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Research Article

Wear Resistance of Ni-Based Alloy Coatings

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In this paper, nickel-based alloy coatings were deposited on the surface of pure copper by jet electrodeposition. The wear resistance of the coatings was studied by a material surface comprehensive performance tester under dry sliding. Hardness testing, friction, and wear testing were performed to characterize the microhardness, surface morphology, and wear resistance of the coatings. The results indicated that adding Fe and W could refine and purify the microstructure. The coatings with additions of 5 wt.% Fe and 7 wt.% W exhibited the highest wear-resistant properties. Moreover, new compound phases NiO, Fe_2O_3, and WO_3 were found on the surface coatings, such that the microhardness was higher than that in the other coatings. Detailed discussions on the influences of Fe and W on the sliding wear are presented.

1. Introduction

Ni-based alloy coatings have been widely used as wear materials [1–6]. The most commonly employed Ni-based alloy coatings are NiFe, NiW, and NiFeW. Ni, as the major element, provides ductility and enhances the corrosion resistance [7–10]. These coatings are widely used in gas turbines and in oil and steel industries, where sliding or erosion between one or more bodies is commonly encountered [11–13]. Ni-based alloy coatings may also be more suitable than Co-based alloy coatings due to their better antiwear properties and lower costs [14–16]. Compared to the conventional coating methods, jet electrodeposition processing results in higher adhesive bonding, less porosity, a more compact microstructure [13, 15], higher hardness, and better wear resistance. The jet electrodeposition can use high current density and plating speed. The coating is more resistant to high-temperature oxidation. Once an oxidation film forms, it is dense, resulting in high wear resistance in the coatings. Previous studies on Ni-based alloy coatings mainly focused on sliding wear properties. However, mechanisms for the friction and wear in Ni-based alloy coatings are important to understand the wear properties, which need to be systematically studied. In this paper, Ni-based alloy coatings have been deposited on pure copper using jet electrodeposition, aiming to study the wear resistance of Ni-based alloy coatings under dry sliding conditions against 45# steel at ambient conditions. In addition, the study of friction and wear mechanisms also provides an experimental basis for the application of Ni-based alloy coatings.

2. Experiment

The Ni-based alloy coatings were deposited on pure copper by jet electrodeposition. The pure copper substrates were machined to dimensions of 10 mm × 8 mm × 6 mm. The substrate was first immersed in a 15 g/L NaOH, 25 g/L Na_2CO_3, 25 g/L Na_3PO_4, and 1 ml/L of OP-10 mixed solution to remove cutting oils and washed in 60°C–70°C hot water and cold water, respectively. Then, the substrate was immersed in a mixed acid solution of 50 g/L phosphate, 50 g/L nitric acid, and 30 g/L acetic acid for polishing. Then, the substrate was etched in a 160 ml/L H_2SO_4 and 80 ml/L H_2O_2 solution for 10 minutes and finally washed with deionized water. The following electrolytes were used: 250 g/L $Ni(NH_2SO_3)_2{\cdot}4H_2O$, 10 g/L $NiCl_2{\cdot}4H_2O$, 40 g/L $Na_3C_6H_5O_7{\cdot}2H_2O$, 40 g/L H_3BO_3, 1.2 g/L $FeCl_2{\cdot}4H_2O$, 80 g/L $Na_2WO_4{\cdot}2H_2O$, saccharin (as stress removal agent and brighteners, 8 g/L), and ascorbic acid (Vc as stabilizer, 2 g/L). A current density (D_K) of 60 A/dm^2, a pH value of 4.0, a temperature of 60°C, jet speed of 3 m/s, and a copper (as the cathode material) were used for Ni coating.

Analytical reagents and deionized water were used for the plating bath, where 5 g/L NaOH or 10 g/L $Ni(NH_2SO_3)_2{\cdot}4H_2O$ was used to control the pH value. The substrate was placed in a cell equipped with a numerical control double-polar pulsed electrical source (SMD300/50, Handan Dashun, China) for electroplating.

All of the coatings were firstly heat-treated at 800°C for 30 min and cooled down to room temperature with the furnace. Then the samples were mechanically polished and washed with deionized water and alcohol.

