Tribological Characteristics of High-Chromium Based Multi-Component White Cast Irons

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Abstract: It has been evaluated the relationship between the microstructure and three-body abrasive wear behavior of high-chromium (18 and 27 mass % Cr) based (3 mass % each of V, Mo, W, and Co) multicomponent white cast iron materials (high-Cr MWCIs). It was also compared to MWCI to determine the service life of the materials. The results indicate that the microstructure of the material is composed of mainly martensite matrix and different types of precipitated carbides. The wear resistances of both the high-Cr MWCIs are higher than MWCI owing to the higher hardness (4–18% increment in hardness), although they contain fewer carbide types. The carbide volume fraction of high-Cr MWCI increases with increase in the Cr content, but the hardness decreases, leading to a reduction in wear resistance. This is because the transition metal significantly consumes C atoms to form more eutectic carbides during solidification, which is exacerbated by the depletion of C in the matrix during heat treatment to form coarser secondary carbides. This means that increasing the addition of Cr does not always lead to an increase in the hardness or wear resistance of the material. In addition, the wear resistance of 27Cr MWCI after tempering (wear rate: 8.80 × 10^{-5} g/m) is higher than that after quenching (wear rate: 9.25 × 10^{-5} g/m) owing to the increase in the fracture toughness of M7C3 carbide. This is contrary to the case of 18Cr-MWCI; the wear resistance after tempering (wear rate: 5.29 × 10^{-5} g/m) is worse than that after quenching (wear rate: 5.11 × 10^{-5} g/m) owing to the reduction in hardness as a stress-relieving effect.

Keywords: abrasive wear; three-body abrasion; multicomponent white cast iron; carbide volume fraction; fracture toughness; hardness

1. Introduction

Since the early 1980s, high chromium cast iron (HCCI) containing 12–30 wt. % Cr and 2.0–4.3 wt. % C has been widely used for the manufacture of components and equipment that are subjected to abrasive conditions, such as crushers, pulverizers, rolling mills, bulldozers, truck buckets, and excavators [1,2]. Karl-Heinz Zum Gahr et al. [3] said that the good wear resistance of HCCI is attributed to the precipitation of hard phases especially M7C3, in the microstructure during the solidification process; a higher volume fraction of M7C3 has been reported to be the most desirable. Besides that, it has been known that hardness and types of abrasive also strongly influence the performance of this metals. R.B. Gundlach and J. L. Parks [4] stated that the wear resistance decreased as increasing hardness of the abrasive. The result also shows that the type of abrasive used in the test was a significant factor in ranking white irons for resistance to high stress abrasion.

The effect of destabilizing heat treatment on the microstructure and wear resistance of HCCI has been also documented. Yi Li et al. [5] have investigated the wear performance of HCCI with three coolant medium (water, 10% PAG, and 20% PAG). The result shows that HCCI with water-cooled had the highest Rockwell hardness good wear resistance and the greatest friction coefficient. Karantzalis et al. [6] reported that the microstructure of HCCI (2.35% C and 18.23% Cr) transformed from mainly austenitic...
matrix in the as-cast state to martensitic one during the heat-treatment process, resulting in higher hardness. Simultaneously, secondary carbides precipitate in the matrix area, the stoichiometry of which strongly depends on the time and temperature of the heat treatment. Sare et al. [7] investigated the effect of heat treatment on the abrasive wear resistance of HCCI. Although the amount of retained austenite and the hardness of HCCI was found to vary with the chemical composition, the wear resistance tended to decrease with an increase in the austenitizing temperature. Tabrett et al. [8] reported that subcritical heat treatment reduced the wear resistance of HCCI owing to the formation of ferrite/carbide. In addition, Fernandez et al. [9] found that the abrasive wear resistance of high-carbon HCCI was better than that of low-carbon HCCI after the heat-treatment process because of the higher hardness and carbide volume fraction (CVF). Even though most of the reported results show that microstructures containing mainly martensite (hardest matrix) are more wear-resistant than those containing other phases (austenite, pearlite, etc.), it is important to maintain the amount of retained austenite to prevent easy cracking. Tong et al. [10] claimed that a greater quantity of retained austenite has a higher abrasive wear resistance owing to the inhibition of fatigue-crack propagation and decrease in fatigue spalling. Qing-yu et al. [11] reported that the abrasion wear resistance and toughness of low-bainite HCCI increase with an increase in the amount of retained austenite, despite having a lower hardness. Xi et al. [12] revealed that retained austenite contributes to the wear resistance substantially at high loads and does not play a significant role at low loads because of its low hardness. This means that retained austenite influences the wear resistance of the material only in certain cases. In addition, the precipitation of secondary carbides during heat treatment should be considered because of their positive strengthening effects on the microstructure and wear resistance of materials [13,14]. In particular, Kishore et al. [15] studied the effect of soaking temperature on carbide precipitation, hardness, and wear resistance of HCCI. The highest wear resistance was obtained at 1100 °C, which was attributed to the disintegration of primary carbides and the highest volume fraction of secondary carbides at this temperature. Therefore, studies on the relationship between the microstructure and wear resistance of HCCI can be considered to have reached saturation point. However, the wear of moving mechanical components is one of the main causes for system failure and involves large operational costs [16]—approximately 210,000 million Euros is spent on material failure due to friction and wear in the mining industry per year (while producing 970 million tons of CO₂ emissions) [17]. The cost increases with the expansion of engineering fields, agriculture, pulp, and paper industry. Hence, continuous efforts are being directed to improve the wear resistance of HCCI.

