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Wear Characteristics of Plasma Sprayed Nickel–Aluminum Composite Coatings

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ABSTRACT: In the present investigation plasma spray intermetallic coating of nickel–aluminide was deposited on mild steel substrates. The response of plasma sprayed nickel–aluminide coatings to the impingement of solid particles has been presented in this study. Nickel pre-mixed with alumina powder is deposited on mild steel substances by atmospheric plasma spraying at various operating power level. The coatings are subjected to erosion wear test. Dry silica sand of average particle size 400 µm is used as the erodent. The erosion rate is calculated on the basis of coating mass loss. The erosion studies are made at different velocities and impingement angles. It is observed that, the erosion wear is strongly influenced by the angle of impact. The test is conducted at room temperature, i.e., at 27°C and 60% RH. Coatings deposited at different power levels are found to exhibit different wear rates under similar test conditions. Microstructure of the coating is analyzed with SEM.

KEY WORDS: NiAl coating, plasma spraying, erosion wear, coating.

INTRODUCTION

INTERMETALLIC COMPOUNDS FIND extensive use in high temperature structural applications [1–4]. In particular, these alloys have potential demand in the aerospace industry and other high performance applications [3,4]. In thermal spray applications, nickel aluminides and their derivative alloys are used as a bond coat material, where their function is to minimize the thermo-mechanical stresses at the substrate-coating interface and also to promote coating adhesion [5]. The coefficient of thermal expansion of these alloys is intermediate between those of ceramics and metals and therefore can take care of interface stresses. Moreover, the reaction leading to the formation of the alloy is highly exothermic leading to better coating adhesion. In addition to wear related application, it is mostly used as a bond coat for ceramic materials [6]. Nickel based coatings are used in applications when wear resistance combined with oxidation or hot corrosion resistance is required [7]. It is the most important strengthening constituent, generally referred to as γ-phase of commercial Ni-base super-alloys used extensively as high temperature

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structural materials for jet engines and aerospace applications. It is responsible for the high strength and creep resistance of the super-alloys at elevated temperatures. Ni_3Al containing about 25% Al has the ability to form protective aluminum-oxide scales, resulting in excellent oxidation resistance.

In the present investigation, attempts are made to deposit nickel–aluminide on steel substrates by a plasma spraying process. Plasma spraying is considered a non-linear problem with respect to its variables, either materials or operating conditions. To obtain functional coating exhibiting selected in-service properties, combinations of processing parameters have to be organized. These combinations differ by their influence on the coating properties and characteristics. To control the spraying process, one must recognize the parameter interdependencies, correlations, and individual effects on coating characteristics. Properties of the plasma sprayed coatings are influenced by the microstructure of the coating. The coating morphology is analyzed with SEM. Solid particle erosion is a process where particles strike against a surface and cause material loss. During flight, a particle carries momentum and kinetic energy, which is dissipated on impact at the target surface. Erosion wear tests were carried out on the coatings to ensure its applicability under different operating conditions.

EXPERIMENTAL DETAILS

Coating Deposition

Nickel and aluminum powders were taken in a ratio of 3 : 1 by weight and were mixed thoroughly in a planetary ball mill to produce an homogeneous mixture. This mixture was sprayed on mild steel substrates of dimensions 50 × 20 × 3 mm. Spraying was done using a 40 kW APS (atmospheric plasma spray) system in the thermal plasma laboratory at NIT Rourkela. The major components of this set-up include a plasma torch, power supply, power feeder, plasma gas supply, control console, cooling water, and spray booth. Prior to spraying, the substrates were grit blasted by compressed air at a pressure of $3\,kgf/cm^2$. A current regulated d.c. power supply was used. A four-stage closed loop centrifugal pump at a pressure of $10\,kgf/cm^2$ supplied cooling water for the system. The primary plasma gas (argon) and the secondary gas (nitrogen) were taken from normal cylinders at an outlet pressure of $4\,kgf/cm^2$. The plasma torch input power was varied from 10 to 24 kW by controlling the gas flow rate, plasma arc current, and the arc voltage. The powder feed rate was kept constant at about 50 g/min by a turntable type volumetric powder feeder. Operating parameters used during the spraying are given in Table 1.

Scanning Electron Microscopy

Specimens of size 10 × 13 × 5 mm were sliced from the coated samples for SEM observation. Both top surface and cross-section of specimens were observed under scanning electron microscope JEOL-JSM-6480LV mostly using the secondary electron imaging. Coating cross-sections were polished in three stages using SiC abrasive papers of reducing grit sizes and then with diamond pastes on a wheel for coating interface analysis.

