

Article

Three-Body Abrasive Wear Performance of High Chromium White Cast Iron with Different Ti and C Content

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Abstract: The need for better wear-resistant materials to reduce cost and save the environment is noteworthy. The striking wear resistance of high chromium white cast iron (HCCI) has made it industry's predominant choice. The three-body abrasive wear resistance performance of HCCI was investigated based on combined Ti and C. The Ti and C content varied in different percentages. The addition of Ti resulted in refined M_7C_3 carbides and TiC crystallization. The hardness was significantly affected by the addition of Ti. The increment in Ti content resulted in a decrease in the hardness, leading to a higher wear rate. However, the individual contribution of C led to higher hardness and, hence, better wear resistance, which is contrary to Ti. Out of the three specimens with 3, 3.5, and 4 wt.% C content, the 4 wt.% C series showed the highest hardness but the lowest wear rate and depth. This study found that the combination of a lower percentage of Ti with a higher percentage of C in HCCI can have a worthwhile result in abrasive wear.

Keywords: abrasive wear; high chromium white cast iron; titanium; carbon



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1. Introduction

Abrasive wear is the phenomenon in materials that takes place between two contact surfaces of different hardness levels [1], where the material surface is scraped off by particles of high hardness [2]. Abrasive wear is one of the most significant occurrences that cause mass loss, damage, and component failure in industry [3,4]. Industrialized nations spend an estimated 1–4% of their gross national product due to abrasive wear loss. Hence, a study for atypical and effective abrasive-wear-resistant materials is highly expected [5,6].

Due to their exceptional wear resistance, high-chromium white cast irons (HCCIs) are extensively used in places that are susceptible to wear [7]. HCCIs are ferrous alloys with chromium content ranging from 12–30 wt.% to 1.6–3.6 wt.% [8]. A significant number of researchers have investigated the contributions of transitional materials to upgrade the wear resistance of cast irons. It has been well articulated in previous research that transitional materials play a remarkable role in modifying their stoichiometry and forming carbides that have an important influence on the wear characteristics of HCCI. These additions target reshaping the eutectic carbide to enhance hardness, upgrading the hardenability of the matrix, and suppressing the pearlite formation in areas with these alloying elements between the eutectic carbides and the matrix [9,10]. The C concentration in the matrix has enormous significance on the carbide volume fraction (CVF). In addition, the CVF, which is increased by higher C content, leads to enhanced hardness and wear resistance [11]. In as-cast conditions, these alloys consist of a mainly metastable austenitic matrix with M_7C_3 carbide [12], which can be transformed into martensite by heat treatment [13]. High hardness and wear resistance of these alloys can be achieved with an abundance of M_7C_3 eutectic carbides. A high percentage of C and Cr results in a high volume of eutectic carbides, leading to superior hardness and wear resistance; however, it is detrimental to fracture toughness [14]. HCCIs solidify as primary austenite dendrites with a network of interdendritic eutectic carbides. Mostly, the austenite matrix will be transformed into

martensite during the destabilization heat treatment process [8,15–18]. Austenitic irons have hardness in the range of 500–520 HV, and this type of cast iron can be used in a few areas. However, heat-treated irons are essential for broader applications. Heat treatment at 920–1060 °C for 1–6 h, which may vary due to different alloy contents, and air quenching at room temperature destabilize the austenite through precipitations of Cr-rich secondary carbides; the purpose of this heat treatment is hardening [19]. The formation of MC carbides with excellent hardness and spherical morphology is expected to toughen the HCCI. In addition, the formation of primary MC carbides is generally seen at the beginning of the solidification, along with being finely distributed in the iron matrix. The addition of Ti, Nb, and V can significantly assist in the production of MC primary carbides, which has been studied by a significant number of researchers. Bedolla et al. [12,13,20] found that NbC and TiC carbide formation was the result of Nb and Ti additions. Xiaojun et al. found that TiC can contribute to generating primary M_7C_3 carbides, which leads to the remarkable refinement of the final grain size without clustering in the matrix [21]. The toughness of the matrix is also an important factor for wear resistance [22]. Methods such as semi-solid forming [23] and rare earth processing [24,25] have been employed to increase the toughness of HCCI by improving the size of the primary M_7C_3 carbides, though these methods have had limited success.

Several studies have been carried out on the erosive wear or abrasive wear of HCCI to find the effect of transition metals. However, papers focused on the combined effect of Ti and C content on the three-body abrasive wear of HCCI are still inadequate. This paper thoroughly investigates the three-body abrasive wear performance of HCCI with different Ti and C contents.

2. Experimental Procedures

2.1. Materials Preparation

In this current study, high-Cr white cast iron, with 27% Cr used as the base metal, was mixed with varied C contents of 3, 3.5, and 4 wt.% and Ti contents of 0, 1, and 2 wt.%. A total of nine specimens were prepared. The manufacturing process of the materials can be explained briefly. A total of 50 kg of raw materials was melted in a high-induction furnace followed by pouring into a sand mold of 53 mm × 250 mm × 15 mm. Second, each material was cut in dimensions of 50 mm × 10 mm × 10 mm using a high-speed precision cutting machine (Refinotech Co., Ltd., RCA-234, Kanagawa, Japan). The material composition is given in Table 1; SPECTROLAB (AMETEK, Inc., Berwyn, PA, USA) was employed to measure this composition. 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 analyze the microstructure before and after etching in 5% nitro-hydrochloric acid. The carbide volume fraction (CVF) was evaluated by ImageJ software [26]. A grinding machine (GS52PF; Kuroda Seiko Co., Ltd., Kanagawa, Japan) was used to clean the surface of the test materials to make sure that the roughness of each specimen was uniform (approximately 0.21 µm).

Table 1. Chemical composition of the specimens (wt.%).

Test Material	C	Si	Mn	Cr	Ti	Fe
3C-0Ti	3.07	0.48	0.43	27.18	0.01	Bal.
3C-1Ti	3.02	0.49	0.44	27.10	1.09	Bal.
3C-2Ti	3.02	0.51	0.44	26.92	1.87	Bal.
3.5C-0Ti	3.48	0.45	0.44	27.34	0.06	Bal.
3.5C-1Ti	3.48	0.46	0.45	27.18	1.18	Bal.
3.5C-2Ti	3.49	0.47	0.45	27.02	2.09	Bal.
4C-0Ti	3.88	0.49	0.41	27.50	0.07	Bal.
4C-1Ti	3.82	0.51	0.42	27.18	1.24	Bal.
4C-2Ti	3.88	0.52	0.42	26.91	2.35	Bal.

