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Wear resistance of plasma coatings on mild steel

M. M. I. AHMED, R. A. ABD EL-KARIM, S. M. EL-RAGHY, F. A. EL-REFAIE, A. E. EL-MEHAIRY
Department of Metallurgical Engineering, Faculty of Engineering, Cairo University, Giza, Egypt

Mild steel was coated by different materials using plasma spray technique. Materials used as coatings are Ni–5% Al and WC–17% Co. The thickness of the coatings varied between 0.05 to 1.5 mm. The porosity of different coatings decreased with increase in thickness of the coat. The roughness of coating material decreased after wear testing. Microstructure study has been conducted for coatings of different materials before and after wear testing. Wear tests have been conducted under different aqueous environments at room temperature. The wear resistance of Ni–5% Al coating was improved by heat treatment. X-ray diffractometry showed the presence of NiO in the outer layer of the Ni–5% Al coating. The thickness of the coating, type of coating, heat treatment conditions, and the environment of testing proved to affect the rate of wear resistance.

1. Introduction

Plasma spraying deposition is one of the most important technologies available for producing high-performance surfaces required by modern industry. This process has been developed significantly over the past ten years. Guidelines have now been established for the selection and use of plasma coatings for a wide variety of applications [1–4]. Examples of these applications are hard face coatings, thermal barrier coatings, coatings for corrosion resistance, and dimensional restoration.

Plasma spraying has many advantages [5, 6]. It is possible to spray metals, ceramics, plastics and a combination of these materials using this technique. Oxidation effects on coatings can be minimized during plasma spraying by using a combination of inert gases such as argon and helium.

In choosing the plasma sprayed material for wear resistance applications, it is very important to consider both the service environment and the type of wear. The types of wear encountered in the present work are abrasive [7], erosive [8] and corrosive [9].

In the present investigation the influence of different parameters on the wear resistance of Ni–5% Al and WC–17% Co coatings will be studied.

2. Materials and experimental techniques

Uncoated and coated mild steel specimens were used. The dimensions of the uncoated specimen were $10 \times 15 \times 3\ mm^3$. The coating materials were Ni–5% Al and WC–17% Co. As-rolled mild steel sheet was degreased and blasted with silicon carbide. Blasting produced a rough surface for good bonding. The specimens were coated using a plasma Technik unit type M-1000. The thickness of coating varied between 0.05 to 1.5 mm. For Ni–5% Al coating, the particle size used was in the range of 5 to 45 μm. The particle size used in the case of WC–17% Co was in the range of 10 to 53 μm. The plasma spraying process involved the following steps: (a) loading the specimen into the chamber of the plasma unit, (b) preheating the work piece to temperature of 100 °C to avoid a high thermal gradient between the substrate and deposit, (c) passing inert gas (argon and hydrogen) through an electric arc for plasma formation, (d) starting the powder flow to the plasma arc using inert carrier gas (Argon) to avoid powder oxidation, (e) deposition of coating on the work piece using gun powder levels of 40 to 100 kW. The specimens were then metallographically examined for the presence of oxides and porosity determination. An optical microscope connected with an overhead screen was used for determining the number of pores by counting them from the screen.

The specimens coated with Ni–5% Al were examined by X-ray diffractometry, using nickel filtered CuKα radiation to detect any compositional change that might occur during the plasma spraying process and to identify the nature of phases which may form under the high cooling rate involved in this process.

Microhardness of the coatings was determined using a Vickers microhardness tester. The microhardness measurements were taken on two sections, parallel and normal to the coat–substrate interface.

