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Studies of the correlation between wear behaviour and bonding strength in two types of ceramic coating

S. SALMAN
Marmara University, Technical Educational Faculty, Goztepe, Istanbul, Turkey
Z. CIZMECIOGLU
Yildiz Technical University, Chemistry–Metallurgy Faculty, Besiktas, Istanbul, Turkey

The plasma-spraying technique is used in this study. Two types of ceramic coating (Al_2O_3–13 wt% TiO_2 and Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2) with and without NiAl bonding coating are subjected to bonding strength and wear tests. Determining the most suitable coating and coating technique and solving an industrial problem are the main objectives of this study. © *1998 Kluwer Academic Publishers*

1. Introduction

Demands for advanced materials have increased with developing technology. Surface modifications and/or surface coatings have been applied to improve the surface properties of materials to obtain optimum productivity from these materials and to protect them against environmental effects. Ceramic coating is one of the most important surface coating techniques whose importance is increasing with recent technological developments. The high wear and corrosion resistivity, low thermal conductivity, electrical insulation and high melting temperature of ceramics can be coupled with good toughness and plastic formability of metals to obtain exceptional material properties. This approach is a good example of developing advanced materials [1, 2].

Ceramic coatings are mostly utilized to improve the life limit of the parts exposed to wear. By employing these coatings, metallic material erosion is reduced without interrupting the working speed. Extended material life is an important economic criterion for countries which import wear-resistant parts, in shrinking their budget for importing these parts.

The experimental bonding strength values of ceramic coatings given by some Czechoslovakian researchers [3, 4] and others [5, 6] show distinct differences. Literature data on the bonding strength of ceramic coatings showed that the plasma-sprayed ceramic coatings possess a higher bonding strength than flame-sprayed coatings do [7]. The bonding strength values of ceramic coatings are lower than those of metallic coatings. According to the information given in [8], the maximum bonding strength value of ceramic coating is approximately 5900 kPa. In a study of an Al_2O_3–2.5 wt% TiO_2 ceramic coating by Grisaffe [9], a maximum bonding strength value of 3920 kPa was reported.

A bonding strength value of pure alumina which was less than the bonding strength value of stabilized alumina was given in [10]. The bonding strength of a ceramic coating with a bonding coating is higher than that without a bonding coating. According to many researchers, the adhesion strength between the substrate and the ceramic coating could be increased by a NiAl bonding coating [11, 12]. The exothermic reaction between Ni and Al during the coating process improves the mechanical properties (strength) of the coating, and this was reported in [3, 13]. NiAl powders generate extra heat in the flame owing to exothermic reactions and the resulting coatings are more adherent and less porous than the usual sprayed coatings. Hebbert [14] showed that the NiAl particles become hotter as they leave the flame. Details of the exothermic effects of Ni_3Al and Al_2O_3 formation were discussed by Knotek *et al.* [15] and Houben and Zaat [16].

In this study, a solution for an industrial problem is sought. The plasma-spraying technique was used. Al_2O_3–13 wt% TiO_2 and Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2 ceramic powders are approved for wear-resistant purposes [17]. The parts of textile machines which experience wear are the gallet rollers. These parts were coated by two types of ceramic coating to improve their wear life.

2. Experimental procedure

The coating powders used in this study were NiAl bonding powder and Al_2O_3–13 wt% TiO_2 and Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2 ceramic powders. The substrate was SAE 1020 carbon steel. The chemical compositions of the substrate and properties of the powders are shown in Table I and Table II, respectively.

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Powder morphology was determined by scanning electron microscopy (SEM). The spherically shaped bonding powder was produced by agglomeration methods and ceramic powders, one of which had a complex shape and the other an angled shape, were produced by the grinding method [18]. The magnified morphology of the bonding powder and the Al_2O_3–13 wt% TiO_2 and Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2 ceramic powders are shown in Fig. 1.

