Microstructure and tribological properties of Cr$_3$C$_2$/Ni$_3$Al composite materials prepared by hot isostatic pressing (HIP)

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HIGHLIGHTS

• A M$_7$C$_3$ (M = Cr, Fe) phase is formed in Cr$_3$C$_2$/Ni$_3$Al composites prepared by hot isostatic pressing.
• The hardness of the Cr$_3$C$_2$/Ni$_3$Al composites increases with increasing addition of Cr$_3$C$_2$.
• The wear resistance of Cr$_3$C$_2$/Ni$_3$Al composites is improved due to the Cr$_3$C$_2$ asperities keep the sliding surfaces apart.
• Excess addition of Cr$_3$C$_2$ (such as 24 vol%) can decrease the wear resistance of Cr$_3$C$_2$/Ni$_3$Al composites.

GRAPHICAL ABSTRACT

Ni$_3$Al-based composites with different Cr$_3$C$_2$ contents were fabricated by the hot isostatic pressing (HIP) technique. The microstructure, phase constitution, and tribological properties of the composites were investigated by scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), X-ray diffraction (XRD), transmission electron microscopy (TEM), and pin-on-disk wear tests. The results revealed that the strengthening phase is distributed homogeneously in the Ni$_3$Al matrix. During the HIP process, M$_7$C$_3$ (M = Cr, Fe) is formed by diffusion of Fe, C, and Cr to the interface between the Cr$_3$C$_2$ particles and Ni$_3$Al matrix. The diffusion process binds the phases and is important for improving the wear resistance of Cr$_3$C$_2$/Ni$_3$Al composites. The wear measurements demonstrated that micro-cutting and fatigue wear are the dominant mechanisms for this tribological pair. The wear resistance of Cr$_3$C$_2$/Ni$_3$Al composites is significantly improved by the addition of Cr$_3$C$_2$ particles. When the content of Cr$_3$C$_2$ is within a certain range, the wear resistance of Cr$_3$C$_2$/Ni$_3$Al composites increases as the Cr$_3$C$_2$ content increases. However, the addition of excess Cr$_3$C$_2$ (for example, 24 vol% in this work) could lead to a decrease in the wear resistance of the composites. In addition, the average friction coefficients and wear of the counterpart decrease with increasing Cr$_3$C$_2$ addition.

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1. Introduction

Ni$_3$Al is one of the most attractive materials among intermetallic compounds because of its high melting point, low density, high temperature strength, and good creep resistance [1–4]. Furthermore, it has a positive temperature-dependence of strength due to its long-range
ordered crystal structure [5–7]. Therefore, Ni3Al alloys are considered to be excellent materials for resisting wear at high temperatures. They have been used for tribological applications in which wear-resistance is the main requirement [8–10]. Recent studies have indicated that the high-temperature mechanical strength and hardness of Ni3Al alloys can be significantly improved by the addition of hard-particle reinforcements [11–13]. When present in iron, cobalt, and nickel matrices, chromium carbide exhibits high hot-hardness and excellent high-temperature oxidation resistance combined with good wetting ability [14–15]. Hence, chromium carbides are chosen frequently as hard-particle reinforcements for addition into Ni3Al-based matrices, to form Cr7C3/Ni3Al composites [8,16]. Cr7C3/Ni3Al composites have been widely investigated as wear-resistant materials in wear applications for many years. Bullock et al. [17] studied directionally solidified Ni-Ni3Al-Cr7C3 composites and found that the composites show better creep resistance than the matrix-only material. The wear performance of chromium-carbide-reinforced Ni3Al matrix composites under ambient temperature was studied by Gong et al. [15–16,18]. The results indicated that composites presented better wear resistance compared with the matrix-only material. This was due to the presence of carbide asperities, which kept the sliding surfaces apart during the wear process. Li et al. [19] prepared a Cr7C3/Ni3Al composite coating on steel by welding. A study of the abrasive wear performance of the composite coating showed that the abrasion-resistance of the Cr7C3/Ni3Al composite coating is twice as high as that of the stellite 12 alloy. This can be attributed to the large volume fraction of carbides, high hardness, and good interfacial bonding between the phases. Therefore, it was expected that the unique properties of Ni3Al alloys and chromium carbides would improve the tribological resistance of materials [11–12,20–21].

