The effect of substrate on the wear behaviour of Ni electroplating coatings

Y. Totik*

Department of Mechanical Engineering, Faculty of Engineering, Ataturk University, 25240 Erzurum, Turkey

Received 16 January 2007, received in revised form 12 October 2007, accepted 23 May 2008

Abstract

The nickel coatings have been used successfully for mild steel protection against corrosion and wear, and provide a surface that is resistant to corrosion and wear. The substrate materials used in the present investigation are AISI 1020, 4140 steel, and CuZn30 brass. All these substrates were coated with electroplating process in nickel sulphamate solutions used for the deposition of functional coatings. The hardness of the AISI 1020, 4140 steel with normalised and CuZn30 brass before and after Ni coating were measured. The microstructural characterisations of uncoated and coated substrates were obtained using optical microscope, Scanning Electron Microscope (SEM). The wear tests of the AISI 1020, 4140 steel and CuZn30 brass before and after Ni coating were performed in Pin-on-disc tribotester. It was observed that the substrate type has effect on the wear behaviour of Ni coatings. In addition, the wear behaviour of Ni coatings on the substrates with high hardness was found better. Also, an increase of hardness in the coating was observed depending on the substrate hardness. While the lowest friction coefficient was recorded in pairs with Ni coated AISI steel substrate with the highest hardness, the highest friction coefficient was recorded in Ni coated CuZn30 substrate having a low hardness.

K e y w o r d s: electroplating, wear, substrate type, pin-on-disc

1. Introduction

Wear is the all time problem of almost all branches of engineering [1]. By most recent estimates, improved attention to friction and wear would save up to 1.6 % of developed countries gross national product, or over $100 billion annually in the USA alone [2]. The magnitude of the financial loss associated with friction and wear arises from the fact that entire mechanical systems, be they automobiles, are frequently scrapped whenever only a few of their parts are badly worn. In the case of an automobile, the energy consumed in its manufacture is equivalent to that consumed in 100,000 miles of operation [3].

The improvement of machine components having high performance is forced by technological requirements after second part of 20th century. Many mechanical parts, such as shafts, gears, springs etc. are subjected to surface treatments, before the delivering, in order to improve wear behaviour. The new and effective lubricants and coatings for frictional parts on engines for reducing the friction should be improved. The effectiveness of these treatments depends both on surface material properties modification and on the introduction of residual stresses [4–7].

Electroplating technique is one of the most cost effective and simple techniques for introducing a metallic coating to a substrate. Nickel coatings are usually sulphur-free, and matt in appearance. These coatings may be specified to improve corrosion and wear resistance, to salvage or build up worn or undersized parts, to modify magnetic properties, to prepare surfaces for enamelling or for organic coating, to function as diffusion barriers in electronic applications and for other purposes. Engineering applications exist in the chemical, nuclear, telecommunications, consumer electronics and computer industries [8–15].

For many years, the nickel coatings have been used successfully for mild steel and alloys for the protection against corrosion and wear. They provide a surface

* Tel.: +90-442-2314858; fax: +90-442-2360957; e-mail address: ytotik@atauni.edu.tr , yasartotik@yahoo.com

Table 1. Chemical composition of steel substrates

Substrate	wt.%							
	C	Mn	P	S	Cr	Mo	Si	Fe
AISI 1020	0.21	0.45	0.03	0.04	–	–	–	99.3
AISI 4140	0.41	0.95	0.03	0.04	0.6	0.18	0.18	97.4

Table 2. Chemical composition of brass substrates

Substrate	wt.%						
	Sn	Pb	Zn	Ni	Si	Fe	Cu
CuZn30	0.022	0.063	30.27	0.019	0.16	0.06	68.5

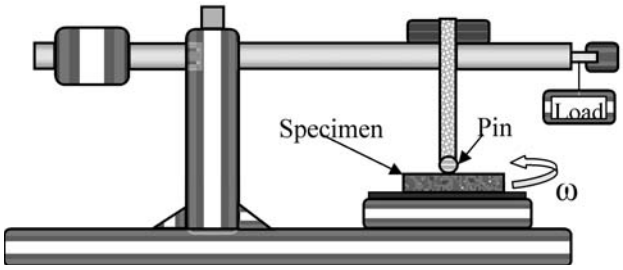


Fig. 1. Schematic representation of the pin-on-disc test configuration.

that is resistant to corrosion and wear. In the recent years, there are very few studies focused on the effects of alloy substrates composition and microstructure on the mechanical properties, the corrosion resistance and the wear resistance of coatings produced by electroplating techniques [16]. For this purpose, in this study the effects of substrate types have been investigated on wear behaviour of the Ni coatings on the different substrates, using electroplating technique.