Table 1. Operating parameters used during the plasma spraying process.

Parameter	Range
Torch input power	0–24 kW
Current	250–480 A
Voltage	40–50 V
Plasma gas (Ar) flow rate	20 L/m
Secondary gas (N_2) flow rate	2 L/m
Powder feed rate	50 g/min
Carrier gas (Ar) flow rate	12 L/m
Torch to base distance	100 mm

Erosion Test

Solid particle erosion (SPE) is a wear process where particles strike against surfaces and promote material loss. During flight a particle carries momentum and kinetic energy, which can be dissipated during impact, due to its interaction with a target surface. Different models have been proposed that allow estimations of the stresses that a moving particle will impose on a target [8]. It has been experimentally observed by many investigators that during the impact the target can be locally scratched, extruded, melted, and/or cracked in different ways [9,10]. The imposed surface damage will vary with the target material, erodent particle, impact angle, erosion time, particle velocity, temperature, and atmosphere [9,11]. Plasma sprayed coatings are used today as erosion or abrasion resistant coatings in a wide variety of applications [12]. Extensive research shows that the deposition parameters like energy input in the plasma and powder properties affect the porosity, splat size, phase composition, hardness, etc. of plasma sprayed coatings [13–17]. Solid particle erosion is usually simulated in the laboratory by one of two methods. The 'sand blast' method, where particles are carried in an air flow and impacted onto a stationary target and the 'whirling arm' method, where the target is spun through a chamber of falling particles. In the present investigation, an erosion apparatus of the 'sand blast' type capable of creating highly reproducible erosive situations over a wide range of particle sizes, velocities, particles fluxes, and incidence angles is used. The test is conducted as per ASTM G76 standards. The jet erosion test rig used in this work employs a 300 mm long nozzle of 3 mm bore and 300 mm long. This nozzle size permits a wider range of particle types to be used in the course of testing, allowing better simulations of real erosion conditions. The mass flow rate is measured by conventional methods. Particles are fed from a simple hopper under gravity into the groove. Velocity of impact is measured using the standard double disc method [18]. In this work, room temperature solid particle erosion test on mild steel substrate coated with nickel–aluminum is carried out at five different impact angles, i.e., 15, 30, 45, 60, and 90°. The nozzle is kept at 100 and 150 mm stand-off distances from the target. Dry silica sand of 40 μm average size particles is used as erodent at three different impact velocities of 31.2, 44.2, and 58.5 m/s. Amount of wear is determined on a 'mass loss' basis. It is done by measuring the mass of the samples at the beginning of the test and at regular intervals in the test duration. A precision electronic balance with +0.1 mg accuracy is used for weighing. Erosion rate, defined as the coating mass loss per unit erodent mass (mg/g), is calculated.

RESULTS AND DISCUSSION

Erosion Wear

Solid particle erosion is a wear process where particles strike against a surface and promote material loss. In case of plasma spray coatings encountering such situations, no specific model has been developed and thus the study of their erosion behavior has been mostly experimental data [19]. Erosion tests were conducted for three different impact velocities (31.2, 44.2, and 58.5 m/s), five impact angles (15, 30, 45, 60, and 90°), and two stand-off-distances (100 and 150 mm). The variations of the coating wear rates with the erodent mass are illustrated in Figures 1–6. It is seen from the figures that rate of erosion of the nickel–aluminum coatings varies with the erodent dose. At a specified feed rate of the erodent, the cumulative mass of erodent changes as the time of exposure advances.

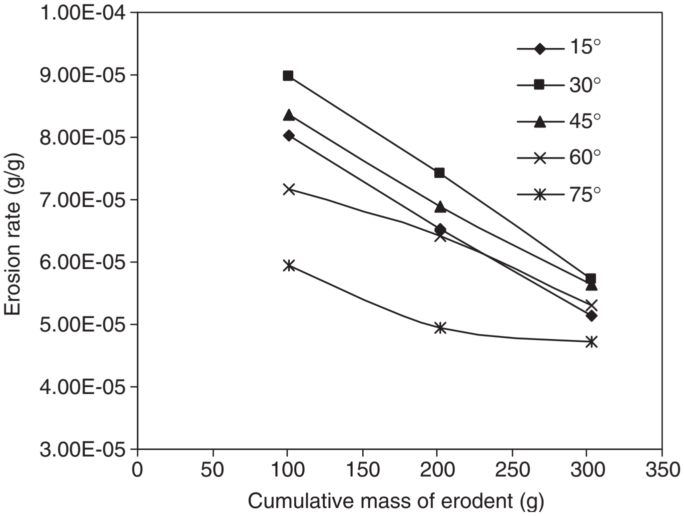

Figure 1. *Erosion rate vs. cumulative mass of erodent (impact vel. 31.2 m/s, SOD = 100 mm).*