Hot isostatic pressing (HIP) is a widely applied powder technique for manufacturing precisely shaped, dense bodies of different types of materials, including metals, ceramics, and others [22–24]. In recent years, it has also been used to produce wear-resistant components for Cr7C3/Ni3Al composites. However, the microstructure and phase constitution of HIP Cr7C3/Ni3Al composite materials have not been investigated systematically in previous studies. The diffusion phenomenon and related phase transformation of Cr7C3/Ni3Al composites during the HIP process have not been clearly understood. It is important to understand the effect of Cr7C3 content on the microstructure and tribological behavior of Cr7C3/Ni3Al composites processed by the HIP technique, for practical applications as well as academic research.

In this paper, Ni3Al-based composites with various Cr7C3 contents were prepared using the hot isostatic pressing technique. The microstructure and phase constitution of the HIP Cr7C3/Ni3Al composites were characterized by field emission scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), X-ray diffraction (XRD), and transmission electron microscopy (TEM). Moreover, the tribological properties of the composite materials were investigated, and the influence of Cr7C3 content on the wear behavior of the composites was analyzed.

2. Experimental details

2.1. Materials

Ni3Al-alloy powders (~40–100 μm) with a chemical composition (wt%) of Ni-9.87 Al-11.63 Fe-0.50 Mn-0.50 Ti-0.2 B and Cr7C3 particles (~20 μm, 99.5% purity) were selected as the raw materials. Powders of the Ni3Al alloy were supplied by the Chalmers University of Technology, where they were synthesized using vacuum melting and inert gas atomization technology. The powders were first mechanically mixed with Cr7C3 particles in a roller ball mill. The mixing process was carried out at a rotational speed of 50 rpm for 24 h. In this work, the Ni3Al-alloy powders were uniformly mixed with 6 vol%, 12 vol%, 18 vol%, and 24 vol% of Cr7C3 particles, respectively. Then, the mixed powders were processed by the HIP method at 1160 °C and 140 MPa for 3 h to obtain the Cr7C3/Ni3Al composites (NAC06, NAC12, NAC18, NAC24). As a reference for comparison, a monolithic Ni3Al-alloy (NAC0) without Cr7C3 powders was also fabricated.

2.2. Characterization and wear tests

The microstructure of the monolithic Ni3Al-alloy and its composites was observed by SEM and EDS (NOVA NANOSEM 450). The phases of the Cr7C3/Ni3Al composites were analyzed by XRD (D8 ADVANCE) and TEM (JEM-2010). In order to avoid interference from the signal of the matrix phase in the XRD pattern, chromium carbides were extracted from the Cr7C3/Ni3Al composites by constant-current electrolysis. This process was carried out in an electrolytic solution of 1.6 mol/L hydrochloric acid, 0.7 mol/L propanetriol, 0.04 mol/L citric acid, and methanol solution for 3 h, with a constant current density of approximately 50 mA/cm². Samples for TEM were firstly mechanically thinned down to 10–20 μm in thickness. Then, the foils were ion-milled using an ion polishing system (Leica RES 101). The ion-milling process consisted of two steps: in the first step, the foils were milled at an incidence angle of 8° under an accelerating voltage of 5 kV for 3 h; in the second step, the samples were continuously thinned under an incidence angle of 3° and accelerating voltage of 3 kV for 1 h. The hardness of the Ni3Al-alloy and Cr7C3/Ni3Al composites was measured using a HRS-150 Rockwell hardness instrument with a load of 150 kg and indentation time of 10 s. Each measurement was conducted three times to verify the reproducibility of the results. The equivalent Vickers hardness was estimated using conversion tables. The pin-on-disc wear tests were performed using an Optimal SRV®4 reciprocal friction and wear tester at room temperature. The pins were composed of the monolithic Ni3Al-alloy and Cr7C3/Ni3Al composites, with dimensions of 3 × 2 × 14 mm. The face with an area of 3 × 2 mm was chosen as the wear surface to be brought into contact with the counterpart disk. The counterpart disk (Ø24 × 7.88 mm) was made of gray cast iron with the chemical composition (wt%) of Fe-3.20 C-1.10 Si-0.80 Mn-0.07 S-0.2 P-1.0 Cu-0.22 V. Before the tribological measurements, all pins and counterpart disks were polished with 1500 grit SiC paper, then rinsed with deionized water, and finally, degreased by acetone. The tribological tests were carried out under a load of 48 N, a stroke of 1.0 mm, a frequency of 50 Hz, and a testing time of 60 min. The mass loss by wear was calculated using the masses of each sample before and after the wear tests. More than three samples were tested for each test condition, and the average value was used. Dividing by the density of each sample, mass loss by wear was converted into volume loss by wear. The data used for the conversion are as follows: the density of the Ni3Al-alloy was 7.5 g/cm³, the density of the Cr7C3 particles was 6.68 g/cm³, and the density of gray cast iron was 7.2 g/cm³.