Conventionally, HCCI is quenched after heating in the temperature range of 1173–1423 K, followed by tempering after heating at 693–813 K to transform the austenite to martensite and precipitate the secondary carbide [11,19,27,28]. However, Purba et al. found that high-chromium-based multi-component white cast iron shows the best erosive wear resistance with quenching only [29]. Many research papers show that the superior wear resistance of the material is the result of increased hardness, even though the toughness needs to be controlled in particular instances by keeping a small portion of austenite in the microstructure after heat treatment [26,30]. As a result, materials with the highest hardness will be chosen that may have a minimal quantity of retained austenite (RA) in the microstructure after destabilization heat treatment within a suitable temperature range. On the other hand, extended research can be conducted on the effect of the heat-treatment temperature on the wear characteristics of specimens. Therefore, the specimens in this research were heated in the temperature range of 1273–1323 K, followed by air force cooling. The phase of the microstructure of the material was identified by using X-ray diffraction (Ultima IV, Rigaku, Japan, with a Cu-K α source). The following formula was utilized to evaluate the volume fraction of RA, (f_{RA}):

$$f_{RA} = \frac{100\%}{1 + G \left(\frac{I_{\alpha}}{I_{\gamma}} \right)} \quad (1)$$

where I_{α} and I_{γ} are the peak intensities of α -Fe (200), (211) and γ -Fe (200), (220), (311), and G is the coefficient proportionate to the distinct composition as suggested in [31].

2.2. Three-Body Abrasive Wear Testing

A rubber wheel three-body abrasive wear machine (KOS21 Co., Ltd., Ehime, Japan) under ASTM G65 was employed to evaluate the abrasion characteristics of each material, as shown in Figure 1a. The applied load was 196 N during the test. The sliding distance was about 430 m, with a sliding speed of 1.2 m/s. For abrasive particles, number 6 silica sand (Figure 1b) with a hardness of 1100 HV and size of 300 μ m was used. In each test, about 2.5 kg of particles was poured into the sand-supply hopper. At the time of the experiment, the abrasive particles were poured spontaneously on the surface of the test material. The following equation was utilized to calculate the wear rate of the specimens:

$$\text{Wear Rate} = \frac{\Delta m}{\pi d t n} \quad (2)$$

where Δm is the material weight loss, d is the diameter of the wheel, t is the time, and n is the rotating speed.

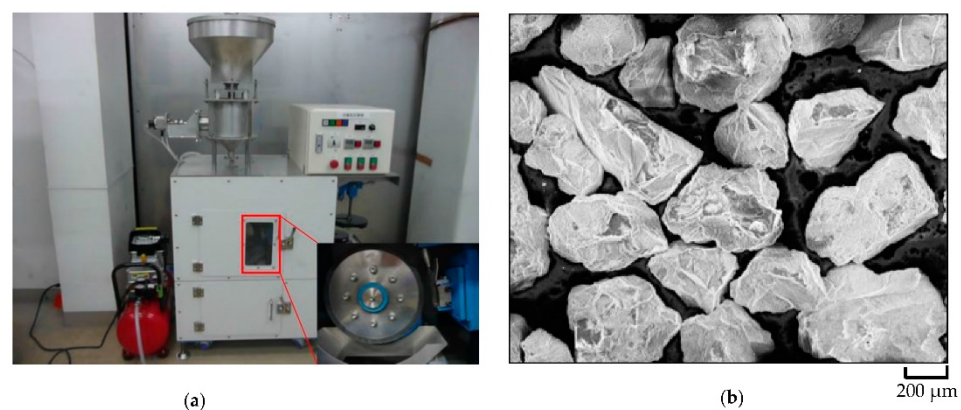


Figure 1. (a) Three-body abrasion machine test according to ASTM G65. (b) Abrasive particles (SiO_2 , 300 μ m).

2.3. Vickers Hardness Test

Each material was cut with dimensions of 10 mm × 10 mm × 10 mm and polished afterward. To evaluate the micro-hardness and macro-hardness (applied load HV 0.1 Kgf and 30 Kgf, respectively) of the materials, Future-Tech Co., Ltd.: FV-800, Kanagawa, Japan Vickers hardness testers were utilized. The micro-hardness signifies the matrix hardness, and the macro-hardness signifies the hardness of the entire material (both matrix and carbide).

3. Results and Discussion

3.1. Microstructural Characterization

The microstructure of materials such as HCCI is one of the most significant factors in analyzing the wear properties of the material. On that account, the test materials were individually etched in 5% nitro-hydrochloric acid for 6 min, followed by observation using the scanning electron microscope. The microstructures of all nine specimens are displayed in Figure 2. It is illustrated by the images that a substantial number of carbides are precipitated in the microstructure. It is shown that irrespective of the percentage of C or Ti, primary eutectic carbide M_7C_3 precipitates in all the specimens. Previously, several studies [32–35] have been carried out to demonstrate the shape of the M_7C_3 carbide. It has been found that the M_7C_3 carbide comprises a hexagonal bravais lattice owing to its hexagonal shape; however, in particular instances, an orthogonal crystal structure can be noticed. With the addition of Ti, TiC starts to appear. The precipitation of TiC has an apparent impact on M_7C_3 carbide. The amount of M_7C_3 carbides begins to decline as a consequence of the rising percentage of Ti. The cause behind the falling amount of M_7C_3 carbide is the behavior of Ti to precipitate ahead of M_7C_3 ; hence, Ti consumes C in the first instance. The deficiency of C to form M_7C_3 leads to the shortfall of M_7C_3 . The amount of M_7C_3 starts to decrease with the precipitation of TiC, and the size of the M_7C_3 carbide shrinks as well. Figure 3 shows the carbide size distribution. It illustrates a downward trend in the average particle size, with values of 12.6, 7.06, and 6.7 μm for the Ti contents of 0, 1, and 2 wt.%, respectively, in the case of 3wt.% C. The same trend is also observed for 3.5 and 4 wt.% C. The possible phenomenon to shrink or refine M_7C_3 carbide is that when the Ti starts to consume the C, the affinity of the C content in the iron melt is low for chromium carbide, resulting in the refinement of M_7C_3 . A previous study is in good agreement with this present study [11]. However, a reverse occurrence is observed when the test materials are enriched with a higher percentage of C. With an enhancement of the C content, the number of M_7C_3 carbides starts to escalate. The amount of M_7C_3 starts to increase with an increase in the C content, and the size of the M_7C_3 carbide increases as well. A trend in the size enhancement of M_7C_3 is observed. The average particle size is 12.6 and 32.6 μm for the C content of 3 and 4 wt.%, respectively, in the case of 0 wt.% Ti. A similar trend is also observed for 1 and 2 wt.% Ti specimens. A plausible explanation for this occurrence is the strong carbide-forming behavior of Cr. A higher percentage of C is segregated by the higher amount of Cr. In addition, the stoichiometry of M_7C_3 might adequately increase the amount of M_7C_3 and increase the size. Figure 4 shows the X-ray diffraction (XRD) pattern of 3.5 wt.% C specimens.