2.1. Surface preparation of substrate before plasma-spraying and coating processes

SAE 1020 steel substrate was cleaned before and after blasting by trichlorethylene and acetone. After cleaning, the substrate was roughened via grit blasting as given in the literature [20, 21] to obtain a good-quality mechanical bonding between the substrate and the ceramic coating. The surface roughness obtained using alumina grid was measured with a Mitutoyo Surftest 201 perthometer. This value was $R_a = 10.93\ \mu m$. Before coating, the roughness values of wear surface of gallet rollers were also measured. The surface roughness of uncoated gallet rollers was $R_a = 9.53\ \mu m$. The plasma-sprayed parameters are shown in Table III [19].

Two types of ceramic coating (Al_2O_3–13 wt% TiO_2 and Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2) with and without a NiAl bonding coating were subjected to bonding strength and wear tests. The SEM surface topographies of the plasma-sprayed ceramic coatings are shown in Fig. 2.

2.2. Bonding strength tests of ceramic coatings

The bonding strength test of ceramic coatings is a kind of tensile test described by the ASTM C-633 Standard test through which the determination of adhesion and cohesive strength of flame and plasma-sprayed ceramic coatings is possible [22].

This test is also used in dentistry widely [12, 23]. Test samples prepared to the ASTM C-633 Standard were tested using an Instron tensile-testing machine. Araldite AW type glue was used for adhering the samples. This glue was used, since its adhesion was much higher than that of the ceramic coatings. The bonding strength test apparatus and testing photograph are shown in Fig. 3 [22].

TABLE I The chemical composition of the substrate [18]

Type of substrate material	C (wt%)	Mn (wt%)	Maximum P (wt%)	Maximum S (wt%)
SAE–AISI 1020	0.18–0.23	70.3–0.6	0.04	0.05

2.3. Wear tests of the ceramic coatings

According to the ASTM G 99-90 Standard, wear testing with a pin-on-disc apparatus was used for ceramic coatings. The test apparatus used in the wear test is shown in Fig. 4 [24]. Circular SiC sandpaper was placed on the disc to produce a wearing surface.

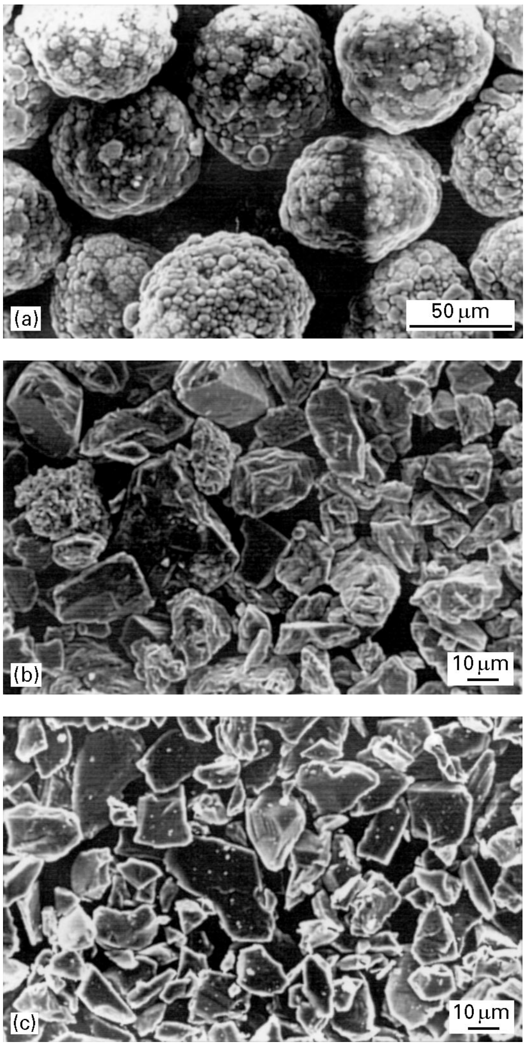

Figure 1 Scanning electron micrographs showing the morphologies the bonding and ceramic powders: (a) NiAl bonding powder; (b) Al_2O_3–13 wt% TiO_2 ceramic powder; (c) Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2 ceramic powder.

