Microstructure and wear resistance of high chromium cast iron containing niobium

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Due to their excellent wear resistance in aggressive environments, high chromium cast irons (HCCIs) are widely used in industrial applications such as mineral processing, cement manufacturing, slurry pumping and pulp and paper manufacturing industries [1-4]. Based on the ratio of carbon versus added alloy elements, HCCIs could present hypoeutectic, eutectic and hypereutectic states [5]. In particular, the hypoeutectic HCCIs (10wt.%-30wt.%Cr and 2wt.%-3.5wt.%C) have been extensively investigated since they demonstrate a good combination of abrasion resistance and corrosion resistance in wet wear applications [6-8]. Recently, much attention has been paid to the hypereutectic HCCIs because they yield more volume fractions of the hard and wear-resistant M₇C₃ carbides in contrast to the hypoeutectic HCCIs, which makes them favorable for many hardfacing applications [1, 5]. However, the poor impact toughness originating from the coarse primary carbides may result in a rather high rejection rate during their casting manufacturing [9].

The enhancement of impact toughness for the hypereutectic HCCIs can be realized either from suitable heat treatments to produce a controlled martensitic matrix structure or from adding other alloy elements to refine the primary carbide. A suitable heat treatment could destabilize the austenitic matrix through precipitating the secondary carbide and accelerate the transformation of austenite to martensite [5]. The alloying process, on the other hand, could be used to modify the carbide types, control their morphologies and adjust the carbon content in the matrix [1, 5, 9-17]. Particularly, the addition of strong carbide-forming elements such as titanium, niobium and vanadium has been found to have an effect on additional microstructure refinement [11-16]. However, little available information has been found concerning the niobium influence on the impact toughness. Moreover, how much of such an element should be combined with the HCCIs to obtain optimal impact toughness and abrasive wear resistance has been seldom reported [13].

In this study, the influence of niobium on the microstructure characteristics and wear resistance of a hypereutectic high chromium white iron containing >30wt.% Cr and >4wt.% C was investigated in detail in both as-cast and heat-treated states. The properties related to the service performance of the HCCIs containing niobium, namely the abrasion resistance in wet application and impact toughness were also examined.

Abstract: In the paper, the effect of niobium addition on the microstructure, mechanical properties and wear resistance of high chromium cast iron has been studied. The results show that the microstructure of the heat-treated alloys is composed of M₇C₃ and M₂₃C₆ types primary carbide, eutectic carbide, secondary carbide and a matrix of martensite and retained austenite. NbC particles appear both inside and on the edge of the primary carbides. The hardness of the studied alloys maintains around 66 HRC, not significantly affected by the Nb content within the selected range of 0.48%-0.74%. The impact toughness of the alloys increases with increasing niobium content. The wear resistance of the specimens presents little variation in spite of the increase of Nb content under a light load of 40 N. However, when heavier loads of 70 and 100 N are applied, the wear resistance increases with increasing Nb content.

Key words: high chromium cast irons; NbC, hardness; impact toughness; wear resistance

Received: 2013-12-05   Accepted: 2014-03-30
1 Experimental procedure
The HCCIs containing niobium were prepared using a mediumfrequency induction furnace. After melting and deslagging, the molten metal was poured into a sand mould, and 3 groups of cast iron Y-block samples were prepared. The chemical compositions of the cast irons were (wt.%) C: ~ 4.8, Cr: ~34, Mn <0.6, Si <0.6, S <0.06, P <0.06, with varied Nb contents of 0, 0.48 and 0.74 (wt.%), respectively. The samples were then heat-treated by destabilization in a conventional electric furnace at 1,050 °C for 2 h, followed by cooling to room temperature in still air. Afterward, the tempering treatment was carried out at 250 °C for 2 h.

The specimens were cut from the centre of the Y-block sample. They were polished and etched with 6% Nital reagent. The microstructures, fractographs and worn surface morphology were observed using an optical microscope (OM) and a scanning electron microscope (SEM, JEOL-JSM5910). X-ray diffraction (XRD) was used to determine the phase constitution of the niobium-containing HCCIs.