The surface roughness of the specimens was determined using surface profilometer type surtronic 3. The surtronic 3 device consists of two parts: the battery operated display traverse unit and the pick-up. The traverse unit contains a drive motor which traverses the pick-up across the surface to be measured. The unit also contains electronic circuits for computing

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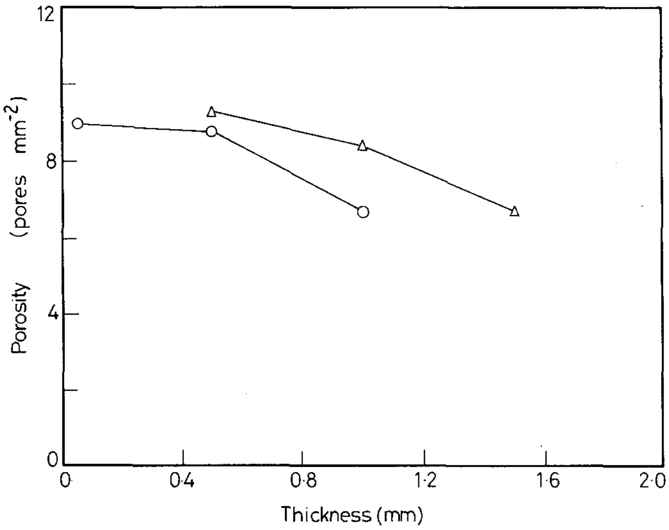

Figure 1 The change in porosity with coating thickness (○ Ni–Al coating, △ WC–Co coating).

and displaying the value of the surface roughness. The pick-up is a variable reluctance type transducer which is supported on the surface to be measured by a skid. As the pick-up traverses across the surface, the movements are detected and converted into a proportional electrical signal.

Some of the specimens coated with Ni–5% Al were heated at 900 °C for different periods of time (0.5, 1 and 2 h). After heat treatment at 900 °C for 1 h some of the specimens were subjected to ageing treatment by heating at 700 °C for different periods of ageing time (0.25, 1, 4 and 8 h).

The wear test was conducted using a magnetic stirrer and a container for the specimen. The difference in weight of the specimen before and after the testing was used to determine the wear rate. Three types of testing media were used: (a) 3% NaCl solution + 5% sand, (b) distilled water + 5% kaolin, (c) distilled water + 5% sand.

Microstructure examinations have been carried out for the specimens before and after wear testing. Two positions have been studied for the specimens before testing, parallel and normal sections to the interface between coating and substrate.

3. Results and discussion

The change in porosity of Ni–5% Al and WC–17% Co with coating thickness is given in Fig. 1. It can be seen from the results that WC–17% Co is more porous than Ni–5% Al. High porosity of coating results from either using coarse particle size or insufficient melting. The coarse particle size used in the case of WC–17% Co resulted in the high porosity of the coat as shown in Fig. 1. The increase in thickness led to a decrease in porosity level in both types of coatings.

Fig. 2 indicates the surface roughness profiles for the two materials. The roughness of WC–17% Co is lower than the roughness of Ni–5% Al. Table I gives the surface roughness values (R_a) determined from the roughness average method.

The change in microhardness with thickness of coating is given in Fig. 3. The hardness for Ni–5% Al was about 165 Hv and for WC–17% Co it was about 670 Hv.

TABLE I Surface roughness values

Coating material	R_a (μm)
Mild steel (no coating)	1.80
WC–17% Co	2.70
Ni–5% Al	10.75

Fig. 4 indicates the effect of coating type on the wear rate of the two coating materials used. The thickness of coating was 0.5 mm and the testing medium was 3% NaCl solution + 5% sand. The wear rate was calculated after 40 h of testing. The wear rate for mild steel (with no coat) was indicated for comparison. In the case of Ni–5% Al, low porosity level, formation of passive film of Al_2O_3 and the good bonding characteristics of this coating [10] contributed to its good wear resistance and the low wear rate observed in Fig. 4. The high hardness of WC helped in reducing the wear rate of WC–17% Co.