Several scholars have explored the addition of transition metals, such as Mo, V [18,19], Nb [20], W [21], and Ti [22] in HCCI, and the wear resistance of HCCI was found to improve with the precipitation of MC, M₆C, or M₂₃C₆. Continuing this research, several transition metals have been simultaneously added to white cast iron to form multicomponent white cast iron (MWCI). Matsubara et al. [23] reported that the good abrasive wear resistance of MWCI (Fe-3% C-10% V-5% Mo-5% W) is caused by the precipitation of extremely hard carbides, viz. proeutectic MC, eutectic MC, and M₂₃C₆, in the martensite matrix. Kusumoto et al. [24] and Opapaiboon et al. [25] also reported similar results; MWCI exhibited higher wear resistance owing to the formation of various carbide deposits in the microstructure, such as VC, (Mo, W)₆C, and Cr₇C₃, despite its lower CVF than that of HCCI. De Mello et al. [26] investigated the abrasion performance of MWCI by using soft and fine abrasive particles. They concluded that the wear resistance of MWCI is strongly influenced not only by the eutectic carbide, but also by the matrix. In addition, the effects of Co (0–10 wt. %) on the high-temperature erosive wear resistance of MWCI (5 wt. % of Cr, V, Mo, and W; and 2 wt. % C) have also been reported previously. It was suggested that Co is not a carbide-forming element and preferably acts as a matrix reinforcement, leading to better wear resistance. However, the reverse trend should occur when the Co content exceeds 5 wt. % owing to hardness reduction [27]. From these results, the wear resistance of MWCI appears to improve at Cr contents > 5 wt. % owing to the possibility of forming
higher CVF. Meanwhile, the C content should also be increased from the hypo-eutectic range (<3 wt. % C) to the eutectic range (3 wt. % C) to maintain C insolubility in the microstructure of the material. While increasing the amounts of Cr and C, the percentage of other transition metals (V, Mo, W, and Co) should be reduced to 3 wt. % to prevent possible brittleness. Recently, we studied the erosive wear behavior of 18–27 wt. % Cr-based MWCI (3 wt. % of V, Mo, W, and Co) at high temperature (873 K) and room temperature [28,29].

However, there is an urgent need to investigate the relationship between microstructure and abrasive wear. This is because abrasive wear is the biggest contributor to mechanical failure (approximately 50%) caused by wear phenomenon compared to other types of wear (erosive, adhesive, corrosive, etc.) [30].

The objective of the present study is to elucidate the relationship between the microstructure and three-body abrasive wear characteristics of 18Cr- and 27Cr-MWCI after destabilizing heat treatment. In addition, the wear characteristics of the high-Cr MWCI were compared with that of the hypo-eutectic MWCI (5 wt. % of V, Cr, Mo, W, Co; and 2 wt. % C) to determine the service life of each material.