3. Results

3.1. Microstructure and phase constitution of the composite materials

Fig. 1 shows the microstructure of the Ni3Al-alloy and Cr7C3/Ni3Al composites with various Cr7C3 contents. As shown in Fig. 1(a), the NAC-alloy exhibits a fairly homogeneous structure. In Fig. 1(b)–(e), it can be observed that the chromium carbides, which form the strengthening phase of the composites, are uniformly dispersed in the matrix. Moreover, the proportion of the strengthening phase in the composites increases with increasing addition of Cr7C3. Fig. 1(f) reveals that the Cr7C3/Ni3Al composites mainly consist of a dark gray phase, an intermediate gray phase, and a light gray phase, as illustrated in the back-scattered electron image. EDS analysis was conducted in order to determine the chemical composition of these three phases, and the results as shown in Fig. 2. Only chromium and carbon were found in the energy spectrum of the dark gray phase (see Fig. 2(a)). In the intermediate gray phase (see Fig. 2(b)), iron and a small amount of nickel were also found in addition to chromium and carbon. Nickel was dominant in

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L. Fu et al. / Materials and Design 115 (2017) 203–212
the matrix, with smaller amounts of aluminum, iron, and traces of chromium and carbon. In order to obtain more information about the continuous distribution of each element over the phase interfaces, EDS line scanning analysis was performed across the chromium carbide particles. As shown in Fig. 3, the changes in distribution of Ni, Al, Cr, and Fe elements at the interface are clearly observed. Nickel and aluminum were mostly found in the matrix. The iron content was significantly higher in the intermediate gray phase but was lower in the matrix phase. The carbon signal was higher in the dark gray phase, lower in the intermediate gray phase, and very low in the matrix phase. However, the poor precision of the carbon signal in the EDS analysis prevents any definite conclusions from these variations. The chromium signal was the highest in the dark gray phase, somewhat lower in the intermediate phase, and very low in the matrix phase.

Fig. 4(a) and (b) present the X-ray diffraction patterns of the Ni$_3$Al-alloy and Cr$_3$C$_2$/Ni$_3$Al composites. The results reveal that the Ni$_3$Al-alloy and Cr$_3$C$_2$/Ni$_3$Al composite matrices have a Ni$_3$Al crystal structure, with peak signals at $2\theta = 43.6^\circ$, $50.8^\circ$, and $74.8^\circ$. The diffraction patterns of Cr$_3$C$_2$/Ni$_3$Al composites do not show obvious signals for carbides, which is attributed to interference from the strong peak of Ni$_3$Al.
3.2. Hardness and tribological properties of the composite materials