Rockwell hardness (HRC) tests were performed to determine the average hardness. Impact tests were carried out on a small pendulum impact testing machine (JB30A-30/15). The impact specimens were prepared to a size of 10 mm × 10 mm × 55 mm with no notch. The abrasive wear resistance test was evaluated using a MLS-225 wet sand rubber wheel testing machine.

Quartz sands of 60–80 mesh were mixed with water in a ratio of 1:3 used as wet wear medium. The applied load was 40, 70 and 100 N, respectively. The weight loss of the test specimens was measured using an electronic analytical balance with a precision of 0.0001 g.

2 Results and discussion
2.1 Microstructure of Nb-containing HCCIs
Figure 1 shows the microstructures of the Nb-containing hypereutectic HCCIs in both as-cast and heat-treated states. The coarse strip and isotropic hexagonal primary carbides and the petal-like eutectic colonies could be found in the as-cast specimens. The eutectic colonies were composed of eutectic carbides and austenite. With the increasing of Nb content, the coarse strip primary carbides were gradually refined and their shape became more isotropic, as shown in Fig. 1(b), (c). After heat treatment, most of the primary carbides became isotropic, which may result from the partial dissolving of the primary carbides during heating. Moreover, the increase of the dispersive secondary carbides was remarkable in the heat-treated specimens. These secondary carbides were originated from the destabilization of the eutectic austenite. It should be noted that the evaluation of volume fraction of various carbides indicated very little change in the total carbide volume fraction with the increasing Nb content.

![Fig. 1: Microstructures of high chromium cast irons (HCCI) with different Nb contents and in different conditions](image)
that most of primary carbide, eutectic carbide and secondary carbide are M_7 C_3 and M_23 C_6 types. The M_23 C_6 carbides were transformed from the M_7 C_3 carbides during the destabilization heat treatment [5]. The findings are well in agreement with the optical microscope observations.

Figure 3 presents the backscattered electron micrographs of the heat-treated specimens. The hexagonal primary carbide, petal-like distributed eutectic carbide and dispersive secondary carbide were found in the specimens. The white NbC particles, presenting in polygon morphologies, were located both inside the primary carbides and on the edge of the primary carbides. From Fig. 3, it can be seen that the amounts of NbC in the specimens increase with increasing Nb content. In addition, the size of NbC particles inside the primary carbides shows little change with the variation of Nb content. The NbC particles inside the primary carbides seem to be cores of the primary carbides. These observations are consistent with the previous report [13].

Niobium could also be dissolved out during the formation of the primary carbides since Nb has quite low solubility in the M_7 C_3 carbides [13]. In order to confirm this, a line scanning of energy-dispersive X-ray spectroscopy across the primary carbides to the matrix was performed, and the results are shown in Fig. 4. The profile clearly indicates that the primary carbide is Cr-enriched phase containing Fe and the matrix is Fe-enriched. The sharp Nb signal peak across the boundary between the primary carbide and matrix indicates the accumulation of Nb at the boundary.
2.2 Mechanical properties of Nb-containing HCCIs

The Rockwell hardness and impact toughness of Nb-containing HCCIs in heat-treated state are presented in Fig. 5. The specimen without Nb addition has an average hardness value of ca. 66 HRC. This value remains almost constant in spite of the variation of Nb addition. In contrast, the impact toughness increases with increasing Nb content as illustrated by the line in Fig. 5. The maximum impact absorbing energy is 2.7 J cm\(^{-2}\), corresponding to the maximum Nb content in this study, which is nearly 1.5 times higher than that of the specimen without Nb addition.

Figure 6 shows the fracture morphologies of the impact specimens with different Nb contents. It can be seen that the fracture morphologies are quite similar, mainly being continuous flat facets. The cleavage fracture features with river patterns could also be found, especially in the specimen without Nb addition [Fig. 6(a)]. The river patterns were caused by the crack moving through the crystal along a number of parallel planes, which are indications of the absorption of energy by local deformation \[^{[18]}\]. These observations suggest that the fracture mechanism is brittle fracture for all the specimens. With increasing Nb content, the cleavage fracture features and the river patterns became less obvious, which corresponds to the slight increase of impact toughness.