TABLE II Properties of bonding and ceramic powders [3]

Powder type	Chemical composition (wt%)	Powder dimension range (μm)	Melting temperature (°C)	Density (g cm^{-3})	Powder morphology
Bonding powder	95Ni–5Al	− 44 + 125	1650	3.42	Spherical
Ceramic powder 1	92Cr_3O_3–5SiO_2–3TiO_2	− 53 + 15	2435	4.8	Complex
Ceramic powder 2	87Al_2O_3–3TiO_2	− 325 + 5	2010	3.4	Angled

TABLE III Plasma spraying parameters [20, 21]

Coating materials	Al_2O_3–13 wt% TiO_2, Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2
Substrate	SAE 1020 steel
Plasma type	Ar + H_2
Argon flow rate ($l\,min^{-1}$)	44
Hydrogen flow rate ($l\,min^{-1}$)	15
Plasma current (A)	500
Arc voltage (V)	60–70
Plasma gun type	Metco 3MB
Nozzle and electrode	W cathode; Cu anode
Nozzle diameter (mm)	8
Injector distance (mm)	100
Injector angle (deg)	90
Powder feed rate ($g\,min^{-1}$)	42
Powder carrier gas ($l\,min^{-1}$)	6

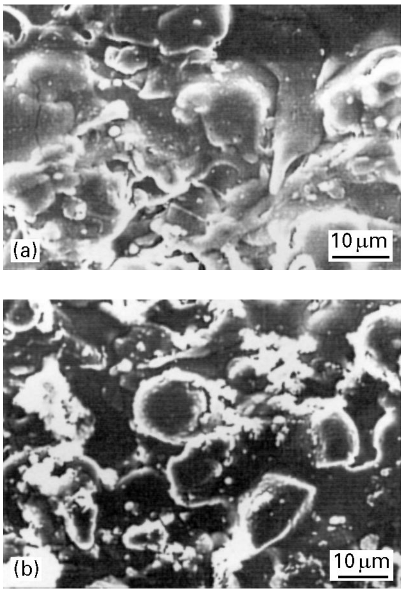

Figure 2 Scanning electron micrographs showing the surface topographies ceramics coatings: (a) Cr_2O_3–5 wt%SiO_2–3 wt% TiO_2 ceramic with the NiAl bonding coating; (b) Al_2O_3–13 wt% TiO_2 ceramic without the NiAl bonding coating.

The wear test conditions are shown in Table IV. The volume loss of the ceramic coatings as a function of testing time was obtained [25–27]. The wear surfaces of the Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2 ceramic coating with the NiAl bonding coating, which gave the highest strength value, and of the Al_2O_3–13 wt% TiO_2 ceramic coating without the NiAl bonding coating, which gave the lowest strength value, are shown in Fig. 5.

3. Results and discussion

The bonding strength results of ceramic coatings are shown in Figs. 6–9. It is clear that the coating with NiAl bonding coating has the highest bonding strength. The bonding strength decreases as the coating thickness increases. This can be explained as a result of increase in shrinkage stresses between the layers. Surface photographs of ceramic coatings are shown in Fig. 10 after bonding strength tests.

