast condition using a pin-on-disc test in the loads of 80, 100, 120 and 140 N. Microstructural characterization, hardness, frictional coefficient and the total weight loss have been assessed in each alloy. For a low load of 80 N, the total weight loss of MWCI (0.5 mg) is much less than that of CWCI (1.3 mg). The total weight loss has been increased to 2.8 mg for MWCI, while it is still less than that of CWCI (~3.7 mg) with increasing the load to 140 N. Investigation shows that the wear resistance of the specimens is strongly depended on the hardness derived from their microstructures. More plastic deformation and detachment of the tribolayers are observed on the surfaces with a lower hardness. The wear rate of specimens has been increased with increasing the load especially in the specimens with lower hardness. It has been found that the specimen with a higher hardness shows a lower frictional coefficient under the range of applied loading.

KEY WORDS: white cast iron; as cast hardening; microstructure; hardness; wear resistance.

1. Introduction

White cast iron has long been considered for the candidate material of wear resistance components subjected to the mining and mineral processing as well as metallurgical and cement industries, due to its excellent wear resistance imparted by the high volume fraction of hard carbides presented in the microstructure.^{1–5)} Conventional white cast iron (CWCI) as a wear resistance material has approximately more than 100 years of application history in the wear resistance industry. The oldest type of white cast iron with a typical microstructure consists of eutectic iron carbide and pearlite has been rationalized by in a relatively low level of hardness (350–500 BHN). The low hardness can be increased by formation of more carbide and/or refinement of matrix structure with fine lamellar pearlitic and/or martensitic structure. Among all of the properties which wear resistance has been reported to be dependent upon, not only type, morphology, amount and distribution pattern of the carbides precipitated from the melt, but the type of matrix structure is also another important research subject. Several authors^{6–10)} have concluded that the modified microstructure with high nickel and/or chromium content followed by subsequent hardening heat treatment played a significant improvement in wear resistance of white cast iron. However, the high nickel and/or chromium contents of the white iron inevitably makes the

price of casting parts relatively high, especially in conjunction with high temperature hardening heat treatment involved in the high chromium irons. Hence, development of a low cost low alloy white cast iron is always practical importance. A systematic alloy design criterion has been practiced to develop a low alloy as cast hardening white iron. Although, wear resistance is not a distinct property of material like hardness and tensile strength, but it is generally concluded that the pearlitic matrix is not preferred for white cast iron because of low wear resistance and toughness properties. There is not a clear comparison between the wear behaviors of conventional pearlitic white cast iron with that of martensitic low alloy iron.^{11,12)} This paper has been aimed at the study of a possible strategy for improving the wear resistance of a conventional white cast iron under sliding condition involved the refinement of matrix from pearlitic to martensitic structure.

2. Materials and Experimental Procedure

The white irons used in this study were made in a laboratory 100 kg capacity induction furnace using high purity raw materials. The white irons were melted and poured at $1450 \pm 10^\circ\text{C}$ into Y-block test standard specimen and examined in the as cast condition. The chemical compositions of white cast irons used in this study are shown in **Table 1**.

The samples for metallography were prepared and etched with 10% ammonium persulfate solution (10 g $(\text{NH}_4)_2\text{S}_2\text{O}_8$, 100 ml water) to reveal the microstructure. This reagent pro-

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Table 1. Chemical composition of investigated white cast irons (in weight percent).

Sample Mark	%C	%Si	%Mn	%P	%S	%Cr	%Ni	%Mo	%Cu
CWCI	3.26	0.61	0.52	0.011	0.023	0.91	0.056	0.053	0.054
MWCI	3.32	0.73	0.77	0.022	0.019	1.42	1.77	0.26	1.59

Fig. 1. The schematic drawing of wear test apparatus used in the present study.

vided a high contrasting resolution between the multiphases when the structure was observed under the light microscope.

Hardness was measured on the Rockwell C scale for the specimens. Friction and wear behavior of the white cast irons were investigated under ambient conditions with a Pin-on-disc tribometer using a laboratory made wear testing machine as shown schematically in **Fig. 1**.