2.3 Wear resistance of Nb-containing HCCIs

The relationship between the wear weight loss and Nb content for HCCI under various loads is shown in Fig. 7. It can be noted that the weight loss for specimens with constant Nb content increases as the applied load increases; but the weight loss presents little variation in spite of the increase of Nb content when the specimens were tested under a light load of 40 N. However, the weight loss of the Nb-containing HCCIs decreases with increasing Nb content when they were evaluated under heavier loads (70 N, 100 N). These results indicate that the wear resistance of the HCCIs with Nb addition is higher than that without Nb addition when they weree under higher loading conditions.

Figure 8 shows the worn surfaces for different Nb-containing specimens under a typical heavy load of 70 N. All the worn specimen surfaces shows a micro-ploughing feature. In addition, some peeling-off pits can also be found, which were mainly from the spallation of the brittle carbides. As Nb content increased, the worn surface became smooth due to the decrease of the peeling-off pits, which may resulted from the decrease of the wear weight loss.

Fig. 5: Hardness and impact toughness of tested specimens

Fig. 6: Fracture morphologies of impact specimens with 0wt.% Nb (a), 0.48wt.% Nb (b), and 0.74wt.% Nb (c)

Fig. 7: Wear weight loss under different loads
and accumulated on the edge of the primary carbides due to its limited solubility in the M7C3 carbide. With regard to the impact toughness, the refinement of the primary carbides and eutectic colonies can prevent the crack propagation and thus results in the improvement of impact toughness.

The wear resistance of the Nb-containing HCCIs is closely related to the hardness of the materials and the counterpart materials. The abrasion resistance of the carbides was more effective than the matrix in the HCCIs since their hardness (1200–1800 HV) was greater than that of the used quartz sands (960 HV). In the wet abrasive conditions, wear with low-stress was controlled by the removal rate of the carbide phase, where the protruding carbides protected the matrix from direct attack by the counterpart abrasive particles. When a light load of 40 N was used, the quartz sand counterpart particles were not easily pressed into the specimen surface and the carbide particles were not easily broken into pieces. Thus, the wear weight loss was moderate under such a low load. However, if larger loads were applied, the quartz particles would possibly be pressed into the soft zone over the specimen surface, which would flake off some brittle carbides to form peeling-off pits. Moreover, the peeling-off hard carbide particles could aggravate the specimen surface wear since they can also play a similar role as the quartz particles. Therefore, the wear weight loss is greater under the heavy loads than that under a light load.

In addition to the M7C3 carbide, NbC carbide also appeared in the alloys. With a higher hardness than that of the M7C3 carbide, NbC carbide shows a higher wear resistance than M7C3 carbide. Increasing the amounts of NbC particles would improve the wear resistance. In addition to the volume fraction of carbides, the particle size of hard and brittle phases presented in the structure was another microstructure variable to affect the abrasive resistance. The smaller sizes of the primary carbides and eutectic colonies, resulting from the increase of Nb content in the alloy, could reduce the peeling-off rates in the wear process. In summary, with increasing Nb content in the HCCI, the harder NbC particles and the refined primary carbides and eutectic colonies prove beneficial to the improvement of wear resistance.

3 Conclusions

The microstructure, mechanical properties and wear resistance of Nb containing high chromium cast irons (HCCI) have been investigated. The metallographic inspection, XRD and SEM backscattered electron investigations indicate:
(1) The microstructure of the heat-treated Nb-containing HCCIs consists of primary carbide, eutectic carbide, secondary carbide, martensite matrix as well as some retained austenite. Most of the carbides are M₇C₃ and M₂₃C₆ types whereas NbC particles appear both inside and on the edge of the primary carbides.

(2) The HCCI shows a similar hardness of about 66 HRC in spite of the variation of Nb content from 0 to 0.74 wt.%. However, the impact toughness increases with increasing Nb content.

(3) The wear resistance of the specimens with and without Nb addition under a light load of 40 N presents little variation. However, when heavier loads such as 70 and 100 N were applied, the wear resistance increases with increasing Nb content due to the formation of harder NbC particles and the refinement of the primary carbides and the eutectic colonies.

References


