

Article

Effects of PVD CrAlN/(CrAlB)N/CrAlN Coating on Pin–Disc Friction Properties of Ti₂AlNb Alloys Compared to WC/Co Carbide at Evaluated Temperatures

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Abstract: Physical vapor deposition (PVD) coatings could affect the friction performance at the contact interface between Ti₂AlNb alloy parts and tool couples. Suitable coating types could improve the friction properties of Ti₂AlNb alloy while in contact with WC/Co carbide. In this study, the linear reciprocating pin–disc friction tests between the Ti₂AlNb alloy and the WC/Co carbide tool couple, with the sole variation of the PVD CrAlN/(CrAlB)N/CrAlN coating were conducted within the temperature range of 25–600 °C. The antifriction properties of the Ti₂AlNb alloy were estimated using the time-varied friction coefficients, the alloy wear rate, worn surface topography, worn surface element, and wear mechanism analysis. The results showed that the PVD CrAlN/(CrAlB)N/CrAlN coating could decrease the average friction coefficient and alloy wear rate compared to the uncoated WC/Co carbide couple. The apparent adhesive wear and abrasive wear of the Ti₂AlNb alloy could be improved due to the PVD coating at evaluated temperatures. The PVD CrAlN/(CrAlB)N/CrAlN coating could be utilized to improve the antifriction properties of the Ti₂AlNb alloy, which may be deposited on the cutting tool to improve the machining performance of Ti₂AlNb alloys in future aerospace machining industry.



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Keywords: PVD CrAlN/(CrAlB)N/CrAlN coating; Ti₂AlNb alloy; WC-Co carbide; pin–disc friction test

1. Introduction

In recent years, the Ti₂AlNb alloy has become one of the research hotspots in the materials science field due to its high yield strength, low density, small thermal expansion coefficient, superior fracture toughness, and good creep resistance [1–3]. The Ti₂AlNb alloy has become an important candidate for the high thrust ratio of aero-engine components such as compressor casings, combustion chamber magazines, compressor discs, and blades [4,5]. The service performances of these components were dependent on the machined surface topography of Ti₂AlNb with various cutting tools [6,7]. The friction performance at the contact interface between Ti₂AlNb alloy parts and the cutting tool couple could affect

the machined surface topography of the Ti₂AlNb alloy [8]. The antifriction properties of Ti₂AlNb with various cutting tools were worthy to be investigated [9,10].

Physical vapor deposition (PVD) coatings could affect the friction performance at the contact interface between Ti₂AlNb alloy parts and tool couples [11,12]. Zhao et al. [13] conducted a comprehensive review of the effects of tool coating on cutting temperature, cutting forces, and tool wear process. They found that the friction performance at the contact interface was dependent on the coating types, which were affected by the evaluated temperature and contact types. The evaluated temperature could affect the physical properties of the tool coating, tool substrate, and workpiece [14,15]. The contact type was mainly dependent on the machining types including turning, milling, drilling, etc. The main characteristic of these machining types was that the contact type could be regarded as the linear reciprocating friction between the workpiece and tool couple [16,17].

The antifriction properties of Ti₂AlNb alloys with various cutting tools could be affected by the evaluated temperatures. Yuan et al. [18] analyzed the antifriction properties of the Ti₂AlNb alloy with the cutting forces and worn machined surface topography during the milling procedure. Li et al. [19] investigated the sliding friction behavior of the TiAl alloy with steel and several ceramic materials including Al₂O₃, Si₃N₄, and WC/Co at room temperature, respectively. They found that the proper selection of ceramic coating materials could improve the alloy's antifriction properties based on the analysis of friction force and worn topography. Alam et al. [20] conducted the dry sliding tests of the Ti-24Al-11Nb alloy with hardened steel at room temperature. The main alloy wear mechanism was the delamination and oxidative wear, and the generated oxide layer could improve the alloy wear. Rastkar et al. [21] also conducted the sliding wear experiments of the Ti-48Al-2Nb-2Mn (at. %) and Ti-45Al-2Nb-2Mn-1B alloys at room temperature. The results showed that plastic deformation and ploughing were the two main friction characteristics of TiAlNb alloys. Zambrano Carrullo et al. [22] also investigated the effects of rotation speed on the tribology properties of Ti₄₈Al₂Cr₂Nb alloys at room temperature. The alloy friction properties could be improved using the generated mixing coating layer. Weller et al. [23] illustrated the internal friction of Ti-Al alloys at evaluated temperatures. The temperature affected the alloys' antifriction properties. Cheng et al. [24] investigated the friction behaviors of Ti-46Al-2Cr-2Nb alloys within the temperature range of 20–900 °C. The results showed that the mating surface material was an important influencing factor to affect the alloy friction properties, which was closely related to the testing temperature. Nuo et al. [25] deposited the TiAl intermetallic compound coatings on the surface of TC4 plates. The high-temperature oxidation excitation and frictional behaviors of TiAl coating over a wide range of temperature values were analyzed. The results showed that the TiAl coatings exhibited excellent wear resistance at both room and high temperatures. Wang et al. [26] investigated the frictional properties of Ti₂AlNb alloys with a layered microstructure. They found that Ti₂AlNb alloys possessed a high wear resistance due to the oxidation of worn surfaces at high temperatures. The poor wear resistance of the Ti₂AlNb alloy was detected at the ambient temperature.

PVD CrAl(X)N coatings have been widely deposited on carbide tools with the physical vapor deposition (PVD) method to improve friction performance in sliding experiments [27,28]. Bobzin et al. [29] analyzed the tribology behaviors of CrAlN coating and CrAlN/MoWS coatings. They found that the multilayer coating obtained good antifriction properties compared to the single-layer CrAlN coating based on the friction coefficient and worn surface topography. Hu et al. [30] analyzed the microstructure and mechanical properties of arc-evaporated CrAlBN coating. The results showed that the CrAlBN coating exhibited good anti-oxidation resistance. Kim and Le [31] analyzed the physical properties of PVD nanolayered CrN/AlBN thin films. They found that the cathode arc current and bias voltage could affect the physical properties of CrN/AlBN thin films. Dai et al. [32] illustrated that the microstructure and mechanical physical properties of coating could affect tribology performance. It was found that a suitable selection of coating types and layers could be utilized to improve the antifriction properties of the Ti₂AlNb alloy.

The superior antifriction properties of the Ti_2AlNb alloy were related to the selection of suitable coating types. The tool coating effects on the analysis of alloy friction properties were affected by the tool geometries and machining parameters in the actual machining procedure, which was difficult to determine. Therefore, it was necessary to conduct the simulated sliding experiment to analyze the friction properties of the Ti_2AlNb alloy with coated tool couples. In this study, the linear reciprocating pin–disc friction tests between the Ti_2AlNb alloy and WC/Co carbide tool couple, with the sole variation of PVD CrAlN/(CrAlB)N/CrAlN coating, were conducted within the wide temperature range of 25–600 °C, respectively. The antifriction properties of the Ti_2AlNb alloy were estimated with the time-varied friction coefficients, the alloy wear rate, worn surface topography, worn surface element, and wear mechanism analysis. The results could determine the suitable coating composition to improve the antifriction properties of the Ti_2AlNb alloy, which may be deposited on the cutting tool to improve the machining performance of Ti_2AlNb alloys.

2. Coating Deposition and Characterization

2.1. Coating Deposition Procedure

The carbide with a submicron grain grade was selected as the tool substrate. The main chemical composition was WC 89.5% and Co 10%. The main mechanical properties of the selected carbide were the density of 14.5 g/cm³, HV30 hardness of 1550, bending strength of 3600 N/mm², and compressive strength of 5500 N/mm². The cemented WC-Co carbide was ground and polished before the coating deposition process. The device for the coating deposition was of the type RD500-SDU, which was obtained from the company of Huasheng, Guangdong, Dongguan. The PVD arc pulse coating method was utilized for the coating deposition process. The coating was deposited using the pulse arc coating method with a deposition temperature of 500 °C. In addition, the heater would start to work when the detected temperature was lower than 480 °C to confirm the deposition temperature of 500 °C.

The process gases included Ar, H₂, and N₂. The gases of Ar and H₂ were utilized to clean the surface of the carbide sample. The N₂ gas was utilized to form the CrAlN/CrAlBN coating with the ionization-N ions. The flow rate of Ar was increased from 30 sccm to 125 sccm during the cleaning process due to the fact that the argon concentration could not be too high at once, which may cause ignition. The flow rate of H₂ was increased from 30 sccm to 125 sccm within the duration time 30 s during the cleaning process. The N₂ gas was utilized to form the CrAlN/CrAlBN coating with the ionization-N ions. The N₂ gas (99.999%) was utilized within the pressure range of 3800–4200 mPa during the whole coating deposition process.

The target sources #1 and #2 were selected as Cr₃₀/Al₇₀ (atomic ratio). The other target sources #3 and #4 were selected as Cr₂₇/Al₆₃/B₁₀ (atomic ratio). Figure 1 depicts the deposition procedure of the CrAlN/(CrAlB)N/CrAlN coating on the WC-Co carbide sample. The bias pressures of each working target source during the deposition process of coating layers 1, 2, 3, 4, and 5 were assumed as 60 V, 160 V, 160 V, 160 V, and 160 V, respectively. The exit pressure of the CrAlN/(CrAlB)N/CrAlN coating deposition was set as 10,000 mPa. Therefore, coating layer 1 could be regarded as Cr_{0.3}Al_{0.7}N. Coating layer 2 could be regarded as Cr_{0.3}Al_{0.7}N. Coating layer 3 could be regarded as Cr_{0.27}/Al_{0.63}/B_{0.1}N. Coating layer 4 could be regarded as Cr_{0.3}Al_{0.7}N/Cr_{0.27}/Al_{0.63}/B_{0.1}N. Coating layer 5 could be regarded as Cr_{0.3}Al_{0.7}N.

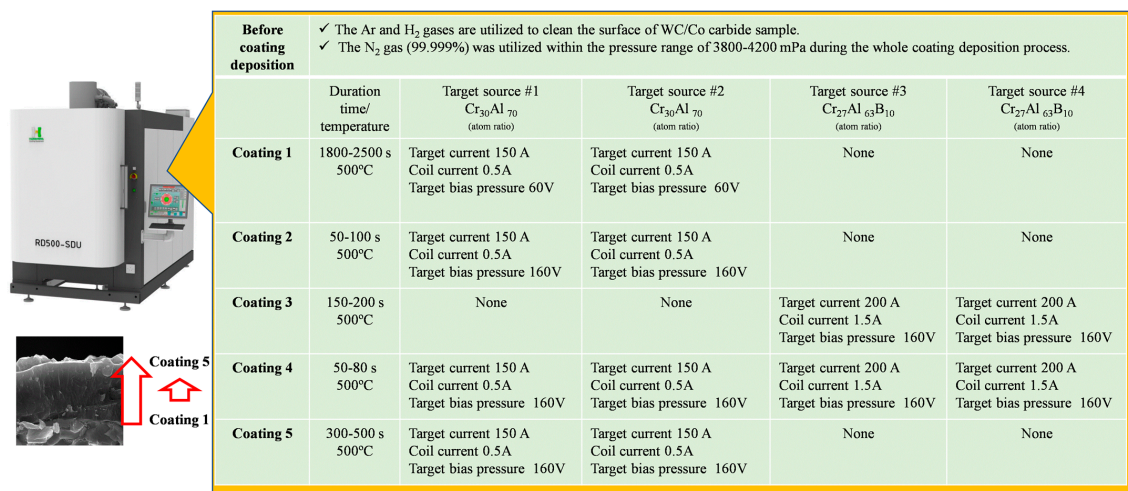


Figure 1. CrAlN/(CrAlB)N/CrAlN coating deposition procedure.

2.2. Characterization

The surface topographies and cross-sectional topography of the PVD CrAlN/(CrAlB)N/CrAlN-coated specimen were captured with SEM (JSM-6510) under the magnification rates of 500X, 3000X, and 8000X. The main chemical element compositions were detected with the coupled energy-dispersive spectrometer (EDS). The surface topography and main elemental mapping images of the coated specimen have been listed in Figure 2a–e. The detected droplets were the typical drawbacks due to the high stacking power accumulation when the high-energy ion bombed with the target materials. The pits were void defects due to the fact that the foreign particles in PVD coatings could not be firmly bound to the coating and spontaneously failed under high-stress effects. The defects on the surface topography of CrAlN/(CrAlB)N/CrAlN coating were the typical characteristics of PVD coating.