In Fig. 5, the results show the relationship between weight loss and time for Ni–5% Al coating of different thicknesses. The testing environment was 3% NaCl solution. It can be seen from the results that the weight

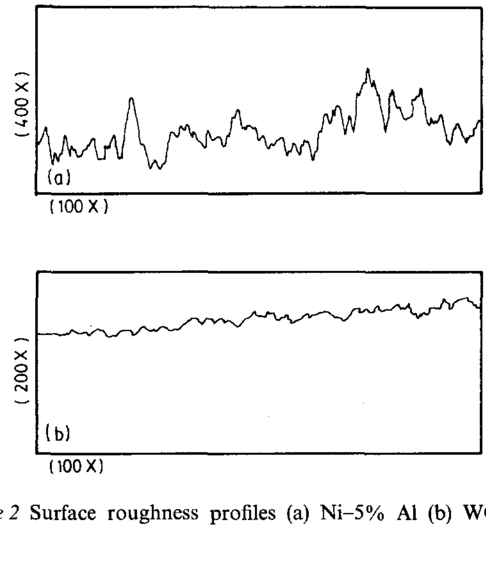

Figure 2 Surface roughness profiles (a) Ni–5% Al (b) WC–17% Co.

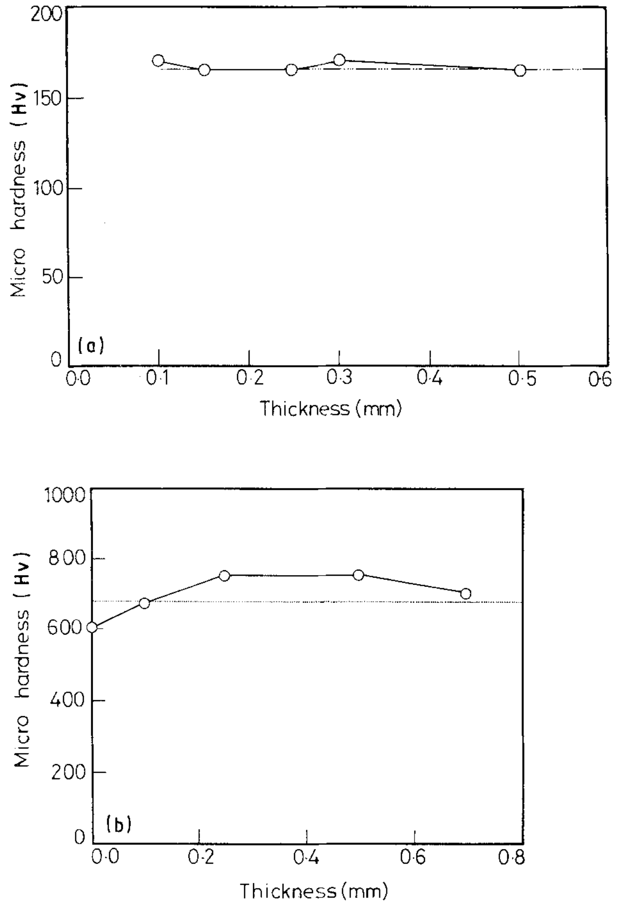

Figure 3 The change in microhardness with thickness of (a) Ni–5% Al and (b) WC–17% Co coating (○ measurements starting from the interface, ...; - - - — - - - , measuring on the surface).

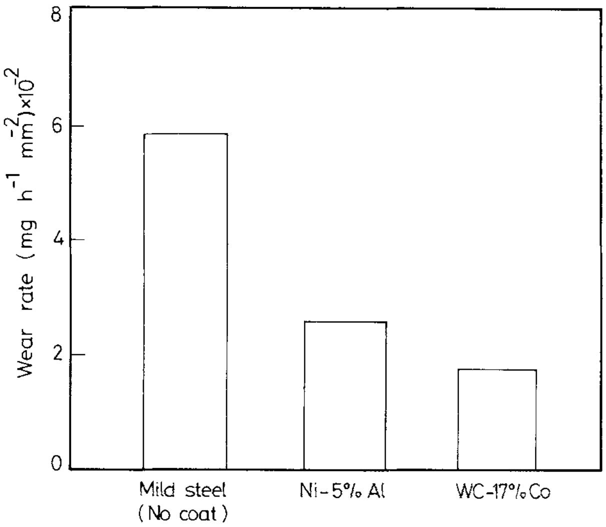

Figure 4 Effect of coating type on the wear rate.

loss decreased with the increase in coating thickness. Thus the higher the coating thickness the more will be the protection for the mild steel.