The microhardness measurements of the alloy coating were performed on a FM-ARS-9000 fully automatic microhardness measurement system (Future-tech Comp., Kawasaki, Japan) employing a load of 100 g for 10 s. The Vickers microhardness values of the coatings were calculated using the average value of five sample measurements.

The microstructural characterization of Ni-based alloy coatings was examined by using the Hitachi S-4800 (Hitachi, East Coast Port City, Honshu Island) scanning electron microscope (SEM).

Dry sliding friction and wear testing without any lubricant were performed on a CFT-I material surface comprehensive performance tester (Lanzhou, Lanzhou Zhongke Kaihua Technology Development co. Ltd, China) at ~26°C and with a relative humidity of ~55%. The mill is 45 steel with the speed of 200 r/min and the wear time of 60 s. The friction pairs are reciprocating, through controlling the weight plate to adjust the load of the friction process of 1 N and 10 N, respectively.

3. Results and Discussion

3.1. Microhardness of Ni-Based Alloy Coatings. The hardness of alloy coating is an important property of material performance, and it is closely related to the wear resistance of materials. The main factors that affect the hardness of the coating include the grain size, the type, and the element contents. The hardness of NiFe, NiW, and NiFeW alloy coatings is much higher than that of pure Ni coating. The microhardness of the alloy coatings was measured by FM-ARS 9000 microhardness tester, and the microhardness of the alloy coatings before and after heat treatment is shown in Table 1.

It can be seen from Table 1 that the microhardness of the alloy coating was improved obviously after trace Fe element was added to Ni-based coating. Because the atomic radius of Fe and that of Ni are very close (the diameter of Fe and Ni is 0.124 nm and 0.125 nm), Fe atomic replacement of Ni atoms forms a replacement solid solution, such as $Fe_{0.64}Ni_{0.36}$, which increases the microhardness value of the alloy coatings. As shown in Figure 1, micro-Fe elements are added to the Ni coating to make the crystal grains more detailed and the grain boundary widened. When the grain is acted on by the external force, the plastic deformation can be dispersed in more grain, and the plastic deformation has a small uniform stress concentration. Therefore, the microhardness of NiFe alloy coating was obviously improved due to the combination of fine grain strengthening and solid solution strengthening. The main element of the coating is Ni in region A and the main element of the coating is Ni, Fe, and W in region D.

Table 1: Microhardness (HV) of Ni-based alloy coatings.

Coatings	Original coatings	800°C
Ni	350	504
NiFe	459	599
NiW	526	654
NiFeW	507	632

It can be seen from Table 1 that the microhardness of NiW alloy coatings was much higher than that of NiFe alloy coatings. Although the atomic radius of the W element is much larger than that of the Ni atom, W is able to form NiW solid solution with Ni element. Due to the difference in atomic radius, the large lattice distortion can be observed, as shown in Figure 1. Increased resistance to dislocation motion results in local stress concentration, and the NiW alloy coating was obviously raised in favor of the improvement of microhardness. Therefore, W further improved the microhardness of the alloy coating due to its own performance and solid solution strengthening.

As shown in Table 1, the microhardness value of NiWFe alloy coating is between NiW and NiFe alloy coating. Because Fe and W codisplace Ni atoms to form NiW and $Fe_{0.64}Ni_{0.36}$ solid solution, the grain size of the NiFeW alloy coating is smaller, as can be seen from Figure 1. Furthermore, the surface was smoother, and the tissue was more compact and uniform. Thus, the microhardness of NiWFe alloy was much higher than that of the binary NiFe alloy and pure Ni coating. The W content of NiFeW alloy coating was lower than that of NiW alloy coating, and microhardness was slightly lower than that of NiW alloy coating. If the Fe exceeds 6%, the microhardness of the coating will continue to increase, and the coating will become brittle. And the performance of the coating will deteriorate after the high temperature oxidation. If the W content exceeds 10%, the performance of the coating will deteriorate. That is, the microhardness of the coating will decrease due to crystalline fracture and transgranular fracture. Therefore, the Fe content is controlled at about 5%, and the W content is controlled at around 7%. The heat treatment can effectively eliminate the coating stress, improve the microcrack, and increase the microhardness of the coating to a certain extent [17]. Microhardness of Ni-based alloy coating has greatly increased after heat treatment at 800°C, as shown in Table 1. Because of the phase transition of Ni and the Ni-based solid solution, the oxide formed on the surface of the coating. The oxide is higher than that of the single-phase metal and solid solution, especially for the WO_3. Moreover, the oxide film was compact and tightly packed on the surface of the substrate, and it has a good protective effect on the substrate and greatly improves the microhardness of the coating.