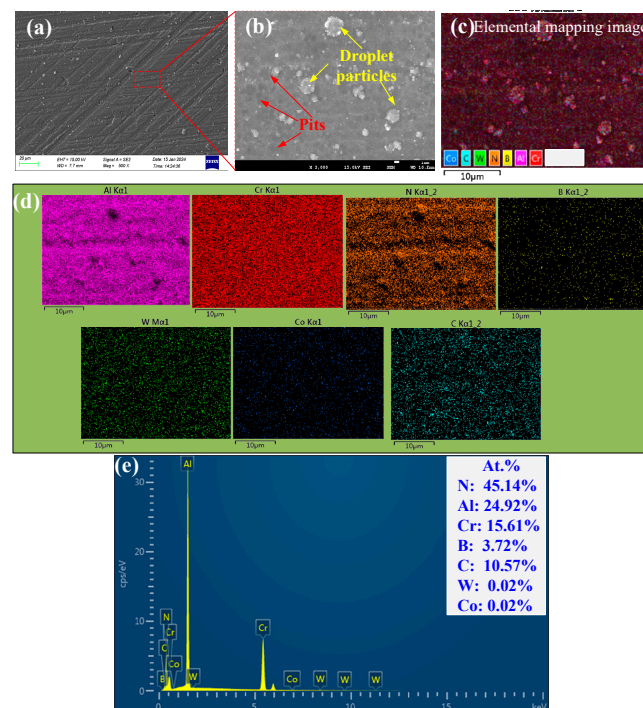


Figure 2. CrAlN/(CrAlB)N/CrAlN-coated sample: (a) surface topography; (b) droplet particles and pits existed on coating surface; (c) elemental mapping image; (d) individual mapping images of main chemical elements; and (e) main chemical element composition on the surface of coated sample.

The phase characterization of the coating was conducted using X-ray diffraction (XRD, Smartlab9kW, Cu-K α radiation) with the diffraction angles 2θ between 10° and 90° . The scanning rate was $0.2^\circ/\text{min}$. The XRD spectrum of the CrAlN/(CrAlB)N/CrAlN coating is listed in Figure 3. Based on the comparison with the former research [33–36], the CrAlN/CrAlBN/CrAlN coating was found to crystallize in a face-centered-cubic (fcc) lattice with a B1 (NaCl) structure (JCPDS 11-0065 card). The JCPDS of WC carbide was #03-065-4539. The evident peaks of WC could be found, which may be due to the thin coating thickness.

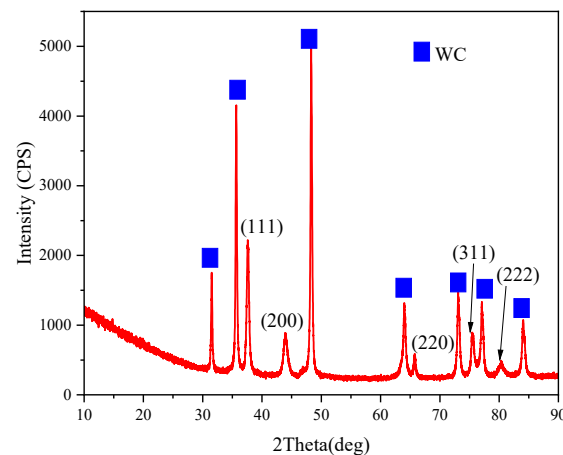


Figure 3. XRD diffraction patterns of CrAlN/CrAlBN/CrAlN coating.

The topography and elemental mapping images of cross-sectional coated specimens have been listed in Figure 4a–d, respectively. The thin coating thickness was detected as $2.78\ \mu\text{m}$. Figure 5 depicts the main chemical element lines within the CrAlN/(CrAlB)N/CrAlN-coated carbide specimen. The chemical element W could represent the existence of the WC/Co carbide substrate. The chemical elements Al and Cr could be regarded as the representative elements of CrAlN/(CrAlB)N/CrAlN coating. It could offer evidence to verify that the coating thickness was about $2.78\ \mu\text{m}$ as depicted in Figure 4a. The coating–substrate contact diffusion layer could be determined at about $0.2\ \mu\text{m}$. The elemental analyses of various points along the line as shown in Figure 6a have been listed in Figure 6b–l, respectively. The measured elemental compositions of various points could give evidence of the main elements including Cr, Al, N, B, W, C, and Co. There is a certain degree of error in the measurement methods of EDS. Thus, the measured chemical element compositions could be only taken as the reference, which could not be taken as the accurate reflection of the coating composition.

The coating nano-hardness was detected with the agilent nano-indenter G200. The maximum load applied to the three-sided pyramidal Berkovic diamond indenter was 5 mN. The experimental loading and unloading rates were $10.00\ \text{mN}/\text{min}$ with a duration of 5 s. The measured nano-hardness HIT was 24.75 and the E^* was 439.14.

The coating–substrate adhesion strength was measured using an Anton Paar scratch tester (scratch speed $10\ \text{mm}/\text{min}$, load range 1–150 N). Figure 7 shows the scratch testing results of the CrAlN/(CrAlB)N/CrAlN-coated carbide specimen. The adhesion between the coating and substrate could be determined with the sound signals and the scratched topography of the coated specimen. The critical Lc1 was commonly utilized to indicate that the first coating defects were found. It was difficult to determine the first coating defect according to the quantitative index. The place at which the coating was slightly failed and the substrate firstly started to expose, which was easy to be detected and determined as the critical Lc1 as 82.36 N in this manuscript. The Lc2 was referred to the beginning of scratch peeling, which indicated that the coating has been completely failed at 127.29 N. The critical load Lc2 was defined as the bonding force of the coating with substrate. Table 1 summarizes the structure and mechanical properties of the CrAlN/(CrAlB)N/CrAlN-coated samples.

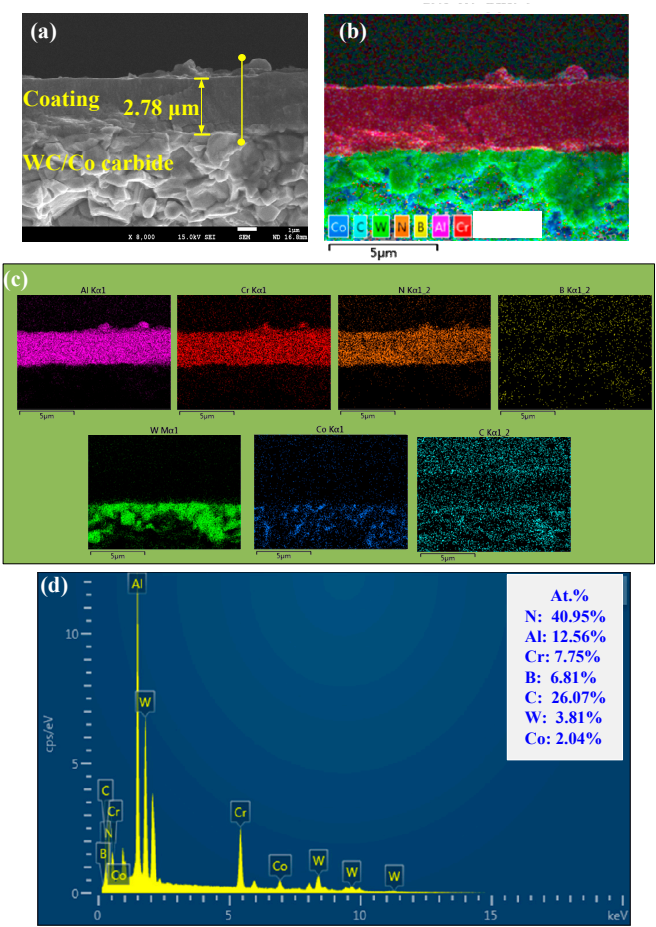


Figure 4. Analysis of coated sample: (a) cross-sectional topography of coated sample; (b) elemental mapping image of cross-section; (c) individual main elemental mapping images of cross-section; and (d) main chemical element composition on the cross-sectional face of coated sample.

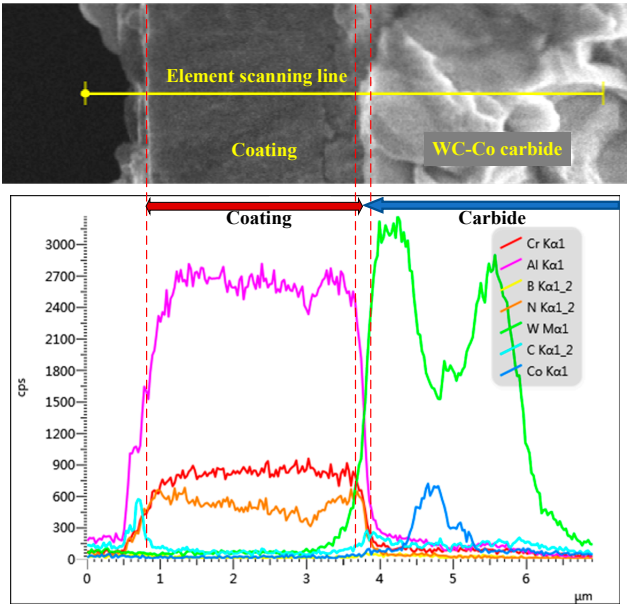


Figure 5. Main chemical element lines within CrAlN/(CrAlB)N/CrAlN-coated carbide specimen.

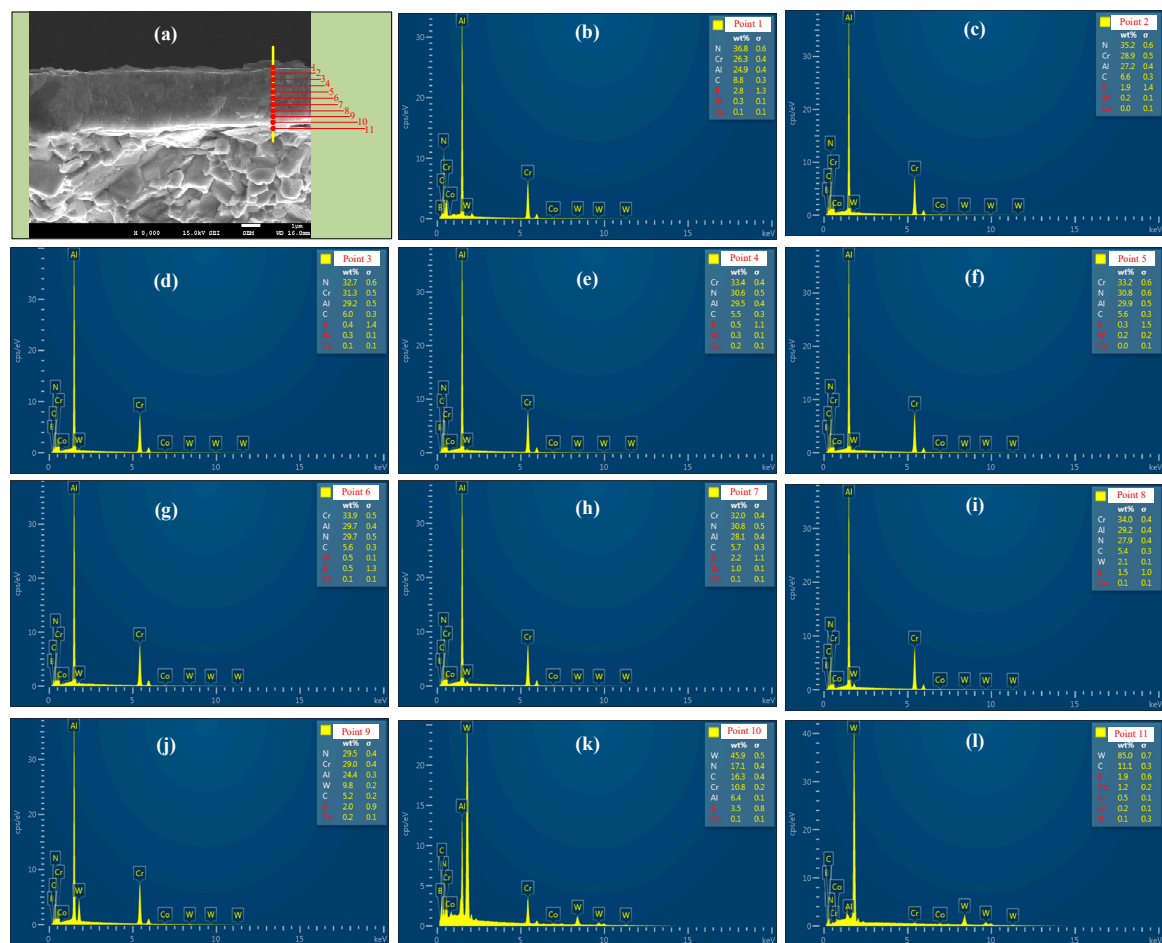


Figure 6. Elemental analyses of various points along the line on the cross-section of coated sample: (a) cross-sectional topography of coated sample and the deposition of various points; chemical element compositions of various points: (b) 1; (c) 2; (d) 3; (e) 4; (f) 5; (g) 6; (h) 7; (i) 8; (j) 9; (k) 10; and (l) 11.