2. Materials and Methods

2.1. Materials Preparation

Two types of MWCI (3 wt. % of V, Mo, W, and Co), viz. 18Cr and 27Cr, were used for investigation of microstructure and wear behavior, and hypo-eutectic MWCI (5 wt. % of Cr, V, Mo, W, and Co) was used for comparison. The composition of each material was measured using a SPECTROLAB metal analyzer (AMETEK, Inc., Berwyn, PA, USA); the results are presented in Table 1.

| Materials   | C  | Cr  | V   | Mo  | W   | Co  | Si  | Mn  | Fe  |
|-------------|----|-----|-----|-----|-----|-----|-----|-----|-----|
| MWCI        | 1.92 | 4.84 | 4.79 | 5.26 | 4.90 | 4.89 | 0.62 | 0.23 | Bal. |
| 18Cr MWCI   | 3.01 | 17.64 | 2.83 | 2.79 | 2.91 | 2.76 | 0.42 | 0.28 | Bal. |
| 27Cr MWCI   | 2.98 | 27.35 | 2.86 | 2.94 | 2.82 | 2.73 | 0.51 | 0.31 | Bal. |

The detailed manufacturing process for each material is described in our previous paper [31]. Briefly, approximately 50 kg of raw material from each sample was melted using a high-frequency induction furnace. Then, the molten metal was poured into a sand mold, and the ingot was cut to dimensions of 50 mm × 50 mm × 10 mm using a high-speed precision cutting machine (Refinetech Co., Ltd., RCA-234, Kanagawa, Japan). The engineering drawings of the Y-block and the test piece are shown in Figure 1.

![Y-block and test piece drawings](image_url)

**Figure 1.** The dimension of Y-block and the finalized test piece.

Generally, HCCI is quenched after heating in the temperature range 1173–1423 K. This is followed with/without tempering after heating at 773–873 K to transform the austenite matrix to martensite and enable the precipitation of secondary carbide [15,32]. In this
study, both the high-Cr based MWCIs were quenched by forced-air cooling and tempered by air cooling within these heating temperature ranges for 3.6 ks. It is known that the hardness of a material considerably affects its wear resistance, although the toughness is also important in certain cases [32–37]. In this study, we selected only the material with the highest hardness; the effect of the destabilization heat treatment temperature will be considered in a future study. Accordingly, 18Cr- and 27Cr-MWCI heated at 1273 and 1323 K, respectively were used in the as-quenched (as-Q) category, and those tempered at 733 and 793 K, respectively were used in the quenched–tempered (as-Q&T) category. The hypoeutectic MWCI was quenched at 1323 K for 3.6 ks and then tempered at 798 K for 10.8 ks, as reported in a previous study [27].

2.2. Metallographic Observation and Hardness Measurement

The test pieces were etched with 5% nitrohydrochloric acid for metallographic observation by optical microscopy (OM; Eclipse MA100, Nikon, Tokyo, Japan). Scanning electron microscopy combined with energy dispersive X-ray spectroscopy (SEM + EDS; JSM-6510A, JEOL, Tokyo, Japan) and X-ray diffraction (XRD; Ultima IV, RIGAKU, Tokyo, Japan) were used to evaluate the microstructure and phase composition. The CVF and size of the carbide particles were calculated using ImageJ software.

Future-Tech Co. Ltd.: FV-800, Kanagawa, Japan Vickers hardness testers were used for measuring macrohardness of materials. The measurement data was obtained by 12 repetition of the test. Prior to the Vickers hardness test, each material was cut to dimensions of 10 mm × 10 mm × 10 mm and polished.

2.3. Three-Body Abrasive Wear Test

The three-body abrasive wear tests (KOS21 Co., Ltd., Ehime, Japan) were carried out according to the ASTM G65 standard using a rubber wheel apparatus type as shown in Figure 2a. The rubber wheel (ϕ: 228.6 mm, width: 12.7 mm) which is rotated at a specific speed (100 ± 1 rpm) pulls the silica sand (SiO$_2$) into the contact area, abrading the surface of the specimen. Three different normal loads were applied for 360 s: 73.5, 147, and 196 N. The SiO$_2$ (Figure 2b) abrasive particles were supplied at a rate of approximately 4.2 g/s from the hopper. The size distribution of SiO$_2$ is shown in Figure 2c. The test was repeated thrice, and the material surface was initially polished using a surface grinder (GS52PF, Kuroda Seiko Co., Ltd., Kanagawa, Japan) to ensure that the roughness of the material was uniform (approximately 0.2 µm) before each test. Prior to the testing, each test specimen was cleaned by immersing in liquid ethanol for 5 min followed by drying with a fan. The same action also was conducted after the test to ensure that no dust adhered to the surface of the specimen. The weights of the samples were measured using an electronic scale (GH-300 produced by A&D Co., Ltd., Tokyo, Japan), and the weight loss was calculated by subtracting the weight before and after the wear test. The wear rate of the materials was calculated by dividing the weight loss by the sliding distance, as shown in Equation (1).