2. Experimental details

The substrate materials used in the present investigation are AISI 1020, 4140 steel, and CuZn30 brass, which are often used in practical applications. The AISI 1020, 4140 steel substrates were normalised at 930 ℃ and 880 ℃, respectively, and the CuZn30 brass substrates were quenched at 730 ℃. The substrates were machined into cylindrical form, 25 mm in diameter and 10 mm in length. Before coating treatment, all the substrates were mechanically polished with silicon carbide papers grit 600–1200 and α-alumina with a grain size of 0.05 μm to a roughness value (Ra) of 0.20 and then degreased with ethanol followed by acetone. The chemical composition of the substrate materials used in the present investigation is given in Tables 1 and 2.

AISI 1020, 1040 steel and CuZn30 brass substrates were coated with electroplating process in nickel sulphamate solutions used for the deposition of functional coatings. Alkaline cleaning and Acid pickle treatments are applied to all substrates to improve adhesion of the coating layers before Ni coating. The coating conditions and composition for nickel electroplating solutions used in the study are given in Table 3.

The hardness of the AISI 1020, 4140 steel with normalised and CuZn30 brass before and after Ni coating was measured as Vickers hardness using a PC Controlled Buehler-Omnimet tester. A standard microhardness tester, equipped with a Vickers indenter and a 0.5 g indention load was used for the hardness measurement. The microstructural characterisations of uncoated and coated substrates were obtained using a Nikkon Epithot 105 optical microscope, a Jeol 6400 Scanning Electron Microscope (SEM). Also the coated and worn surfaces were examined using profilometer.

The wear tests of the AISI 1020, 4140 steel with normalised and CuZn30 brass before and after Ni coating were performed in Teer POD2-Pin-on-disc tribotester, using the test configuration shown in Fig. 1. WC-6%Co ball was used with a diameter of 5 mm as a counterpart. After samples were cleaned by ultrasound in acetone for 5 min, a pair of pins and disc was inserted into the test machine. A particular load

Table 3. Coating conditions and composition for nickel electroplating solutions

Nickel Sulphate ($NiSO_4 \cdot 6H_2O$) (g l^{-1})	Nickel Chloride ($NiCl_2 \cdot 6H_2O$) (g l^{-1})	Boric Acid (H_3BO_3) (g l^{-1})	PH	Cathode Current Density (A m^{-2})	Temperature (℃)
240	45	50	4.3	0.05	55

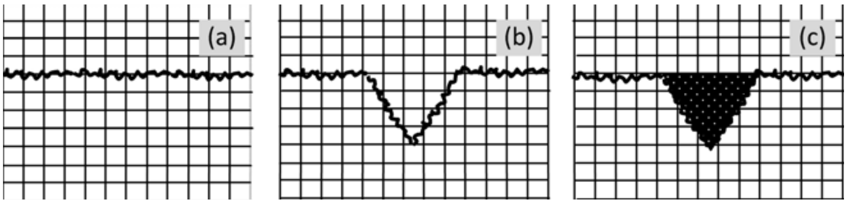


Fig. 2. a) The surface profile, b) the wear track and c) their superposition used in calculating the wear volume and measured by a surface profiler before and after wear tests.

T a b l e 4. Wear test conditions from pin-on-disc tribo-test

Parameters	Experimental conditions
Applied load (N)	10
Velocity (mm s^{-1})	80
Rot. speed (RPM)	150
Scar diameter (mm)	10
Environment	Air
Temperature (℃)	$\sim$ 21
Duration (s)	600
Roughness, Ra (μm)	0.2
Test ball diameter (mm)	5

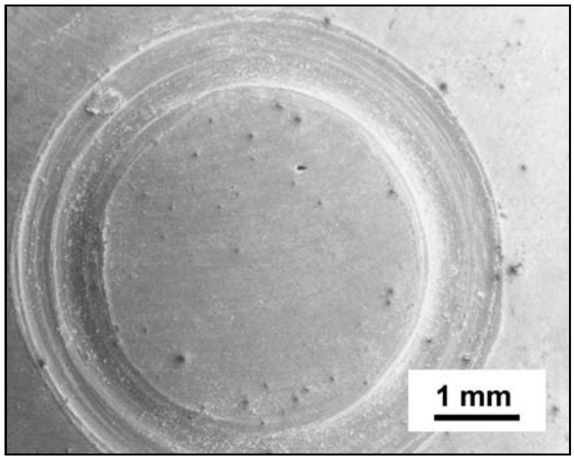


Fig. 3. SEM image of the wear track after 600 s.

