Effect of interaction between cementite and pearlite on two-body abrasive wear behaviors in white cast iron

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Abstract: The wear interaction of cementite and pearlite in the white cast iron (WCI) was investigated using the two-body abrasive wear test under contact loads of 20, 35, and 50 N. The wear behavior, wear surface morphology, sub-surface structure, and wear resistance were evaluated using X-ray diffraction, microhardness testing, and nano-indentation. The results indicated that when the Cr content was increased from 0 to 4 wt%, there was a significant increase in the microhardness (H) and elasticity modulus (E) of the cementite. This yielded a 15.91%- and 23.6%-reduction in the degree of wear resistance and surface roughness, respectively. Moreover, no spalling and breaking of cementite was observed with increasing Cr content during the wear process, indicating improved wear resistance of the bulk cementite. In addition, the hard phase (cementite) and tough matrix (pearlite) composite structure exhibited a good protective and supporting effect. Thus, it was concluded that the interaction mechanism of the wear phase contributed to the reduction of the wear weight loss of the composite during the wear process. The contribution of the interaction between the hard wear-resistant phase and the tough phase in WCI to the wear resistance decreased with increasing hardness of the pearlite matrix.

Keywords: two-body abrasive wear; white cast iron (WCI); wear resistance; interaction

1 Introduction

As wear-resistant materials, chromium white cast iron (WCI), boron WCI, and particle reinforced metal matrix composite consist of a tough metal-based phase (e.g., austenite, martensite, ferrite, and pearlite) and a hard wear-resistant phase (e.g., carbide, ceramic hard-phase). These materials are extensively used in various industrial fields, such as mining grinding, mineral handling, and oil sand slurry pumping [1–4]. Generally, the wear resistance of WCIs depends on the hard carbides and metal matrix composite structure, both of which play an important role in the resistance to abrasive wear.

Carbides resist the wear process by protecting the metal matrix from further cutting during the wear process; on the other hand, the toughness of the metal matrix (e.g., pearlite matrix, martensite matrix, and steel/iron) provides support to the worn carbide leading to plastic compensation for the carbide during the wear process. The combined protective and supporting effect leads to the reduction in the wear weight loss of the composite; this effect is referred to as the interaction between the hard wear-resistant phase and the tough phase in WCI [5–7]. Carbide, which is an important hard phase in this material, plays a key role in resisting the wear process, and thus, the properties of carbide

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directly affect the abrasion properties of material. In previous studies, numerous alloying elements, such as Cr, Mn, Mo, V, and Ti [8], have been added to WCI, and their effect on the mechanical, physical, and abrasive properties of cementite has been investigated [9, 10]. The findings indicated that Cr, which is a carbide-forming cementite, has a significant effect on the properties of each phase comprising of WCI [11–15]. However, these investigations were mainly focused on the relationship between, for example, the Cr content and the morphological changes, hardenability, graphitization tendency, and mechanical properties of the carbide.

In addition, several studies have reported that the cementite and metal matrix in WCI behave synergistically during the abrasive wear process; however, only a few studies have investigated the interaction in this material. The mechanical properties and abrasive behavior of each phase in WCI are only partially understood because the separate preparation of each phase is impossible. Moreover, the analysis of the abrasive properties characterizing each phase of the material is difficult. Consequently, the investigation of the synergistic effect associated with (or interaction between) different phases in WCI during the abrasive wear process with Cr content changes is challenging, as reported in previous studies [18]. Furthermore, though the reported improvements in the interaction are based on empirical observations, the underlying mechanism remains unclear [16–21].

Umemoto et al. [8–10] successfully produced single-phase bulk carbide using mechanical alloying (MA) and spark plasma sintering (SPS). This combination of techniques is a suitable for investigating phase interactions. In this study, the chemical composition was determined for each single phase of the prepared WCI. Subsequently, the bulk matrix and carbide with different Cr content levels were prepared based on the determined compositions. The contribution of each phase to the wear process was evaluated by assessing the interaction and wear mechanism, WCI, bulk matrix, and bulk carbide using wear tests performed under the same abrasive conditions.

In this study, the effect of Cr content on the wear

behaviors of WCI was investigated using two-body abrasive wear tests. The interaction between cementite and pearlite in the material was determined, and the contribution of each phase to abrasive wear was also assessed.