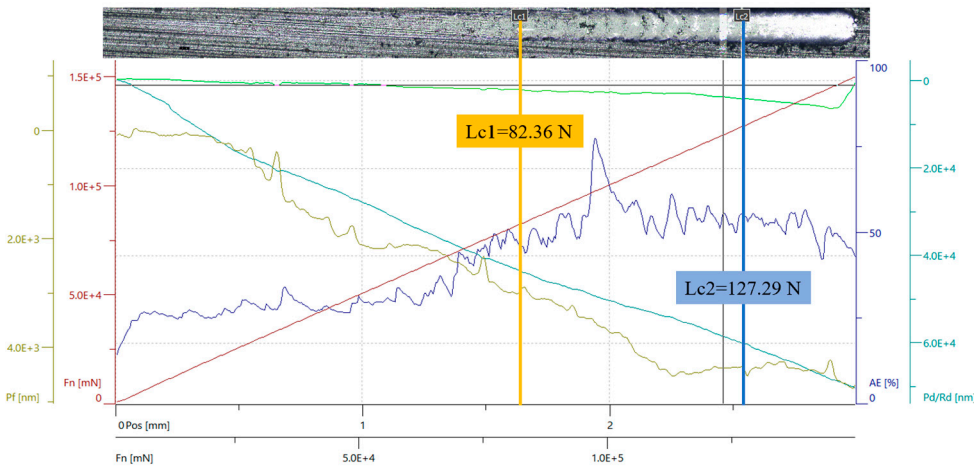


Figure 7. Scratch testing results of the CrAIN/(CrAlB)N/CrAIN-coated carbide specimen.

Table 1. Structure and mechanical properties of the CrAIN/(CrAlB)N/CrAIN-coated samples.

Coating Structure	Coating Thickness	Nano-Hardness HIT	E*	Lc1	Lc2
B1 NaCl	2.78 μm	24.75 GPa	439.14	82.36 N	127.29 N

3. Materials and Experiment

3.1. Ti_2AlNb Alloys

The hot-forged Ti_2AlNb alloy was obtained from the aerospace company with tensile strength ≥ 1000 MPa (at room temperature) and ≥ 800 MPa (at 650 °C) [37]. The main chemical composition of Ti_2AlNb alloy was Al at 9.9–11%, Nb at 41.6–44%, Mo at $\leq 1.5\%$, and Ti as the matrix. Figure 8 shows the metallographic microstructure of Ti_2AlNb alloy. The factory report of Ti_2AlNb alloy showed that the microstructure of Ti_2AlNb alloy was the bimodal or tristate organization of $2+O+B_2$. The particles of α_2/O were uniformly distributed for the hot-forged Ti_2AlNb alloy.

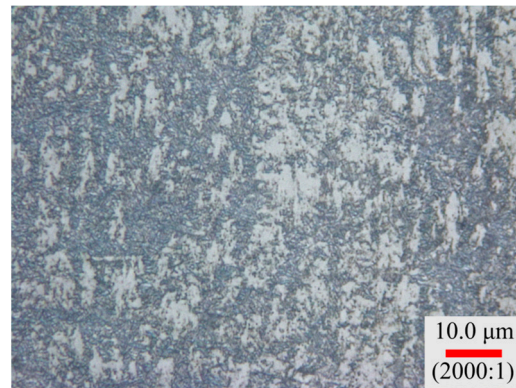


Figure 8. Metallographic microstructure of hot-forged Ti_2AlNb alloy.

3.2. Sample Preparation

In this research, the Ti_2AlNb specimen was machined with the size of 27 mm $\times$ 15 mm $\times$ 3 mm. The cemented carbide was machined as a flat-head pin with a size of ϕ 4.8 mm $\times$ 12.7 mm. Several carbide specimens were deposited with PVD CrAlN/(CrAlB)N/CrAlN coating as described in Section 2. The prepared specimens are summarized in Figure 9.

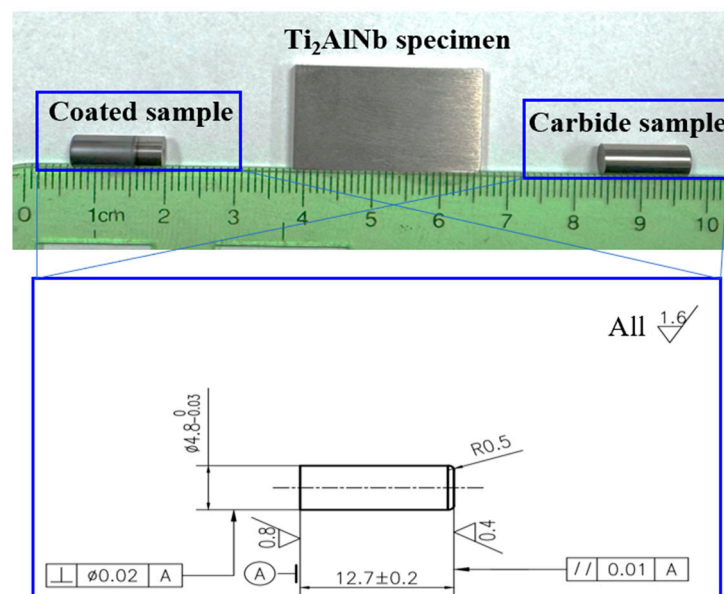


Figure 9. Prepared samples.

3.3. Pin–Disc Friction Tests at Evaluated Temperatures

Figure 10 depicts the pin–disc friction experimental device. The pin–disc friction tests were conducted on a high-speed reciprocating tribology tester of the type MDW-02. The

coated and uncoated carbide specimens were selected as the above samples. The Ti_2AlNb alloys were fixed as in the sample below. The main experimental indices included the load of 40 N, reciprocating friction speed of 40 mm/s, and reciprocating distance of 10 mm. The testing temperature values were selected with the temperature (25 °C), 300 °C, and 600 °C, respectively. The experimental friction duration time was 600 s. The wear loss of CrAlN/(CrAlB)N/CrAlN-coated and uncoated carbide tool couples could be neglected due to the very small quality loss before and after the pin–disc friction experiment.

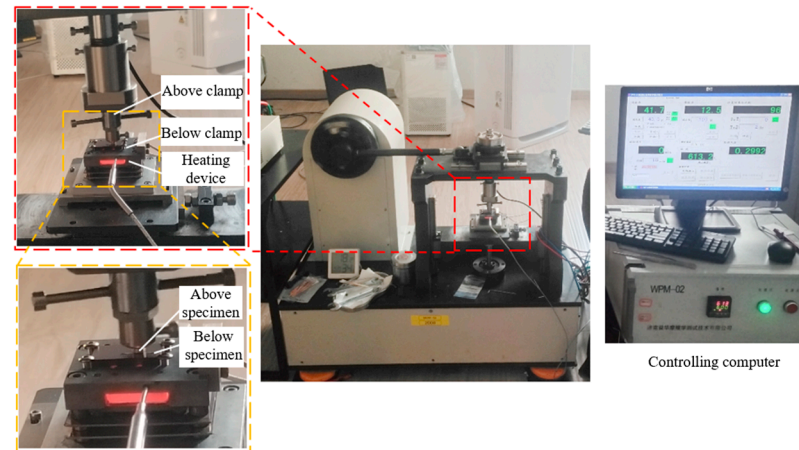


Figure 10. Pin–disc friction experimental device.

3.4. Experimental Characterization

The weighing sensor was utilized to determine the time-varied friction coefficient between Ti_2AlNb specimens and different flathead pins at various wear environments. The friction coefficient could be determined with Equation (1):

$$\mu = \frac{F_f}{F_n} \quad (1)$$

where F_f and F_n were the friction force detected using the weighing sensor and the normal force of the worn sample, respectively.

The wear amount was measured with a precision balance with an accuracy of 0.1 mg. Each specimen was measured more than three times to decrease the error. The wear rate could be calculated using Equation (2). After the tribological tests, the wear morphologies of the Ti_2AlNb specimen surface were analyzed with laser confocal microscopy.

$$I_w = \frac{\Delta m}{F \times S} \quad (2)$$

where Δm was the mass loss of the Ti_2AlNb specimen, F was the applied load, and S was the sliding distance.

The worn surface topography and its chemical element composition of Ti_2AlNb alloy were measured with SEM (JSM-6510) using the coupled energy–dispersive spectrometer (EDS). The surface roughness and surface topography of Ti_2AlNb alloy, uncoated carbide sample, and coated sample before and after the friction tests were obtained with the laser confocal microscope VK-X250K (Keenshi company, Osaka, Japan). More than three positions were selected and averaged as the measurement results of line surface roughness.

4. Results and Discussion

4.1. Friction Coefficient and Wear Rate of Ti_2AlNb Alloy

Figure 11 depicts the variation curve of the friction coefficient with the increase in duration time for (a) the CrAlN/(CrAlB)N/CrAlN-coated carbide specimen and the

Ti₂AlNb alloy and (b) the WC-Co carbide specimen and the Ti₂AlNb alloy at varied temperatures. Figure 12 summarizes the average friction coefficients and wear rates of the Ti₂AlNb alloy with uncoated and coated carbide specimens at various testing temperatures.

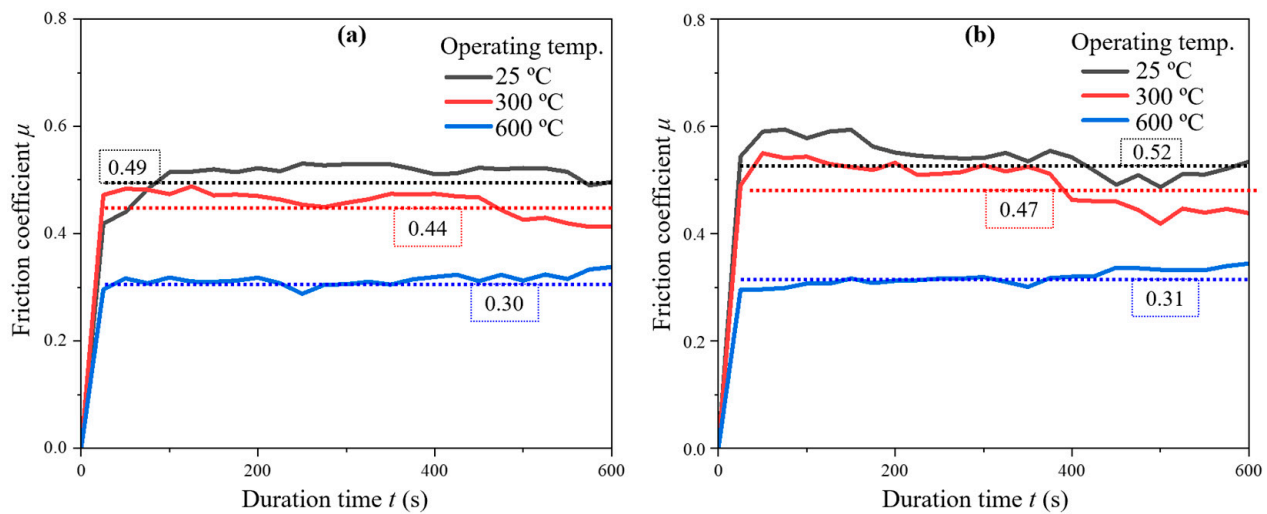


Figure 11. Friction coefficient vs. duration time for (a) CrAlN/(CrAlB)N/CrAlN-coated carbide specimen and Ti₂AlNb alloy and (b) WC-Co carbide specimen and Ti₂AlNb alloy at varied temperatures.