was applied and the rotation disc started. The wear tests were carried out at a linear speed of $0.08\,m\,s^{-1}$ and at a load of 10 N. The atmosphere used was air with a relative humidity of $\sim$ 45 % and temperature of $\sim$ 21 ℃. The experimental data were recorded continuously during the wear tests: coefficient of friction and time. The wear friction test conditions are given in Table 4. After 600 s, the wear experiments were stopped, and the worn specimens were removed. Then the worn surfaces were examined using profilometry.

The wear coefficient K was calculated using the wear equation which takes the following form:

$$K = \frac{V}{NL}, \tag{1}$$

where V is the wear volume, N is the load, L is the sliding distance. To calculate the wear volume, the profiles were recorded on the Mitutuyo profilometer before and after coating. Then, from the superimposed profiles, the wear volume was calculated, as shown schematically in Figs. 2 and 3.

The microstructures and wear track of uncoated and coated substrates were characterised using a Nikkon Epithot 105 optical microscope, a Jeol 6400 Scanning Electron Microscope (SEM).

3. Results and discussion

The hardness measurements of the AISI 1020, 4140 steel and CuZn30 brass substrates before and after coating are shown in Fig. 4. From the figure it can be seen that the hardness of the AISI 1020 and 4140 steel substrates after coating treatment is about 320 and 362 HV while the hardness of AISI 1020 and 4140 steel substrates before coating treatment is about 183 and 210 HV, respectively. Also the hardness of the CuZn30 brass substrates after coating treatment is about 295 HV while their hardness before coating treatment is about 117 HV. It is observed that nickel electroplating increases the hardness value of all the substrates considerably. An increase of the coating hardness was ob-

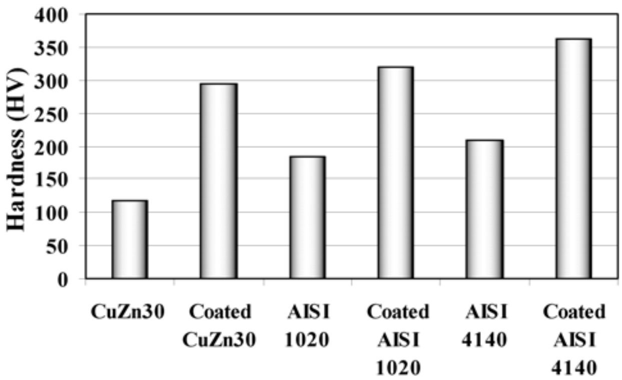


Fig. 4. The hardness values of all substrates before and after coating.