2 Experimental and calculation methods

2.1 Wear specimen preparation

The WCI and its corresponding single-phase bulk samples were prepared separately. WCI samples with Cr content of 0, 2, and 4 wt% were prepared. These samples were of the same volume fraction and Fe₃C-type carbide and were prepared at medium frequency (melt capacity: 18 kg). The original materials contained Fe–Cr alloy compound, Fe–Mn alloy compound, Fe–Si alloy compound, pig iron, and pure iron, among others. The main chemical components of the WCI samples are listed in Table 1. A Cr-to-C atomic ratio of less than 4 to 1 was used to produce a microstructure consisting of M₃C-style cementite and pearlite at room temperature (298.15 K). The WCI samples with Cr content of 0, 2, and 4 wt% were referred to as W0, W2, and W4, respectively. The melt was heated to $1,550 \pm 10$ °C and held at this temperature for 2 min. Subsequently, pure aluminum was added to remove oxygen from the melt, and the melt was then poured into silicate sand molds at $1,450 \pm 10$ °C, thereby resulting in the formation of Y-block ingots, in accordance with ASTM A781. The riser was removed, and the surface of each ingot was polished to a dimension of 3 mm using a grinding machine. Thereafter, ϕ 4.9 mm $\times$ 30 mm cylindrical two-body wear samples were cut using a spark cutting machine [22, 23].

In addition, single phases comprising WCI with different Cr content levels, i.e., the single-phase

Table 1 The chemical compositions of chromium white cast iron (wt%).

Samples	C	Cr	Mn	Si	S	Fe
W0	2.55–2.65	0	0.60	0.67	<0.03	Bal.
W2	2.48–2.52	2	0.60	0.67	<0.03	Bal.
W4	2.40–2.45	4	0.60	0.67	<0.03	Bal.

bulk cementite (SBC) and the single-phase bulk pearlite (SBP), were prepared using the spark plasma sintering (SPS) technique and the smelting/casting technique, respectively. First, single-phase chemical compounds of as-cast WCI with different content levels of Cr were examined using an electronic probe (see Tables 2 and 3 for the main chemical compounds comprising cementite and pearlite). Second, SBC and SBP were prepared in accordance with the respective compositions. SBC was prepared using mechanical alloying (MA) and SPS technique. A planetary ball mill was used to mix the alloy powder under a vacuum condition at room temperature (298.15 K). The alloyed powders included pure iron, graphite, chromium, and manganese powder (iron: 99.0 mass%, size <30–50 μm ; graphite: 99.0 mass% <10 μm ; chromium: 99.9 mass% <45 μm ; manganese: 99.9 mass% <25 μm), which were mixed as shown in Table 2. A ball-to-powder weight ratio of 10:1 was employed for a total mixing time of 100 h. Subsequently, the alloyed powders were compacted into a graphite die under vacuum and were then sintered via SPS (temperature: 1,173 K, time: 300 s, applied pressure: 30 MPa). The alloyed powder was then processed into $\phi 30 \text{ mm} \times 10 \text{ mm}$ SBC. Thereafter, $\phi 4.9 \text{ mm} \times$ two-body abrasive samples of bulk cementite were cut using a spark cutting machine. Furthermore, the SBP was melted in accordance with the chemical compositions presented in Table 3. A solidification temperature of $1,550 \pm 10^\circ\text{C}$ was employed for 5 min, and the melts were poured into Y-block ingots in preparation for the processing of WCI.

The phase structure and hardness of the sintering bulk were examined. And then the results revealed that the cementite and pearlite in the WCI are present in the single bulk phase. Thus, the abrasive properties of the SBC and SBP samples were determined.

Table 2 The chemical compositions of cementite (wt%).

Single phase cementite	C	Cr	Mn	Fe
C0	6.64	0	0.081	Bal.
C2	6.74	6.30	0.074	Bal.
C4	6.89	9.76	0.072	Bal.

Table 3 The chemical compositions of pearlite in white cast iron (wt%).

Single phase pearlite	C	Cr	Mn	Si	Fe
P0	1.75	0	0.71	0.38	Bal.
P2	1.57	1.05	0.72	0.34	Bal.
P4	1.44	2.74	0.72	0.44	Bal.