3.2. Wear Resistance of Ni-Based Alloy Coatings. The coatings after heat treatment at 800°C for 30 min were wear-tested on CFT-I material surface comprehensive performance tester

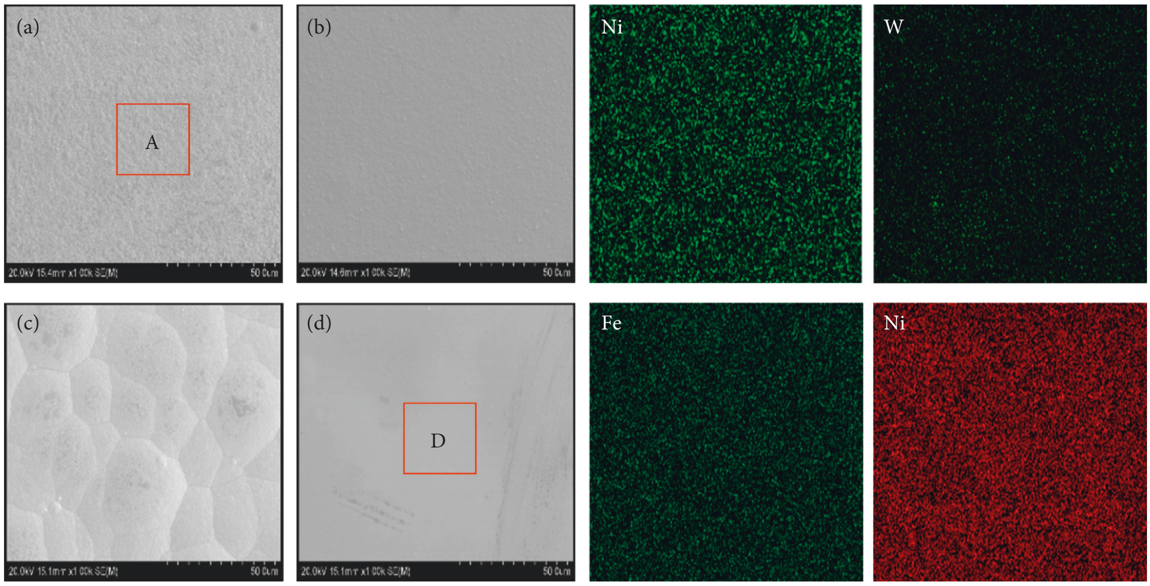

Figure 1: SEM micrographs of Ni-based alloy coatings and elements distribution: (a) Ni, (b) NiFe, (c) NiW, and (d) NiFeW.

by dry sliding friction. Select 45 steel for grinding, and attach the prepared sample to the friction disc with a double-sided adhesive. By adjusting the formers, the friction is controlled to 1 N and 10 N, respectively. Because the pressure regulation range is small, the sample quality error is larger before and after friction, so the friction coefficient is used to characterize the wear resistance. The relation curves between friction coefficient and time at different loads are shown in Figures 2 and 3.

The friction coefficient of the four coatings was quite different. The friction coefficient of NiWFe alloy plating is the most stable during the whole wear process, and the numerical minimum is 0.18. The friction coefficient of Ni coating was unstable in the whole process of wear, and the maximum value was between 0.6 and 0.9, as shown in Figure 2. The friction coefficient of NiW and NiFe alloy coatings was smaller than that of Ni coating, and the friction coefficient of NiW alloy coating was the smallest among these coatings. Under the 10 N load, the average friction coefficient of NiW alloy coating was the largest, and the friction coefficient of NiFe alloy coating was lower than that of Ni and NiW alloy coating, as shown in Figure 3. No obvious differences between the values under 1 N load can be clearly observed.