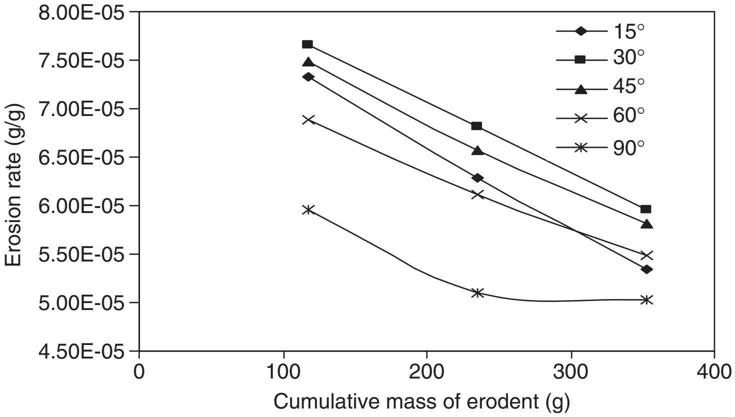

Figure 2. *Erosion rate vs. cumulative mass of erodent (at impact velocity of 44.2 m/s and SOD = 100 mm).*

The decrease in the wear rate of various plasma sprayed coatings with erosion time (or erodent dose) has been reported earlier by Levy [20]. He has shown that the incremental erosion rate curves of a large number of materials start with a high rate at the first measurable amount of erosion and then decreases to a much lower steady-state value. In this work, a similar trend is found in nickel–aluminide coatings subjected to erosion at various impact angles. This can be attributed to the fact that the fine protrusions on the coating parts are relatively loose and can be removed with less energy than what would be necessary to remove a similar part from the bulk of the coating. Consequently, the initial wear rate is high. With increasing exposure time the rate of wear starts decreasing and in the transient erosion regime, a sharp drop in the wear rate is obtained. As the coating surface gradually becomes smoother, the rate of erosion becomes almost steady.

The rate of erosion of the coating is also found to be greatly affected by the angle of impingement of the eroding particles. Figures 7 and 8 show the variation of erosion wear

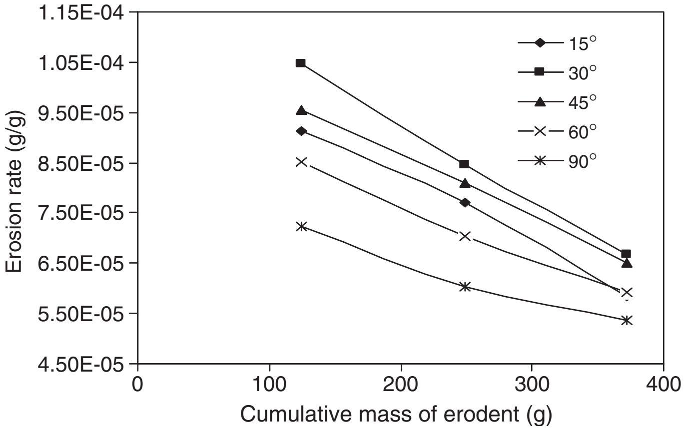

Figure 3. *Erosion rate vs. cumulative mass of erodent (impact vel. 58.5 m/s, SOD = 100 mm).*

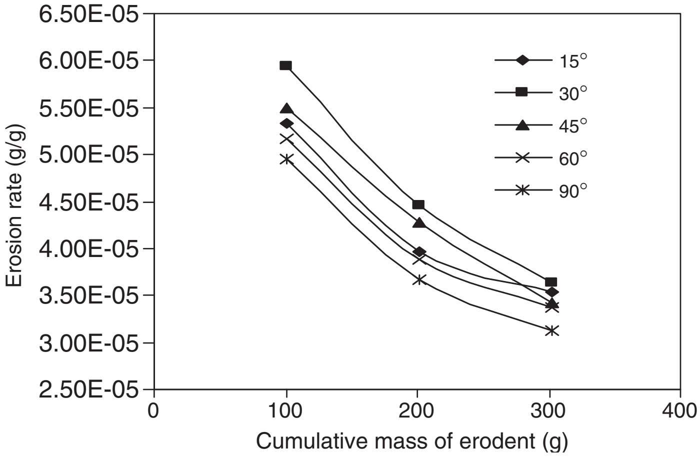

Figure 4. *Erosion rate vs. cumulative mass of erodent (impact vel. 31.2 m/s, SOD = 100 mm).*