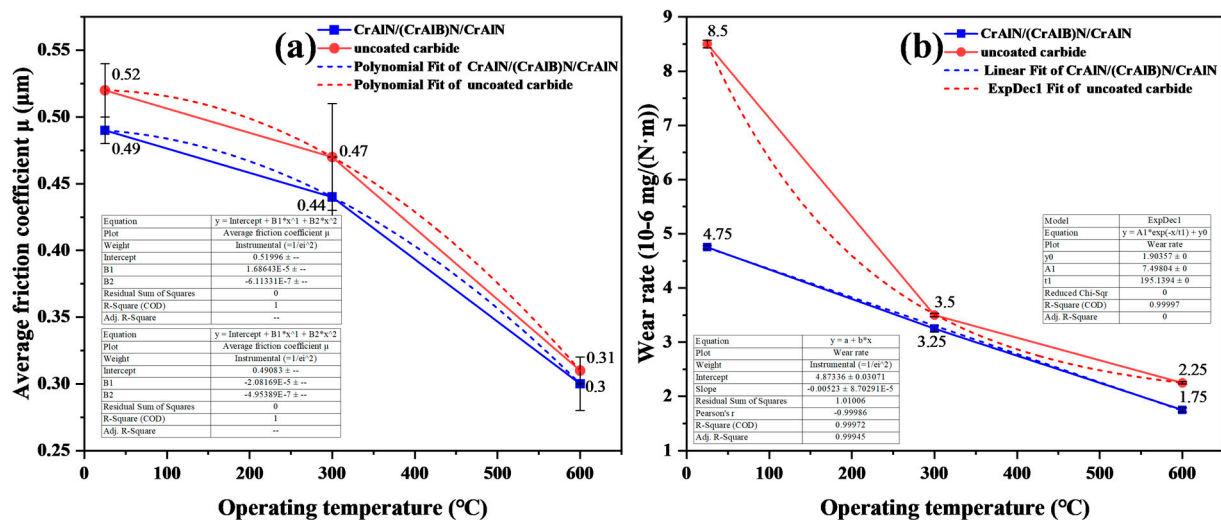


Figure 12. Analysis of friction and wear rates: (a) average friction coefficient and (b) wear rate of Ti₂AlNb alloy with uncoated and CrAlN/(CrAlB)N/CrAlN-coated carbide specimens at various testing temperatures.

The friction coefficients of the Ti₂AlNb alloy rubbed with uncoated and coated samples were increased sharply at the beginning within the running time interval, and then gradually attained the steady stage with the increase in time. The running time interval at 600 °C was slightly longer than that at 25 °C and 300 °C. The friction coefficient was varied and floated at a steady stage. It was illustrated that the adhesion-shear behaviors existed throughout the pin–disc friction tests [19]. After a numerical fitting analysis, it was found that the average friction coefficient and wear rate of the Ti₂AlNb alloy after the friction test with a coated tool were lower overall than those of the Ti₂AlNb alloy after the friction test with an uncoated carbide tool. The average friction coefficients both decreased quadratically with the increase in testing temperature. The wear rate of the Ti₂AlNb alloy after the friction test with a coated tool decreased linearly, while the wear rate of the Ti₂AlNb alloy after the friction test with an uncoated carbide tool decreased inversely.

The friction coefficients and wear rates of the Ti_2AlNb alloys rubbed with both coated and uncoated samples at 600 °C were lower than those at 25 °C and 300 °C. The friction coefficient of the Ti_2AlNb alloy rubbed with CrAlN/(CrAlB)N/CrAlN-coated sample was decreased by 10.01% when the testing temperature was increased from 25 °C to 300 °C, and which was decreased by 38.26% when the testing temperature was increased from 25 °C to 600 °C. The wear rate of the Ti_2AlNb alloy rubbed with the CrAlN/(CrAlB)N/CrAlN-coated sample was decreased by 31.58% when the testing temperature was increased from 25 °C to 300 °C, and was decreased by 63.15% when the testing temperature was increased from 25 °C to 600 °C. The friction coefficient of the Ti_2AlNb alloy rubbed with an uncoated cemented carbide sample was decreased by 9.06% when the testing temperature was increased from 25 °C to 300 °C, and was decreased by 41.37% when the testing temperature was increased from 25 °C to 600 °C. The wear rate of the Ti_2AlNb alloy rubbed with the uncoated cemented carbide sample was decreased by 58.82% when the testing temperature was increased from 25 °C to 300 °C, and was decreased by 73.53% when the testing temperature was increased from 25 °C to 600 °C. The obtained results also illustrate that the friction properties of Ti-Al alloys were related to the experimental temperature as shown in the literature [23].

The friction coefficient and wear rate of the Ti_2AlNb alloy rubbed with the CrAlN/(CrAlB)N/CrAlN coating were smaller than those rubbed with the cemented carbide within the temperature range of 25–600 °C. The friction coefficient of the Ti_2AlNb alloy rubbed with the CrAlN/(CrAlB)N/CrAlN coating was reduced by 6.24%, 7.22%, and 1.31% compared to that with the uncoated cemented carbide at 25 °C, 300 °C, and 600 °C, respectively. The wear rate of the Ti_2AlNb alloy rubbed with the CrAlN/(CrAlB)N/CrAlN coating was reduced by about 50%, 7.14%, and 22.22% compared to that with the uncoated cemented carbide at 25 °C, 300 °C, and 600 °C, respectively. It was illustrated that the existence of the CrAlN/(CrAlB)N/CrAlN coating could improve the wear resistance of Ti_2AlNb alloys.

Compared to the cemented carbide material, the Ti_2AlNb alloy exhibited better wear resistance when it was rubbed with the CrAlN/(CrAlB)N/CrAlN-coated carbide. The friction coefficients and wear rates of Ti_2AlNb alloys were decreased with the increase in temperature. It was indicated that the Ti_2AlNb alloy exhibited good friction reduction and anti-wear properties at high temperatures.

4.2. Topography of Worn Ti_2AlNb Alloy Surface

Figure 13 summarizes the surface morphology of the worn Ti_2AlNb alloy with the CrAlN/(CrAlB)N/CrAlN-coated carbide specimen after wear tests at specific temperatures. The typical plough zones were detected on the wear trajectories of the Ti_2AlNb alloy surfaces. It was suggested that the abrasive wear was the main wear mechanism. Figure 13a,b depict that the evident ploughing of the worn surface was detected after friction tests at temperatures 25 °C and 300 °C. The morphology of the adhesion transfer layer and shallow spalling existed. This was due to the fact that as friction and wear proceeded, the raised portions of the test piece surface gradually detached from the friction balls due to the adhesive action, which could induce the formation of wear debris [27]. The generated abrasive debris was not excluded in time and remained at the bottom of the surface topography at the beginning stage of wear. Figure 13c shows that the depth of the wear track on the worn surface of the Ti_2AlNb alloy after the friction test at a temperature of 600 °C was slightly smaller than that at temperatures of 25 °C and 300 °C. It was found that uniform wear marks and smooth wear surfaces were found on the worn surface of the Ti_2AlNb alloy after the high-temperature friction test compared to that after the low-temperature friction test. Massive adhesive spots were detected on the worn surface. This was due to the fact that the softer surface of the contacted material would undergo shear damage, some material of which could be transferred onto the harder surface of the contacted material. It could be illustrated that adhesive wear existed in the abrasion procedure. The abrasion of the Ti_2AlNb alloy belonged to the slight abrasion wear at the high temperature of 600 °C. The

high-temperature abrasion resistance of the Ti_2AlNb alloy at 600 °C was higher than the low-temperature abrasion resistance of the Ti_2AlNb alloy at 25 °C and 300 °C.

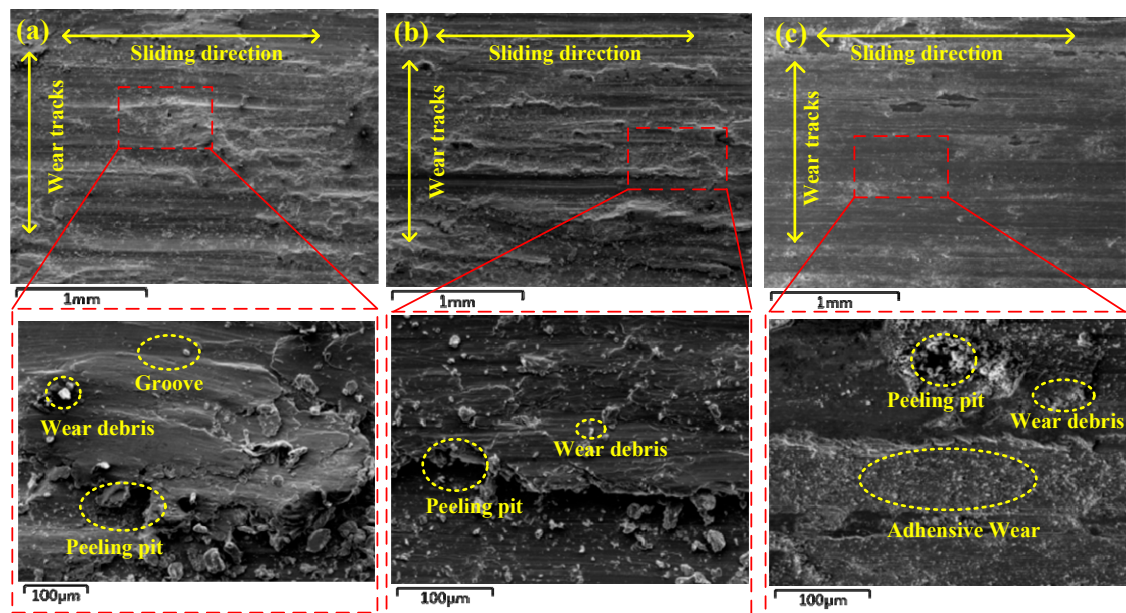


Figure 13. Surface morphology of worn Ti_2AlNb alloy with CrAlN/(CrAlB)N/CrAlN-coated carbide specimen after wear tests at specific temperatures: (a) 25 °C; (b) 300 °C; (c) 600 °C.

Figure 14 shows the surface morphologies of worn Ti_2AlNb alloys with uncoated carbide specimens after wear tests at specific temperatures. The apparent adhesive transfer and plastic flow of material were found on the surface of the Ti_2AlNb alloy at all testing temperatures, which belonged to the typical type of adhesive wear. The parallel furrows at the abrasion marks were the typical characteristics of abrasive wear. Massive flaking pits were found along the wear direction. Some sporadic white dots were detected at all the abrasion marks, which belonged to the locally loosened debris. Figure 14a–c depict that the wear marks on the surface of the Ti_2AlNb alloy were gradually smoother, and the adhesion area was gradually reduced with the increase in temperature. At the testing temperature of 600 °C, the worn surface of the Ti_2AlNb alloy was flatter, and the wear marks of the worn alloy were flatter and smoother compared to that at low temperature. It was found that the surface had less debris, less material adhered to the surface, and there less flaking. It was indicated that the micro-cracks were generated due to the stresses induced by the friction loading conditions. The fatigue wear would be generated with the eventual surface layer spalling. Similar tribological behaviors were found in reference [38].

Figure 15 depicts the surface morphologies of the worn Ti_2AlNb alloy with uncoated and CrAlN/(CrAlB)N/CrAlN-coated carbide specimens after wear tests. Figure 16 shows the surface roughness of the worn Ti_2AlNb alloy and worn pin specimen at various testing temperatures. The surface roughness of the original Ti_2AlNb alloy specimen before the friction test was measured as 1.253 μm . The surface roughness value of the original CrAlN/(CrAlB)N/CrAlN-coated sample surface was detected as 1.465 μm . The surface roughness value of the original uncoated carbide specimen surface was measured as 0.676 μm . Figure 16a shows that the Ti_2AlNb alloys possessed good surface quality after high-temperature friction tests. All the worn Ti_2AlNb alloys possessed better surface quality after the high-temperature friction tests. However, Figure 16b shows that the surface quality of the uncoated and coated pin specimens exhibited the opposite trend of change in surface roughness, which indicated that the wear resistance of uncoated carbide was poor at high temperatures, and the CrAlN/(CrAlB)N/CrAlN coating could improve the wear resistance of cemented carbide at high temperatures.

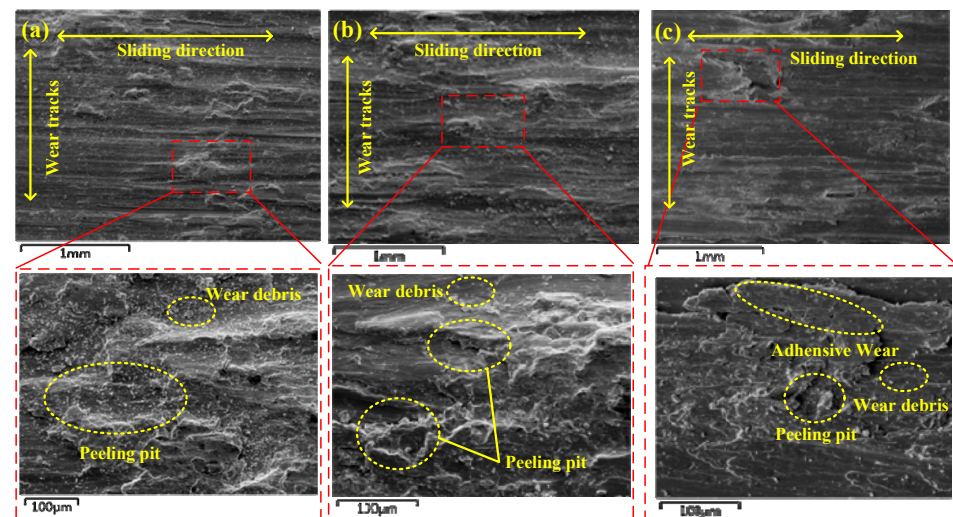


Figure 14. Surface morphology of worn Ti_2AlNb alloy with uncoated carbide specimen after wear tests at specific temperatures: (a) 25 °C; (b) 300 °C; (c) 600 °C.