$$\text{Wear rate} = \frac{\Delta m}{\pi dt n} \quad (1)$$

where $\Delta m$ is the material weight loss (kg), $d$ is the diameter of the wheel (m), $t$ is the time (s), and $n$ is the rotating speed (rpm).
3. Results and Discussion

3.1. Microstructure Characterization

To know the phase of each material’s microstructure, it has been used X-ray diffraction (XRD), as shown in Figure 3a–c. The result shows that only the martensite matrix is indexed in MWCI and the high–Cr MWCIs. Because only the materials with the highest hardness after quenching (1173–1423 K) with/without tempering (773–873 K) were selected, the amount of retained austenite in the specimens may be too small for detection by XRD. In addition, some carbides are detected in MWCI and both the high–Cr MWCIs. This reveals that V is dissolved in $M_7C_3$ and $M_{23}C_6$ with Cr and C in the high–Cr MWCIs while it crystallizes as VC in MWCI. In addition, W and Mo are simultaneously dissolved in $M_2C$ in all the specimens. Moreover, Co is not detected in any type of carbide, implying that it is not a carbide-forming element. The presence of $M_7C_3$ and $M_3C$ peaks in the XRD pattern of MWCI confirms that there are more carbide types in MWCI than in both the high–Cr MWCIs. The peak intensities of $M_7C_3$ and $M_3C$ are low; hence, these phases were not observed in the SEM microphotographs of MWCI.

The microstructures of the materials after etching with 5% nitrohydrochloric acid for several minutes are shown in Figure 4. The microstructure is composed of matrix (dark area) and carbide (bright area). SEM and EDS were used to determine the distribution of
each added element (Figure 5). It is known that C atoms have high affinity for the added transition metals, promoting the formation of carbides in the microstructure during the solidification process. Based on the thermodynamic data of carbides, the enthalpies of mixing (ΔHmix) of Cr–C, V–C, Mo–C, and W–C to form corresponding Cr7C3, VC, Mo6C, and W6C carbide types are −14.98, −46.09, −21.35, and −10.78 kJ/mole, respectively. It is known that larger the negative value of ΔHmix stronger is the ability to solidify in the microstructure [38,39]. However, Mo and W do not solidify as M2C either in the MWCI or in the high–Cr MWCIs; rather, they form M2C. Moreover, V is dissolved as VC in MWCI, whereas it co-exists with Cr and C to form M2C3 in the high–Cr MWCIs. The presence of M2C3 in MWCI is difficult to observe owing to the small amount of Cr. In addition, the matrix is mostly composed of Fe and Co, which is in accordance with previous studies [27,28]. The stoichiometries of all the carbides were determined by point analysis at 10 random locations using SEM and EDS. Although V has a stronger ΔHmix than Cr, the small amount of V hinders its ability to form VC. Moreover, the simultaneous dissolution of Mo and W with C in M2C carbide also prevents the formation of M6C. Thus, it can be considered that the ability of each transition metal to form carbides is highly dependent on its content and not only on the value of ΔHmix. From Figure 5, the M2C3 carbide of high–Cr MWCIs appears to be the major type of precipitated hard phase, and its particle size increases with increase in the Cr content. The carbide particle sizes are discussed in detail in Section 3.5.

Figure 3. X-ray diffraction patterns of (a). MWCI; (b). 18Cr MWCI as–QT; (c). 27Cr MWCI as–QT.

Figure 4. Optical micrograph of: (a). MWCI; (b). 18Cr MWCI as–QT; (c). 27Cr MWCI as–QT.