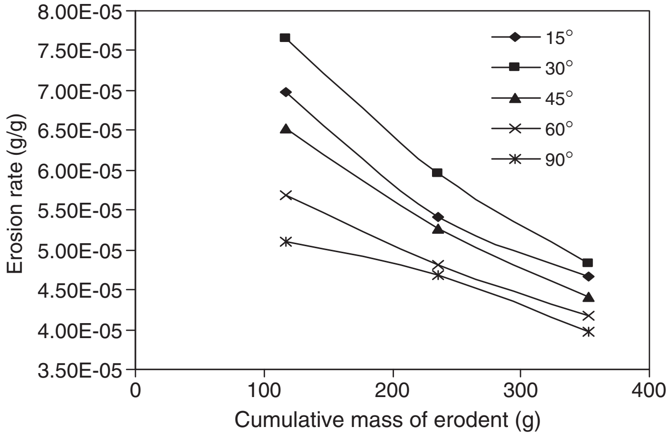

Figure 5. *Erosion rate vs. cumulative mass of erodent (impact vel. 44.2 m/s, SOD = 150 mm).*

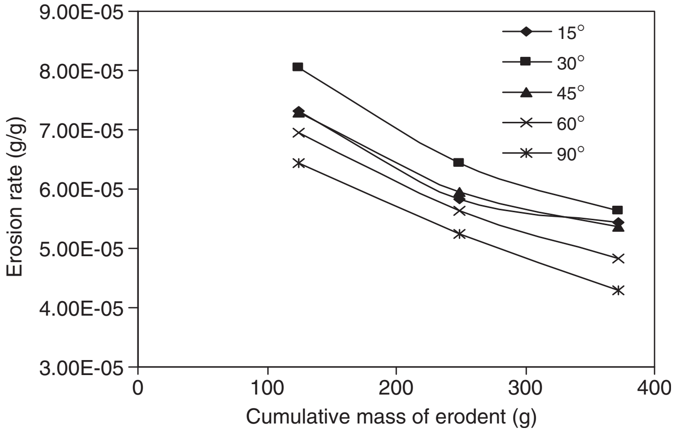

Figure 6. *Erosion rate vs. cumulative mass of erodent (impact vel. 58.5 m/s, SOD = 150 mm).*

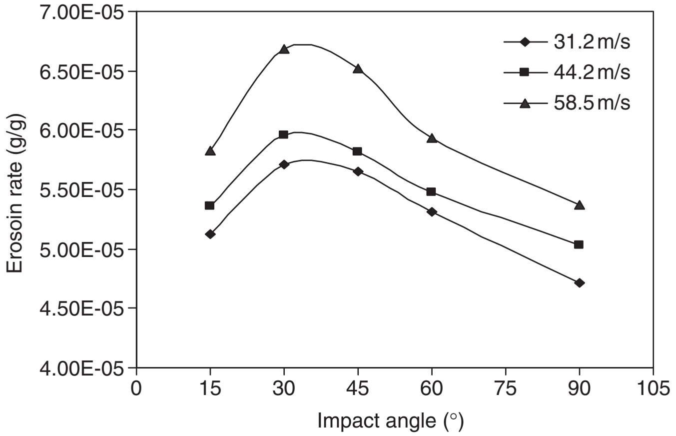

Figure 7. *Erosion rate vs. angle of impact at different impact velocities (exposure time = 6 min, SOD = 100 mm).*

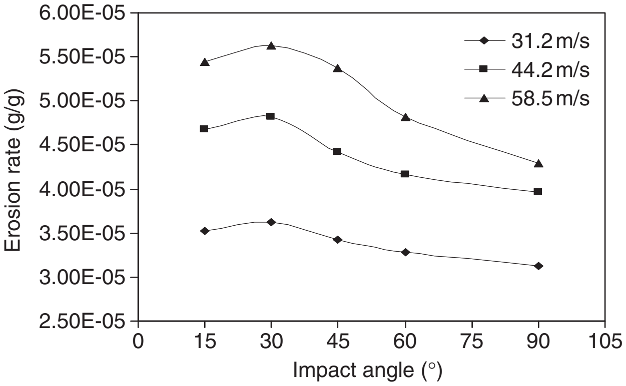

Figure 8. Erosion rate vs. angle of impact at different impact velocities (exposure time = 6 min, SOD = 150 mm).