The carbide precipitation characteristics of 27 Cr appear to be compactly dispersed. The dispersion of the supplemented transition metal in the microstructure is challenging to identify. That being so, the 4 wt.% C test specimens with 0, 1, and 2 wt.% Ti were analyzed by EDS mapping. The results are illustrated in Figure 5a–c. It can be found from the microphotographs of the SEM-EDS images that the dark carbides are predominantly inhabited by Cr. A dense distribution approach of M_7C_3 increases with the increase in C content. However, the reverse behavior is noticed with the increase in Ti content. The inadequacy of M_7C_3 is because of the advanced precipitation of TiC. The higher percentage of C and Ti results in the agglomeration of TiC due to the greater affinity of C.

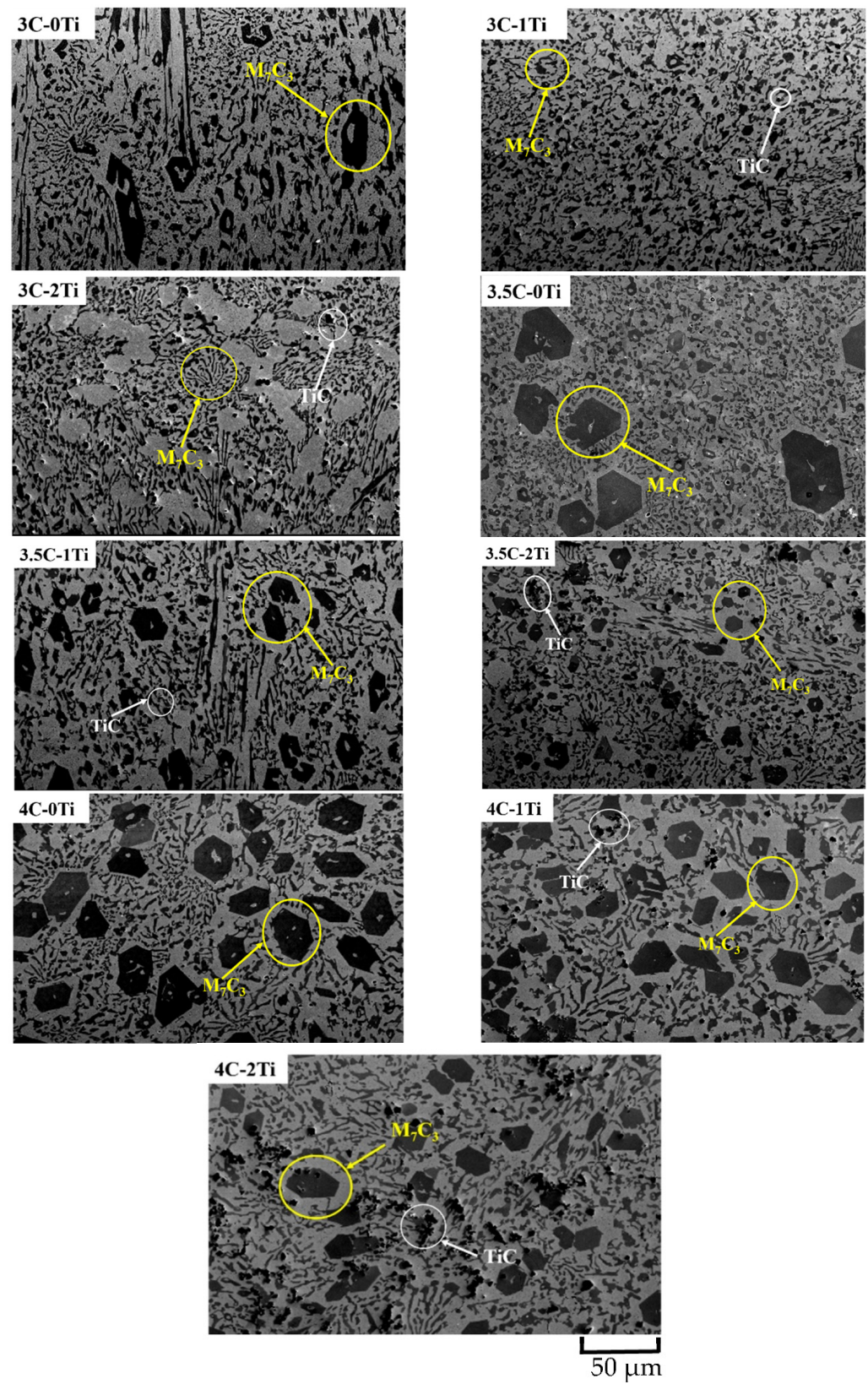


Figure 2. Microphotograph of matrix and carbide through SEM (yellow circles denote M_7C_3 carbides, and white circles denote TiC carbides).