Rockwell hardness measurements were conducted on the samples NAC0, NAC06, NAC12, NAC18, and NAC24. Table 1 lists the Rockwell hardness of samples and their equivalent Vickers hardness values. It can be observed that the hardness of the Ni3Al-alloy is approximately 43 HRC. When 6 vol% Cr3C2 was added into the materials, the hardness of the Cr3C2/Ni3Al composites was significantly improved to approximately 48 HRC. When 24 vol% Cr3C2 was added, the hardness of the Cr3C2/Ni3Al composite increased to 58 HRC. These results suggest that the hardness of the Cr3C2/Ni3Al composites increases with increasing addition of Cr3C2. In fact, the improvement in hardness of the Cr3C2/Ni3Al composites is not only because of the added hard Cr3C2 particles but also due to the diffusion of Cr into the matrix material, resulting in a solution hardening effect on the Ni3Al matrix.

Fig. 5 shows the variation of average friction coefficients of the samples as a function of Cr3C2 content. It is clear that the average friction coefficient of the Ni3Al-alloy is approximately 0.85. The friction coefficient of the composites decreased with increasing addition of Cr3C2. Finally, the friction coefficient of the composites dropped to ~0.5 for the specimen NAC24, which had 24 vol% Cr3C2 added to it. The volume losses by wear of the Ni3Al-alloy and composites with different Cr3C2 contents are given in Fig. 7(a). The wear rate of the monolithic Ni3Al-alloy was quite high. However, the volume loss by wear decreased remarkably for the sample with 6 vol% Cr3C2-addition. It was less than half of the volume loss of the monolithic Ni3Al-alloy. The volume loss by wear of the composites was the lowest (~0.24 mm3) for 18 vol% Cr3C2 addition. However, it then increased (0.4 mm3) when the Cr3C2 content was 24 vol%. Fig. 7(b) presents the volume loss by wear of the counterpart disk (gray cast iron) for different composites. Fig. 7(b) shows that the damage to the counterpart disk by the Cr3C2/Ni3Al composites decreased as the Cr3C2 content was increased, resulting in a reduction in the wear rate of the counterpart material.

4. Discussion

4.1. Microstructure and phase constitution of the composite materials

The observed microstructure reveals that the Cr3C2/Ni3Al composites are composed of three phases. The XRD and TEM analyses indicate that the matrix phase is Ni3Al, the intermediate gray phase that is stable up to temperatures near its melting point (1390 °C). The temperature of the HIP process in this study is approximately 1160 °C. Therefore, the matrix phase retains the Ni3Al crystal structure. It is well known that Cr and C may form several different stable carbides, namely, Cr3C2, Cr7C3, and Cr23C6. The thermodynamic results, see Fig. 2). Moreover, the Fe atoms move by an uphill diffusion process (see Fig. 3) because of the reaction with carbon, which can reduce the chemical potential. During the cooling process, the dissolved Cr and C atoms may resolidify into a more stable structure. It is well known that Cr and C may form several different stable carbides, namely, Cr3C2, Cr7C3, and Cr23C6. The thermodynamic

![Fig. 3. EDS line scanning analysis across a carbide particle of sample NAC12.](image)

Therefore, for the X-ray diffraction analysis in our work, chromium carbides were extracted from the Cr3C2/Ni3Al composites. The XRD pattern of the carbide extract (see Fig. 4(c)) indicates that two phases exist in the composites, namely, Cr3C2 and M7C3 (M = Cr or Fe). TEM was applied to determine the phase structure of the composites. Fig. 5(a) and (b) show TEM images of the matrix phase and the intermediate gray phase, respectively. Fig. 5(c) and (e) show the electron diffraction pattern and EDS spectrum of the matrix phase in Fig. 5(a). The electron diffraction pattern in Fig. 5(c) exhibits the [011] zone axis of the Ni3Al fcc structure, and its chemical composition coincides with the EDS results of the matrix, mentioned above. Fig. 5(d) and (f) show the electron diffraction pattern and EDS spectrum of the intermediate gray phase in Fig. 5(b). The results suggest that Fig. 5(d) shows a [012] zone axis pattern of the M7C3 hcp structure, which mainly consists of C, Fe and Ni elements.