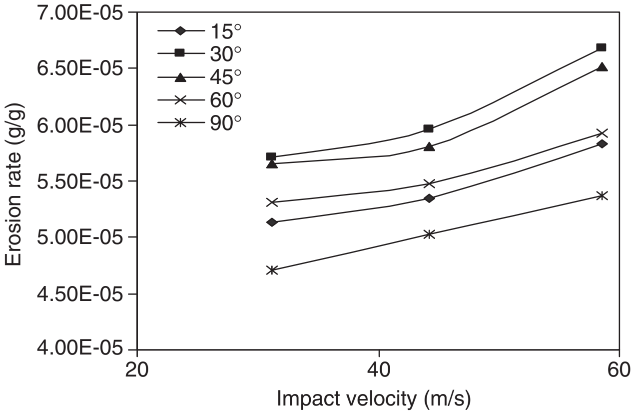

Figure 9. Erosion rate vs. impact velocity at different impact angles (exposure time = 6 min, SOD = 100 mm).

rate with the angle of impact at different impact speeds and stand-off distances. It is seen that initially with increase in impact angle the erosion rate increases, but beyond 30° the rate keeps decreasing monotonically. This trend is similar for different impact speeds and stand-off distances.

It is evident from Figures 9 and 10 that the effect of impact velocity on coating erosion is also very significant. It is seen that with increase in the impingement velocity the coating mass loss due to erosion increases. This trend is found for different impact angles and stand-off distances.

Coating Morphology

The micrograph of Ni–Al ball-milled powder (feed stock) is shown in Figure 11. The variation in particle shape and size is observed. Particles are irregular in shape, some are also elongated. The micrographs of the Ni–Al mix powders processed at 10 and 20 kW power, collected at 100 mm stand-off distance is shown in Figure 12(a)

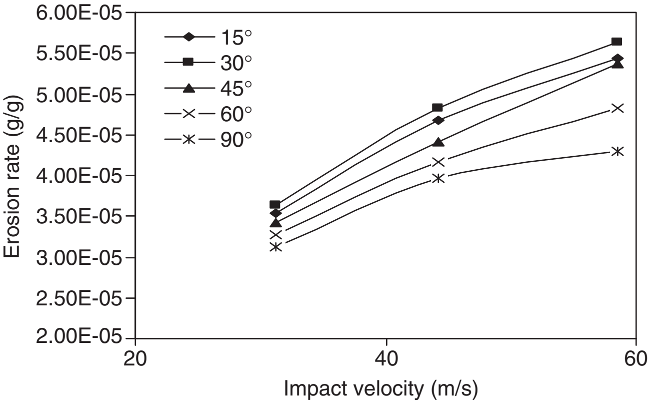

Figure 10. *Erosion rate vs. impact velocity at different impact angles (exposure time = 6 min, SOD = 150 mm).*