2.2 Two-body abrasion wear test

The samples were subjected to a two-body wear resistance test using the ML-100 type abrasion tester in accordance with the China JB/T 7506-1994 standard under dry atmospheric and room temperature conditions (298.15 K) [17], as shown in Fig. 1. The samples were fixed on the abrasive tester during spiral motion under applied pressures of 20, 35, and 50 N. An SiO_2 sandpaper (mesh: 40–120; hardness: 800–900 HV) [6] was used, as shown in Fig. 2. Testing was performed on a wear track with a length of $\sim 5.96 \text{ m}$. The weight loss of the sample is an important index for quantifying the wear resistance. The weight loss was obtained as the

Fig. 1 Two-body abrasive wear tester.

Fig. 2 The morphology of SiO_2 abrasive at initial wear stage.

average of five measurements performed using an electronic balance (minimum accuracy level: ~0.01 mg). At the end of each wear test, the samples were cleaned ultrasonically for 1 min in an alcohol solution. The samples were then blow-dried with an electric hair drier, and at the end of each test, the sandpaper was replaced with a new one.

In addition, the wear-surface and sub-surface microstructure were characterized using the metallographic technique, where an oblique section method is used to analyze the wear mechanism and behaviors. The oblique section schematic of the two-body abrasive sample is shown in Fig. 3. The angle between the wear surface and the metallographic surface is less than 10°. Furthermore, the worn-surface and the sub-surface structure were characterized simultaneously using scanning electron microscopy (SEM).

2.3 Interaction between cementite and pearlite

The wear resistance is characterized by analyzing the weight loss of the worn sample. Generally, the wear weight loss decreases with increasing wear resistance. The weight loss of each sample was measured using an electronic balance. Thereafter, the interaction between two phases (cementite and pearlite) undergoing the wear process was calculated using a mathematical equation [18]. This equation describes the relationship between the weight loss values of the WCI subjected to the wear process. The weight loss model is based on the following equation:

Fig. 3 Schematic diagram of sample prepared for taper-section method.

$$\Delta W_w = (\Delta W_M \quad \Delta W_C \quad \Delta W_I) \begin{pmatrix} 1-\alpha\% \\ \alpha\% \\ 1 \end{pmatrix} \quad (1)$$

where ΔW_w , ΔW_M , and ΔW_C are the weight loss values of the WCI, and the worn weight loss of SBP and SBC alone, respectively. ΔW_I is the weight loss resulting from the interaction, and α represents the percentage of cementite in WCI. ΔW_w , ΔW_M , ΔW_C , and α in Eq. (1) can be directly obtained experimentally. The ΔW_I values can be obtained through calculation based on other wear parameters (see Eq. (1)) where ΔW_w , ΔW_M , and ΔW_C are the values of weight loss resulting from the wear of WCI, SBC, and SBP, respectively, and ΔW_I is the value of weight loss resulting from interaction. α is the percentage of cementite content. ΔW_w , ΔW_M , ΔW_C , and α can be measured experimentally. In this case, the interaction (ΔW_I) can be estimated from Eq. (1).

2.4 Test specimen examination and analysis

The worn samples were prepared metallographically and then polished and etched in a 4 vol% initial solution. Subsequently, the microstructure was examined using SEM–energy dispersive spectroscopy (EDS) to determine the chemical component distribution (Tescan VEGA II XMU, Brno, Czech Republic); a continuous scanning voltage of 20 kV was used. The phase composition of each sample was determined using X-ray diffraction (XRD) with copper K α radiation at 40 kV and 200 mA as the X-ray source (MXP21VAHF diffractometer). The stress-strain relationship characterizing each sample was evaluated via a Nano indenter G200 nanoindentation device with a Berkovich diamond tip indenter (loading speed: 0.05 N/s; maximum fix indentation depth: 900 nm; Poisson's ratio of each sample: 0.18). The microhardness was measured using the HXD-1000TMC tester, in accordance with ASTM E384-08 [19–23].