![Fig. 4. XRD pattern of (a) Ni3Al-alloy; (b) NAC12 composites and (c) carbide extract of sample NAC12.](image)
The equations for the standard Gibbs energy of formation ($\Delta G_f^0$) of these carbides are [26]:

$$\Delta G_f^0(Cr_3C_2) = -54344 - 19.57 \times 10^4 \frac{T}{K} \pm 9400 \text{J/mol} \quad (1)$$

$$\Delta G_f^0(Cr_7C_3) = -92067 - 41.5 \frac{T}{K} \pm 2800 \text{J/mol} \quad (2)$$

$$\Delta G_f^0(Cr_{23}C_6) = -236331 - 86.2 \frac{T}{K} \pm 10000 \text{J/mol} \quad (3)$$

Substituting the experimental temperature (T) in the expression above, the standard Gibbs energies of formation ($\Delta G_f^0$) of Cr$_3$C$_2$, Cr$_7$C$_3$, and Cr$_{23}$C$_6$ are about $-82.4$ kJ/mol, $-151.5$ kJ/mol, and $-359.9$ kJ/mol, respectively. According to the standard Gibbs energy of formation ($\Delta G_f^0$), Cr$_{23}$C$_6$ carbide has the highest tendency of formation from dissolved Cr and C. However, the XRD analysis and TEM results detected the M$_7$C$_3$ (M = Cr, Fe) structure instead of the M$_{23}$C$_6$ (M = Cr, Fe) structure in this work. This is because the reaction is not only influenced by thermodynamic factors but also depends on kinetic
factors. On the other hand, the above Gibbs' free energy calculations are based on a pure Cr–C system. In fact, the Cr and C atoms on the outer edges of Cr₃C₂ particles diffuse and dissolve into the matrix, resulting in a disturbed Cr/C ratio at the dissolved region of carbide. Additionally, some iron and a small amount of nickel diffuse into the dissolved region of the carbide, altering the thermodynamic equilibria for the formation of chromium carbides. Considering the existence of the Fe element, the isothermal section diagrams of the Fe-Cr-C system at 1160 °C and 900 °C are shown in Fig. 8. The chemical composition (as seen in Fig. 5(f)) of the intermediate gray phase suggests that the atomic fractions of Cr, C, Fe, and Ni elements are 36.11, 47.28, 14.18, and 2.43, respectively. This chemical composition is located just inside the region corresponding to M₇C₃ + C(Graphite) in the isothermal section diagrams at 1160 °C and 900 °C, as shown by the solid circle in Fig. 8. Therefore, the M₇C₃ (M = Cr, Fe) structure is detected in the diffusion phase. This result is also consistent with results in the literature [25,27–28]. The size of the Cr₃C₂ particles is quite large. Most particles are not completely decomposed during the high-temperature period. The carbide core, i.e., the dark gray phase, still retains the Cr₃C₂ structure after the cooling process.

4.2. Wear resistance of the composite materials

Fig. 9 shows the back-scattered electron images of the worn surfaces of the Ni₃Al-alloy and Cr₃C₂/Ni₃Al composites with various Cr₃C₂ contents. The results suggest that many layers of wear debris cover the surface of NAC0, as shown in Fig. 9(a). Parallel grooves on the worn surface of NAC06 are found in Fig. 9(b). However, the quantity of wear debris is...
decreased in sample NAC06. With increasing Cr$_3$C$_2$ addition (see Fig. 9(c)–(e)) the amount of wear debris decreases. Furthermore, the grooves are increasingly shallow and are even interrupted near the chromium carbide particles. It is well known that the development and survival of the layers of wear debris is associated with many factors, including the depth of grooves, ductility of the material, chemical affinity of the surface, etc. In this case, it is reasonable that the debris particles adhere with greater difficulty to hard Cr$_3$C$_2$ particles rather than the ductile matrix. Deeper grooves are not easy to form as more Cr$_3$C$_2$ is added. Therefore, it is difficult to form layers of wear debris on the surfaces of samples with high Cr$_3$C$_2$ contents. Fewer debris layers are found on the surfaces of composites with high Cr$_3$C$_2$ contents. The analysis of average friction coefficients of samples showed that samples with high Cr$_3$C$_2$ contents have relatively low friction coefficients, as shown in Fig. 6. This low friction could be attributed to the decrease in debris layers on the surfaces of these materials. Similar results have been reported in related literature [29]. Although a detailed analysis of this result was not conducted in this work, it can be studied in our further work.