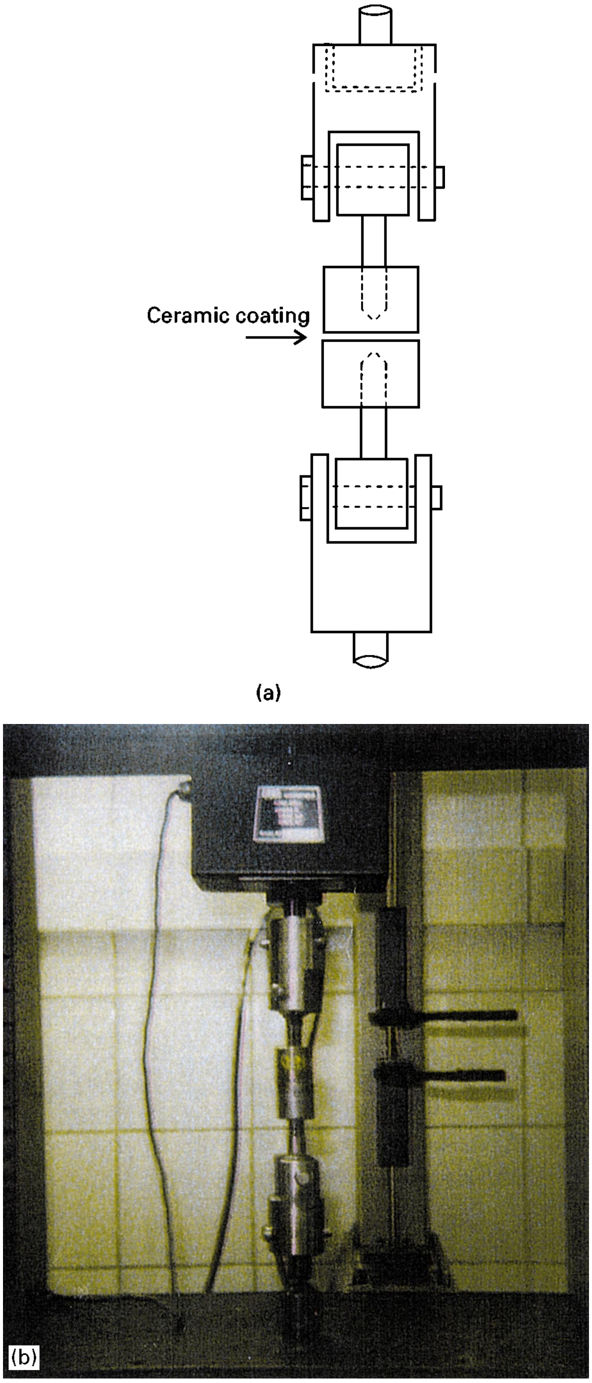

Figure 3 (a) Bonding strength standard test apparatus; (b) bonding strength testing photograph.

The adhesion between the NiAl bonding coating, substrate and ceramic coating can be attributed to the additional energy coming from the exothermic reaction between Ni and Al during the coating process as explained in the introduction. It is also observed that additional energy has aided the increased coating strength.

The wear test conditions given in Table IV were used to obtain the test results which are given in Fig. 11. The highest wear resistance of ceramic coatings was observed with NiAl bonding coating. If Fig. 5 is examined, this reason can be understood clearly.

The cross-section micrograph of Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2 with the NiAl bonding coating is

TABLE IV Wear test conditions

Condition	Temperature (°C)	SiC grid number	Applied weight (kgf)	Applied time (min)	Disc velocity (rev min^{-1})	Wear distance (m)	Coatrd bonding thickness (mm)	Coated ceramic thickness (mm)	Coated material diameter (mm)	Coated material height (mm)
1	22	1200	0.218	2	55	66	0.15	0.3	8	34
2	22	1200	0.218	4	55	132	0.15	0.3	8	34
3	22	1200	0.218	6	55	198	0.15	0.3	8	34
4	22	1200	0.218	8	55	264	0.15	0.3	8	34
5	22	1200	0.218	10	55	330	0.15	0.3	8	34

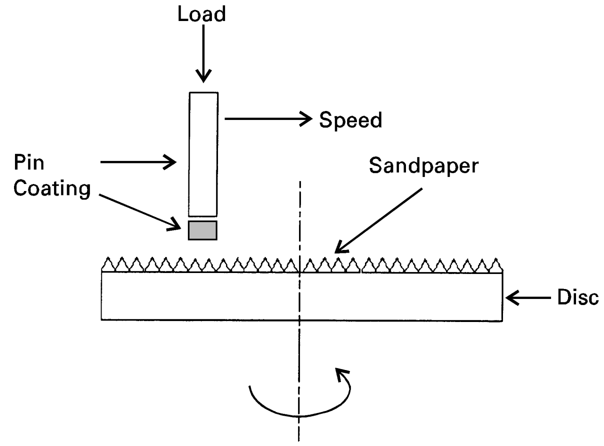

Figure 4 Wear testing apparatus [21].