3 Results and discussion

3.1 Solidification structure of WCI, SBC, and SBP

Figures 4(a) and 4(b) show the microstructures of

the WCI with Cr content of 0 and 4 wt% (the corresponding SBC and SBP are indicated in each case). The W0 and W4 samples were evaluated using XRD, as shown in Fig. 5. According to the XRD patterns, the phase composition of W0 and W4 included alpha ferrite (α -Fe) and M_3C -type carbide, but no graphite and M_7C_3 -type carbide. Generally, as the Cr content increased, the amount of M_7C_3 -type carbide precipitation from Cr WCI increased. This is consistent with the results indicating that for Cr content of <4 wt% the WCI microstructure contained only one M_3C -type carbide. The volume fraction of carbide was calculated using Leica software. A carbide volume fraction of ~18.81 vol% was obtained for each of the prepared samples. Hence, the prepared WCI W0, W2, and W4 samples were characterized by the same type of carbide, M_3C , and carbide content. In other words, the carbide content and pearlite matrix were the same for different WCI samples.

Fig. 4 Microstructures of WCI, single bulk cementite, and single bulk pearlite matrix: (a) the microstructure of W0 sample corresponding block matrix and block cementite; (b) the microstructure of W4 sample corresponding block matrix and block cementite.

Fig. 5 XRD patterns of samples with 0 and 4 wt% chromium contents.

The microstructures of SBC and SBP, corresponding to 0 wt% Cr and 4 wt% Cr WCI, were examined using SEM (see Figs. 4(a) and 4(b)). The SBP was composed of a parallel layer structure, and the interlayer spacing decreased with increasing Cr content, as in the case of the pearlite matrix comprising the WCI. In the case of SBC, pits resulting from the solidification of the powder during SPS were observed. However, the number of voids increased only slightly with increasing Cr content.

The micro-Vickers hardness values of SBC and SBP are given in Table 4, which shows that the hardness of the single-phase bulk is similar to that of the corresponding phase of WCI. In summary, the microstructure and hardness of SBC and SBP are similar to those of the corresponding phase in the cast iron. Therefore, W0, W2, and W4 samples as well as the corresponding SBC and SBP were prepared. These samples, which satisfied the interaction requirements, were then prepared for the wear tests and used in the calculations.

3.2 Two-body abrasive wear behavior of Cr WCI

The wear resistance of the WCI was evaluated

Table 4 Hardness (H), elastic modulus (E), and H/E of cementite in white cast iron.

Cementite in WCI	Hardness, H (GPa)	Elastic modulus, E (GPa)	H/E
C0	3.61	190.00	0.019
C4	4.93	197.20	0.025

using a two-body abrasive wear tester. Figure 6 shows the relationship between the weight loss and the Cr content. The results indicate that for a given load (20, 35, and 50 N), the weight loss of the material decreased with increasing Cr content because when Cr was added, a considerable improvement was observed in the wear resistance of WCI. This was mainly achieved by increasing the hardness, as shown in Fig. 7. The micro-Vickers hardness of the M_3C -type carbide and the pearlite matrix ranged from 858 to 1,054 HV and 261 to 360 HV, respectively. According to Richardson's theory [24], the rate of weight loss is mainly determined by the ratio of H_m/H_a , where H_m and H_a are the material and abrasive hardness, respectively. In this study, the hardness range of the abrasive (SiO_2) was 800–900 HV. The hardness of the carbide determined the wear resistance of WCI, and hence, the H_m/H_a ranged from 0.95 to 1.31. For $H_m/H_a > 0.6$ –0.8, the abrasive is regarded as a soft abrasive, where the degree of wear decreases with increasing wear resistance. The hardness of the carbide was greater than that of the abrasive. Additionally, the weight loss of the WCI specimen decreased only slightly with the increasing Cr content, but increased with decreasing load, i.e., the wear resistance decreased for a given amount of Cr content added.

To determine the effect of the abrasive behaviors on the microstructure and properties of the samples, the wear surface and grinding morphologies were

Fig. 6 The relationship between the wear weight loss and chromium content at applied pressure 20, 35, and 50 N.

Fig. 7 Microhardness of cementite and pearlite matrix with different chromium contents.

examined using SEM. As shown in Fig. 8(a), under a 50 N load, the main wear mechanism of the sample involves microcutting and ploughing. Parallel furrows, plastic deformation areas, and embedded SiO_2 abrasives occurred on the wear surfaces. Compared with the wear surface of the W0 sample, the surface of the W4 sample consisted of wider parallel furrows, more plastic deformation areas, and fewer embedded abrasives, as shown in Fig. 8(b). This is mainly because the abrasive-induced fracture led to abrasive tip passivation that prevented the pressing of the tip onto the sample surface, thereby resulting in wide furrows.

