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Neural Network Analysis for Erosion Wear of Nickel-Aluminide Coatings on Steel by Plasma Spraying

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ABSTRACT

In the present investigation plasma spray inter metallic coating of Nickel-aluminide was deposited on mild steel substrates. The response of plasma sprayed nickel-aluminide coatings to the impingement of such solid particles has been presented in this work. 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. An erosion test setup developed in our laboratory is used to simulate real time erosive situations. Dry silica sand of average particle size 400 micron is used as the erodent. The erosion rate is calculated on the basis of 'coating mass losses. The erosion studies are made and different velocities and impingement angles. A computational technique (ANN analysis) is used to predict the rate of erosion wear under various operational conditions. This technique involves database training to predict property parameter evolutions in process having large number of interdependent variables. This paper presents the database construction, implementation protocol and also the set of predicted results related to the erosion wear rate of nickel-aluminide coating. It is shown that the erosion wear is strongly influenced by the angle of impact. The test is conducted at room temperature i.e.27^{o}C and 60% RH. Ni_3Al coatings deposited at different power levels (10, 12, 16, 20, 24 kW) are found to exhibit different wear rate under similar test conditions.

INTRODUCTION

Inter metallic compounds find extensive use in high temperature structural applications [1-4]. In particular, these alloys have potential demand in aerospace industry and other high performance applications [3, 4]. In thermal spray applications, nickel aluminides and their derivative alloys are used as bond coat materials, 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. The nickel-aluminide (Ni_3Al) has drawn enormous attention because of its technological and scientific interest. In addition to wear related application, it is mostly used as 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 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 (mild steel) with varying the particle size. Erosion wear tests were carried out on the coatings to ensure its applicability. 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 during impact due to its interaction with a target surface. Erosion is a non-linear process with respect to its variables: either materials or operating conditions. To obtain the best functional output coatings exhibiting selected in-service properties and the right combinations of operating parameters are to be known. These combinations normally differ by their influence on the erosion wear rate or coating mass loss. In order to achieve certain values of erosion wear rate accurately and repeatedly, the influence parameters of the process have to be controlled accordingly. Since the number of such parameters in erosion wear is too large and the parameter-property correlations are not always known, statistical methods can be employed for precise identification of significant control parameters for optimization. Neural computation can be used as a tool to process very large data related to a spraying process and to predict any desired coating characteristic the simulation can be extended to a parameter space larger than the domain of experimentation.

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 get homogeneous mixture. This mixture was sprayed on mild steel substrates of dimensions 50×20×3 mm. Spraying is done is using a 40 kW APS (atmospheric plasma spray) system in the thermal plasma laboratory at NIT Rourkela. This is a typical plasma spray system operating in the non-transferred mode. The major components of this set up include the 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 the pressure of $3kgf/cm^2$. A current regulated dc 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 $4kgf/cm^2$. 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 gm/min by a turntable type volumetric powder feeder. Weighing method is accepted widely to calculate the deposition efficiency. Weighing of samples is done using a precision electronic balance with ± 0.1 mg accuracy. Operating parameters used during the spraying are given in table-1.

Table 1 Operating parameters used during the plasma spraying process

Parameter	Range
Torch input power	10-24 kW
Current	250-480 Amp
Voltage	40-50 Volt
Plasma gas (Ar) flow rate	20 lpm
Secondary gas (N_2) flow rate	2 lpm
Powder feed rate	50 gm/min
Carrier gas (Ar) flow rate	12 lpm
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, and 11**]**. The imposed surface damage will vary with the target material, erodent particle, impact angle, erosion time, particle velocity, temperature and atmosphere [9, 12**]**.

Plasma sprayed coatings are used today as erosion or abrasion resistant coatings in a wide variety of applications [13]. 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 [**14-18**].

Solid particle erosion is usually simulated in 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 (self-made) of the 'sand blast' type is used. It is capable of creating highly reproducible erosive situations over a wide range of particle sizes, velocities, particles fluxes and incidence angles, in order to generate quantitative data on materials and to study the mechanisms of damage. 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 method. Particles are fed from a simple hopper under gravity into the groove. Velocity of impact is measured using double disc method [19].Some of the features of this test set up are:

- Vertical traverse for the nozzle: provides variable nozzle to target standoff distance, which influences the size of the eroded area.
- Different nozzles may be accommodated: provides ability to change the particle plume dimensions and the velocity range.
- Large test chamber with sample mount that can be angled to the flow direction: by tilting the sample stage, the angle of impact of the particles can be changed in the range of $0^0 – 90^0$ and this will influence the erosion process.