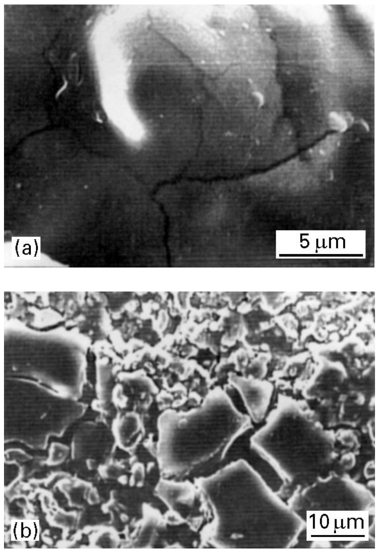

Figure 5 Scanning electron micrographs showing wear surfaces of coatings: (a) Cr_2O_3–5 wt% SiO_2–3wt% TiO_2 ceramic with NiAl bonding coating; (b) Al_2O_3–13 wt% TiO_2 ceramic without the NiAl bonding coating.

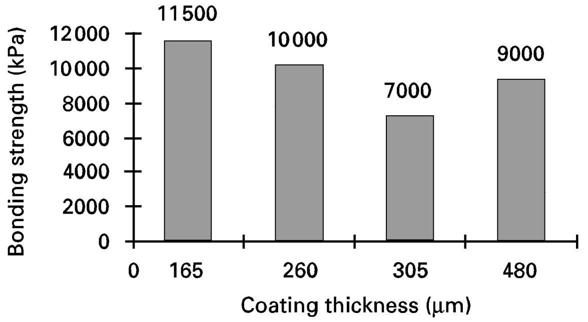

Figure 6 Bonding strength of the plasma-sprayed Al_2O_3–13 wt % TiO_2 ceramic coatings without the NiAl bonding coating as a function of coating thickness.

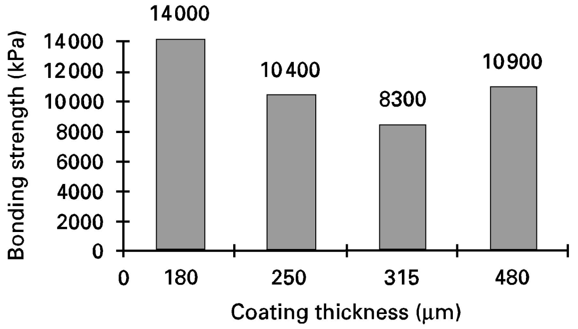

Figure 7 Bonding strength of the plasma-sprayed Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2 ceramic coatings without the NiAl bonding coating as a function of coating thickness.

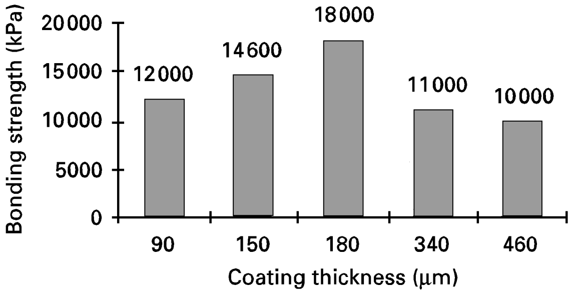

Figure 8 Bonding strength of the plasma-sprayed Al_2O_3–13 wt% TiO_2 ceramic coatings with the NiAl bonding coating as a function of coating thickness.

given in Fig. 12a with which the highest mechanical properties (wear resistance and bonding strength) were obtained. The cross-section micrograph of Al_2O_3–13 wt% TiO_2 without the NiAl bonding coating is given in Fig. 12b for which the lowest mechanical properties (wear resistance and bonding strength) were obtained. The microstructure of both coatings consisted of a lamellar structure interspersed with micron- and submicron-sized pores. As these micrographs show, decohesion along the lamellae interface in Fig. 12b is much greater than in Fig. 12a.

The ceramic coating–bonding coating interface has minimum mismatch with respect to ceramic coating–substrate interface because the NiAl interlayer bonding coating compensates thermal expansion differences between the ceramic coating and the substrate interfaces.