In addition, the grinding morphology changed significantly due to the addition of Cr. Figures 9(a) and 9(b) show the grinding morphologies of the W0 and W4 samples, respectively. As indicated by the regions enclosed by the blue dashed lines in Fig. 9, the average aspect ratio of the morphology associated with 0 wt% Cr is larger than that corresponding to 4 wt% Cr. The grinding morphologies of the W0 and W4 samples consisted of ribbon-like and block-shaped features, respectively, because the increase in hardness led to a decrease in the toughness of the sample, and consequently, spalling during the two-body abrasive wear process. Hence, many fracture plastic areas were generated on the wear surface, as shown in Fig. 9(b).

To evaluate the effect of wear on the surface morphology of WCI with different Cr content levels,

the degree of wear-induced roughness was examined using 3D laser scanning microscopy. From the obtained stereogram, the geometric morphology is shaded according to the irregularity of the worn surface. Figures 10(a) and 10(b) show the 3D worn-surface topographies of the W0 and W4 samples.

Many continuous parallel furrow protuberances occurred on the surface, and the 3D images show that the surface morphology resulted from abrasive cutting. The two different damage geometries observed were generated through the microcutting and the plough-cutting mechanisms.

Fig. 8 SEM images of wear surface of W0 and W4 sample under 50 N load: (a) W0 and (b) W4.

Fig. 9 SEM images of wear debris under 50 N load: (a) W0 and (b) W4.

Fig. 10 3D profile images of worn surface under 50 N load: (a) W0 and (b) W4.

In addition, the relationship between the surface roughness and the Cr content was investigated using 3D laser scanning microscopy for different worn-surface areas, with five measurements performed per area (see Fig. 11). The results indicate that in ascending order of the degree of surface roughness, the samples are as follows: $W0 < W2 < W4$. The surface roughness decreased significantly as the Cr content was increased from 0 to 2 wt% and then gradually decreased (the highest difference between $W0$ and $W4$ worn-surface roughness was $0.85 \mu\text{m}$). The surface roughness changed gradually because the microhardness of the carbide and the matrix improved, thereby preventing the pressing of the abrasive on the surface of WCI. Hence, the shallow worn layer led to a decrease in the value of the surface roughness (R_a). In summary, compared with low-Cr-content WCI, high-Cr-content WCI was characterized by a higher hardness, shallower plough depth, smaller roughness degree, and better wear-resistance properties.

3.3 Quantitative investigation of the interaction between cementite and pearlite

Similarly, the worn weight loss of SBC and SBP (ΔW_C and ΔW_M , respectively) were also measured via a two-body abrasive wear test. Subsequently, the wear weight loss of each component in WCI was determined (see Fig. 12) based on Eq. (1). The weight loss values obtained indicated a negative interaction of $W0$, $W2$, and $W4$ (i.e., ΔW_I), and the

Fig. 11 Surface roughness of samples with different chromium content.

Fig. 12 The interaction relationship between carbide and pearlite matrix with different chromium content.

strength of the interaction decreased (in general) with increasing Cr content. This interaction indicated the degree of interdependence between the hard phase and the tough matrix of WCI. Generally, the hard carbide provided protection to the pearlite matrix, and this tough matrix supported the cementite during the entire wear process. Moreover, a strong interaction relationship occurred between the carbide and pearlite in WCI with low Cr content than that in WCI with high Cr content (see Fig. 12). This is because the strength of the interaction is directly related to the performance of each phase (especially for the M_3C -type carbides) in the WCI.

Therefore, in this study, the effect of the Cr content on the micro-mechanical performances of carbide in WCI was established via nanoindentation. The load-displacement curves obtained for the $W0$ and $W4$ samples under a 50 N load are shown in Fig. 13. The curves reveal complex correspondence behavior attributed to three main factors. Compared with the cementite in the $W0$ sample, the cementite in the $W4$ sample (i) experienced a smaller strain under the same applied load. Under the same wear load, this cementite underwent a significant deformation leading to a strong interaction with the pearlite matrix, (ii) was characterized by a higher hardness, and therefore, exhibited greater resistance to abrasive scraping, i.e., exhibited a higher wear resistance, and (iii) exhibited excellent elastic recovery (i.e., a high H/E ratio, where H and E are the hardness and elastic moduli, respectively). The H ,