The characteristics of worn surfaces reported above may indicate that micro-cutting wear is the dominant mechanism occurring on the surface of the Ni$_3$Al-based composite materials. The micro-cutting effect is weakened when the Cr$_3$C$_2$ content in the composites is increased. Previous works [16,18] have studied the wear mechanism of the Ni$_3$Al alloy. They noted that a wear-resistant sub-surface layer forms first under the worn surface of the Ni$_3$Al alloy, due to its plastic deformation and strain-hardening. Then, the sub-surface layer may break into filings and fall off from the worn surface in the following wear process. Finally, these filings will act as wear debris particles and cause micro-cutting of

![Fig. 9. Back-scattered electron images of the worn surface morphologies of Ni$_3$Al-alloy and Cr$_3$C$_2$/Ni$_3$Al composites: (a) sample NAC0; (b) sample NAC06; (c) sample NAC12; (d) sample NAC18; (e) sample NAC24.](image)

![Fig. 10. Secondary electron images of the worn surfaces of Ni$_3$Al-alloy and Cr$_3$C$_2$/Ni$_3$Al composites: (a) sample NAC0; (b) sample NAC06; (c) sample NAC12; (d) sample NAC18; (e) sample NAC24.](image)
the surface of materials. Based on the wear process for the Ni3Al alloy, the Cr3C2 particles added to the composites may impact their wear behaviors in the following ways: on the one hand, the hard Cr3C2 asperities in the surface separate the sliding surfaces and avoid direct contact between the composite testing material and the disk; on the other hand, the thickness of the sub-surface layer is decreased and the size of the wear debris particles is smaller because the hardness of the composites is increased by the Cr3C2 particles. In addition, the carbide strengthening phase in the Cr3C2/Ni3Al composites may block the cutting process of the wear debris particles. Therefore, the micro-cutting effect is reduced and the grooves are gradually shallowed by the addition of Cr3C2 particles in the composites. These phenomena are so clearly visible in the secondary electron images of the worn surfaces of Ni3Al-alloy and Cr3C2/Ni3Al composites, as shown in Fig. 10. Because of this, the wear loss of Cr3C2/Ni3Al composites decreases with increasing Cr3C2 addition for a certain range of Cr3C2 content, as shown in Fig. 7(a). But, there is an unexpected increase in the volume loss of sample NAC24 with 24 vol% Cr3C2. Zhu et al. [30] suggested that optimal addition of Cr3C2 can improve the strength of materials, but excess Cr3C2 addition could lead to a decrease in strength. In this study, cross-sectional observations of pins were recorded after wear testing. As shown in Fig. 11, there are no micro-cracks below the worn surfaces of samples NAC0, NAC06, NAC12, and NAC18, but there are obvious cracks in sample NAC24. The results indicate that excess Cr3C2 addition (such as 24 vol%) results in the formation of vertical micro-cracks even after wear testing (as shown in Fig. 11 (e)). Therefore, the volume loss by wear is lowest for NAC18, which has 18 vol% Cr3C2 content, while that of NAC24 with 24 vol% Cr3C2 content is worse.