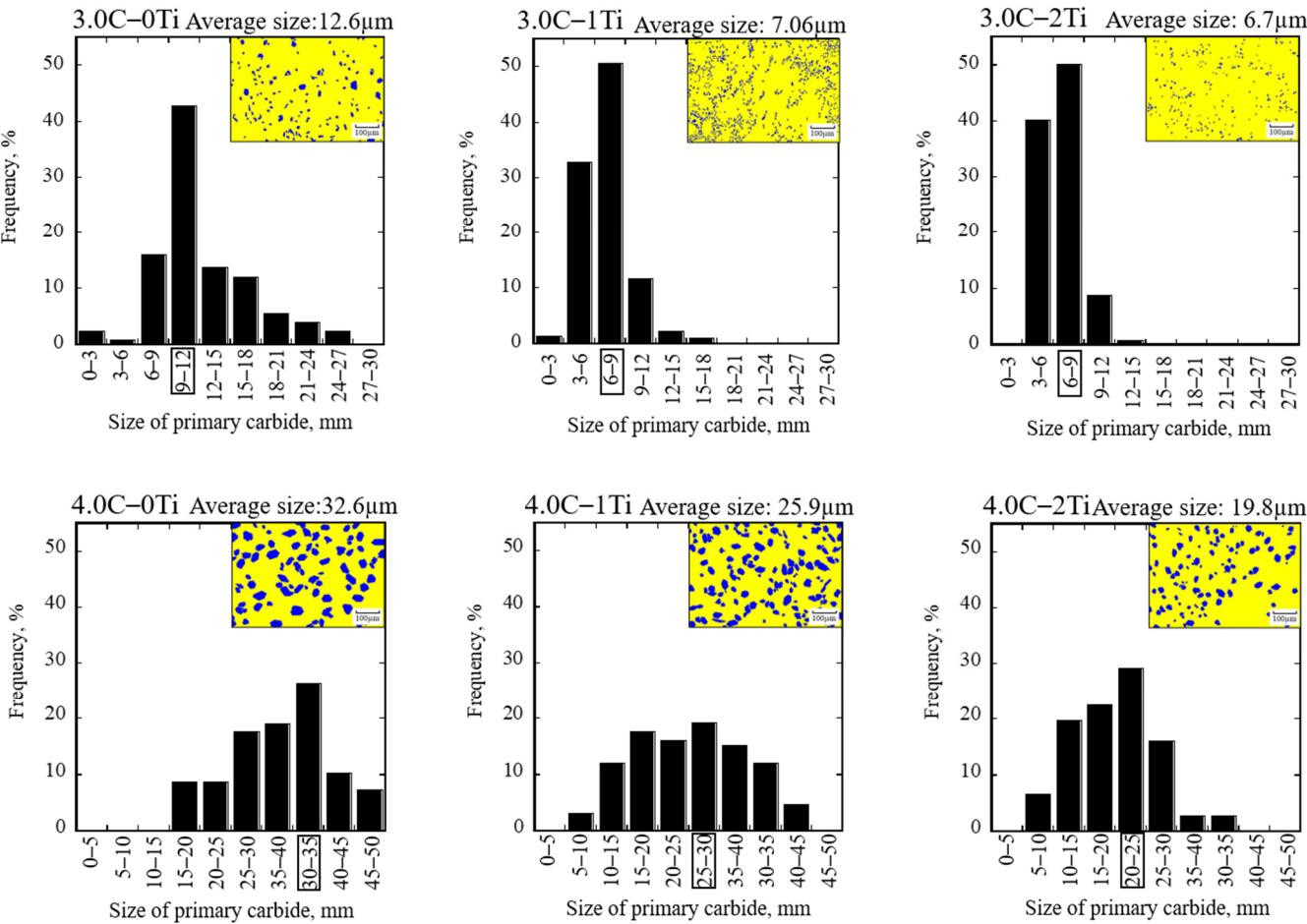


Figure 3. Carbide size distribution for the 3 wt.% C and 4 wt.% C specimens.

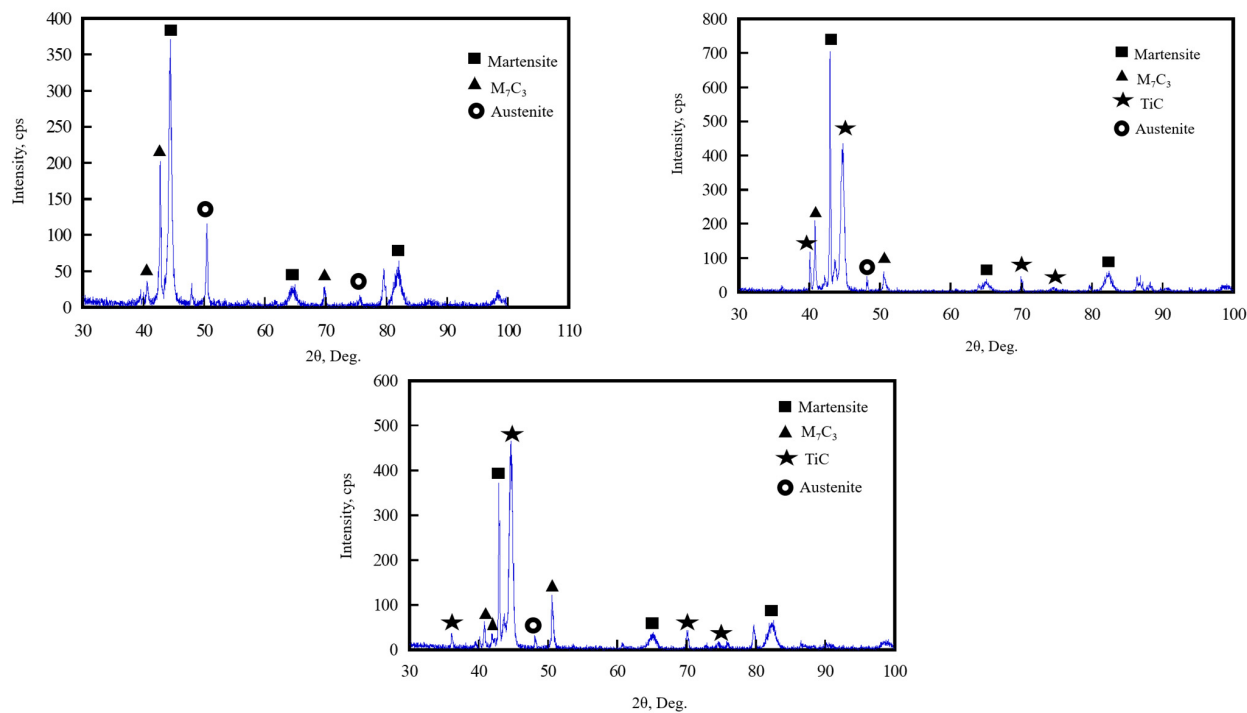


Figure 4. X-ray diffraction (XRD) patterns of the 3.5 wt.% C specimens.

