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# Variations in microstructure of high chromium cast irons and resultant changes in resistance to wear, corrosion and corrosive wear

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ABSTRACT

High chromium cast irons are widely used in many industrial machineries and facilities that are attacked by wear in dry condition or corrosive environments. Appropriate selection of materials with optimum microstructure can extend their service life and thus minimize the maintenance cost. For the white cast irons, their resistances to wear and corrosion largely depend on the concentrations of chromium and carbon. In this study, microstructures of a series of high chromium white cast irons (wt%Cr = 30, wt%C = 1, 2, 3, 4, 5 and 6, wt%Mn = 2, wt%Si = 0.5, balanced by iron) were cast and characterized, and corresponding resistances to wear, corrosion and corrosive wear were evaluated, respectively. It was demonstrated that the corrosion resistance of these high chromium alloys largely depended on the Cr concentrations in the matrix and the volume fraction of carbides, while the wear resistance was dominated by the volume fraction of carbides. Efforts were made to correlate the variations in performance of these alloys during wear, corrosion and corrisive wear tests with their microstructures.

## 1. Introduction

High chromium cast irons (HCCIs) are excellent wear-resistant materials and have been widely used for wear-affected equipment operated under extreme conditions, such as facilities in the slurry pumping systems used in the oil sands handling, mineral processing, coal and cement industries. The exceptional wear resistance of HCCIs results primarily from the high volume fraction of hard chromium carbides, although the toughness of the matrix also contributes to the wear resistance [1–3]. The high nominal concentration of chromium helps to prevent the formation of graphite and stabilize the carbides. Meanwhile, copper, manganese, nickel and molybdenum are typically added to suppress the formation of pearlite during cooling [4,5].

The wear behavior of HCCIs has been well investigated [6,7] and the relationship between microstructure and properties has also been extensively studied [2,8,9]. However, when a corrosive environment is involved, the HCCIs may degrade to a large degree. Although experimental evidences have indicated that the corrosion rate (CR) of HCCIs could be low in many industrial environments where the HCCIs are used, the synergistic attack of corrosion and wear, i.e. corrosive wear, often results in severe damage to corrosion-resistant materials. Clearly, for many industrial operation processes, materials with high resistance not only to corrosion and wear alone but also to wear in corrosive environments are highly desired.

However, the comprehensive database regarding the resistances of HCCI, one of the most important industrial materials, to wear, corrosion and corrosive wear has not been fully established, and the information provided in literature is limited [4,10,11]. In this study, a series of HCCIs with precisely controlled chemical compositions were prepared, including hypoeutectic, eutectic and hypereutectic HCCIs. Microstructures of the HCCIs were characterized using X-ray diffraction (XRD) and scanning electron microscope (SEM)/EDX, and their resistances to wear, corrosion and corrosive wear, respectively, were investigated.

## 2. Experimental procedure

Six cast plates of HCCI, having with same nominal chemical contents of chromium (30 wt%), silicon (0.5 wt%) and manganese (2 wt%) with various concentrations of carbon: 1, 2, 3, 4, 5 and 6 wt%, balanced by iron, were made in a sand mold. Prior to machining, the cast plates were solution treated at 1160 °C and immediately cooled down by a blast of compressed air, followed by heat treatment at 950 °C for 5 h and subsequent cooling by the flow of compressed air. These plate castings were then cut into specimens with various dimensions: (a) 12 mm × 12 mm × 10 mm for microstructure characterization and corrosion tests; (b) 76 mm × 25 mm × 10 mm for

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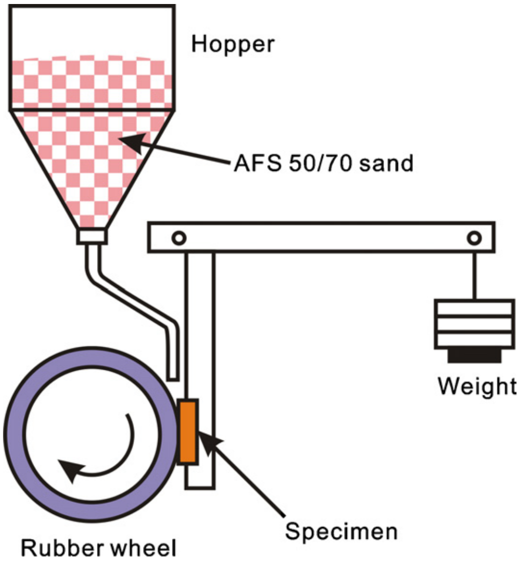

**Fig. 1.** Schematic illustration of an ASTM G65 abrasion tester.

dry sand/rubber-wheel tests, using an Accutom-5 automatic precision cut-off machine (Struers A/S, Denmark).

The wear resistance of HCCIs was evaluated using a dry sand/rubber wheel apparatus [12,13] (see Fig. 1) following the “procedure A” described in ASTM G65-04. AFS 50/70 sand (U.S. Silica Company, WV, USA) was used, and the sand flow rate was adjusted to 300–400 g/min. A contact load of 130 N was selected. The total number of revolution was 6000, responding to a total sliding distance of 4309 m. The wear resistance of HCCIs was ranked in terms of the volume loss, mm$^3$.