The friction coefficient of alloy coating is positively correlated with the microhardness of the alloy coating. The friction coefficient of alloy coating is related to wear mechanism under different loading conditions. The morphology of SEM under different loading conditions is shown in Figure 4. The coating surface shows a parallel grinding groove after wearing, and the depth and width of the surface of different alloy coatings are different. The plastic deformation can be observed in some regions caused by the grinding particles in 10 N; however, no obvious cracks and large flakes were observed. Region B is mainly Fe_2O_3 and a small amount of Ni, NiO, and Ni_3Fe. Region C is mainly Ni, NiO, and WO_3.

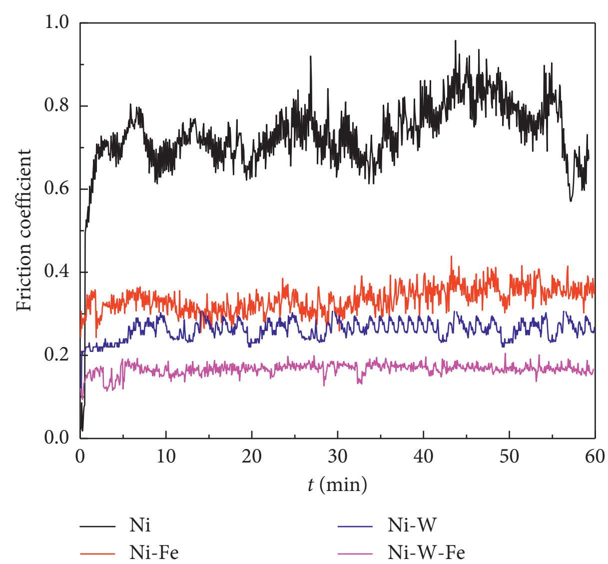

Figure 2: Relationship between friction coefficient and time for 1 N.

Ni alloy coating has deep wear and deep groove after the wear of 1 N, and the edge of the groove is uneven; thus, the unstable friction coefficient fluctuates greatly. A small amount of debris can be seen in the groove. The abrasive wear is shown in Figure 4, and the wear resistance was poor. The microhardness of NiFe and NiW alloy plating was larger. The abrasion of the groove was obviously shallow and narrow, and no obvious wear particles were found. There was an adhesive wear at 1 N for NiW and good wear resistance for NiFe. NiFeW alloy coating does not have obvious rolling groove, and only deep abrasions and furrows appear. The edge of the furrow is very smooth, and it can be seen that the NiWFe alloy coating only has adhesion wear at 1 N for NiFeW. Therefore, its wear resistance was the best. After heat treatment at 800°C, more flocculated Fe_2O_3

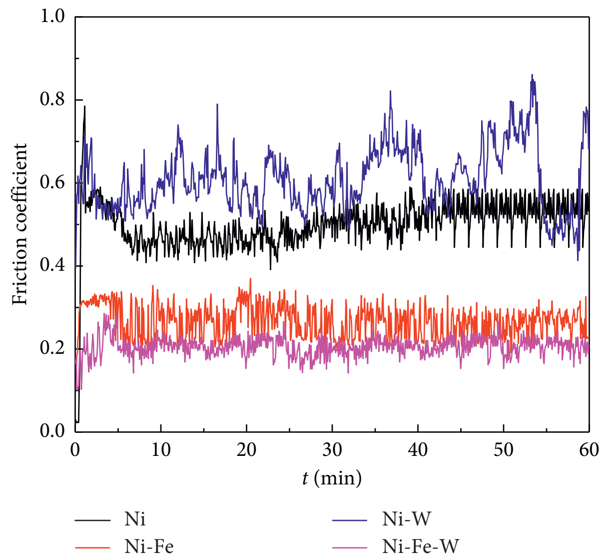

Figure 3: Relationship between friction coefficient and time for 10 N.