The effect of testing medium on the wear resistance of the coating material is indicated in Fig. 6. In this figure the relation between weight loss and time is given for both coatings. It can be concluded that NaCl solution is the most severe testing medium for the coatings used in the present work. The presence of chloride ions was the cause of low corrosive wear resistance. These ions have high penetration power through the surface [11]. The use of a coating–substrate system in a corrosive environment introduces galvanic corrosion. Potential difference measurements showed that both types of coating have more negative potential than steel substrate. Thus, mild steel will be the anode in the galvanic cell and it is more likely to be attacked than the coating. In the case of distilled water plus sand the wear mechanism gives lower weight loss than the corrosion wear mechanism. For kaolin suspension the weight loss was the lowest and this is due to the fine grain size of kaolin powder used in the test (the test was conducted at the same speed).

Fig. 7 indicates the effect of coating porosity on its wear rate. The decrease in porosity level of the coating leads to a decrease in wear rate of the material.

In Fig. 8 a comparison is given for the surface roughness values for the two coatings used before and after testing in NaCl solution. After testing, the surface roughness of both coatings decreased. In the case of mild steel, its surface roughness increased after testing and this is due to pitting.

Some of the specimens coated with Ni–5% Al have been heat treated at 900 °C for three different periods of time (0.5, 1, and 2 h). By examining the results in Fig. 9, it can be seen that the time of 1 h heat treatment gives the lowest amount of weight loss. The weight loss increased again for time of heat treatment of 2 h. By comparing Figs 6a and 9, it is clear that heat treated samples have high wear resistance. Heat treatment process homogenizes the structure and produces a thin diffusion zone [12] between the substrate and

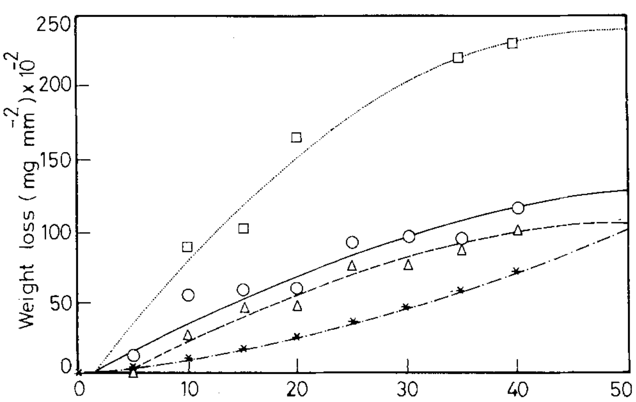

Figure 5 The change in weight loss with time for Ni–5% Al coating of different thicknesses (□ mild steel no coat, ○ 0.05 mm, △ 0.5 mm, $*$ 1.0 mm).