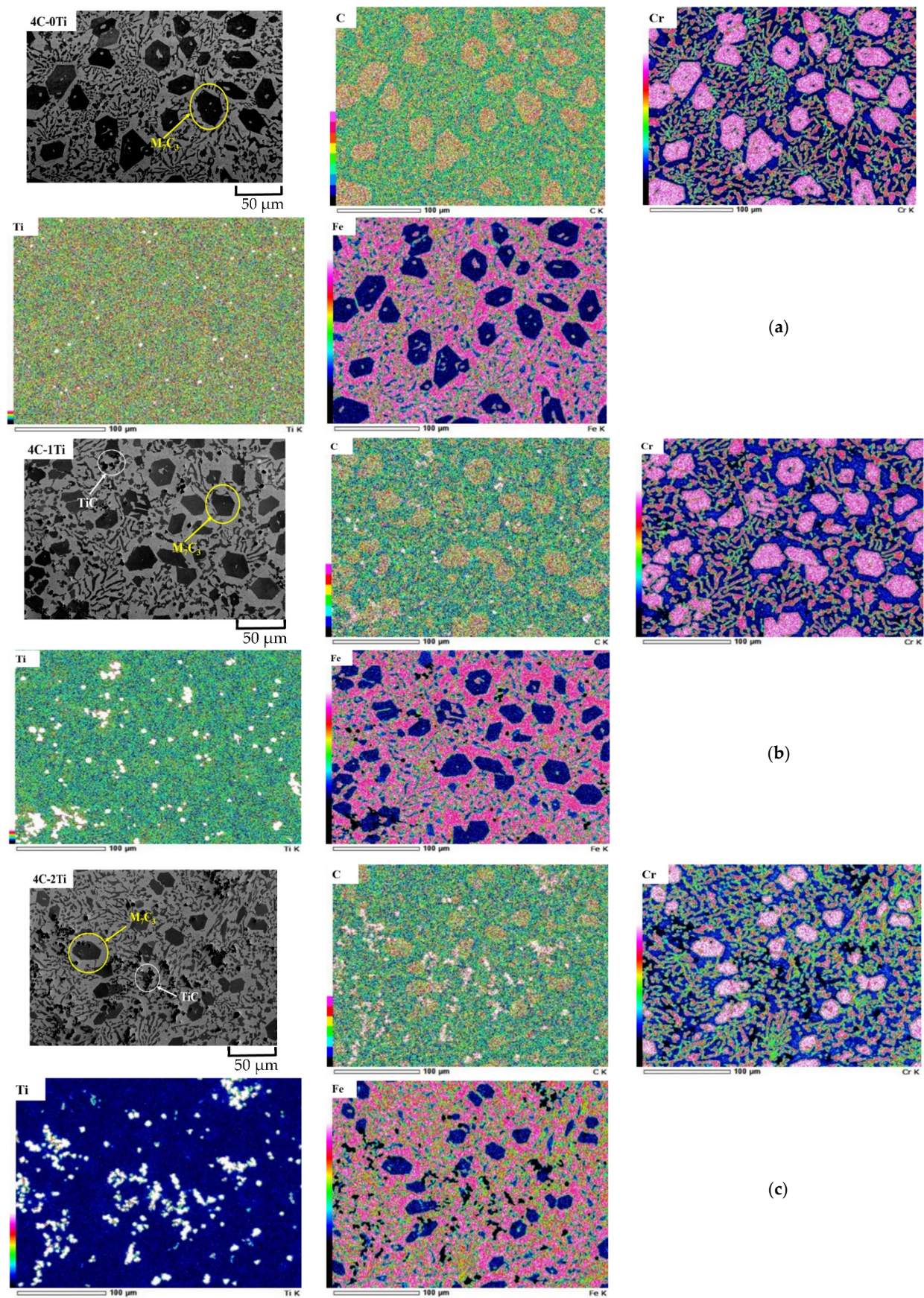


Figure 5. Distribution of chemical elements through SEM-EDS analysis of the 4 wt.% C specimen's wear surface: (a) 4C-0Ti specimen, (b) 4C-1Ti specimen, and (c) 4C-2Ti specimen.

3.2. Hardness of Materials

Conventionally, the abrasive wear property of HCCI is significantly influenced by the hardness of the material. However, toughness also plays a major role [36–38]. Because of this issue, the hardness analysis was performed on all the test materials. Table 2 represents the macro-hardness (the overall hardness of the test materials, including the matrix and carbide together), micro-hardness (matrix alone), and carbide volume fraction (CVF). It was ascertained that the increase in Ti content results in a decrease in C due to the formation of TiC that decreases both the macro- and micro-hardness for all the specimens. C reduction causes the refinement of the M_7C_3 carbide, which has been mentioned before as a reason for hardness mitigation. However, a previous study showed that the hardness of HCCI increases with the increase in Ti content in as-cast conditions [39]. On the other hand, in this study, the increase in C content led to superior hardness (both macro-hardness and micro-hardness) for all the specimens. The reason behind the higher hardness might be the enhanced number of M_7C_3 carbides. According to the result, the 4C-0Ti specimen showed the highest values in both macro-hardness and micro-hardness. Regarding the CVF, all the specimens exhibited around 40% CVF with a negligible difference. It seems that the hardness of the material is not vastly dependent on the CVF. This finding is in good agreement with a former study [40].

Table 2. Vickers hardness and carbide volume fraction of each test specimen.

Test Material	3C-0Ti	3C-1Ti	3C-2Ti
Macro hardness	870HV	815HV	768HV
Matrix hardness	643HV	558HV	524HV
CVF	41.2%	39.0%	39.2%
Test material	3.5C-0Ti	3.5C-1Ti	3.5C-2Ti
Macro hardness	916HV	863HV	792HV
Matrix hardness	665HV	612HV	549HV
CVF	42.3%	39.3%	39.1%
Test material	4C-0Ti	4C-1Ti	4C-2Ti
Macro hardness	964HV	956HV	878HV
Matrix hardness	748HV	672HV	623HV
CVF	39.4%	41.0%	40.5%

3.3. Three-Body Abrasive Wear Characteristics

To investigate abrasive wear characteristics, three-body abrasive wear tests were performed. Figure 6a illustrates the abrasive wear performance as a function of wheel rotation, where the X-axis indicates the total test cycle, and the Y-axis indicates the amount of wear loss. The results show that each of the test specimens undergoes a similar wear loss tendency where the material loss escalates with the increase in the wheel cycles. Among all the specimens, the 4C-0Ti exhibited the lowest wear loss; however, with the increase in Ti content and the decrease in C content, the amount of wear loss increases. The basis behind the remarkable wear resistance performance of 4C-0Ti is thought to be its higher hardness. Figure 6b depicts the relationship between the wear rate and the hardness of each specimen. The dot plot illustrates the hardness, and the bar graph shows the wear rate. It can be seen that the amount of wear decreases as the hardness of each specimen increases. The C content plays a major role in influencing the Vickers hardness value, hence minimizing the wear rate, according to the graph. The specimens with 4 wt.%C demonstrated the lowest wear rate in comparison with each C content. However, the wear rate of the 4C specimens increased with increasing Ti content. The specimens with lower C content and higher Ti content led to a lower Vickers hardness, resulting in poor wear resistance. This finding is in good agreement with a previous study [41].