![Fig. 11. Cross-sectional morphologies after wear testing of Ni3Al-alloy and Cr3C2/Ni3Al composites: (a) sample NAC0; (b) sample NAC06; (c) sample NAC12; (d) sample NAC18; (e) sample NAC24.](image)

![Fig. 12. Worn surface morphologies of the counterpart disks of Ni3Al-alloy and Cr3C2/Ni3Al composites: (a) sample NAC0; (b) sample NAC06; (c) sample NAC12; (d) sample NAC18; (e) sample NAC24.](image)
The worn surface morphologies of the counterpart disk of the Ni3Al-alloy and Cr7C3/Ni3Al composites with various Cr7C3 contents are given in Figs. 12. From these figures, some fatigue cracks can be found on the surface of the counterpart disk for the samples NAC0 and NAC06. The counterpart disk for sample NAC0 even exhibits some spalling. As the Cr7C3 content in the Ni3Al-based composites is increased, the fatigue cracks on its disks become less obvious and the amount of wear debris decreases progressively. This is because the initiation and propagation of cracks on the worn surfaces is associated with shear stresses on the contacting surfaces and the frequency of cycle stress [31]. However, shear stresses are caused by friction, which is related to the layer of debris on the contacting surfaces in this work. Fig. 9 and Fig. 12 show that the quantity of debris layers on the surfaces of both pins and disks decreases with increasing Cr7C3 content in the composites. Therefore, shear stresses on the worn surfaces of disks are reduced by the addition of Cr7C3. Decreasing shear stress on the surface should lower the risk of crack initiation and propagation on the surface of the disk, thus decreasing wear of the disk. This also explains why volume loss by wear results from the disks.

Table 2 shows the chemical composition of the wear debris from different samples. The results indicate that the wear debris is composed of a mixture of the Cr7C3/Ni3Al composite and their counterpart disks. The debris from tests on NAC0 and NAC24 contains a higher weight percentage of nickel which mainly originates from the composites, compared to iron which mainly originates from the counterpart disk. This suggests that the volume loss of NAC0 and NAC24 composites is more severe compared to the wear of their respective counterpart disks. Coincidentally, the volume loss by wear of the NACO (0.84 mm³) and NAC24 (0.43 mm³) composites is higher than the wear of their respective counterpart disks (0.65 mm³ and 0.17 mm³) in Fig. 9.

5. Conclusions

Ni3Al-based composite materials with different Cr7C3 contents were fabricated by the hot isostatic pressing (HIP) technique. The microstructure and phase constitution of the Cr7C3/Ni3Al composite materials revealed that the chromium carbide strengthening phase is distributed homogeneously in the Ni3Al matrix, and the proportion of the strengthening phase in the composites increases with increasing Cr7C3 addition. During the HIP process, the M7C3 (M = Cr, Fe) phase is formed in the Cr7C3/Ni3Al composite. diffusion and recrystallization at the interface between the Cr7C3 particles and Ni3Al matrix. Therefore, Cr7C3/Ni3Al composite materials are mainly composed of partially dissolved Cr7C3 particles, with the M7C3 (M = Cr, Fe) phase forming at the interface between the original particles and the Ni3Al matrix phase. The Ni3Al and Cr7C3 phases in the Ni3Al-based composites create a strong diffusion bond via the formation of M7C3 (M = Cr, Fe) diffusion phase. The hardness of the Cr7C3/Ni3Al composites increases with increasing Cr7C3 addition, which is attributed to the high hardness of Cr7C3 particles and the solid solution strengthening effect of chromium in the matrix phase. Under specified friction and wear conditions, the wear resistance of Cr7C3/Ni3Al composites is significantly improved with increasing addition of Cr7C3, within a certain range of Cr7C3 content. However, further increase in Cr7C3 content (such as 24 vol% in this work) results in a decrease in wear resistance because of the decrease in strength. Moreover, damage to the counterpart disks of the Cr7C3/Ni3Al composites decreases as the Cr7C3 content is increased. The observations of worn surface morphologies suggest that micro-cutting and fatigue wear are the dominant mechanisms for this tribological pair.

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