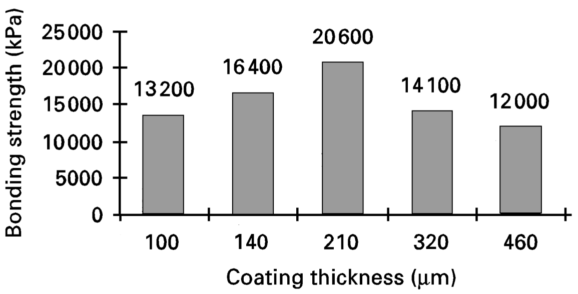

Figure 9 Bonding strength of the plasma-sprayed Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2 ceramic coatings with the NiAl bonding coating as a function of coating thickness.

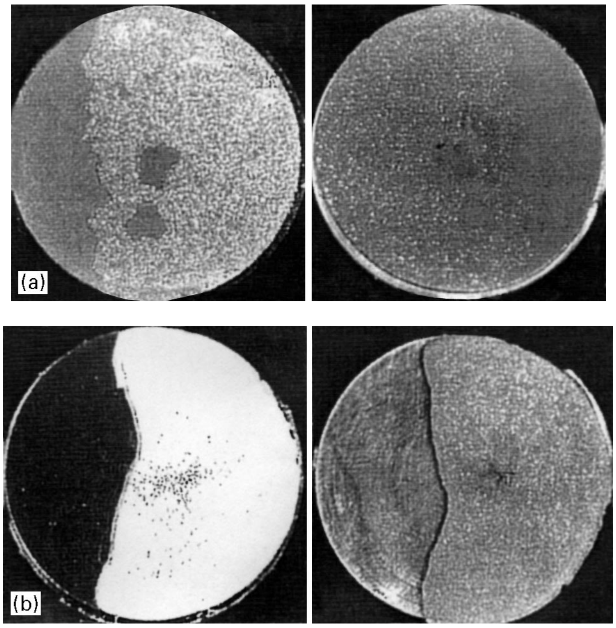

Figure 10 Surface photographs of ceramic coatings after bonding strength tests: (a) Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2 ceramic with the NiAl bonding coating; (b) Al_2O_3–13 wt% TiO_2 ceramic without the NiAl bonding coating.

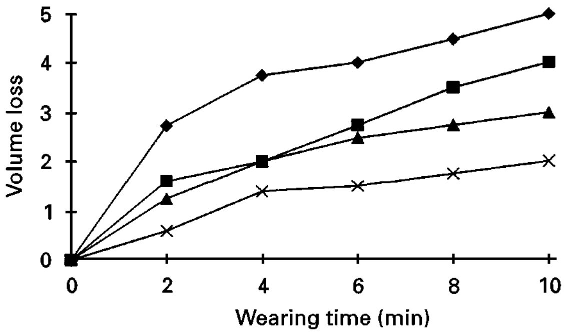

Figure 11 Volume loss of plasma sprayed ceramic coatings as a function of wear time (◆), without the NiAl bonding coating of Al_2O_3–13 wt% TiO_2 ceramic; (■), without the NiAl bonding coating of Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2 ceramic coating; (▲), with the NiAl bonding coating of Al_2O_3–13 wt% TiO_2 ceramic coating; (×), with the NiAl bonding coating of Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2 ceramic coating.

The optimum coating parameters were obtained. Quite profitable results were obtained using plasma-spraying techniques, a bonding coating (the optimum coating thickness is approximately 150 μm) and a ceramic coating (the optimum ceramic coating thickness is approximately 200 μm). Fig. 13 shows some coated gallet rollers in service conditions. The coating process of the gallet rollers was done on the basis of the optimum coating parameters obtained after the experiments in this study.