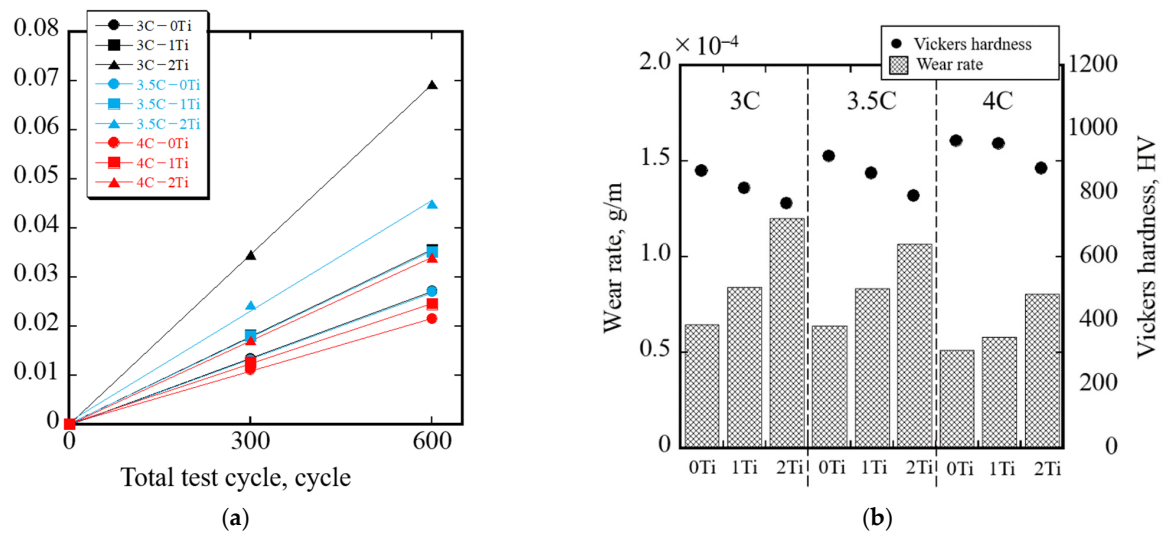


Figure 6. Wear rate in terms of the test cycles and Vickers hardness: (a) relationship between wear loss and test cycle and (b) relationship between wear rate and Vickers hardness.

Worn surface observation is significant for analyzing wear behavior. From the worn surface observation results in Figure 7, it can be seen that all the test materials show the wear mark characteristics of abrasive wear, as denoted by the white arrows. Following the microstructural characterization that has been discussed before, these SEM images illustrate that the unevenness of the carbide becomes larger with the enlargement of the carbide's average grain size. This trend is firmly observed with the increase in hardness. It can be stated that the wear mechanism preferentially scrapes away the matrix structure. As a consequence, the unevenness of the carbide is confirmed. In addition, as represented by the yellow circles, several areas of localized wear were noticed in the Ti-added specimens.

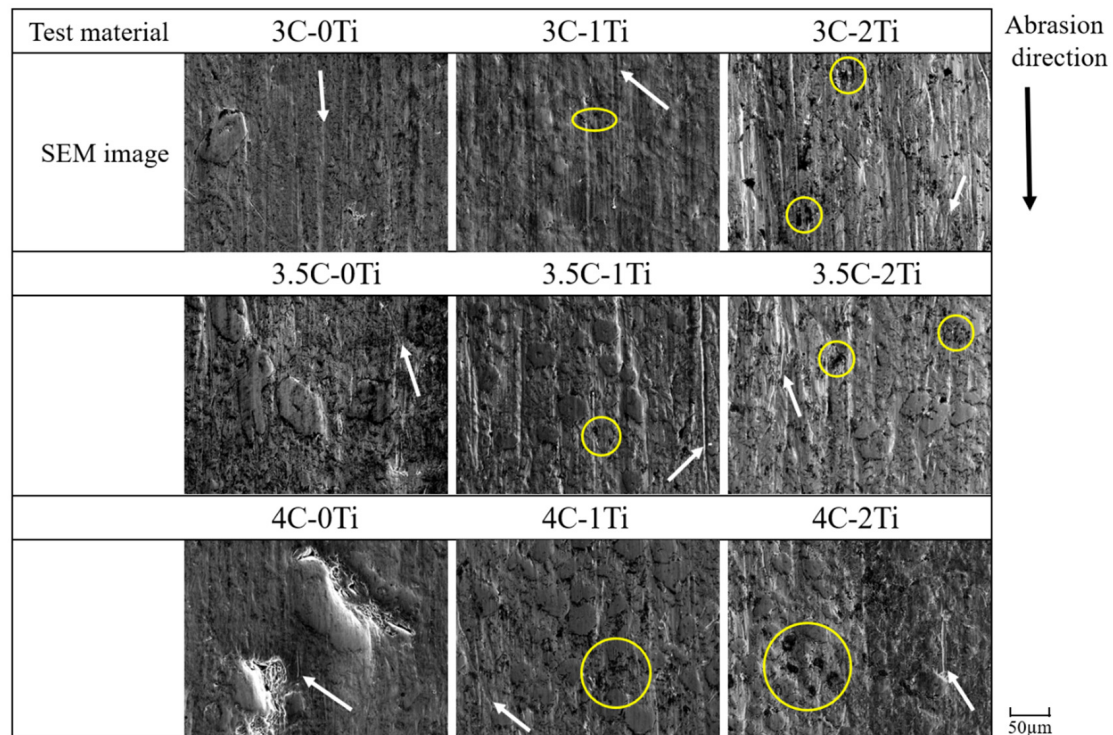


Figure 7. Microphotograph of the specimen's worn surface after abrasive test through SEM. The white arrows denote the wear marks, and the yellow circles indicate localized wear in the Ti-added specimens.

Figure 8 shows the wear mechanism schematic of the 4C-0Ti worn specimen in four steps. In Step 1, crystallized M_7C_3 is observed in the matrix structure. In Step 2, the dispersed sand particles during the abrasive wear test strike the matrix structure, resulting in wear in the matrix that eventually leads to peeling in the matrix. During this process, the M_7C_3 carbides experience several cracks. Furthermore, the wear accelerates, and the M_7C_3 carbide cracks, making it easier to peel off, which is shown in Step 3. As a result, the carbide falls off, and the wear from the matrix accelerates, which is shown in Step 4. The specimens with added Ti show a severe wear phenomenon to the contrary. With the supplement of Ti, the TiC is crystallized in the matrix. Further addition of Ti, such as 2 wt.%, promotes TiC to precipitate densely, making the M_7C_3 carbides finer. During this process, the agglomeration of TiC happens. During the time of the abrasive test, the TiC clusters severely collide with the sand particles, which results in the falling out of TiC. It is considered that TiC falling out of the microstructure promotes wear from the falling traces and causes localized wear. During this period, the localized wear of a single TiC is limited. However, with dense TiC, carbides fall off in large numbers, which leads to greater localized wear. Thus, the hardness of the Ti-added specimens is reduced. The wear rate of the 2 wt.% Ti specimens, in particular, is thought to be increased due to this local wear.