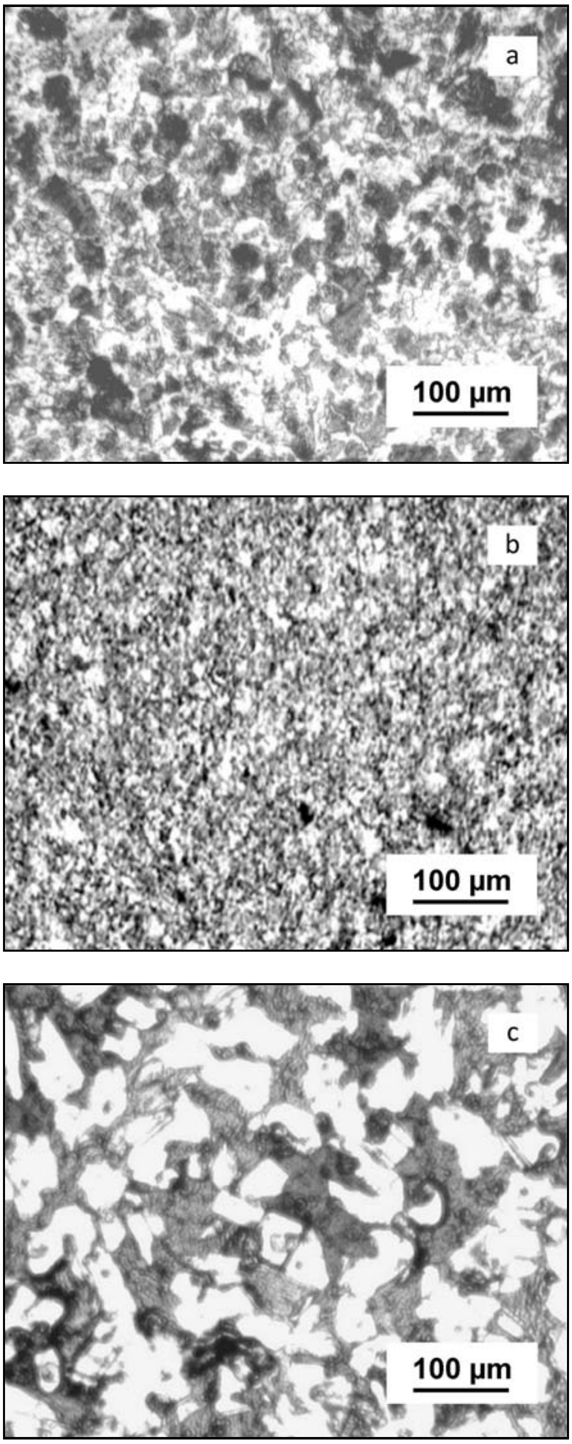


Fig. 5. Microstructures of substrates: a) AISI 1020 steel, b) AISI 4140 steel and c) CuZn30.

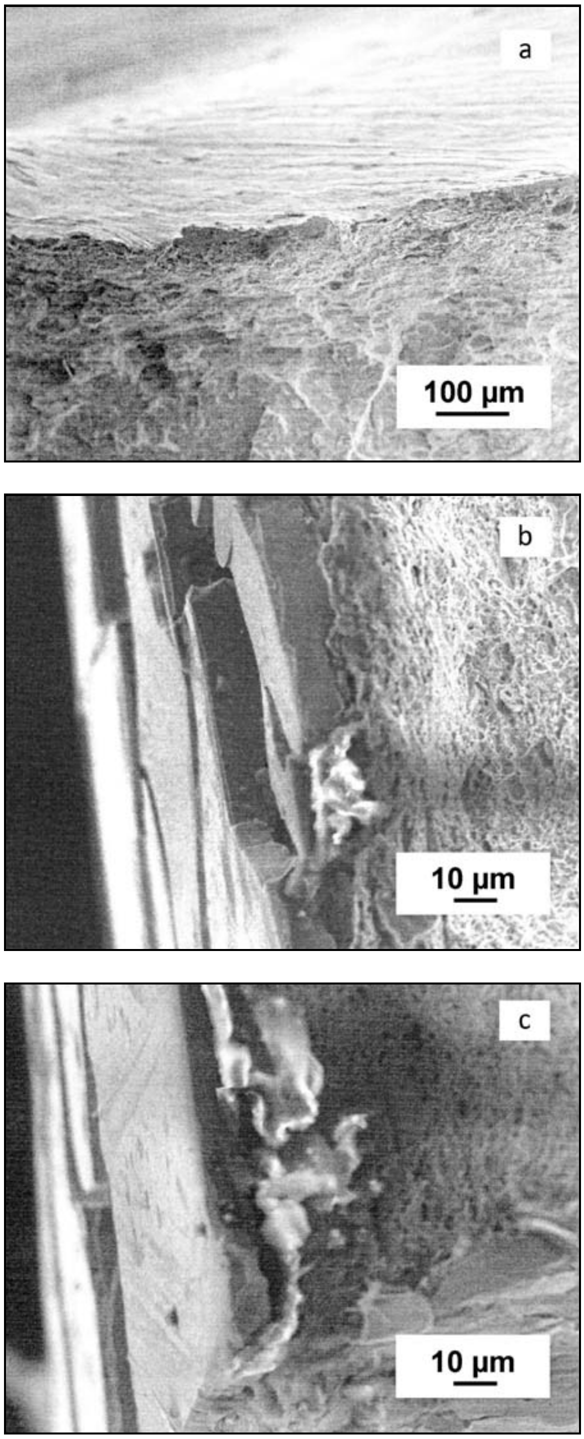


Fig. 6. The interfaces of coatings and substrates: a) AISI 1020 steel, b) AISI 4140 steel and c) CuZn30 brass.

served depending on the substrate hardness. For hard coating on a softer substrate (CuZn30), spallation failure often results from interfacial detachment [17]. It is believed that the reason for the increase in the hardness values is high resistance of the hard substrates to plastic deformation.