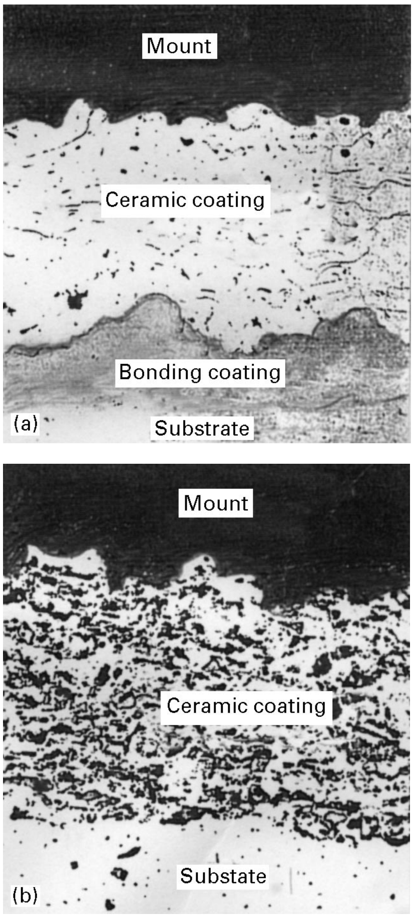

Figure 12 The cross-section micrograph of ceramic coatings: (a) Cr_2O_3–5 wt% SiO_2–3wt% TiO_2 ceramic with the NiAl bonding coating; (b) Al_2O_3–13 wt% TiO_2 ceramic without the NiAl bonding coating. (Magnifications, 1000 ×).

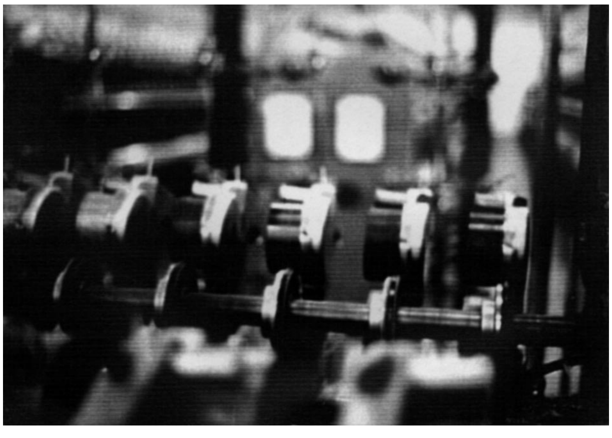

Figure 13 Photographs of some coated gallet rollers in service conditions (four coated gallet rollers on the right).

In service conditions, the wear values have been obtained for 14 months, and these values are similar to those obtained in laboratory conditions. Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2 ceramic coatings with bonding coatings produced via the plasma-spraying technique have the highest wear resistance values.

In this study, the solution of an industrial problem, which is an important problem in textile industry of Turkey, is sought. Some ceramic-coated gallet rollers surface were exposed to wear. Quite profitable results have been obtained from the Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2 ceramic coatings with bonding coatings using the plasma-spraying technique.

The gallet rollers are quite expensive to wear. It is continuously required to replace gallet rollers which are imported by paying considerable amounts of foreign currency. These gallet rollers must be replaced once a month before the application of ceramic coating. After application of ceramic coating, these gallet rollers had been observed for a period of 14 months. At the end of observation period, no replacement was needed because the surface of the gallet rollers showed no lack of quality.

By this method, utilized in the industrial area in Turkey, the metallic erosion was reduced, the working speed was not interrupted, and the number of imported parts (wear-exposed parts such as the gallet rollers) was reduced, helping the economy.

4. Conclusions

1. Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2 amd Al_2O_3–13 wt% TiO_2 ceramic coatings with and without a NiAl bonding coating were applied on a SAE 1020 carbon steel.
2. The plasma-sprayed coatings were tested for strength and wear properties.
3. The Cr_2O_3–5 wt% SiO_2–3 wt% TiO_2 ceramic coating with the NiAl bonding coating applied using plasma-spraying technique gives the better strength and wear properties.
4. The improvement with application of the NiAl bonding coating is due to the exothermic reaction occurring during the coating process.
5. By applying the plasma-spraying technique, the wear limit of the gallet rollers of textile industry was extended from 1 month to more than 14 months.

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