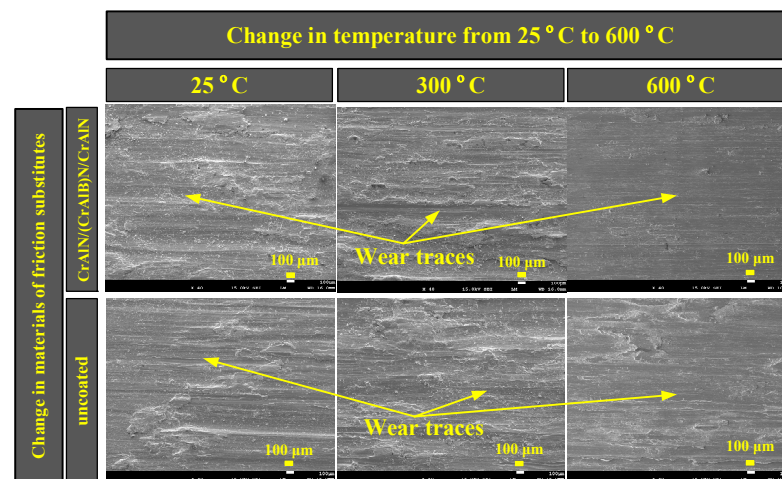


Figure 15. Surface morphology of worn Ti_2AlNb alloy with uncoated and CrAlN/(CrAlB)N/CrAlN-coated carbide specimens after wear tests.

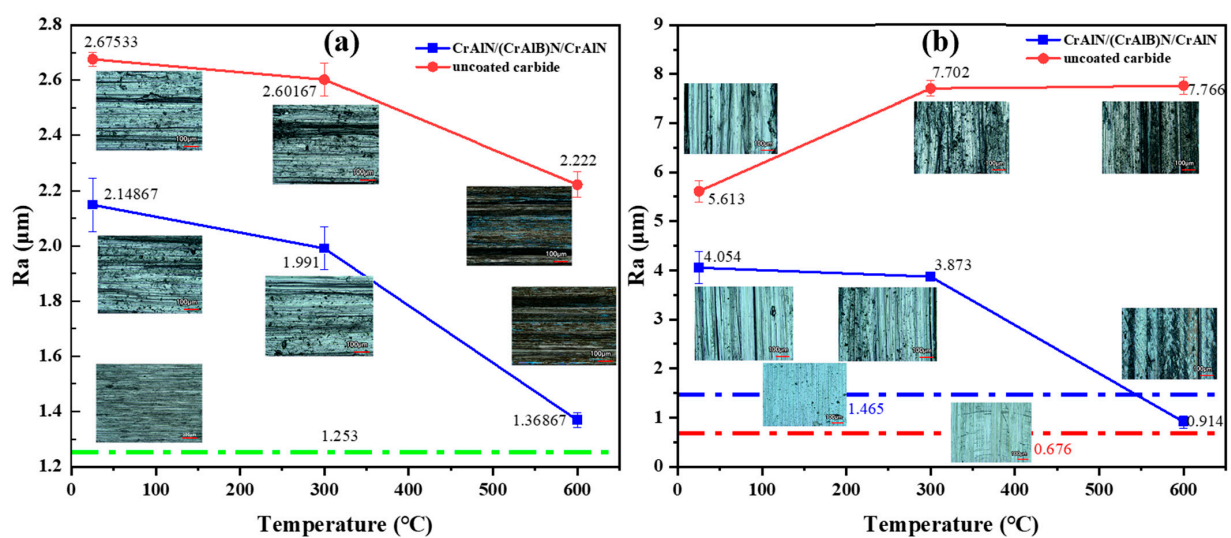


Figure 16. Surface roughness values of (a) worn Ti_2AlNb alloy; (b) worn pin specimen vs. testing temperatures.

The Ti₂AlNb alloy lost material through various wear mechanisms. Many scratches along the sliding direction were detected on the surface of the Ti₂AlNb alloy after the wear process. The morphology of the wear trajectory indicated that abrasive wear and adhesive wear were the main wear mechanisms. The worn surface of the Ti₂AlNb alloy was smoother, the scratches were not obvious, the surface roughness was reduced, and the adhesive wear was dominant at the high temperature of 600 °C. During the friction test at the temperature of 600 °C, the abrasive debris on the worn surface was compacted under the action of frictional stress. The wear surface of the Ti₂AlNb alloy was relatively smooth to reduce the contact friction coefficient [26].

4.3. Element Analysis of Worn Ti₂AlNb Alloy Surface Rubbed with CrAlN/(CrAlB)N/CrAlN-Coated Carbides

The chemical element analysis was carried out to investigate the adhesive material on the worn surface of the Ti₂AlNb alloy at specific temperatures. Figure 17a shows the SEM morphology of the worn surface of the Ti₂AlNb alloy rubbed with the CrAlN/(CrAlB)N/CrAlN-coated carbide at temperature (25 °C). Figure 17b–d depict the main chemical element distribution on the surface of the Ti₂AlNb alloy rubbed with the CrAlN/(CrAlB)N/CrAlN-coated carbide at temperature (25 °C). Figure 17b,d depict that the contents of the C element, Cr element, and Ni element on the worn surface after abrasion were significantly increased. It was indicated that the CrAlN/(CrAlB)N/CrAlN coating material adhered to the surface of the Ti₂AlNb alloy. It was due to this fact that there was bonding energy resistance at the contact interface between the CrAlN/(CrAlB)N/CrAlN coating and the Ti₂AlNb alloy, which could induce adhesive wear. Figure 17c,d show no evident change in chemical element compared to the original element composition of the Ti₂AlNb alloy. Figure 17a depicts that the obvious grooves were found on the worn surface topography. It was indicated that the main wear mechanism between the CrAlN/(CrAlB)N/CrAlN coating and the Ti₂AlNb alloy was adhesive wear and abrasive wear during the pin–disc friction tests at room temperature (25 °C).

Figure 18 depicts the SEM and EDS surface images of the worn Ti₂AlNb alloy with the CrAlN/(CrAlB)N/CrAlN-coated specimen at a testing temperature of 300 °C. Both abrasive and adhesive wear with obvious severe ploughing marks and adhesive particles are displayed on the wear surface as shown in Figure 18a. Figure 18b,d depict that little variation in the contents of the Ti element, Al element, Mo element, and Nb element was found at the worn surface. The little increase in the C element and O element contents indicated that the material transfer occurred during the wear process, which belonged to the slight adhesive wear. Figure 18c,d show that the sequence of the main chemical element content was Ni > C > O on the worn surface of the Ti₂AlNb alloy. The contents of the Fe and Cr elements increased, but the contents of the Ti, Al, and Mo elements decreased, which indicated that the adhesive region was mainly the CrAlN/(CrAlB)N/CrAlN coating material. The accumulation of some peeled coatings was covered on the worn surface of the Ti₂AlNb alloy.

Figure 19 depicts the SEM and EDS surface images of the worn Ti₂AlNb alloy with the CrAlN/(CrAlB)N/CrAlN-coated specimen at a testing temperature of 600 °C. Figure 19b shows that the content of the O element on the worn surface of the Ti₂AlNb alloy increased significantly. The remaining element contents of the CrAlN/(CrAlB)N/CrAlN coating remained almost unchanged. It was illustrated that the oxidation occurred during the high-temperature friction test. Figure 19c,d show that the content of the O element was the highest compared to that of the other types of chemical elements. The contents of the C and Cr elements increased slightly, and the contents of the original elements of Ti₂AlNb alloy reduced significantly. It was indicated that the material transfer and oxidized film all occurred on the surface of Ti₂AlNb alloy during pin–disc friction tests at the high temperature of 600 °C; thus, the friction coefficient decreased. This phenomenon was similar to that in reference [24].

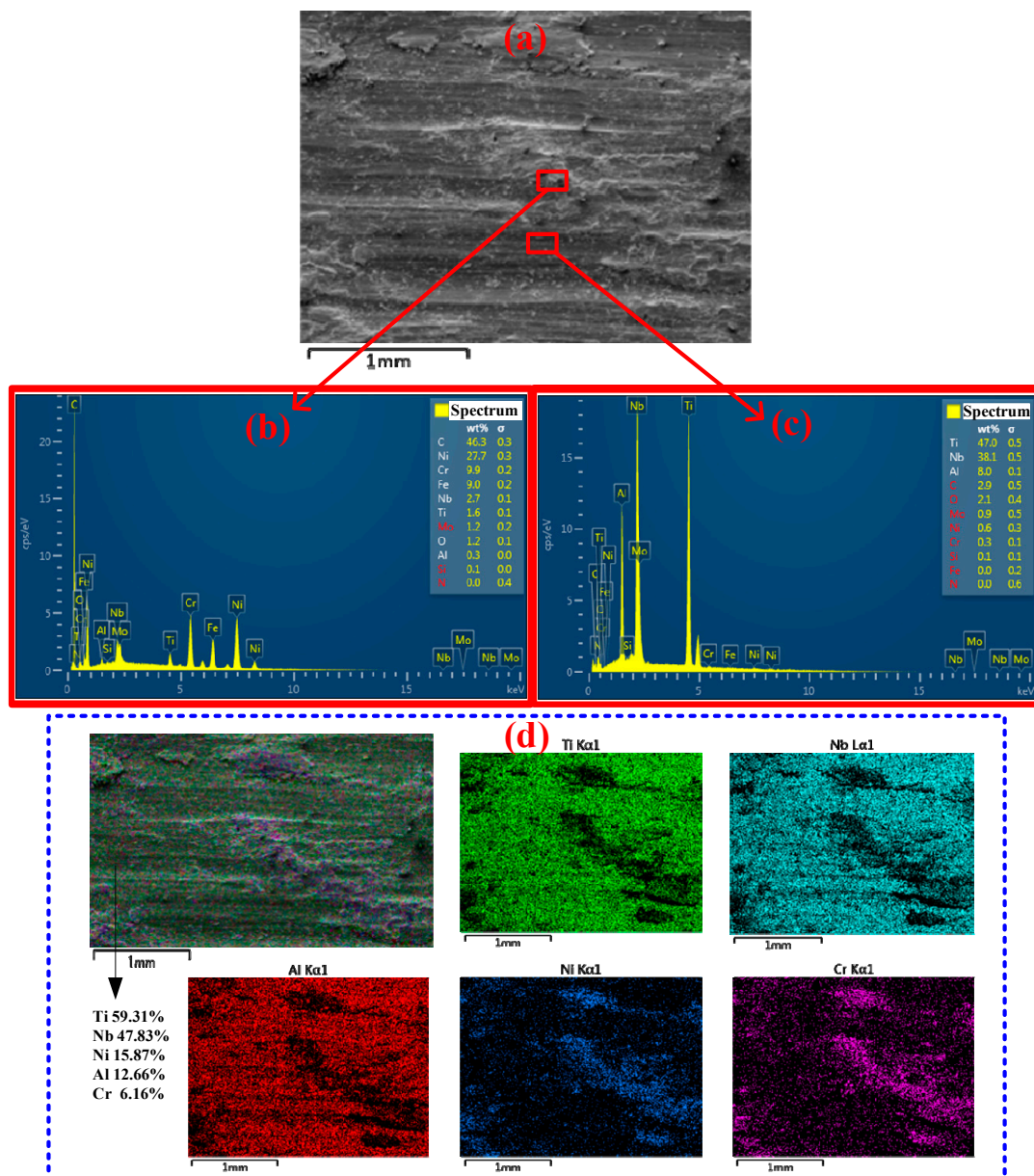


Figure 17. SEM and EDS surface images of worn Ti_2AlNb alloy with $\text{CrAlN}/(\text{CrAlB})\text{N}/\text{CrAlN}$ -coated specimen at a testing temperature of 25°C : (a) SEM surface image; (b) Element analysis result of one selected point; (c) Element analysis result of another selected point; (d) Element mapping of worn surface image.