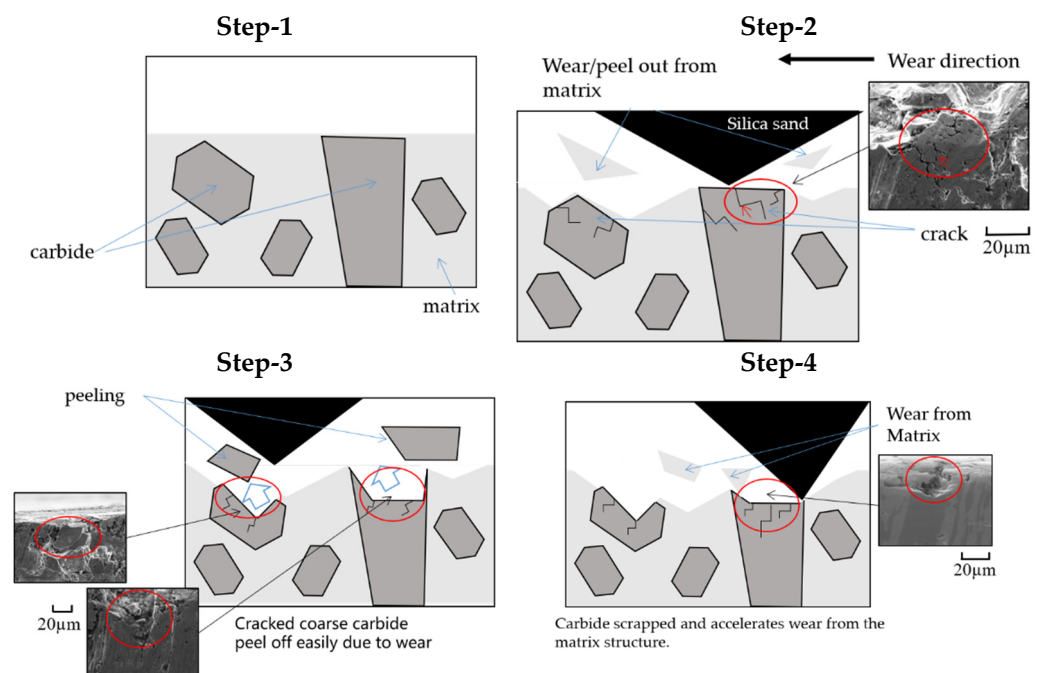
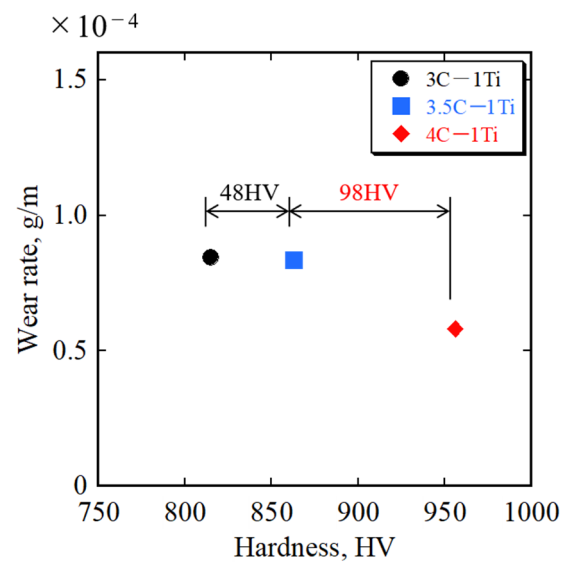


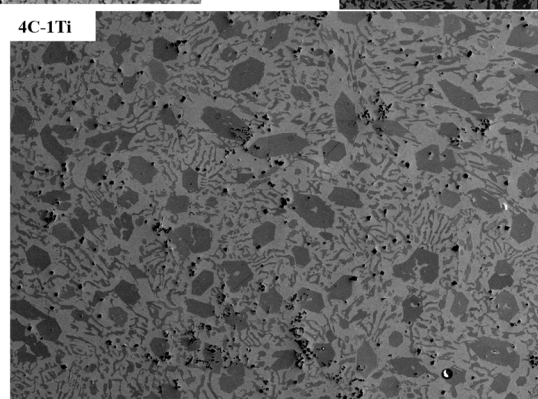
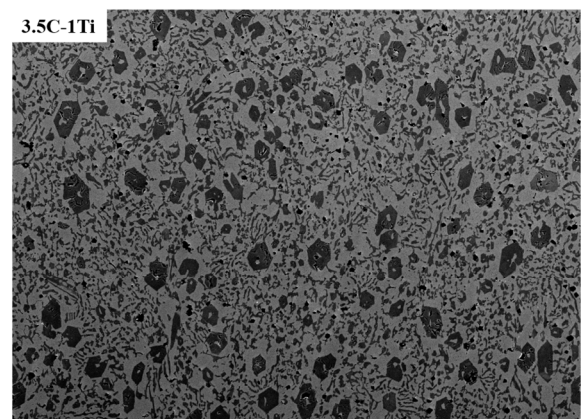
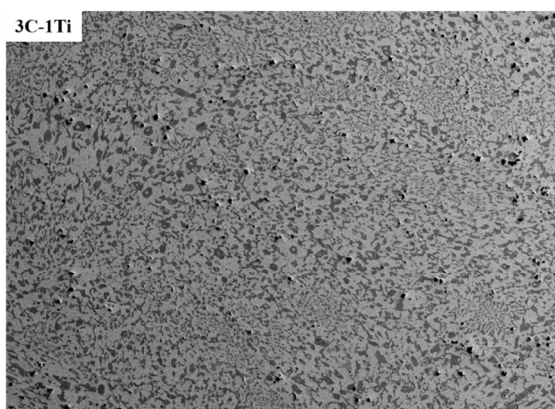
Figure 8. Wear process schematic where Step 1, Step 2, Step 3, and Step 4 depict the wear mechanism of the material (HCCI).