Microstructures and chemical compositions of the HCCIs were analyzed using a Hitachi S-2700 SEM equipped with an ultrathin window X-ray detector. The volume fraction of carbides and ferrous matrix were measured quantitatively using Image-pro plus software package (Media Cybernetics, Inc., USA). The crystalline structures were determined by XRD using a Rigaku rotating Co anode system (40 kV, 160 mA) at a scan rate of $2^\circ\ \mathrm{min}^{-1}$ within the angle range of 45–127°.

In order to evaluate the corrosion resistance of HCCIs, tap water and a 0.5 mol/L $H_2SO_4$ solution were used to simulate mediate and harsh environments, respectively. Linear polarization and Tafel measurements were carried out using a commercial electrochemical system (PC4-750, Gamry Instruments, Inc., PA, USA) to determine the corrosion rate of HCCIs. A saturated calomel electrode (SCE) was used as the reference electrode and a platinum plate with an area of 2 cm$^2$ was used as the counter electrode. The Tafel plots were recorded by scanning the potential at 1 mV/s in the range of ±0.25 V vs. open corrosion potential (OCP). The linear polarization resistance was measured at a scanning rate of 0.125 mV/s within the range of ±30 mV vs. OCP. All specimens were mounted using epoxy resin with a surface area of 1.44 cm$^2$ exposed to the corrosive solution. Prior to each electrochemical measurement, the target surface was ground with silicon carbide papers of 240-, 400-, and 600-grit successively and then rinsed with deionized (DI) water and acetone, followed by stabilization in the corrosive solution for 60 min during which the corrosion potential was recorded. The corrosion potential of each specimen was reported as the average of the values for the last 30 min of measurement. The CR in terms of penetration rate was calculated according to the ASTM G102-89 standard as follows:

$$\mathrm{CR} = K\frac{i_{cor}}{\rho}EW \tag{1}$$

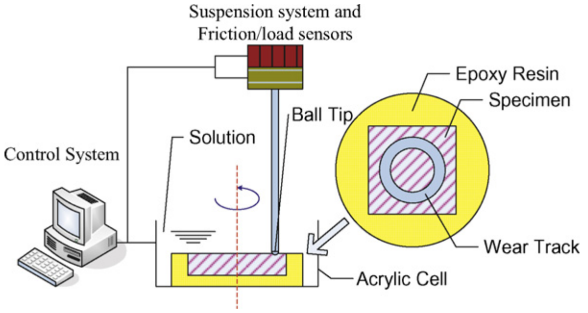

**Fig. 2.** Schematic illustration of the apparatus for corrosive sliding wear tests.

$$i_{cor} = \frac{B}{Rp} \tag{2}$$

$$B = \frac{ba \cdot bc}{2.303(ba + bc)} \tag{3}$$

where CR is given in mm/year; $i_{cor}$ (μA/cm$^2$) is the corrosion current density; *ba* and *bc* correspond to the anodic and the cathodic Tafel slopes, respectively; *Rp* is the linear polarization resistance; *B* is the Stern-Geary constant; *EW* is the alloy equivalent weight; $\rho$ is the density in g/cm$^3$; and *K* is a constant of $3.27 \times 10^{-3}$ mm g/(μA cm year). All electrochemical measurements were performed at room temperature.

Corrosive sliding wear tests were carried out using a Universal Micro-Tribometer (UMT-2 Multi-Specimen Test System, Center For Tribology, Inc., USA) under a normal load of 10 N for 20 min at a sliding speed of 240 mm/s. A schematic diagram of apparatus for the corrosive wear testing was illustrated in Fig. 2. The specimen was mounted using epoxy resin, and ground up to 600-grit using silicon carbide papers, followed by acetone cleaning. The diameter of the circle wear track was 6 mm, and its width was measured using a calibrated microscope system. Silicon nitride balls with a diameter of 3.969 mm were used. The volume loss of HCCIs during corrosive wear was calculated by combining the wear track width and the diameter of the ball tip, and results of volume loss are presented in μm$^3$.

## 3. Results and discussion

### 3.1. X-ray diffraction and SEM observation

Fig. 3 illustrates XRD patterns of six HCCI specimens with different nominal carbon concentrations, which demonstrates that the specimens consist of a ferrous matrix (PDF: 6-0696) and M(Fe, Cr)$_7$C$_3$ carbides (PDF: 36-1482).

It was confirmed that austenite phase expected in the as-cast structure had transformed to martensite (possibly mixed with minor ferrite) after the heat treatment. However, a small amount of retained austenite (PDF: 31-0619) was observed in the specimens especially those with higher carbon concentrations, which was consistent with the reported results [9]. With increasing wt%C, the volume fraction of ferrous matrix in HCCIs decreased, while the carbides increased, since more carbon promoted the formation of carbides. Besides, the XRD peaks of the martensite phase slightly shifted to lower angles with increasing carbon, implying that the lattice constants of the ferrous phase increased probably due to the super-saturation of carbon in the matrix. The volume fraction of manganese carbides was too small to be identified in all XRD profiles.

In order to examine the microstructure of the cast HCCIs in detail, all specimens were observed carefully using a SEM and obtained images are presented in Fig. 4. As shown, the HCCIs consisted of M(Fe, Cr)$_7$C$_3$ carbides dispersed in the ferrous matrix. The