Figure 20 depicts the worn surface morphology of the $\text{CrAlN}/(\text{CrAlB})\text{N}/\text{CrAlN}$ -coated specimen after friction tests with the Ti_2AlNb alloy at various testing temperatures. Figure 20 shows that the pin surface morphology gradually improved when the testing temperature was changed from 25°C to 600°C . The coating was seriously damaged at the testing temperature of 25°C and the surface was smooth at the testing temperature of 600°C . The obvious grooves and adhesive particles on the pin surface can be detected in Figure 20a,b. Combined with the aforementioned surface wear of the Ti_2AlNb alloy, it could be clearly determined that the wear mechanisms at testing temperatures of 25°C and 300°C were mainly abrasive wear and adhesive wear. The coating exfoliation was observed on the pin surface at a testing temperature of 600°C . The slight scratching and adhesion on the Ti_2AlNb alloy surface and the increased content of the O element indicated that the oxide film of the Ti_2AlNb alloy could be formed and the wear of the Ti_2AlNb alloy

could be reduced very well. Combined with the above SEM and EDS analyses of the worn surface of the Ti_2AlNb alloy, it could be further found that the friction reduction and wear resistance of the Ti_2AlNb alloy and the $\text{CrAlN}/(\text{CrAlB})\text{N}/\text{CrAlN}$ -coated cemented carbide were better at the testing temperature of 600 °C.

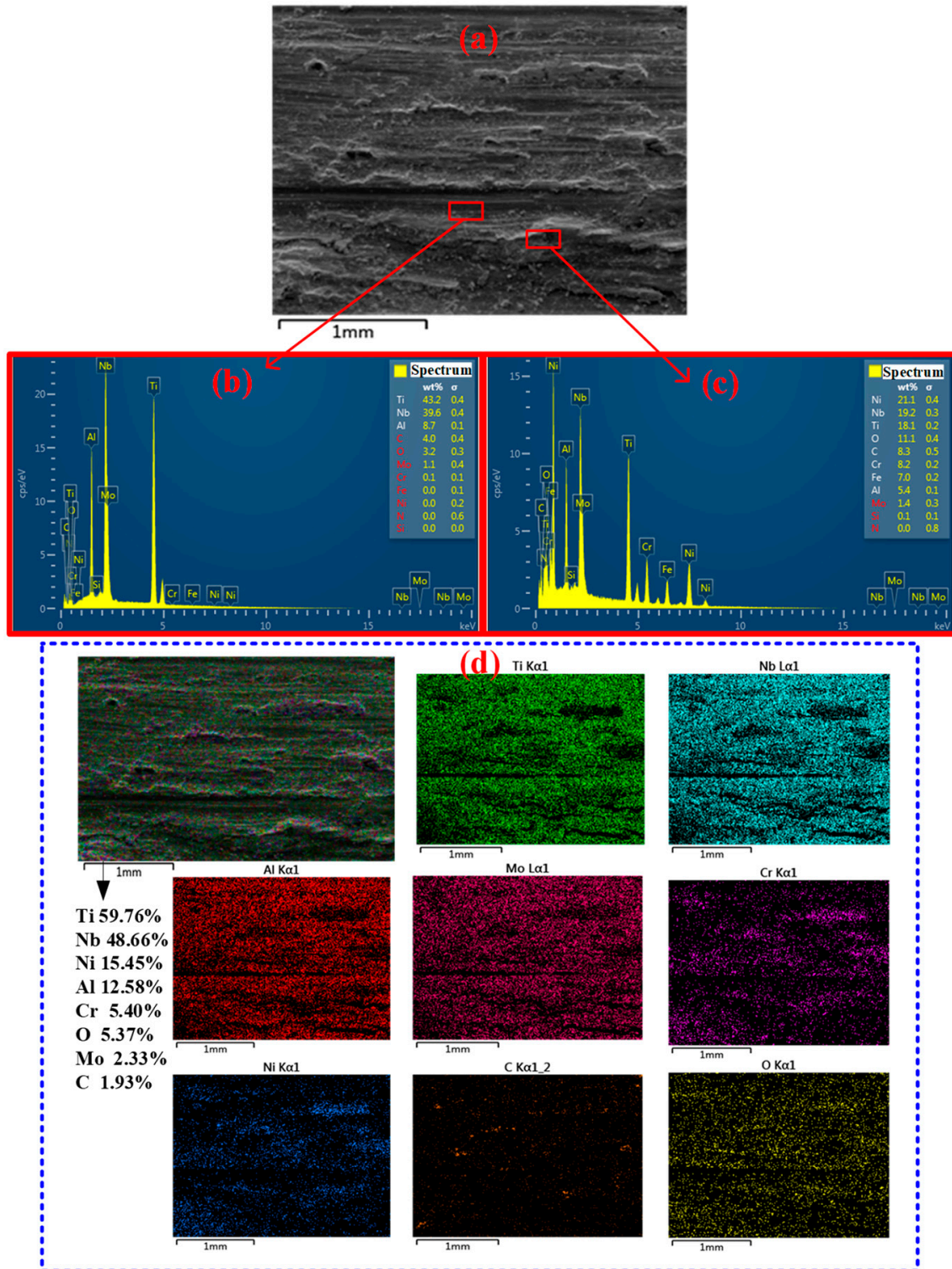


Figure 18. SEM and EDS surface images of worn Ti_2AlNb alloy with $\text{CrAlN}/(\text{CrAlB})\text{N}/\text{CrAlN}$ -coated specimen at a testing temperature of 300 °C: (a) SEM surface image; (b) Element analysis result of one selected point; (c) Element analysis result of another selected point; (d) Element mapping of worn surface image.

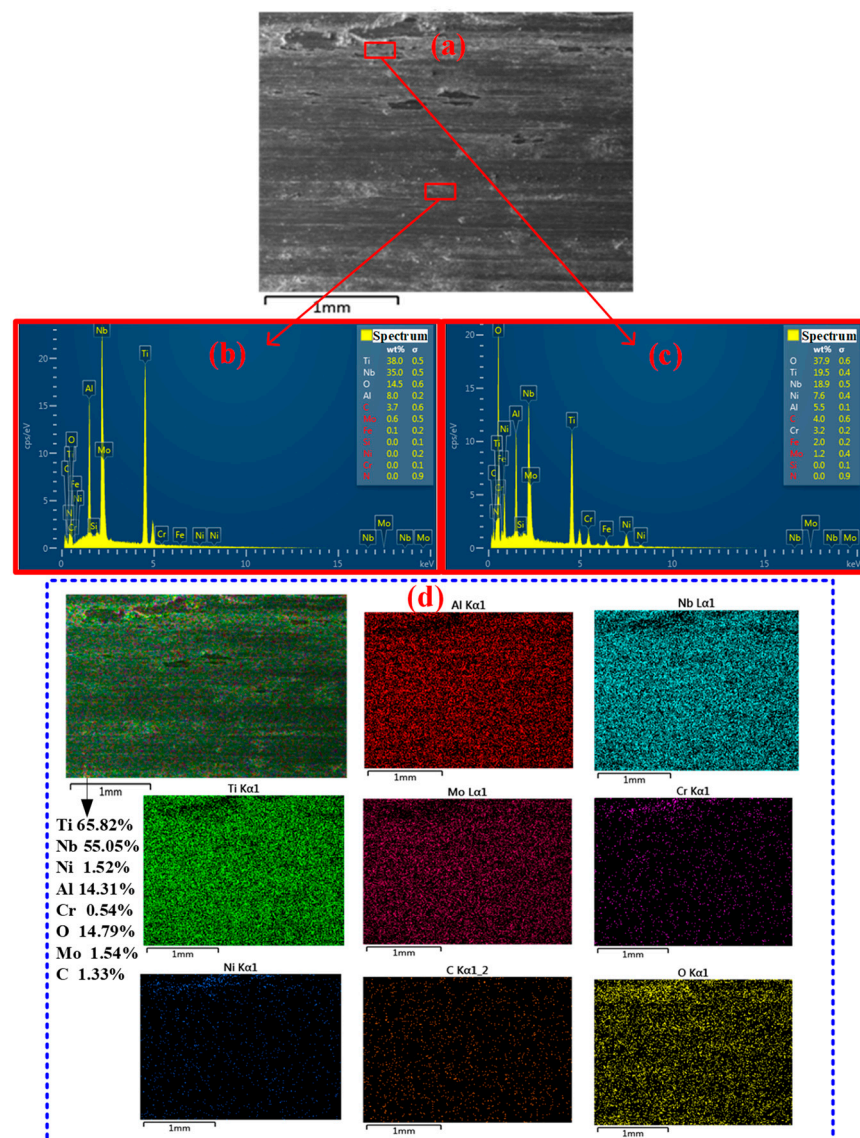


Figure 19. SEM and EDS surface images of worn Ti_2AlNb alloy with $\text{CrAlN}/(\text{CrAlB})\text{N}/\text{CrAlN}$ -coated specimen at a testing temperature of 600 °C: (a) SEM surface image; (b) Element analysis result of one selected point; (c) Element analysis result of another selected point; (d) Element mapping of worn surface image.

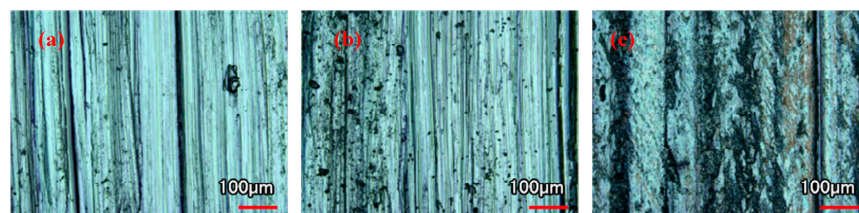


Figure 20. Surface morphology of worn $\text{CrAlN}/(\text{CrAlB})\text{N}/\text{CrAlN}$ -coated specimen after friction tests with Ti_2AlNb alloy at temperatures of (a) 25 °C; (b) 300 °C; and (c) 600 °C.

4.4. Element Analysis of Worn Ti_2AlNb Alloy Surface Rubbed with Uncoated Carbides

Figure 21 depicts the SEM and EDS surface images of the worn Ti_2AlNb alloy with an uncoated carbide specimen at the testing temperature of 25 °C. Figure 21b depicts the chemical element distribution at the furrows of the Ti_2AlNb alloy worn surface. A small content increase in the C element and the O element was detected at the furrows,

respectively. It was indicated that slight adhesive wear occurred. It could be determined that the abrasive wear was the main wear mechanism with the combination of the surface morphology of Figure 21a. This phenomenon is similar to that in reference [38]. Figure 21c shows the chemical element distribution at the adhesion on the worn surface of the Ti₂AlNb alloy. The sequence of main element contents was Ni > Nb > Cr. It was indicated that a large amount of cemented carbide material covered the worn surface of the Ti₂AlNb alloy. As shown in Figure 21d, the cemented carbide abrasive debris adhered to the surface of the Ti₂AlNb alloy due to the contact stress.

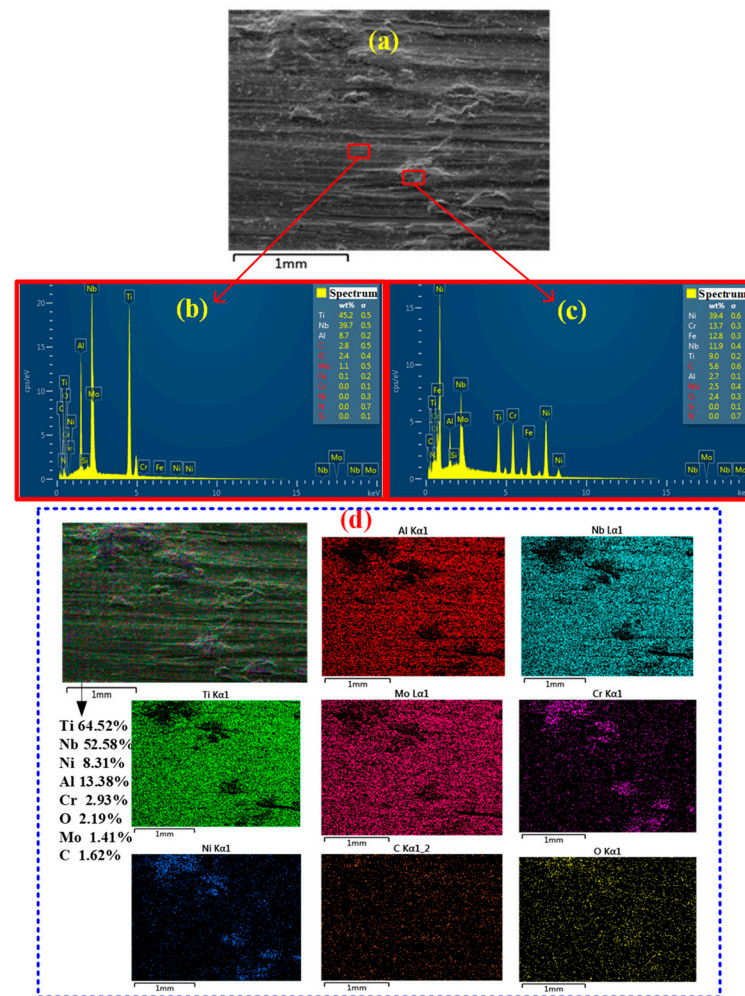


Figure 21. SEM and EDS surface images of worn Ti₂AlNb alloy with uncoated carbide specimen at a testing temperature of 25 °C: (a) SEM surface image; (b) Element analysis result of one selected point; (c) Element analysis result of another selected point; (d) Element mapping of worn surface image.