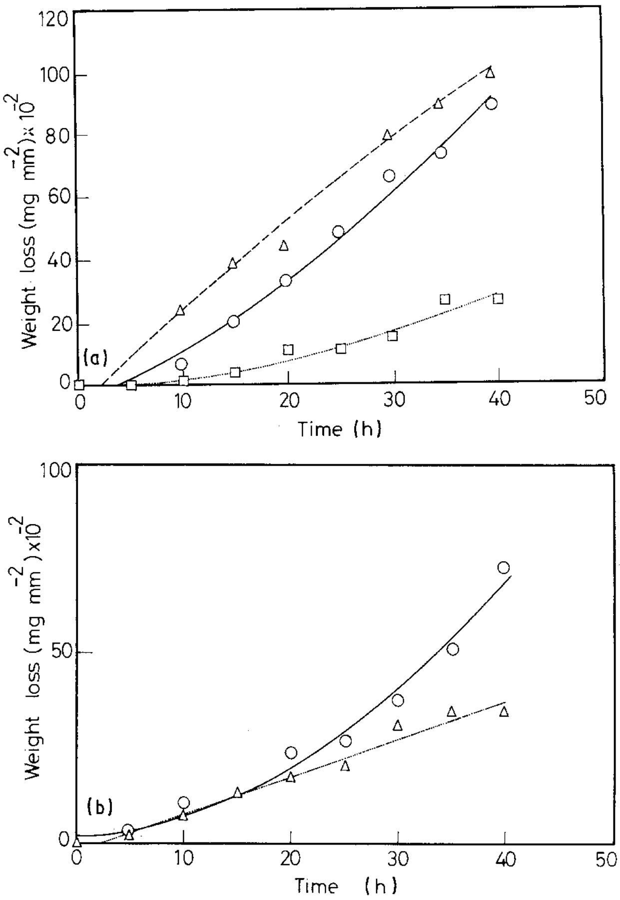

Figure 6 Effect of testing medium on the wear resistance of (a) Ni–5% Al. (△ water + 3% NaCl + 5% sand, ○ distilled water + 5% sand, □ water + 5% kaolin) and (b) WC–17% Co (○ water + 3% NaCl + 5% sand, △ distilled water + 5% sand).

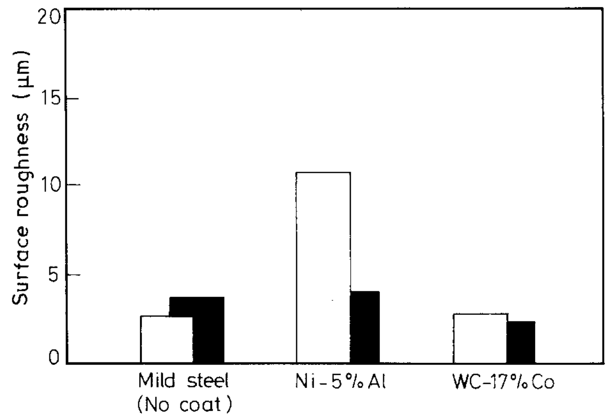

Figure 8 The change in surface roughness after wear testing (□ before testing, ■ after testing in tap water + 3% NaCl + 5% sand).

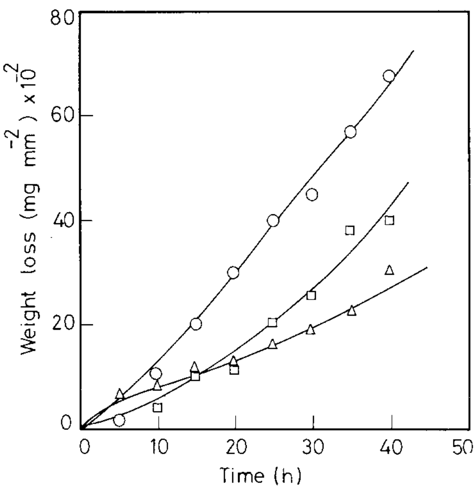

Figure 9 Effect of heat treatment at 900 °C on the amount of weight loss for specimens coated with Ni–5% Al (testing medium is water + 3% NaCl + 5% sand) (○ 1/2 h, △ 1 h, □ 2 h).

the coating. This will enhance the bonding and increase the wear resistance as obtained. Also, the binding effect of the NiO (formed during heat treatment) helped in reducing the amount of weight loss.

Some of the heat treated specimens were subjected to ageing treatment at 700 °C for different periods of time and then examined in wear testing. The results are shown in Fig. 10. It is clear from these results that the ageing time which gives the best wear resistance was 4 h. It has been suggested by many authors [13, 14] that the Ni–Al system in the range of 5–12% Al shows precipitation hardening. The aluminium solute can be dissolved at high temperatures and if precipitation upon cooling can be suppressed, it can be