In this work, room temperature solid particle erosion test on mild steel substrate coated with nickel-aluminide feed materials(at 20 kW) is carried out under five different impact angles 15°, 30°, 45°, 60° and 90°. The nozzle is kept at 100mm stand-off distance from the target. 400µm average size dry silica sand particles are used as erodent with three different impact velocities 31.2m/s, 44.2m/s and 58.5m/s and pressure 4-7kgf/cm^2. 7cm^2 area of each coating sample is exposed to the compressed air jet carrying erodent. Amount of wear is determined on '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.

ARTIFICIAL NEURAL NETWORK (ANN) ANALYSIS

Erosion wear rate not only depends on the mass flow, impact angle and velocity of the erodent, also depends on the spraying parameters. Only the spraying process is dependent on around 150 factors, hence we cannot account all the factors during the experiment. To account all the factors, Prediction of erosion wear rate properties by some numerical technique is one of the most important requirements. Artificial neural networks have the ability to tackle the problem of complex relationships among variables that cannot be accomplished by more traditional methods. Simple linear regression is not an answer for process like these that have nonlinear properties. Another advantage of using neural network model is that it can predict an output with accuracy even if the variable interactions are not completely understood. Artificial neural networks (ANN), which is a technique that involves, database training to predict property-parameter evolutions. This section presents the database construction, implementation protocol and a set of predicted results related to the erosion wear rate. The details of this methodology are described by Rajasekaran and Pai [20].

NEURAL NETWORK MODEL: Development and Implementation

An ANN is a computational system that simulates the microstructure (neurons) of biological nervous system. The most basic components of ANN are modeled after the structure of brain. Inspired by these biological neurons, ANN is composed of simple elements operating in parallel. It is the simple clustering of the primitive artificial neurons. This clustering occurs by creating layers, which are then connected to one another. The multilayered neural network has been utilized in the most of the research works for material science. A software package NEURALNET for neural computing developed by Rao and Rao [21] using back propagation algorithm is used as the prediction of erosion wear rate at different impact angles and velocities.

The database is built considering experiments at the limit ranges of each parameter. Experimental result sets are used to train the ANN in order to understand the input-output correlations. The database is then divided into three categories, namely: a validation category, which is required to define the ANN architecture and adjust the number of neurons for each layer. a training category, which is

Table 2 Input parameters selected for training

Input Parameters for Training	**Values**
Error tolerance	0.0001
Learning parameter(ß)	0.1
Momentum parameter(α)	0.002
Noise factor (NF)	0.0001
Maximum cycles for simulations	2000,000
Slope parameter (£)	0.6
Number of hidden layer neuron	6
Number of input layer neuron (I)	2
Number of output layer neuron (O)	1

exclusively used to adjust the network weights and a test category , which corresponds to the set that validates the results of the training protocol. The input variables are normalized so as to lie in the same range group of 0-1. To train the neural network used for this work, about 45 data sets on selected substrates are taken. It is ensured that these extensive data sets represent all possible input variations within the experimental domain. So a network that is trained with this data is expected to be capable of simulating the plasma spray process. Different ANN structures (I-H-O) with varying number of neurons in the hidden layer are tested at constant cycles, learning rate, error tolerance, momentum parameter and noise factor and slope parameter. Based on least error criterion, one structure, shown in table 2, is selected for training of the input-output data. The network optimization process (training and testing) is conducted for 2000,000 cycles for which stabilization of the error is obtained. Neuron numbers in the hidden layer is varied and in the optimized structure of the network, this number is 6. The number of cycles selected during training is high enough so that the ANN models could be rigorously trained. Fig.1 presents the optimized three layer network.

Fig 1. The three layer neural network

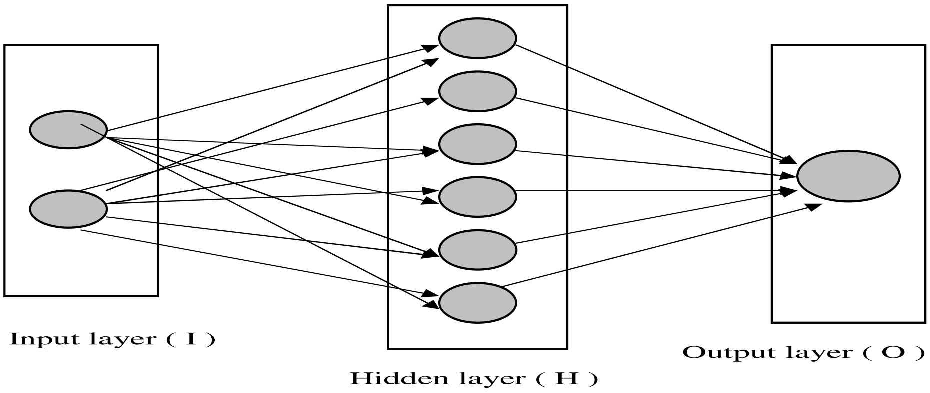
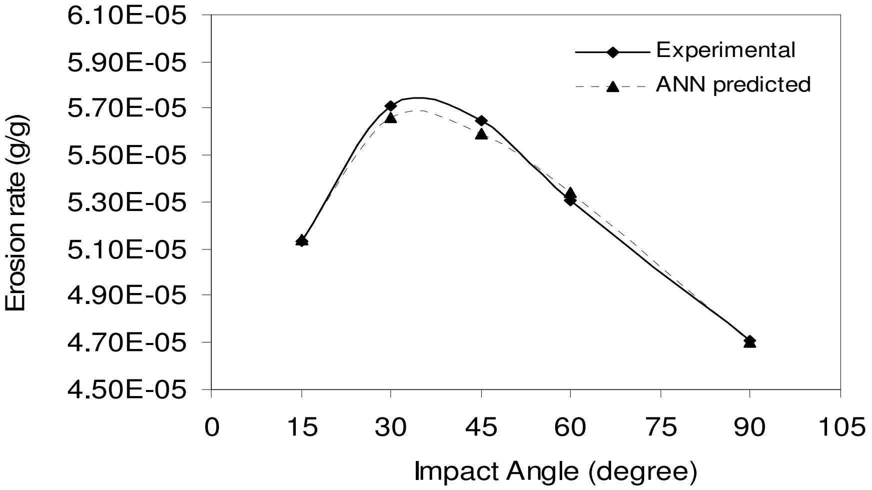