As the wear resistance of a material is related to its microstructure and mechanical properties due to the changes in microstructure that may take place during the wear process, it seems that in wear research emphasis should be placed on microstructure [18–20]. The microstructures of AISI 1020, 4140 steel

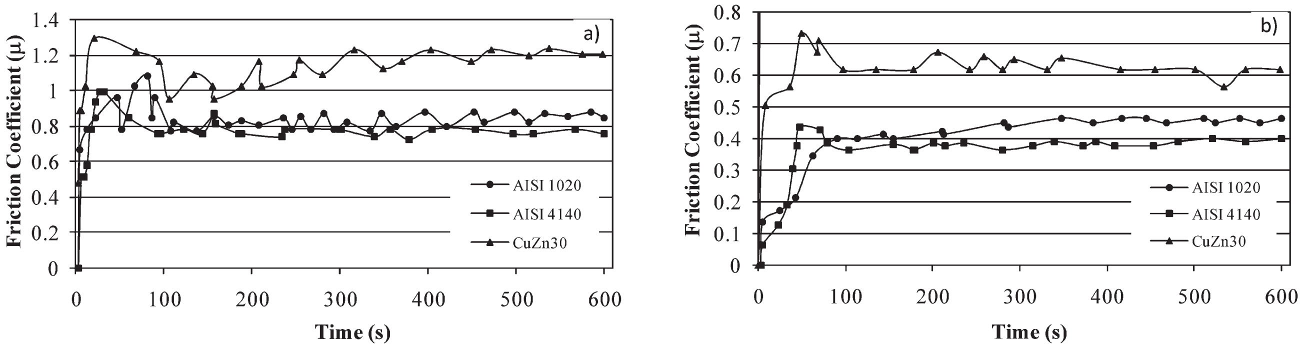


Fig. 7. Variations of the friction coefficients with the sliding time for a) the uncoated substrates and b) the coated substrates.

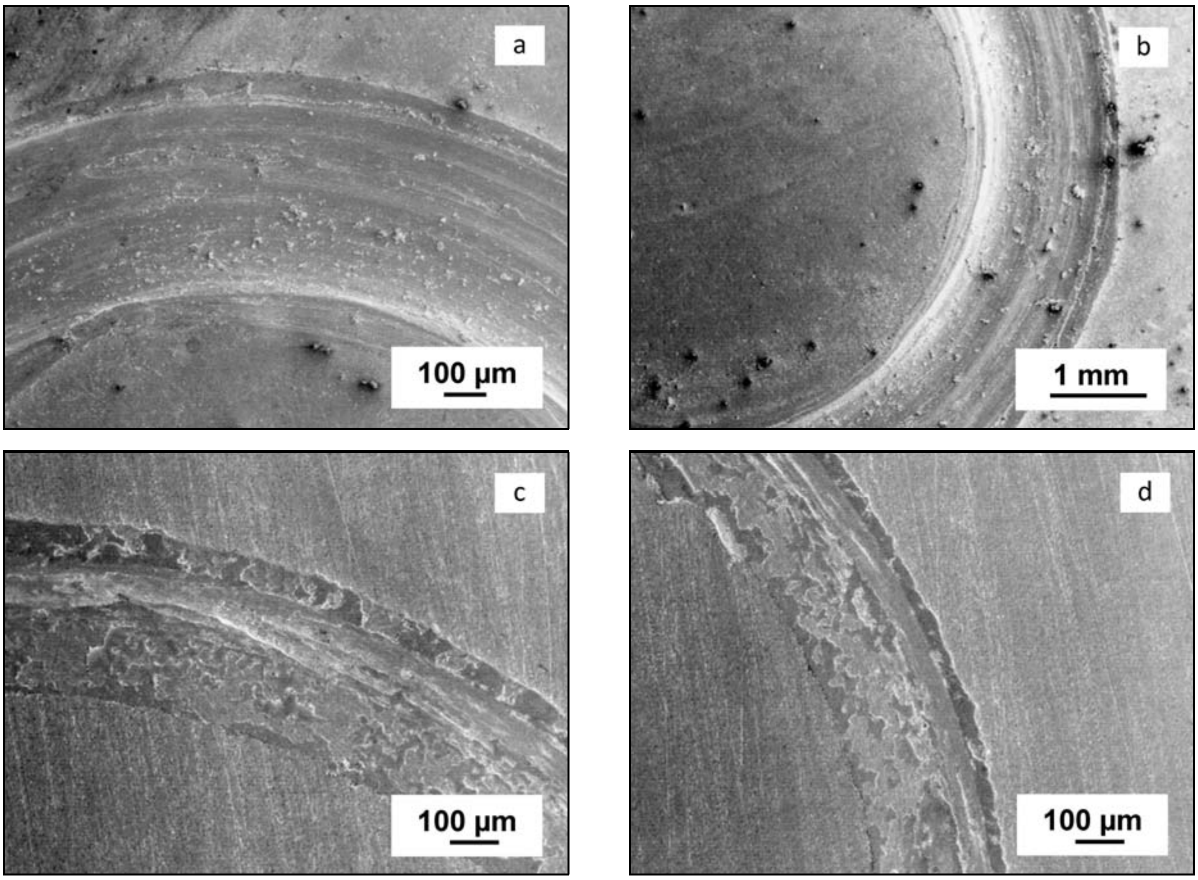
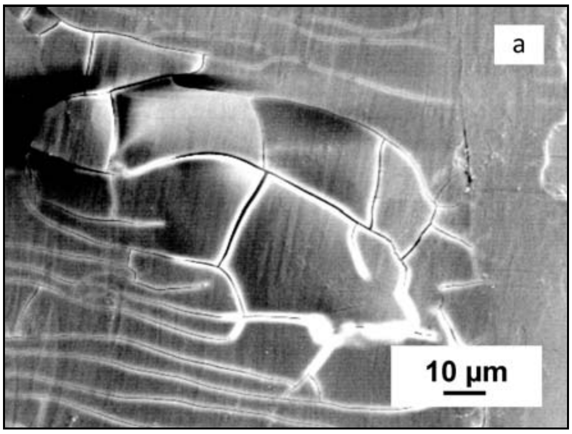