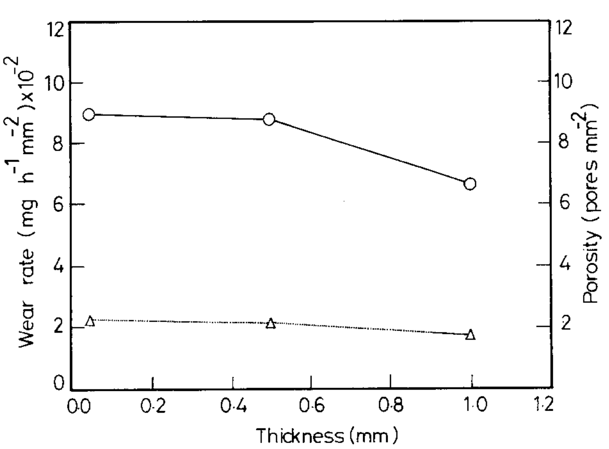

Figure 7 Effect of coating porosity on the wear rate for Ni–5% Al coating (○ porosity, △ wear rate, water + 5% sand + 3% NaCl).

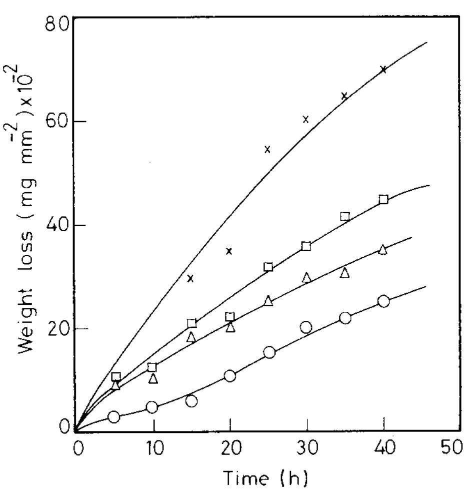

Figure 10 Effect of ageing treatment on the weight loss of specimens coated with Ni–5% Al (testing medium is water + 3% NaCl + 5% sand) (× 1/4 h, □ 1 h, ○ 4 h, △ 8 h).

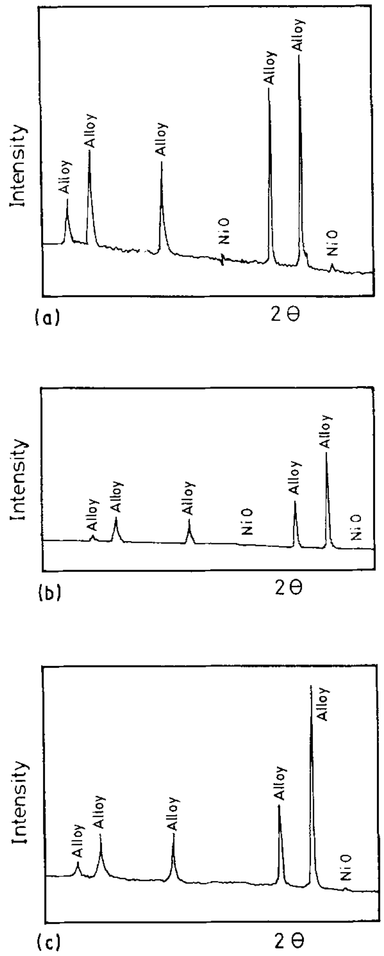

Figure 11 X-ray chart for specimen (a) just after coating, (b) tested for 1 h in wear testing and (c) tested for 8 h in wear testing.

controlled by the ageing treatment. Thus the decrease in weight loss observed in Fig. 10 can be attributed to precipitation hardening, sintering and/or the binding effect of the formed NiO. By comparing Figs 9 and 10, it can be seen that there is a little improvement in the wear resistance after the ageing treatment. From the present results it can be concluded that heat treatment at 900 °C for 1 h improved the wear resistance of the Ni–5% Al coats.