The specimens in the form of pin were rubbing against on a 100Cr6 steel disc with a hardness of 62HRC under unlubricated condition. The steel disc was 50 mm in diameter and 10 mm in thickness. The wear experiments were carried out using various applied normal loads of 80, 100, 120 and 140 N at sliding speed of 0.2 m/s (120 rpm) for a sliding distance of 1000 m. The weight loss of specimens after wear test were measured by weighing the specimens. Before the wear test, the specimens were polished with 0.25 μm grit emery paper and cleaned ultrasonically. The morphology, composition and structure of worn surfaces of the specimens were analyzed with MV2300 Cam-Scan type scanning electron microscope (SEM) coupled with an energy dispersive X-ray analyzer (EDS). Phase constitution was undertaken by XRD in a SIEMENS 5000 diffractometer using Cu $K\alpha$ radiation in a 2θ angle ranging of 30–100°. The tribological behavior of the studied specimens was discussed in terms of friction coefficient, weight loss and wear behavior.

3. Results and Discussion

3.1. Microstructural Characterization and Hardness

The as cast microstructure of CWCI and MWCI which related with cast hardness compared with the optical micrographs is shown in **Fig. 2**. The general microstructural feature of CWCI is shown in **Fig. 2(a)** which is characterized by a mixture of ledeburite and large islands of pearlite in the as cast condition. The higher magnification light micrograph in **Fig. 2(b)** indicates that the coarse pearlite is largely associated with austenite phase transformation products formed on continuous cooling after solidification in the CWCI. The

Fig. 2. Optical microscopic photographs of: (a) and (b) for the CWCI; (c) and (d) for the MWCI.

as cast microstructure of MWCI is dominantly martensite associated with some retained austenite and M_3C eutectic carbide (**Figs. 2(c)** and **2(d)**).

The plate martensite is nicely contrasted by blue color, while the retained austenite is stained by white color in the same contrasting sensitivity to M_3C eutectic carbide. Although, the pearlite is appeared with sufficient contrast (dark area) in these micrographs, a clear and exact interfacial boundary is also obtained between pearlite with martensite/retained austenite microconstituent (**Fig. 2(d)**). The MWCI has been alloyed with a moderate amounts of Ni, Cr, Mo and Cu in such a way that on continuous cooling to room temperature from casting condition, a substantial phase transformation of austenite to martensite is accomplished (**Figs. 2(c)**, **2(d)**).

A mixture of martensite and retained austenite pools is the primary differences between the microstructure of modified and conventional irons. This demonstrates that the alloying elements render a significant hardenability effect in the MWCI, so that an increasing in hardness has been observed from 42HRC for the CWCI to 60HRC for the MWCI. This increasing in hardness can be due to the presence of much finer pearlite and martensite/retained austenite microphases developed on continuous casting to room temperature in the MWCI (**Figs. 2(b)** and **2(d)**).

3.2. Wear Results

The results of weight loss for the white cast iron specimens tested with various normal loads are shown in **Fig. 3**. A meaningful trend has been found between the total weight loss and applied load with the microstructure of irons. **Figure 4** shows the worn surface evolution associated with different loads for the two irons. At 80 N loading for CWCI (**Figs. 4(a)** and **4(b)**), the worn surface is mainly smooth, but with increasing the load up to 140 N, the surface of iron is characterized in some area by rough detachment layers and grooves (**Fig. 4(b)**). The same feature can be seen on the worn surface of MWCI specimens with increasing the normal load (**Figs. 4(c)** and **4(d)**).

The higher wear resistance of MWCI specimen in comparison to CWCI specimen can be attributed to its higher

Fig. 3. The total weight loss as a function of different applied load for the CWCI and MWCI specimens (sliding distance: 1 000 m, temperature: 27°C).

Fig. 4. SEM micrographs of the worn surfaces after 1 000 m sliding distance for the CWCI at: a) 80 N, b) 140 N; and for the MWCI at: c) 80 N, d) 140 N.

hardness due to the refinement of structure from pearlite to martensite. With comparing the worn surface of specimens under the same loads, a deeper groove is formed at a higher normal load because of more plastic deformation generated under the wear test. On the other hand, it is evident from the electron micrographs shown in Fig. 4 that the CWCI specimens reveal much deeper grooves and more plastic deformation under higher normal loads in comparison to the MWCI specimens.