Fig. 8. SEM images of the wear track of a) CuZn30 brass substrate, b) AISI 4140 steel substrate, c) coating on AISI 1020 substrate and d) coating on AISI 4140 substrate.

and CuZn30 brass substrates obtained before the coating treatment were observed under an optical microscope after polishing and chemical etching, and are shown in Fig. 5. The steel substrates contain ferrite, pearlite and metallic carbides, as shown in Fig. 5a,b. Also the microstructure of CuZn30 brass substrate forms with α-solid solutions because zinc has extensive solid solubility in copper up to 39 % Zn, as shown in Fig. 5c.

From the interface shown in Fig. 6, it can be seen that the interface between the coating and AISI 4140 and 1020 substrates has a more uniform distribution than CuZn30 substrate. The interfacial mechanical interlocking effect plays an important role in improving adhesion due to the substrate hardness in the coating treatment. It was observed that the nucleation density and size of the Ni crystallites on the AISI 4140 substrate are higher and smaller than those on the CuZn30 substrate.

The friction coefficient-time relation of the un-



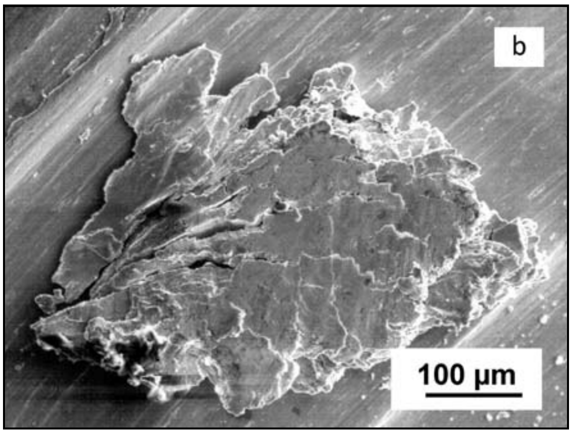


Fig. 9. a) The cracks in the coating on the CuZn30 substrate after a sliding time of 300 s, and b) the oxide particles that exist on the wear track.

coated and coated substrates obtained from the pin--on-disc tests used to evaluate the tribological properties are also given in Fig. 7a and b, respectively. The results on the frictional behaviour of the mating pair substrate-ball are also included for comparison purposes. For the all substrates, as seen in Fig. 7a, the steady state is achieved after about 110 s. In the transition period, the friction coefficient reaches a maximum value of 1, 0.9 and 1.3 for AISI 1020, 4140 and CuZn30 substrates, respectively. These values are the result of the formation of large quantities of debris generated during wear. This debris had formed from fragmentation under contact pressure at the as-cast surface. The values of the friction coefficient were found approximately 0.8, 0.7 and 1.2 for AISI 1020, 4140 and CuZn30 substrates, respectively, and these values almost lie up to the end of the test. The lowest friction coefficient was found for the AISI 4140 substrate. This reduction in the coefficient of friction was attributed to the fact that hardness value increases.