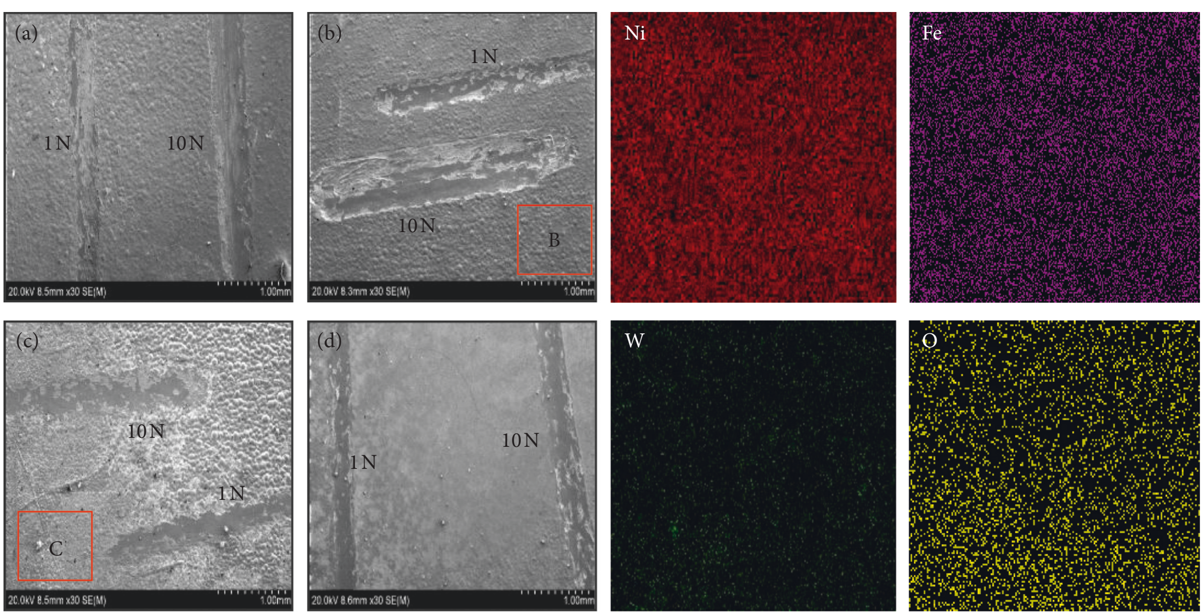

Figure 4: Wear SEM micrographs of Ni-based alloy coatings at different loading conditions and elements distribution: (a) Ni, (b) NiW, (c) NiFe, and (d) NiFeW.

appeared in NiFe alloy coating, and a hard alloy oxide WO_3 was present in NiW alloy coating, which will be buffered and resistant to wear and wear resistance. Fe_2O_3 and WO_3 co-exist in NiWFe alloy plating, and the hard phase WO_3 was surrounded by flocculated Fe_2O_3. The dense arrangement of the two seems to form a "protective shell" on the surface of the matrix to wrap the matrix in the shell. The protection of the matrix was good in the wear process, and the coating shows high wear resistance and good stability.

When the load goes up to 10 N, hard phase WO_3 was first worn in NiW alloy coating [18] due to lack of protection layer, unable to withstand wear pressure. The wear mechanism changes under different load conditions, while the adhesive wear under low load becomes abrasive wear. It can be seen that the furrow has become deep (Figure 4). There are a small number of hard phases falling off. And the detached hard particles are in contact with the coating. Notably, the contact surfaces between the friction pairs become rougher, and the frictional resistance increases. The wear was more serious, showing obvious abrasive wear. The friction coefficient of NiFe alloy coating was better than that of Ni and NiW alloy coating, because there is less hard phase in NiFe alloy coating, shown in Figure 4. The flocculated Fe_2O_3 formed after heat treatment, which slows down the wear and formation of a stable protective transfer layer between the coating and the friction pair, and the friction coefficient between the two is reduced.

Figure 5(a) shows the X-ray diffraction spectra of the surfaces of the oxidized NiFeW alloy coating of 800°C, which are mainly composed of mixed Ni, WO_3, NiO, and Fe_2O_3, and Figure 5(b) shows the XRD spectrum of the untreated NiFeW alloy coating, which is mainly composed of mixed Ni, NiFe, and NiW (solid solution) and a microscale WC_X.