Figure 22 depicts the SEM and EDS surface images of the worn Ti₂AlNb alloy with an uncoated carbide specimen at the testing temperature of 300 °C. Figure 22b shows the chemical element distribution at the furrows of the Ti₂AlNb alloy's worn surface. There was almost no change in main element contents compared to the original element content of the Ti₂AlNb alloy. It was indicated that no material transfer or oxidation occurred, and only the abrasive wear occurred. Figure 22c depicts the worn surface adhesion of the Ti₂AlNb alloy at the element distribution image. The sequence of main chemical element contents was Ni > Cr > C at the adhesion as shown in Figure 22c,d. The contents of the Ti, Al, and Nb elements were small. It was illustrated that the worn surface of the Ti₂AlNb alloy was covered by cemented carbide material.

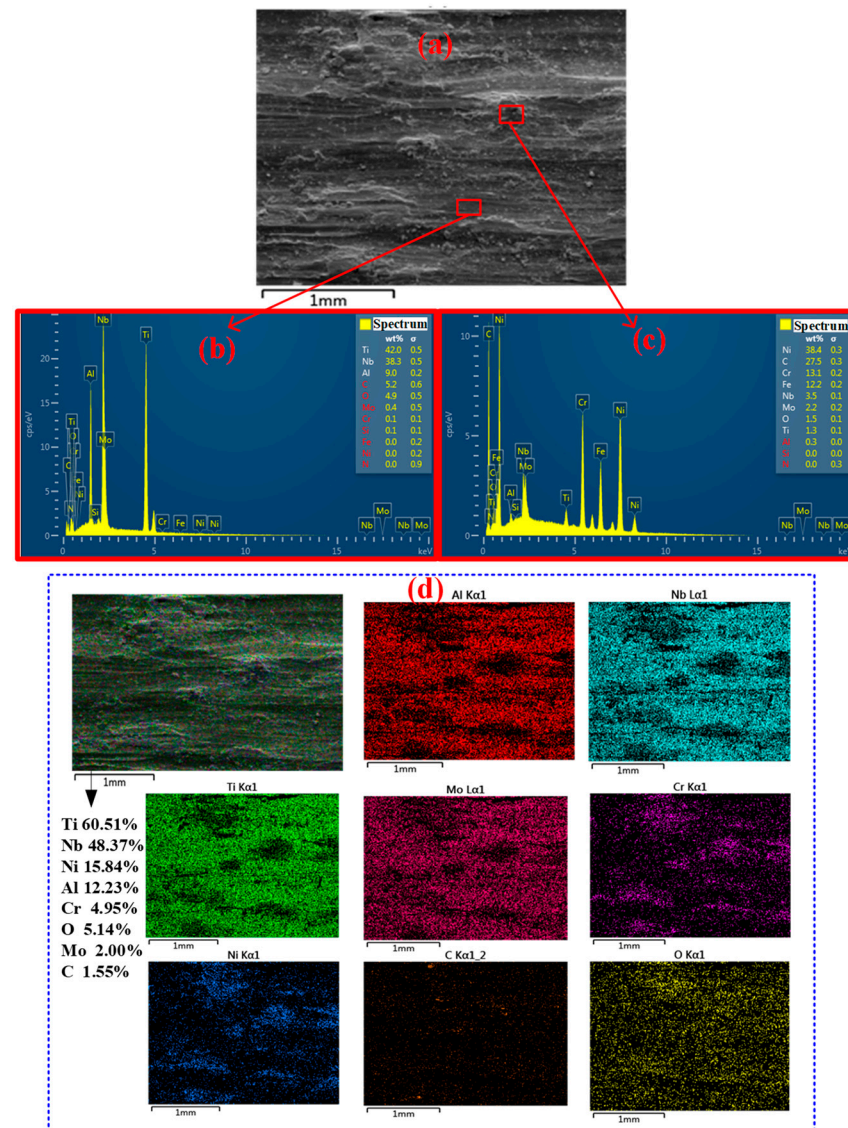


Figure 22. SEM and EDS surface images of worn Ti_2AlNb alloy with uncoated carbide specimen at a testing temperature of 300 °C: (a) SEM surface image; (b) Element analysis result of one selected point; (c) Element analysis result of another selected point; (d) Element mapping of worn surface image.

Figure 23 depicts the SEM and EDS surface images of the worn Ti_2AlNb alloy with an uncoated carbide specimen at a testing temperature of 600 °C. Compared to Figures 21 and 22, the O element on the worn surface significantly increased. It was illustrated that some chemical elements may undergo oxidation to form oxide films. The existence of oxide films could increase the wear resistance of the Ti_2AlNb alloy.

Figure 24 depicts the worn surface morphology of uncoated cemented carbide specimens after the friction tests with the Ti_2AlNb alloy at various temperatures. The obvious scratches on the surface of the pin specimen along the friction sliding direction can be observed in Figure 22a. The small increase in the C and O elements on the surface of the Ti_2AlNb alloy indicated that the pin surface had shear failure. The material on the pin surface adhered to the surface of the Ti_2AlNb alloy due to the friction stress, which indicated that the adhesive wear was the main wear mechanism at 25 °C. Massive peeling materials appeared on the pin surface at 300 °C and 600 °C. Combined with the analysis of the worn surface of the Ti_2AlNb alloy, these exfoliations were covered on the surface of Ti_2AlNb alloy under the action of pressure and temperature. Compared with Figure 18, it was found that the surface morphology of uncoated cemented car-

bide samples with the CrAlN/(CrAlB)N/CrAlN coating was poor, which also confirmed that the CrAlN/CrAlBN/CrAlN coating can be used to improve the wear resistance of cemented carbide.

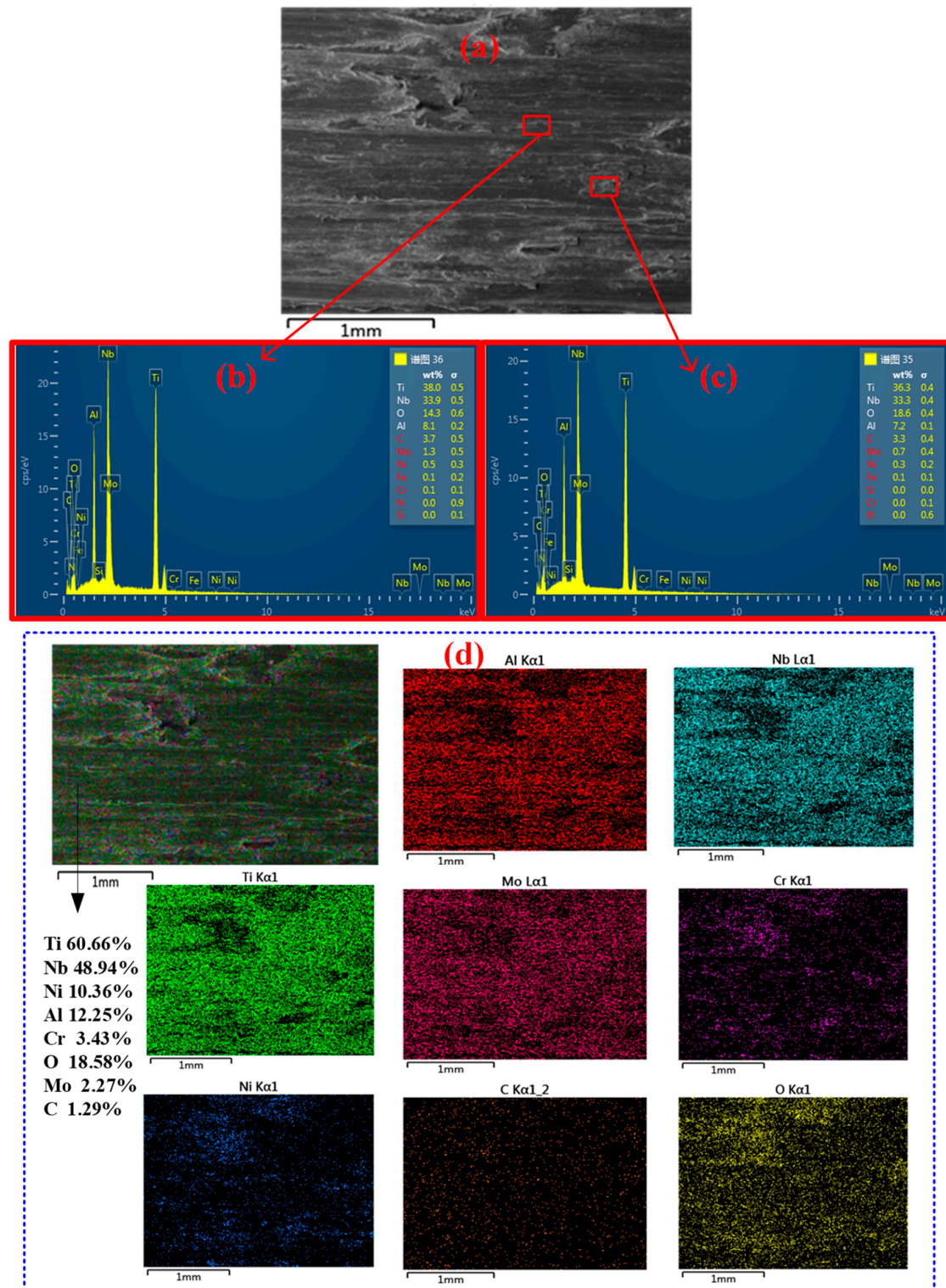


Figure 23. SEM and EDS surface images of worn Ti_2AlNb alloy with uncoated carbide specimen at a testing temperature of 600 °C: (a) SEM surface image; (b) Element analysis result of one selected point; (c) Element analysis result of another selected point; (d) Element mapping of worn surface image.

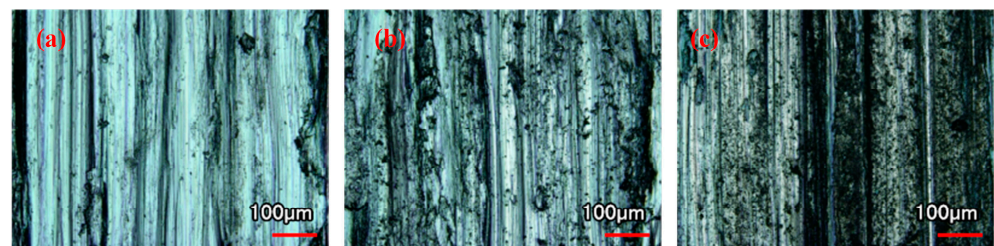


Figure 24. Surface morphology of worn uncoated carbide specimen after friction tests with Ti_2AlNb alloy at temperatures of (a) 25 °C; (b) 300 °C; and (c) 600 °C.

5. Conclusions

In this research, the time-varied friction properties of the Ti_2AlNb alloy with the WC/Co carbide tool couple, with the sole variation being the PVD CrAlN/(CrAlB)N/CrAlN coating, were conducted. Several conclusions have been summarized as follows.

- The Ti_2AlNb alloy exhibited good antifriction properties at high temperatures. The lowest friction coefficient and wear rate of the Ti_2AlNb alloy when it was contacted with the uncoated and CrAlN/(CrAlB)N/CrAlN-coated carbide were all obtained at the high temperature of 600 °C. It was related to the fact that the worn surface of the Ti_2AlNb alloy generated an oxidized film, and the surface became smoother when it was rubbed with a tool couple at high temperature.
- Superior antifriction properties of the Ti_2AlNb alloy were obtained when it was contacted with the CrAlN/(CrAlB)N/CrAlN-coated carbide. The friction coefficient and wear rate of the Ti_2AlNb alloy rubbed with uncoated carbide were increased by 6.12% and 78.95%, 6.81% and 7.69%, and 3.33% and 28.57% compared to that with the CrAlN/(CrAlB)N/CrAlN-coated sample at testing temperature 25 °C, 300 °C, and 600 °C, respectively.
- The apparent adhesive wear and abrasive wear of the Ti_2AlNb alloy could be improved due to the PVD CrAlN/(CrAlB)N/CrAlN coating at evaluated temperatures based on the topography and chemical analysis of the worn surface. The wear loss of the CrAlN/(CrAlB)N/CrAlN-coated and uncoated carbide tool couples could be neglected.