Figure 7b shows the friction coefficients – time relation for the Ni coated substrates. As seen from Fig. 7b, there is little change in the time required for stability of the process applied to Ni coating on the substrate, but a substantial decrease in the friction coefficient is observed. The values of the coefficient of friction were found approximately 0.44, 0.36 and 0.6 for Ni coated AISI 1020, 1040 and CuZn30 substrates, respectively. This reduction in friction coefficient can be also explained by an increase of the hardness. It can be said that the coatings on the substrates with harder and fine grains have low friction coefficient and are observed to have resistance against wear.

The morphology of the final wear track on the electroplated Ni coatings sliding against WC-6%Co ball is shown in Fig. 8. The wear mechanism of electroplated Ni coatings includes adhesive and abrasive wear, and the latter one is primary. The adhesion occurred in initial stage and the abrasive and adhesion wear becomes dominant in last stage. The width of the wear track enlarged as the contact area between the pin and all the uncoated substrates increased. The width of the wear track decreased with the increasing substrate hardness. The amount of the debris removed from the uncoated substrates toward the sides of the wear track was much more than that in coated substrate. Besides, the narrowest wear track was obtained in the coated AISI 4140 substrate (Fig. 8d). Consequently, the tribological behaviour for electroplated Ni coatings would be different with respect to different substrates. Those differences may be due to the different mechanical and microstructure properties of the substrates.

Figure 9 illustrates the SEM images of the wear track surface obtained in last stage of the wear process. There were a few cracks in the coatings on the CuZn30 substrate after a sliding time of 300 s as shown in Fig. 9a, but this situation was not observed on the steel substrates. At the last stage of wearing, oxidised particles were observed in the wearing zone. The oxide particles that exist on the surface would lead to abrasive wear of the electroplated Ni coatings (Fig. 9b).

Figure 10 shows the wear coefficients (rates) for uncoated and coated substrates under 10 N load and at sliding speed of 80 mm s^{-1}. It can be seen that changing the substrate type also causes a change in the contact conditions confirmed by the coefficient of friction. It was found that the uncoated substrates have a higher wear rate as compared to the coated substrate. The coated specimens of AISI 4140 substrate having the lowest wear rate were also obtained. In addition, Fig. 11 indicates that the wear rate decreases with the increase of the hardness of electroplated Ni coatings.

4. Conclusions

The effects of substrate on the wear behaviour of Ni electroplating coatings were studied. It was found that the substrates have effects on the wear behaviour of Ni

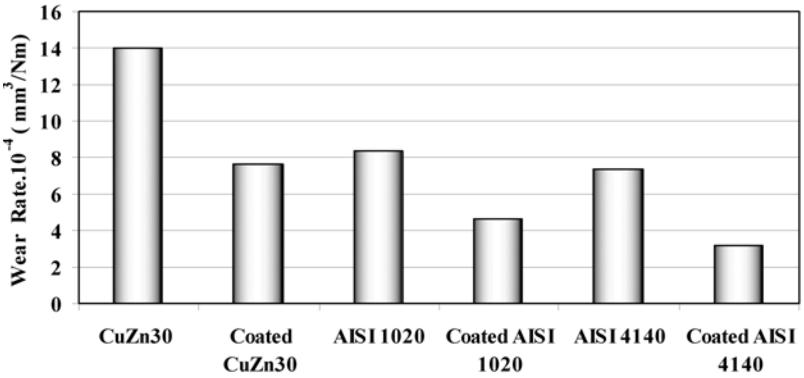


Fig. 10. Wear rate vs. the substrate type.