The SEM images of NiFeW alloy coating after the wear are shown in Figure 6 under different loads. Figure 6 shows the change of wear load, and the wear mechanism and morphology of NiFeW alloy coating have not changed greatly, under a certain amount of pressure. Oxide film density is suitable at 800°C after oxidation, and the protective effect on the matrix is in the process of wear and tear. Therefore, wear-resisting performance for NiFeW alloy coating under 800°C treatment was very good and provided guidance to actual production and application. Region A is mainly Fe_2O_3, NiO, and WO_3 and Ni, Fe, and W of coating substrate.

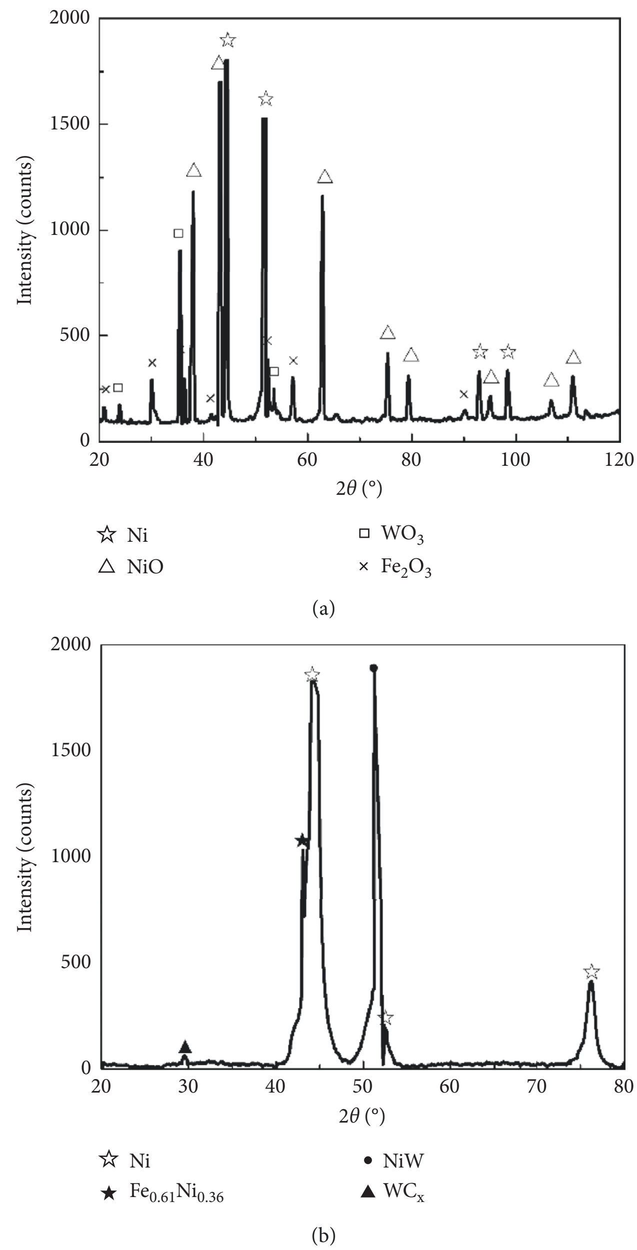

Figure 5: X-ray diffraction patterns of (a) the NiFeW coating oxidized at 800°C and (b) the untreated NiFeW coating.