In general, the austenite matrix of MWCI transforms into martensite or bainite, and a small amount of retained austenite exists during the destabilization heat treatment. In addition, transition metals can still react with adjacent C atoms in the matrix to form secondary carbides [9,11–13]. Similar results are obtained in the present study; the matrix has a needle-like morphology (Figure 6) indicating that martensite is the primary matrix. Plenty of fine secondary carbides (M23C6), which precipitated during the destabilization heat treatment, are observed in the matrix. The secondary carbide particles in 27Cr MWCI appear to be coarser than those in 18Cr MWCI, which is attributed to its higher Cr content.
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Table 2 shows the CVFs of each test material obtained from five SEM microphotographs using ImageJ software. It is evident that the CVF of the eutectic carbide increases with the addition of Cr owing to the microsegregation process in iron melts during solidification. Consequently, 27Cr MWCI has a higher CVF of eutectic carbide than that in MWCI and 18Cr MWCI. However, there is no significant difference between the CVFs of as–Q and as–Q&T high–Cr MWCIs with the same Cr content, which may be attributed to the high thermal properties of the eutectic carbide. The CVF of secondary carbide (M23C6) also
shows the same trend—it increases with increase in the Cr content, but there is no significant difference between the secondary CVFs of as–Q and as–Q&T in 18Cr MWCI and 27Cr MWCI. In addition, the MWCI has a higher amount of \( M_{23}C_6 \) than that of 18Cr MWCI, but there is no significant difference in the amount of \( M_{23}C_6 \) in MWCI and 27Cr MWCI, which must be caused by the difference in the overall chemical composition and the heat treatment process. The effects of all these factors on the hardness and three-body abrasive wear of each material is discussed in the following section.

### Table 2. The carbide volume fraction of each material.

| Material       | Eutectic Carbide (%) | Secondary Carbide (%) |
|----------------|----------------------|-----------------------|
|                | MC \( M_7C_3 \) \( M_2C \) \( M_{23}C_6 \) |
| MWCI           | 8.03 ± 0.41          | 8.79 ± 0.27           | 5.08 ± 0.25 |
| 18Cr MWCI      | -                    | 19.13 ± 0.96          | 2.41 ± 0.13 | 2.51 ± 0.13 |
| as–Q           | -                    | 19.15 ± 0.96          | 2.21 ± 0.11 | 3.21 ± 0.16 |
| as–QT          | 23.96 ± 1.19         | 2.6 ± 0.13            | 5.67 ± 0.28 |
| 27Cr MWCI      | -                    | 24.75 ± 1.24          | 2.71 ± 0.14 | 5.69 ± 0.28 |
| as–Q           | -                    | 23.96 ± 1.19          | 2.6 ± 0.13  | 5.67 ± 0.28 |
| as–QT          | 24.75 ± 1.24         | 2.71 ± 0.14           | 5.69 ± 0.28 |

#### 3.2. Hardness

The Vickers hardness value of each material is shown in Figure 7 obtained from 12 repeated measurements, and the error bars show the standard deviations. The hardness of high–Cr MWCIs is significantly higher than that of MWCI, which is consistent with the improvement in the CVF. However, the opposite is true when comparing only the as–Q and as–Q&T high–Cr MWCIs. It is believed that the material containing more Cr will naturally bind more C during the microsegregation process, which can be confirmed by the higher amount of CVF. However, with excessive addition of transition metals, a lower concentration of C is embedded in the matrix zone. Eventually, the hardness of the material decreases as the Cr content increases. In addition, the depletion of C in the matrix during the destabilization heat treatment to form coarser secondary carbides must also be associated with the reduction of material hardness with increase in the Cr content. Meanwhile, the lower micro-or macro-hardness of the tempered specimens compared to the quenched ones must be caused by the stress-relieving phenomenon. 18Cr MWCI as–Q exhibits the highest hardness (1022.00 ± 51.10) HV50, while MWCI exhibits the lowest values (867.00 ± 43.34) HV50. The hardness values are related to the three-body abrasive wear behavior of each material. However, it can be argued that a higher amount of transition metal or CVF in white cast iron does not always guarantee a harder material when the carbon content in the matrix is too low.

#### 3.3. Three-Body Abrasive Wear Performance of Materials

Most of the previous studies reveal that the wear rate of white cast iron increases with increasing the load [12,40]. Similar results are obtained in the present study—the two representative materials exhibit greater material losses at higher given loads, as depicted in Figure 8. To obtain abrasive wear data closer to that in actual engineering application, observations were focused on the highest applied load; the results are shown in Figure 9. The abrasive wear rate reported herein is the average value of three measurements, and the error bars show the standard deviations.