After mild steel specimens were coated with Ni–5% Al, an X-ray examination was conducted for these specimens in three different stages. First, the specimens were examined after plasma spraying (time of wear testing = 0), second, after heat treatment and finally after wear testing. The X-ray charts are given in Figs 11 and 12. It is clear from these charts that after plasma spraying NiO was formed. The appearance of several peaks on the X-ray chart was an indication for crystallinity of the deposited layer. NiO in the coat was detected in the outer layer only. Samples exposed to wear tests for 1 to 8 h showed (NiO + alloy) composition. After 16 h of wear the NiO peaks disappeared indicating that the composition of the coat is essentially γ-phase. The oxidation extent increased by heat treatment as shown in Fig. 12a. The structure distribution is indicated in Fig. 12b.

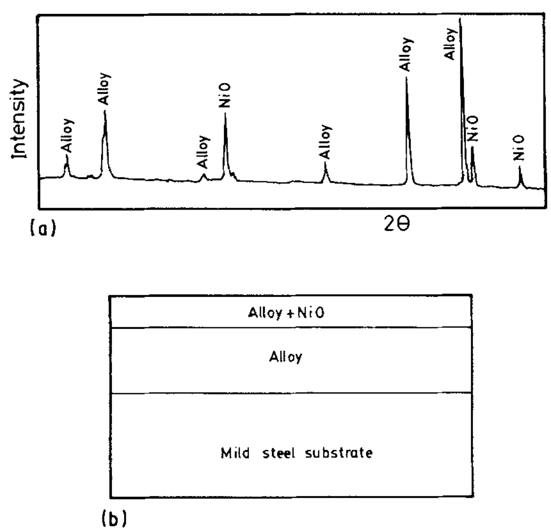

Figure 12 (a) X-ray chart for heat treated specimen at 900 °C for 1 h and (b) Structure distribution of mild steel and coating after heat treatment.

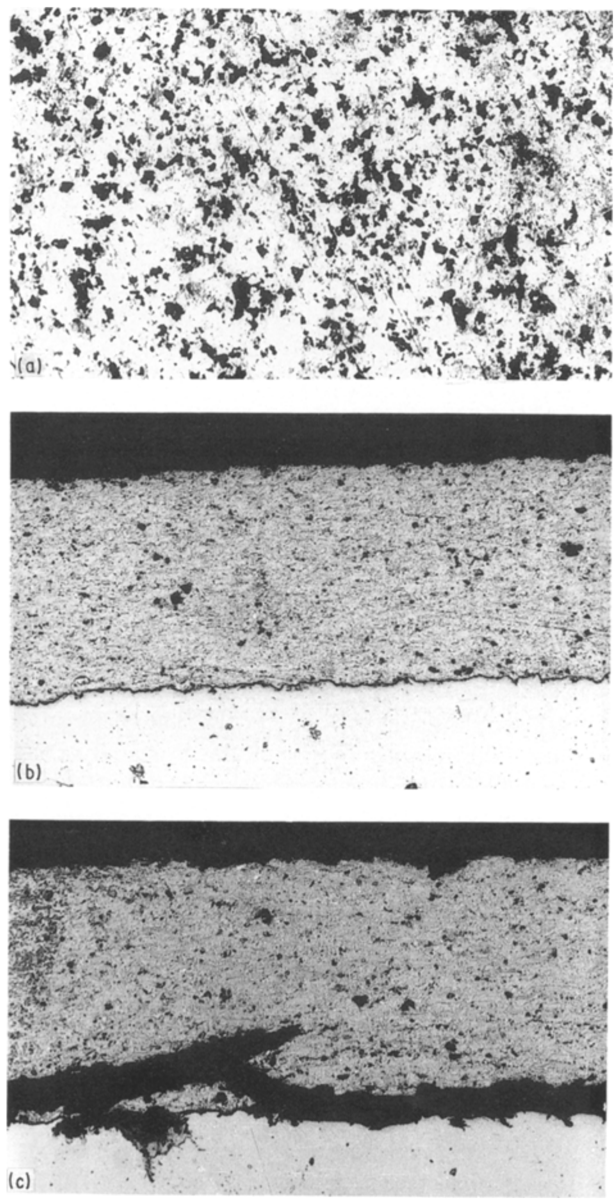

Figure 13 Optical micrographs of WC–17% Co coating. (a) Parallel section (b) Normal section before testing and (c) Normal section after testing (61 ×).