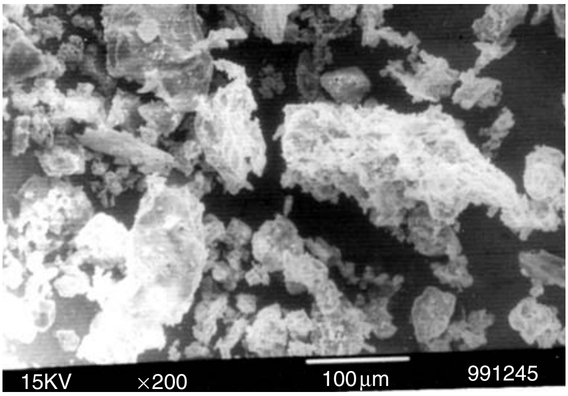

Figure 11. *Surface morphology of Ni–Al powders, after ball milling.*

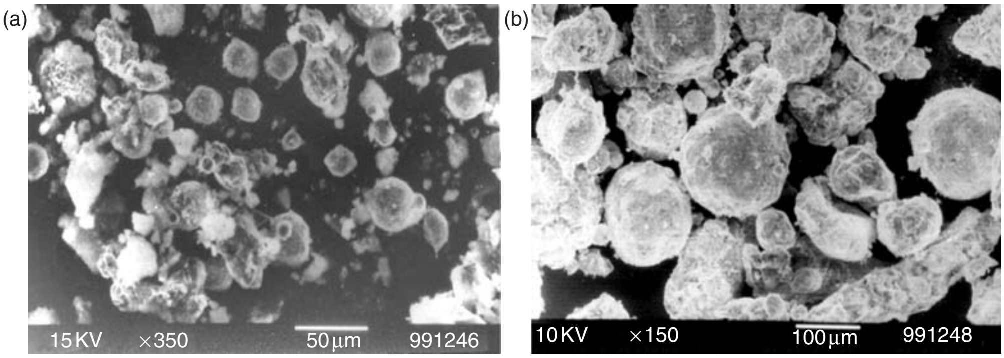

Figure 12. *Surface morphology of Ni–Al spheroidised powders: (a) processed at 10 kW power level, 100 mm TBD; (b) processed at 20 kW power level, 100 mm TBD.*

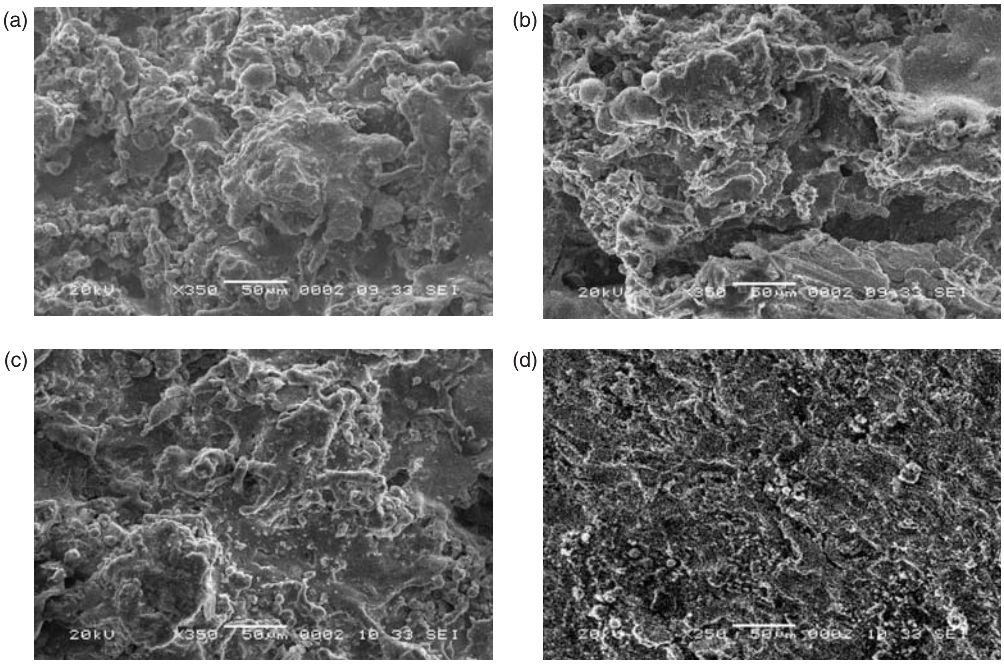

Figure 13. *Surface morphology of the coatings deposited at: (a) 10; (b) 16; (c) 20; and (d) 24 kW.*

and (b), respectively. Comparing these two figures, it is found that there is an appreciable change in shape and dimension of the particles. This may be due to the fact that with increased power level during spray deposition, more particles attain melting temperature and hence take on a spherical shape during solidification from the molten stage. This affects the coating quality and properties.

The typical surface morphology of the coatings deposited at different power levels are shown in Figure 13. It can be seen that the surface morphology of the coatings differ with deposition condition, i.e., affected by operating parameters of the plasma torch.

CONCLUSIONS

A mixture of commercial grade nickel and aluminum powder is coatable on metal substrates by a thermal plasma spraying technique. The coating developed in this study is harder than that of the substrate materials; hence, these coatings can be recommended for tribological applications. The solid particle erosion wear resistance of these coatings is fairly good. The rate of erosion of the coating is found to be greatly affected by the angle of impact and the velocity of impact of the eroding particles. For brittle materials subjected to erosion, the maximum wear rate occurs at 90° impact and for ductile material it is between 15 and 30°. In the present investigation, the peak erosion rate is recorded at 30° for the coatings regardless the impact velocity and the stand-off distance. This implies the ductile behavior of the coating under study. The coating morphology is also largely affected by the torch input power.

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