3.3. Improving the Wear Resistance of Alloy Coatings. The wear resistance increases with the increase of microhardness of alloy coating at a certain range, and wear resistance is a characterization parameter of material properties under certain conditions [19, 20]. The wear resistance of NiWFe alloy coating was better than that of other coatings at the conditions in this experiment. It may not be suitable to be applied under other conditions, but it can be used to improve the wear resistance of the coating. The wear resistance of materials has an important guiding effect on the practical application of materials. The wear resistance of the material surface can be improved through a variety of different ways. Zhang [21] improved the wear resistance of carbon steel by substrate surface cementing WC, because WC itself was very hard. The WC layer also wraps the substrate like "armor," which has great effect on the microhardness, strength, high temperature resistance, and fatigue resistance of the modified substrate materials. Huang et al. [22] used laser cladding method to prepare $FeCoCr_xNiB$ high entropy alloy coating on 45# steel substrate, modify the crystal structure by changing the content of the alloy element, and change the microhardness of the coating to improve the wear resistance. Xu [23] used brush coating method to successfully prepare NiMo alloy coating on 45# steel substrate, as NiMo alloy coating has a crystalline structure of substitution solid solution, in which Ni is as a solvent and Mo as solute. The bonding strength of the coating and substrate was high, and it has high microhardness, abrasion resistance, and corrosion resistance. The alloy coating has high wear resistance and high temperature oxidation resistance. Pogrebnjak et.al. [24–26] used plasma jets method to successfully prepare Ni and Ni alloy coatings. The review is concerned with the current status of research on the use of plasma jets for the modification of surface properties of metalware, as well as of investigations of doping and mass transfer of elements, before and after pulsed plasma jet and high-current electron beam melting are presented. Newly formed phases like Cr_3Ni_2 and CrB and intermetallic compounds with molybdenum like Fe_7Mo_6, Fe_3Mo, and possibly Fe Mo were found, almost a factor of 20 increase in friction wear resistance and several times increase in coating to substrate adhesion. It was found that the electron beam processing leads to an almost ten-fold increase in the friction wear resistance, a three-fold growth in microhardness (relative to that of the substrate), and a significant increase in the resistance to corrosion in acid media. Therefore, the high-temperature oxidation resistance and wear resistance of copper substrate can be improved through various surface treatments.

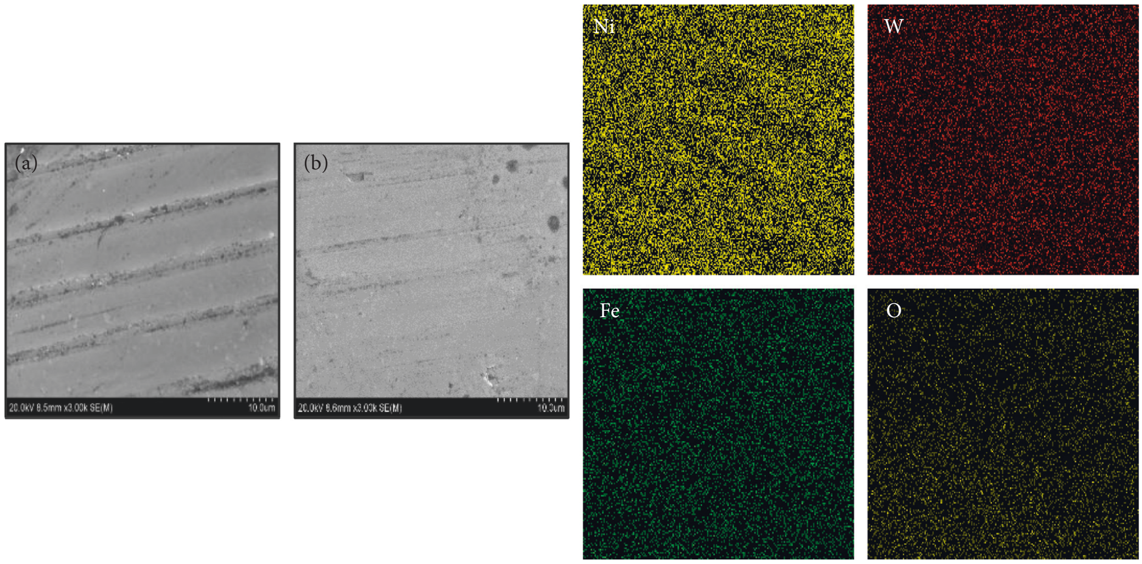

Figure 6: Wear SEM micrographs of NiFeW alloy coatings and elements distribution: (a) 1 N and (b) 10 N.

4. Conclusions

(i) The microhardness and wear resistance of alloy coatings were positively correlated in some conditions, and the microhardness and wear resistance of NiFe and NiW alloy coatings were significantly improved. The alloy element forms the solid solution and strengthens the solid solution to the substrate.

(ii) W element plays an important role in improving coating substrate microhardness, and no flocculent Fe_2O_3 wrapped around the hard phase WO_3 at the condition of 800°C. The as-deposited structure made the coating occurred serious abrasive wear and accelerated the wear rate of the coating, and the friction coefficient for the coating was higher.