Despite having more carbide types, the abrasive wear rate of MWCI \((1.588 ± 0.191) \times 10^{-4} \text{ g/m} \) is significantly higher than that of both the high–Cr MWCIs. The significant increase in the abrasive wear resistance is attributed to the higher CVF and the higher hardness of the high–Cr MWCIs than those of MWCI. However, the increment in CVF with increase in the Cr content is not consistent with the wear resistance in the cases of as–Q and as–Q&T high–Cr MWCIs. This result differs from those of previous studies. The reduction in the abrasive wear resistance is definitely due to the significant consumption.
of C by Cr to produce a larger volume fraction of $\text{M}_7\text{C}_3$, resulting in a smaller amount of C in the matrix area. In addition, more secondary carbide ($\text{M}_{23}\text{C}_6$) formation during the destabilization heat treatment process may also deplete the C atoms in the matrix, which worsens the abrasive wear resistance of the material. Both these arguments can be verified by the decrease in microhardness (matrix only) with an increase in the Cr content. Therefore, it is reasonable to argue that a wider variety of carbide types embedded in the microstructure of a material does not necessarily guarantee better abrasive wear resistance; rather, it is more influenced by the CVF. However, in materials with the same types of carbides, the abrasive performance strongly depends on the solubility of C in the matrix and is not significantly affected by the CVF (eutectic and secondary carbides).

But, when comparing only the high–Cr MWCI samples with the same Cr content, the wear rate of 18Cr-MWCI as–Q ($0.511 \pm 0.061 \times 10^{-4} \text{ g/m}$) is lower than that of as–Q&T ($0.529 \pm 0.065 \times 10^{-4} \text{ g/m}$), which may be attributed to the higher hardness. However, the same is not true in the case of 27Cr MWCI. Despite its lower hardness, the as–Q&T specimen ($0.880 \pm 0.106 \times 10^{-4} \text{ g/m}$) is more resistant to abrasives than the as–Q specimen ($0.920 \pm 0.110 \times 10^{-4} \text{ g/m}$). This suggests that the hardness of the material is not always the main factor that determines the three-body abrasive wear performance of high–Cr based MWClis, and additional factors may be involved. Hence, we investigated the abrasive wear behaviors of the materials from another point of view.
3.4. Three-Body Abrasive Wear Mechanism

Figure 10 shows the morphologies of the worn surfaces of the specimens after the wear test at the highest applied load (196 N). The grooves represent the three-body abrasive wear zone; 18Cr MWCI as–Q exhibits better abrasion resistance than the others. In the high-magnification SEM image, micro-cutting is observed mainly in the material matrix (top right corner of Figure 10). It is believed that microcutting occurs along the matrix owing to the lower microhardness (matrix only) than the macrohardness (1100 HV), and it can be suppressed by increasing the hardness of the material. In addition, micro-pits, mostly localized in the carbide region, are observed on all the worn surfaces. This may be caused by the brittleness of carbides, which leads to easy peel off. It is interesting to note that almost all the M7C3 carbides peel off easily in the case of 27Cr MWCI as–Q, whereas they are intact in 27Cr MWCI as–Q&T. However, it is difficult to ascertain the different behaviors of M7C3 carbides in as–Q and as–Q&T 18Cr–MWCI. Therefore, cross-sectional studies of the most abraded material surfaces were carried out.

The cross-sectional SEM images of the specimens are shown in Figure 11. MWCI exhibits severe wear, whereas mild wear is observed in 18Cr MWCI as–Q, consistent with the observations of worn surface morphologies. The matrix of 18Cr MWCI as–Q&T seems...
worse than that of as–Q, which may be attributed to the lowering of the hardness after tempering. However, the matrix conditions of 18Cr MWCI as–Q and Q&T are better than those of 27Cr MWCI as–Q and Q&T, which may also be ascribed to its higher hardness. Interestingly, the main carbide (M₇C₃) and the matrix of 27Cr MWCI as–Q show abrasive wear, whereas the carbide phase is intact in the case of 27Cr MWCI as–Q&T. This may be the reason for the increase in the wear resistance of 27Cr-MWCI after tempering. Because the size of M₇C₃ in 27Cr MWCI is much larger than that in 18Cr MWCI, direct peel-off of M₇C₃ is possible. However, this tendency is reduced by the stress-relieving effect of tempering. Therefore, the characteristics of M₇C₃ should be thoroughly evaluated to prevent the speculation results provided in the next section. It can be considered that the abrasive particle would first scrape the matrix, leaving micropitting paths, and then impact the carbide particles with concentrated stress, producing pits on the worn surface. Once the abrasive impacts the M₇C₃ carbide, the coarser ones easily peel out because of their brittle nature. Therefore, the main abrasive wear mechanism in the present study is micropitting, and the sub-mechanism is micropitting.