The results showed that PVD CrAlN/(CrAlB)N/CrAlN coating could be utilized to improve the antifriction properties of the Ti_2AlNb alloy, which may be deposited on the cutting tool to improve the machining performance of Ti_2AlNb alloys in future aerospace machining industry.

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References

- Li, Z.X.; Chang, B.H.; Wang, J.C.; Zhang, H.Y.; Liang, Z.Y.; Liao, Z.Y.; Wang, L.; Liu, C.M.; Du, Y. Dual-droplet transition control for improving forming quality and composition homogenizing in dual-wire additive manufacturing of Ti₂AlNb alloy. *Int. J. Mach. Tools Manuf.* **2024**, *195*, 104114. [\[CrossRef\]](#)
- Zhang, P.H.; Zeng, W.D.; Zhang, F.; Ma, H.Y.; Xu, J.W.; Liang, X.B.; Zhao, Y.Q. Fracture toughness of Ti₂AlNb alloy with different Al content: Intrinsic mechanism, extrinsic mechanism and prediction model. *J. Alloys Compd.* **2023**, *952*, 170068. [\[CrossRef\]](#)
- Kumar, A.; Maurya, A.; Kandadi, V.M.; Mahato, A. Introduction of rolling motion at the tool-tip in metal cutting. *Int. J. Mach. Tools Manuf.* **2023**, *186*, 104001. [\[CrossRef\]](#)
- Li, Z.; Sui, S.; Ma, X.; Tan, H.; Zhong, C.L.; Bi, G.J.; Clare, A.T.; Gasser, A.; Chen, J. High deposition rate powder- and wire-based laser directed energy deposition of metallic materials: A review. *Int. J. Mach. Tools Manuf.* **2022**, *181*, 103942. [\[CrossRef\]](#)
- Yu, Z.; Li, Z.; Guo, Y.; Fu, R.; Xu, T.; Liu, C. Homogenizing the composition of in-situ fabricated Ti₂AlNb-based alloy via manipulating the droplet transfer mode of twin-wire arc additive manufacturing. *J. Alloys Compd.* **2022**, *923*, 165992. [\[CrossRef\]](#)
- Senkevich, K.S.; Pozhoga, O.Z.; Kudryavtsev, E.A.; Zasyupkin, V.V. The effect of hydrogenation on the fracture of Ti₂AlNb-based alloy during ball milling. *J. Alloys Compd.* **2022**, *902*, 163794. [\[CrossRef\]](#)
- Zhang, H.; Zhang, Y.; Liang, H.; Liu, Y. Influence of cooling rates on microstructure and tensile properties of a heat treated Ti₂AlNb-based alloy. *Mater. Sci. Eng. A* **2021**, *817*, 141345. [\[CrossRef\]](#)
- Chen, X.; Xie, F.Q.; Ma, T.J.; Li, W.Y.; Wu, X.Q. Microstructural evolution and mechanical properties of linear friction welded Ti₂AlNb joint during solution and aging treatment. *Mater. Sci. Eng. A* **2016**, *668*, 125–136. [\[CrossRef\]](#)
- Grigoriev, A.; Polozov, I.; Sufiarov, V.; Popovich, A. In-situ synthesis of Ti₂AlNb-based intermetallic alloy by selective laser melting. *J. Alloys Compd.* **2017**, *704*, 434–442. [\[CrossRef\]](#)
- Li, Z.; Cui, Y.; Wang, L.; Zhang, H.; Liang, Z.; Liu, C.; Du, D. An investigation into Ti-22Al-25Nb in-situ fabricated by electron beam freeform fabrication with an innovative twin-wire parallel feeding method. *Addit. Manuf.* **2022**, *50*, 102552. [\[CrossRef\]](#)
- Abukhshim, N.A.; Mativenga, P.T.; Sheikh, M.A. Heat generation and temperature prediction in metal cutting: A review and implications for high speed machining. *Int. J. Mach. Tool. Manfu.* **2006**, *46*, 782–800. [\[CrossRef\]](#)
- Shalaby, M.A.; Veldhuis, S.C. Wear and tribological performance of different ceramic tools in dry high speed machining of Ni-Co-Cr precipitation hardenable aerospace superalloy. *Tribol. Technol.* **2019**, *62*, 62–77. [\[CrossRef\]](#)
- Zhao, J.F.; Liu, Z.Q.; Wang, B.; Hu, J.R.; Wan, Y. Tool coating effects on cutting temperature during metal cutting processes: Comprehensive review and future research directions. *Mech. Syst. Signal. Process.* **2021**, *150*, 107302. [\[CrossRef\]](#)
- Zhao, J.F.; Liu, Z.Q.; Wang, Q.Q.; Jiang, J.M. Measurement of temperature-dependent thermal conductivity for PVD Ti_{0.55}Al_{0.45}N ceramic coating by time domain thermo-reflectance method. *Ceram. Int.* **2019**, *45*, 8123–8129. [\[CrossRef\]](#)
- Liu, Q.; Liao, Z.R.; Axinte, D. Temperature effect on the material removal mechanism of soft-brittle crystals at nano/micron scale. *Int. J. Mach. Tool. Manuf.* **2020**, *159*, 103620. [\[CrossRef\]](#)
- Liao, Z.R.; Monaca, A.; Murray, J.; Speidel, A.; Ushmaev, D.; Clare, A.; Axinte, D.; M'Saoubi, R. Surface integrity in metal machining-Part I: Fundamentals of surface characteristics and formation mechanisms. *Int. J. Mach. Tools Manuf.* **2021**, *162*, 103687. [\[CrossRef\]](#)
- Monaca, A.; Murray, J.W.; Liao, Z.R.; Speidel, A.; Robles-Linares, J.A.; Axinte, D.A.; Hardy, M.C.; Clare, A.T. Surface integrity in metal machining-Part II: Functional performance. *Int. J. Mach. Tools Manuf.* **2021**, *164*, 103718. [\[CrossRef\]](#)
- Yuan, Z.J.; Gao, G.F.; Wang, Y.; Fu, Z.X.; Xiang, D.H. Correction to: Experimental study on a two-dimensional ultrasonic vibration platform and milling of Ti₂AlNb intermetallic alloy. *Int. J. Adv. Manuf. Tech.* **2022**, *122*, 2793. [\[CrossRef\]](#)
- Li, C.X.; Xia, J.; Dong, H. Sliding wear of TiAl intermetallics against steel and ceramics of Al₂O₃, Si₃N₄ and WC/Co. *Wear* **2006**, *261*, 693–701. [\[CrossRef\]](#)
- Alam, M.O.; Haseeb, A.S.M.A. Response of Ti-6Al-4V and Ti-24Al-11Nb alloys to dry sliding wear against hardened steel. *Tribol. Int.* **2002**, *35*, 357. [\[CrossRef\]](#)
- Rastkar, A.R.; Bloyce, A.; Bell, T. Sliding wear behaviour of two gamma-based titanium aluminides. *Wear* **2000**, *240*, 19–26. [\[CrossRef\]](#)
- Zambrano Carrullo, J.C.; Pereira Falcón, J.C.; Amigó Borrás, V. Influence of process parameters and initial microstructure on the oxidation resistance of Ti48Al2Cr2Nb coating obtained by laser metal deposition. *Surf. Coat. Technol.* **2019**, *358*, 114–124. [\[CrossRef\]](#)
- Weller, M.; Chatterjee, A.; Haneczok, G.; Clemens, H. Internal friction of γ-TiAl alloys at high temperature. *J. Alloys Compd.* **2000**, *310*, 134–138. [\[CrossRef\]](#)
- Cheng, J.; Li, F.; Qiao, Z.H.; Zhu, S.Y.; Yang, J.; Liu, W.M. The role of oxidation and counterface in the high temperature tribological properties of TiAl intermetallics. *Mater. Des.* **2015**, *84*, 245–253. [\[CrossRef\]](#)
- Nuo, C.; Xiao, H.Q.; Zhao, X.X.; Ren, L.R.; Tian, Y.X.; Zhou, X. Friction and wear behaviour of laser-cladded TiAl coating on TC4 substrate from room temperature to 800 °C. *JOM* **2023**, *75*, 3285–3293.
- Wang, W.; Zhou, H.H.; Wang, Q.J.; Jin, J.; Sun, Y.L.; Wang, K.S. High-temperature tribological behaviour of the Ti-22Al-25Nb (at.%) orthorhombic alloy with lamellar O microstructures. *Metals* **2018**, *9*, 5. [\[CrossRef\]](#)
- Wang, Y.; Gao, G.F.; Zhang, K.; Wang, Y.; Wang, X.B.; Xiang, D.H. Modelling of tribological behavior and wear for micro-textured surfaces of Ti₂AlNb intermetallic compounds machined with multi-dimensional ultrasonic vibration assistance. *Tribol. Int.* **2024**, *191*, 109167. [\[CrossRef\]](#)

28. Bobzin, K.; Kalscheuer, C.; Carlet, M.; Schmauder, S.; Guski, V.; Verestek, W.; Tayyab, M. 3D deformation modeling of CrAlN coated tool steel compound during nanoindentation. *Surf. Coat. Technol.* **2021**, *453*, 129148. [[CrossRef](#)]
29. Bobzin, K.; Kalscheuer, C.; Möbius, M.P. Triboactive CrAlN+MoWS coatings deposited by pulsed arc PVD. *Surf. Coat. Technol.* **2023**, *475*, 130178. [[CrossRef](#)]
30. Hu, C.; Chen, L.; Moraes, V. Structure, mechanical properties, thermal stability and oxidation resistance of arc evaporated CrAlBN coatings. *Surf. Coat. Technol.* **2021**, *417*, 127191. [[CrossRef](#)]
31. Kim, S.K.; Le, V.V. Deposition of nanolayered CrN/AlBN thin films by cathodic arc deposition: Influence of cathode arc current and bias voltage on the mechanical properties. *Surf. Coat. Technol.* **2010**, *204*, 3941–3946. [[CrossRef](#)]
32. Dai, Y.; Li, K.M.; Xiang, Q.; Ou, M.G.; Yang, F.; Liu, J. Microstructure and tribology behaviors of WC coating fabricated by surface mechanical composite strengthening. *Appl. Surf. Sci.* **2023**, *619*, 156759. [[CrossRef](#)]
33. Li, M.S.; Jiang, Q.Y.; Fan, Y.Z.; Wang, R.D. Structure and mechanical properties of (CrAl)N and (CrAlSiY) N coating prepared by asymmetrical bipolar DC magnetron sputtering. *AER-Adv. Eng. Res.* **2016**, *85*, 1054–1060.
34. Liu, X.L.; Lin, Z.; Zhao, H.J.; Sun, F. Study on microstructure, mechanical properties, tribological properties and service performance of CrAlN and CrAlBN coatings deposited on powder metallurgy high-speed steel (PM-HSS) and shaper cutter by arc ion plating technique. *Coatings* **2024**, *14*, 486. [[CrossRef](#)]
35. Drnovšek, A.; Kukuruzovič, D.; Terek, P.; Miletić, A.; Čekada, M.; Panjan, M.; Panjan, P. Microstructural, mechanical and oxidation resistance of nanolayer sputter-deposited CrAlN hard coatings. *Coatings* **2023**, *13*, 2096. [[CrossRef](#)]
36. Chen, W.L.; Hu, T.; Hong, Y.; Zhang, D.D.; Meng, X. Comparison of microstructures, mechanical and tribological properties of arc-deposited AlCrN, AlCrBN and CrBN coatings on Ti-6Al-4V alloy. *Surf. Coat. Technol.* **2020**, *404*, 126429. [[CrossRef](#)]
37. Zhang, H.Y.; Yan, N.; Liang, H.Y.; Liu, Y.C. Phase transformation and microstructure control of Ti2AlNb-based alloys: A review. *J. Mater. Sci. Technol.* **2021**, *80*, 203–216. [[CrossRef](#)]
38. Cheng, F.; Lin, J.; Liang, Y. Friction and wear properties of a high Nb-containing TiAl alloy against WC-8Co, Si₃N₄, and GCr₁₅ in an unlubricated contact. *Intermetallics* **2019**, *106*, 7–12. [[CrossRef](#)]

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