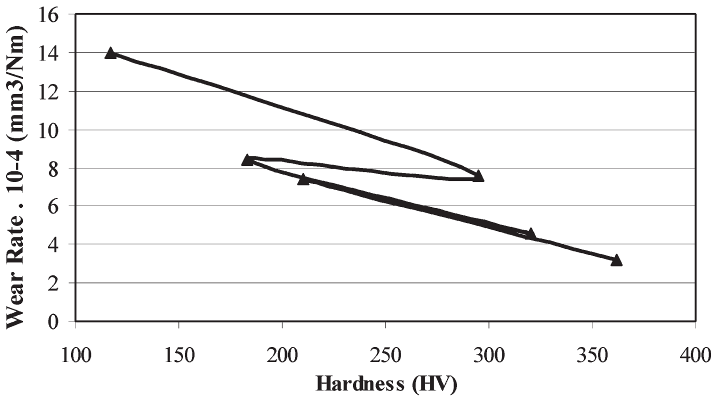


Fig. 11. Relationship between the hardness and wear rate of the electroplated Ni coatings.

coatings and that the wear behaviour of Ni coatings on the substrates with high hardness is better.

The Ni coatings on the substrates with fine grains and having high hardness were obtained as more dense and uniform, and as a result of this an increase in the wear resistance was observed.

An increase of hardness in the coating was observed depending on the substrate hardness. While the lowest friction coefficient was recorded in pairs with Ni coated AISI steel substrate with the highest hardness, the highest friction coefficient was recorded in Ni coated CuZn30 substrate having a low hardness.

The wear rates in the uncoated substrate are higher than those in the coated substrate. The lowest wear rate was obtained in the substrates with the highest hardness (AISI 4140). On the other hand, the wear rates decrease with the increase of the substrate hardness.

The width of the wear track and the amount of the debris removed reduce by increasing substrate hardness. The wear track occurred uniformly in the coatings on the hard substrates.

Acknowledgements

This work was supported by Engineering Faculty, Ataturk University. The author would like to thank the Mechanical Engineering Department.

References

[1] TAYLOR, B. J.—EYRE, T. S.: Tribol. Let., *12*, 1979, p. 79.
[2] JOST, H. P.: Wear, *136*, 1990, p. 1.
[3] LUDEMA, K. C.: Friction, Wear and Lubrication: A Textbook in Tribology. Boca Raton, CRC Press 1996, p. 4.
[4] KHEDKAR, J.—KHANNA, A. S.—GUPT, K. M.: Wear, *205*, 1997, p. 220.
[5] TOTIK, Y.—SADELER, R.—ALTUN, H.—GAVGALI, M.: Mater. and Design, *24*, 2003, p. 25.
[6] MELANDER, M.: J. Heat Treating, *2*, 1985, p. 145.
[7] HEIMANN, R. B.: Plasma Spray Coatings. New York, NY USA Publishers Inc. 1996.
[8] WANG, L.—ZHANG, J.—GAO, Y.—XUE, Q.—HUA, L.—XUA, T.: Scripta Mater., *55*, 2006, p. 657.
[9] GRAY, J. E.—LUAN, B.: J. Alloys Compd., *336*, 2002, p. 88.
[10] ASHASSI-SORKHABI, H.—RAFIZADEH, S. H.: Surface and Coating Technol., *176*, 2004, p. 318.
[11] BALDWIN, K. R.—ROBINSON, M. J.—SMITH, J. E.: Corrosion Science, *35*, 1993, p. 1267.
[12] EL-SHARIF, M. R.—SU, Y. J.—CHISHOLM, C. U.—WATSON, A.: Corrosion Science, *35*, 1993, p. 1259.

[13] HEYDARZADEH SOHI, M.—JALALI, M.: J. Mater. Processing Technol., *138*, 2003, p. 63.
[14] WANG, L.—GAO, Y.—XUE, Q.—LIU, H.—XU, T.: Surface and Coatings Technol., *200*, 2006, p. 3719.
[15] WANG, L.—GAO, Y.—XU, T.—XUE, Q.: Applied Surface Science, *252*, 2006, p. 7361.
[16] LIU, Z.—GAO, W.: Surface & Coatings Technol., *200*, 2006, p. 3553.
[17] BULL, S. J.: Tribol. Int., *30*, 1997, p. 491.
[18] WANG, Y.—LEI, T. C.—GAO, C. Q.: Tribol. Int., *23*, 1990, p. 47.
[19] RIGNEY, D. A.—GLAESER, W. A.: Wear of Materials. New York, ASME 1977.
[20] WANG, Y.—LEI, T.: Wear, *194*, 1996, p. 44.