This behavior can be attributed to the less hardness of CWCI specimens. In Fig. 4(b), the detachment of tribolayer is obvious. This detachment is resulted from the concentration of plastic strain beneath the tribolayer which affecting the nucleation and growth of crack at the interface between tribolayer with the bulk material, and so the propagation of crack through tribolayer has been increased. Because of the less hardness of CWCI specimen, more plastic deformation takes place on the aforementioned specimen specially under higher normal loads, and so the wear rate of these specimens has been accelerated by the detachment of tribolayer compared to the MWCI specimens. Furthermore, it is obvious

Fig. 5. EDS surface analysis for the MWCI at: a) 80 N and b) 140 N.

that at the same magnification, microploughing detached with differences in size and morphology can be seen in these photographs. These observations illustrate the effective role of the hardness on the worn surfaces.

3.3. Wear Behavior

In these wear results, it is assumed that the microstructure plays an important role in the weight loss. The carbon content of both cast irons are chosen to be identical and consequently the volume fraction of hard M_3C eutectic carbide are almost the same in the microstructures (Table 1, Fig. 2). The only differences in the microstructures are the austenite decomposition products developed on continuous cooling after solidification. Therefore, at the normal load of 80 to 140 N for the two white irons, the presence of martensite associated with more hardness developed in the MWCI seems to be more resistance to shear stress and plastic deformation than that of coarse pearlite formed in the CWCI (Fig. 3). This condition has been lead to lesser weight loss and more frictional coefficient in the MWCI in comparison to CWCI.

Figure 5 shows an example of EDS analysis of the worn surface in the MWCI specimen. The presence of oxygen in the EDS analysis has been related to the formation of oxides in these wear conditions. The temperature at the sliding interface depends both on the ambient temperature and frictional power dissipation, the latter has been affected by the sliding velocity and loading [10, 11]. An increase in normal load can accelerate the oxidation due to the higher temperature developed at the interfaces. Therefore, the wear rate of specimens under higher normal loads has been accelerated by the hard oxide layer.

The variation of average steady-state coefficient of friction as a function of normal loading is shown in Fig. 6 for

Fig. 6. Frictional coefficient as a function of normal loading for the CWCI and MWCI.

the two white cast irons. It is evident that an increase in normal loading can lead to more plastic deformation of the surface as well as increasing the interaction between the pin and disc, and so the real contact area between the pin and disc has been increased which resulted in the higher frictional coefficient.

The lower frictional coefficient of CWCI specimen in comparison to the MWCI specimen is attributed to its higher hardness. With increasing the hardness of specimen, less plastic deformation takes place and the real contact area between pin and disc is decreased. For CWCI, as shown in Fig. 6, the frictional coefficient has been increased from 0.47 to 0.95 with increasing the load from 80 to 140 N. However, for the MWCI, the increasing in frictional coefficient is much more than that of CWCI, from 0.66 to 1.3 respectively.

4. Conclusions

(1) The MWCI has been microstructure developed with the moderate variation in chemical composition of CWCI using 1.42Cr, 1.77Ni, 0.26Mo and 1.59Cu. The multiphase microconstituents are identified with sufficient contrast by color metallography using 10% ammonium persulfate reagent. The overall microstructural feature is characterized

by a mixture of M_3C eutectic carbide, fine pearlite and martensite/retained austenite microphases in the MWCI.

(2) The tribological behavior of CWCI has been reduced with the modification in microstructure from pearlite to martensite developed in the MWCI for all of the investigated normal loading. The high hardness of MWCI (60HRC) is associated with more resistance of the contact surface against on plastic deformation, microcrack and detachment of tribolayers.

(3) The wear resistance has been correlated directly with the microstructure, hardness and normal loading in the white cast irons. The total weight loss is decreased for the MWCI specimens in comparison to CWCI. At 80 to 140 N normal loading for the MWCI, the total weight loss is from 0.5 to 2.8 mg while the associated weight loss has been increased from 1.3 to 3.7 mg for the CWCI, respectively.

(4) The increasing in frictional coefficient from 0.95 to 1.3 μ at the high normal load of 140 N in the CWCI and MWCI has been associated with the increasing in real contact area, and for the MWCI a more increasing in frictional coefficient is attributed with increasing the hardness of contact surface. At the low normal load of 80 N, the frictional coefficient for the CWCI and MWCI has been changed to 0.47 and 0.66, respectively.

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