In order to eliminate the difference in the wear rate due to local wear, a comparison was drawn among the specimens with 1 wt.% Ti and three different amounts of C contents. The graph in Figure 9a illustrates the relationship between the wear rate and hardness. Comparison between the 3 wt.% C and 3.5 wt.% C specimens reveals that the wear rate was nearly identical, and the hardness difference was about 50 HV. In general, the abrasive wear rate falls with the rise in hardness. However, in this current case, such behavior was not observed. As a consequence, the carbide grain size is focused on in Figure 9b. The carbide grain size of the 3.5 wt.% C specimen was 19.8 µm, whereas the 3 wt.% C specimen contained 7.1 µm carbide grains. In comparison with the 3.5 wt.% C specimen, the 3 wt.% C specimen had finer carbide crystallization. This implies that fine carbides are effective in improving abrasive wear properties. When comparing the 3.5 wt.% C and 4 wt.% C test materials, the 4 wt.% C test material showed better performance in both the wear rate and hardness, while the 3.5 wt.% C test material had finer carbide crystals. As there was a large difference (100 HV) in hardness, it is inferred that the improvement in the abrasive wear

characteristics of the 4 wt.% C test material is because of higher hardness. In view of this, a suggestion can be made that when the difference in hardness is large, the effect of the carbide grain size is small. In conclusion, when the hardness difference is about 50 HV, the fine carbides are effective in improving abrasive wear. However, with a hardness difference of 100 HV, the effect of the fine carbide is smaller. Hardness improves the abrasive wear resistance properties.



(a)



(b)

Figure 9. (a) Wear rate of various hardness for specimens with similar Ti content but different C content and (b) SEM images of the specimens to show the effect of the carbide grain size on the wear resistance properties.

To comprehend the wear phenomenon more explicitly, the wear depth of each test specimen was investigated using a 3D laser microscope, which is illustrated in Figure 10a,b. The result shows that an increase in Ti content leads to a greater wear depth. On the contrary, an increase in C content results in a shallower wear depth. It was identified that with an escalating wear rate, the depth of wear tends to be deeper. Among all the test specimens, 4C-0Ti was confirmed to have the lowest wear depth.

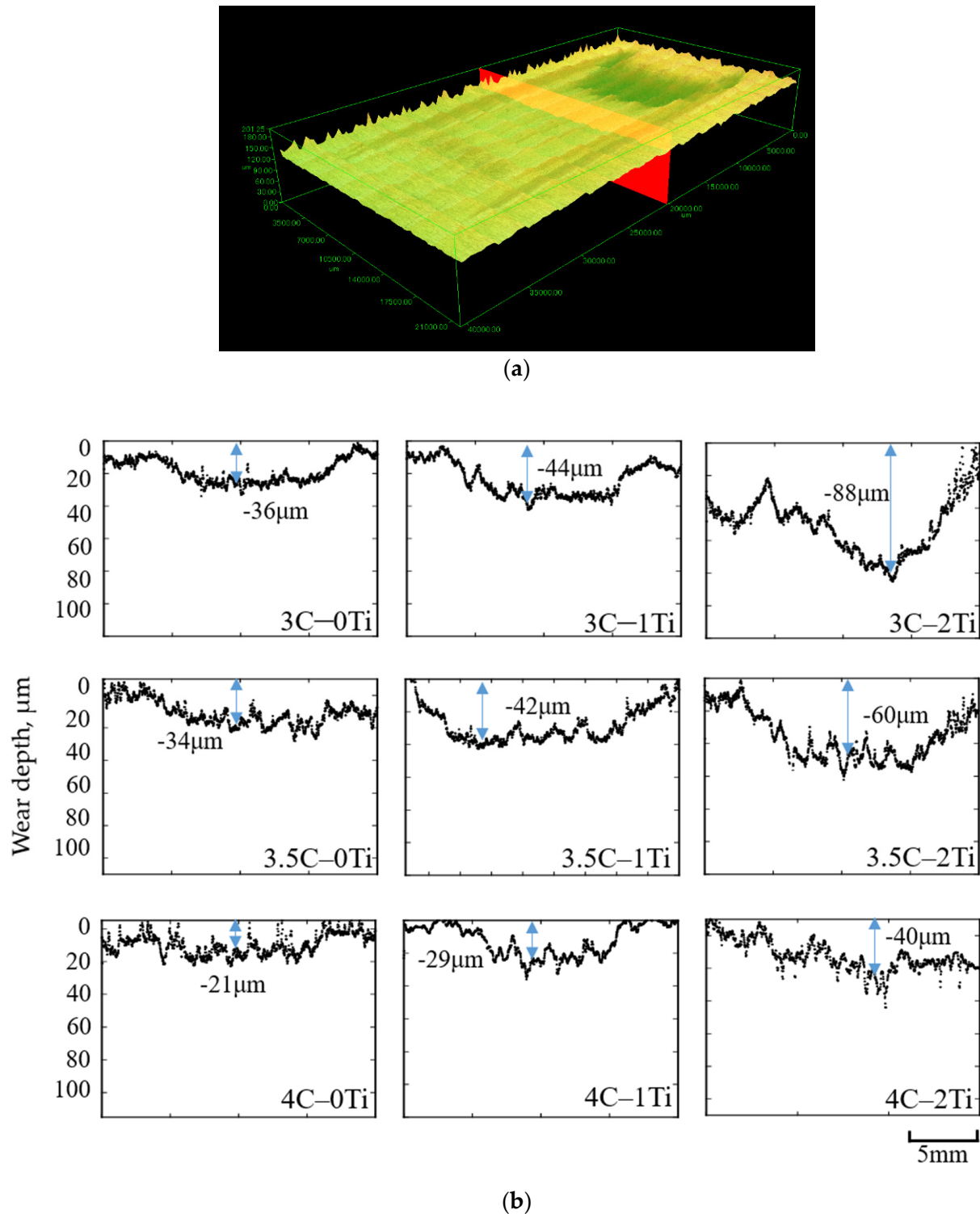


Figure 10. (a) Wear depth observation using 3D laser microscope and (b) wear depth of each specimen.

4. Conclusions

After the investigation of the effects of Ti and C on the three-body abrasive wear performance of HCCI, the following conclusions can be extracted:

1. The addition of Ti causes the M_7C_3 carbides in the microstructure to become finer and TiC to crystallize. The hike in Ti content results in a decrease in the microstructure hardness.
2. From the rubber wheel abrasive test, it can be concluded that the overall hardness of the microstructure increases, leading to a lower wear volume and improved abrasive wear resistance.
3. The hardness of the microstructure, hardness of the matrix, and morphology of carbide crystallization have a notable effect on the abrasive wear resistance.
4. The highest C results in better wear resistance, while the 4C-0Ti composition exhibits better hardness, a lower wear rate, and a shallower wear depth.

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Conflicts of Interest: The authors declare no conflict of interest.

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