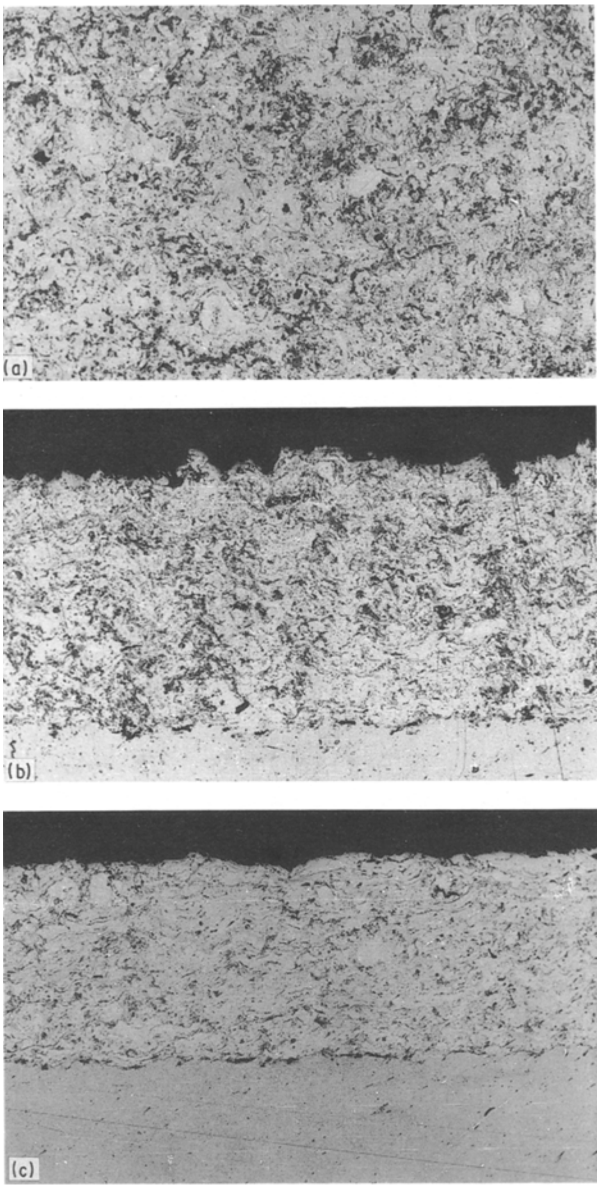

Figure 14 Optical micrographs of Ni–5% Al coating. (a) Parallel section (b) Normal section before testing and (c) Normal section after testing (61 ×).

The results of metallographic examination of the coating are shown in Figs 13 and 14. The black spots in these micrographs represent the pores. By comparing the figures, it can be seen that the level of porosity in WC–17% Co coating is higher than in case of Ni–5% Al. In Figs 13b and 14b the coating layer, the interface and the substrate are shown. A separation between the coating layer and the substrate is shown in Fig. 13c. This separation is due to corrosive wear and local galvanic corrosion.

4. Conclusions

The conclusions are as follows.

(1) The porosity level of the coating materials decreased with the increase in thickness. After wear testing, the surface roughness of the coating materials decreased.

(2) The increase in coating thickness led to an increase in wear resistance. The wear rate decreased with the decrease in porosity of coating. The wear resistance of both coatings has its lowest value in 3% NaCl solution.

(3) Heat treatment at 900 °C for 1 h improves the wear resistance of the Ni–5% Al coats. Ageing treatment did not greatly improve the wear resistance of the heat treated Ni–5% Al coat.

(4) X-ray diffractometry for Ni–5% Al coating indicated the crystallinity of the deposited layer and the formation of NiO after plasma spraying.

(5) Structure characterization after wear testing showed the presence of separation at the interface between the WC–17% Co coating and the substrate.

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