(iii) The microhardness of NiFeW alloy coating was higher, and the hard phase WO_3 and flocculent Fe_2O_3 appeared after heat treatment at 800°C. NiFeW alloy coating has a small friction coefficient, wear resistance, and high-temperature oxidation resistance.

Data Availability

The photograph data used to support the findings of this study are all included within the article. The data are available to be accessed when needed.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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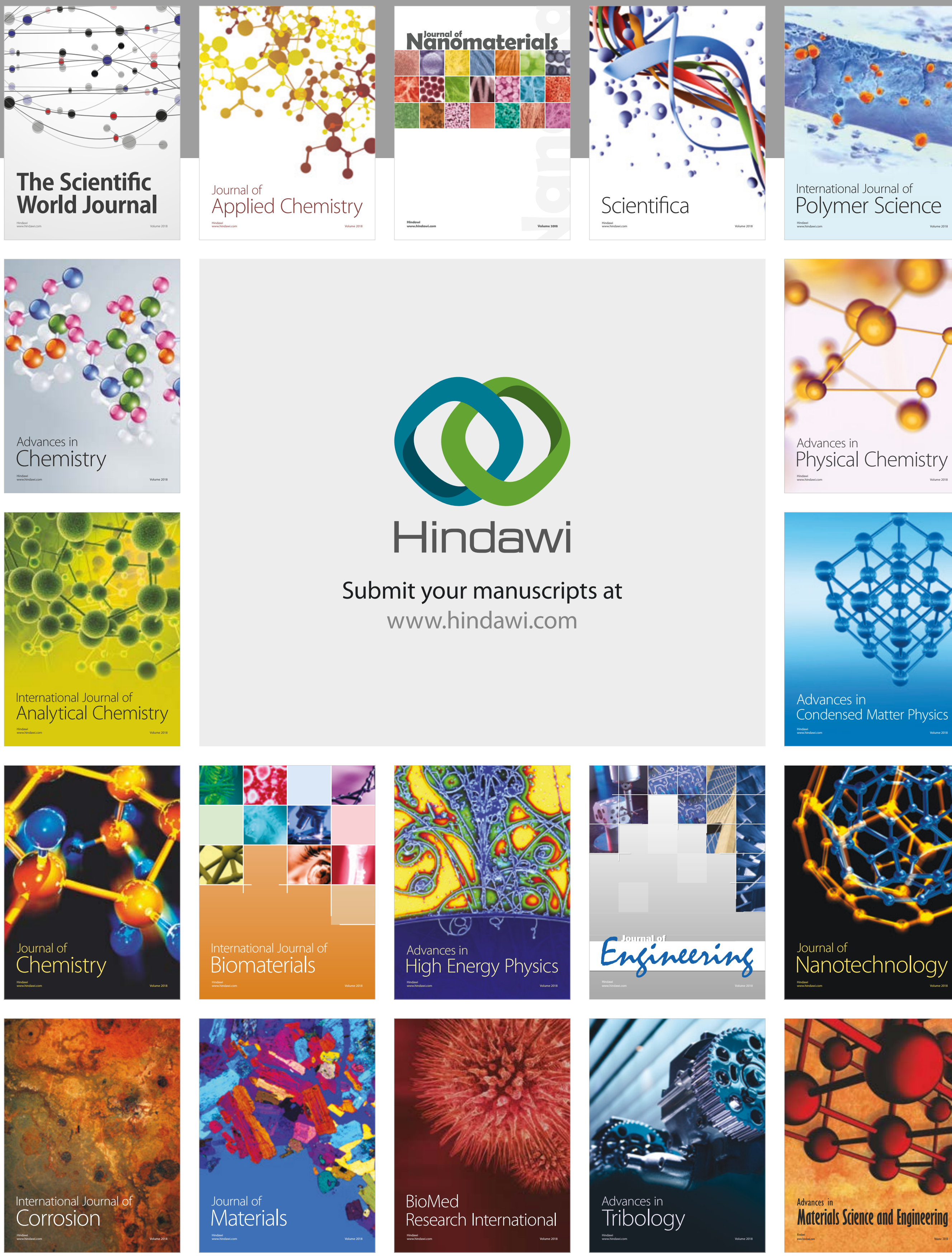
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