E , and H/E obtained from the curves are listed in Table 4. The statistical results showed that all three values increased with increasing Cr content, and the mechanical properties of the specimens were affected significantly. The toughness and microhardness of carbides in WCI with added Cr atoms were higher than those of the sample with no Cr addition because when Cr was added to WCI, many Cr atoms entered the Fe_3C lattice through substitution, thereby replacing some of the Fe atoms leading to the formation of new Fe–Cr and Cr–C bonds. However, the Fe–Cr and Cr–C bond energies are higher than the Fe–Fe and Fe–C bond energies, respectively. This study revealed that the metal–carbon (i.e., in this case, Cr–C bond) and metal–metal bonds (i.e., Cr–Fe bond) promote the hardness and toughness of cementite, respectively. Hence, Cr addition increased the strength of the metal–metal bonds, leading to increased toughness and hardness of the M_3C crystals [24–27].

Subsequently, the interaction between cementite and pearlite was investigated by analyzing the sub-surface layer morphology. Figures 14(a) and 14(b) show the wear sub-surface of the W0 and W4 samples. The pearlite matrix was easily cut down by the SiO_2 abrasive leading to the formation of grooves. Consequently, the cementite protruded from the matrix, thereby preventing the abrasive from wearing the matrix. Furthermore, many fracture cracks formed in the cementite that peeled off partially from the worn surface (as indicated by the red arrows in Fig. 14(a)). The fractured

cementite was unable to protect the material surface, resulting in reduced wear resistance of the W0 sample. However, when the hardness and toughness increased due to Cr addition of 4 wt%, the fracture and spalling of the carbide decreased. Moreover, the carbide protruded from the worn surface, resulting in distinct cutting grooves (as indicated by the red arrows in Fig. 14(b)). This showed that in addition to the hardness, improved toughness is an important factor that determines hard-phase-induced improvement in the wear resistance of WCI.

In addition, a physical model of the two-body abrasive wear can be used to explain the mechanism governing the carbide/pearlite matrix interaction during the wear process. The entire wear process can be divided into five stages, as shown in Figs. 15(a)–15(e). (i) The carbide and the pearlite matrix

Fig. 13 Load–displacement curves for cementite in W0 and W4 sample.

Fig. 14 Micrographs of the taper-sections through the wear surface for W0 and W4 samples under contact 50 N: (a) W0 and (b) W4.

Fig. 15 Physical models of the two-body abrasive wear: (a) before the abrasive wear, (b) the second, (c) third, and (d) fourth period of the wear process, and (e) the end of wear surface.

of the WCI lay in the same worn surface prior to the abrasive wear process (see Fig. 15(a)). (ii) Pearlite was present in relatively low amounts, owing to the low hardness of the matrix in the initial stage of wear, as shown in Fig. 15(b). (iii) Some carbides protruded from the wear surface, thereby offering protection to the surrounding matrix with the increasing wear. Similarly, the matrix supported the cementite (see Fig. 15(c)). (iv) Cementite fractured and spalled off the worn surface, leading to a decrease in the protective effect of this phase (see Fig. 15(d)). The weight loss increased, and the wear resistance decreased at this stage. (v) During the last stage of the wear process, the cementite spalled off the worn surface, and then, the matrix protruded from this surface [28]. The composite wear mass loss increased only slightly.

In summary, when Cr was added to WCI, the hardness and toughness properties of the cementite improved, leading to an increase in the wear resistance of WCI. However, the interaction between the matrix and the cementite decreased because the combined protective and supporting effect decreased.

4 Conclusions

The interaction between cementite and pearlite with different Cr content levels in WCI was investigated using the two-body abrasive wear technique for wear testing. The major conclusions of this study are summarized as follows:

1) During the wear process, the carbide protected

the pearlite matrix and the matrix supported the carbide. The wear interaction involved a combination of these protection and support processes.

2) The increased Cr content led to a significant increase in the H , E , and H/E of the carbide, and thus, the wear resistance improved under loads of 20, 35, and 50 N. The wear resistance increased by 15.91%.

3) The roughness of the WCI decreased by 23.6% with increasing Cr content, owing to the increased hardness.

4) Brittle fracture and cracks formed due to abrasive microcutting were observed on the surface of the low-Cr cementite. However, when the Cr content was increased to 4 wt%, parallel grooves formed on the cementite surface, owing to the improved toughness of cementite.

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