![Cross-sectional condition of each material after three-body abrasive wear test.](image)

**Figure 11.** Cross-sectional condition of each material after three-body abrasive wear test.

### 3.5. Size, Hardness, and Fracture Toughness of Primary M7C3 Carbide

Typically, a higher Cr content produces a larger M₇C₃ carbide particles, which is also observed in the present study (Figure 12). The size of M₇C₃ carbide was measured using ImageJ software from five different locations in the SEM image. The fracture toughness of this hard phase was evaluated through microindentation, as illustrated in Figure 13, and Equation (2) was used for calculation [41,42]. As mentioned before, M₇C₃ of MWCI is not involved, as its lower abrasive wear resistance is caused by the lower CVF compared with that of the high–Cr MWCLs. In addition, only the hexagonal primary M₇C₃ carbide is intact after the test, as shown in the SEM images of the worn surface and cross-section (Section 3.4), which is one of the main abrasive wear factors, particularly in the case of 27Cr MWCI. Therefore, the measurements were conducted only on the primary M₇C₃ carbide, as shown in Figure 14, to minimize the possibility of data errors. In addition, the hardness of the main carbide was measured to determine the relationship between its hardness and fracture toughness. The obtained results (from 10 measurements) suggest that the addition of Cr not only increases the size of M₇C₃ but also effectively enhances the hardness of this carbide. Nevertheless, the fracture toughness is reduced with coarsening and hardening of M₇C₃. This is in good agreement with many published scientific papers [43–45].
addition, the carbide hardness of as–Q&T is lower than that of as–Q in 18Cr MWCI and 27Cr MWCI; this must be caused by the stress-relieving phenomenon during the tempering process, which results in higher toughness.

\[ K_c = \alpha (EP)^{1/2} \left(\frac{d}{2}\right) a^{3/2} \]

(2)

where \( K_c \) is the fracture toughness (Pa.m\(^{1/2}\)), \( E \) is the Young’s modulus of M\(_7\)C\(_3\) carbide (310 GPa) [42], \( \alpha \) is the calibration factor (0.026), \( P \) is the load (2.9 N), \( a \) is the half-length of the crack, and \( d \) is the diagonal length of indentation.

Figure 12. The M\(_7\)C\(_3\) carbide size distribution of high–Cr MWCI materials.
Figure 13. Schematic of micro-indentation using Vickers's hardness machine test.

Figure 14. Footprint images after micro-indentation and properties (hardness and fracture toughness) of M₇C₃ carbide.

From the above findings, it can be concluded that a higher M₇C₃ carbide fracture toughness of 27Cr MWCI as–Q&T can provide better wear resistance because of its ability to withstand peel-off. On the other hand, the matrix hardness is more important in the case of 18Cr MWCI; a harder matrix (as–Q) provides better wear resistance. Thus, it is crucial to correlate the three-body abrasive wear characteristics of the material and the
microstructure constituents (CVF, matrix hardness, and carbide fracture toughness) to determine the service life of the material.

4. Conclusions

The relationship between the microstructure and the three-body abrasive wear resistance of MWCI and the high–Cr MWCIs can be summarized as follows:

1. The wear resistance of the high–Cr MWCIs is higher than that of MWCI owing to their higher CVFs.
2. The wear resistances of as–Q and as–Q&T 18Cr MWCI are better than that of 27Cr MWCI because of the higher matrix hardness, despite their low CVFs (eutectic and secondary carbide).
3. The wear resistance of 27Cr MWCI is slightly increased by the tempering process owing to the higher fracture toughness of the $M_7C_3$ carbide. This is contrary to the case of 18Cr MWCI; its wear resistance is more influenced by the matrix hardness.
4. It is important to consider all the microstructure constituents to accurately evaluate the three-body abrasive wear resistance of high–Cr MWCI.

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