Fig.2 Comparison plot for predicted and experimental values of Erosion rate [Impact velocity =31.2m/s]



ANN PREDICTION OF EROSION WEAR RATE

The prediction neural network was tested with nine data sets from the original process data. Each data set contained inputs such as impact velocity, impact angle and an output value i.e. erosion wear rate was returned by the network. As further evidence of the effectiveness of the model, an arbitrary set of inputs is used in the prediction network. Results were compared to experimental sets that may or may not be considered in the training or in the test procedures. Fig. 2 presents the comparison of predicted output values for erosion wear rate with those obtained experimentally at three different impact velocities 31.2m/s, 44.2m/s and 58.5m/s.

Fig.3 Comparison plot for predicted and experimental values of Erosion rate
[Impact velocity =44.2m/s]

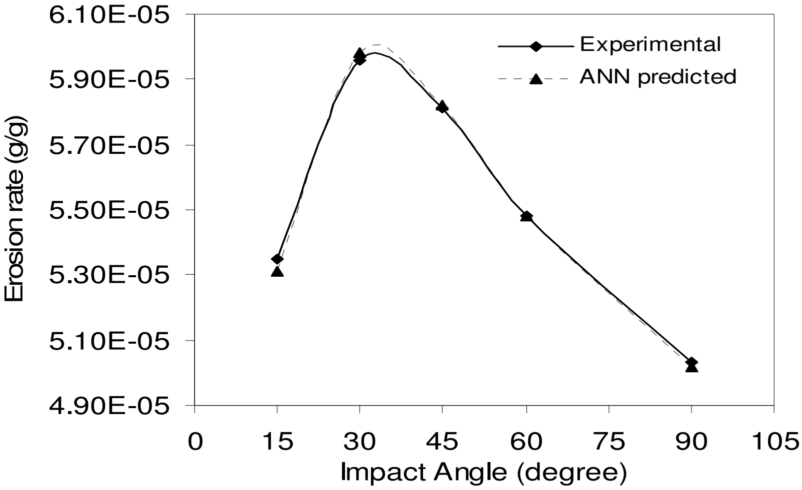


Fig.4 Comparison plot for predicted and experimental values of Erosion rate
[Impact velocity =58.5m/s]

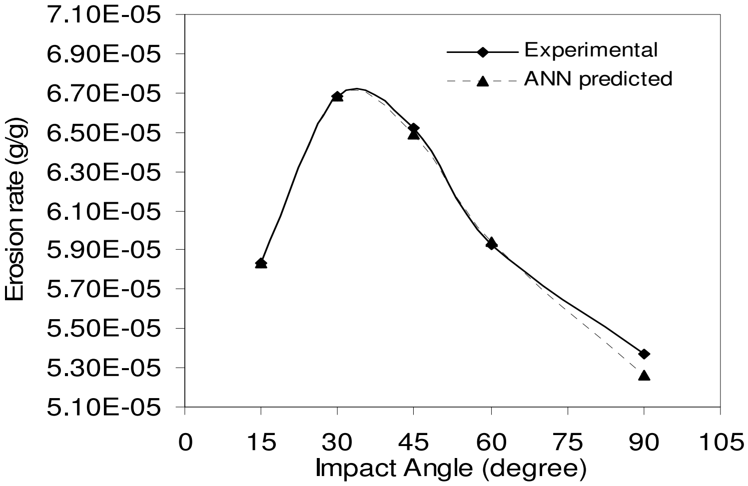


Fig.5 Predicted Erosion rate for different impact velocities with impact angle

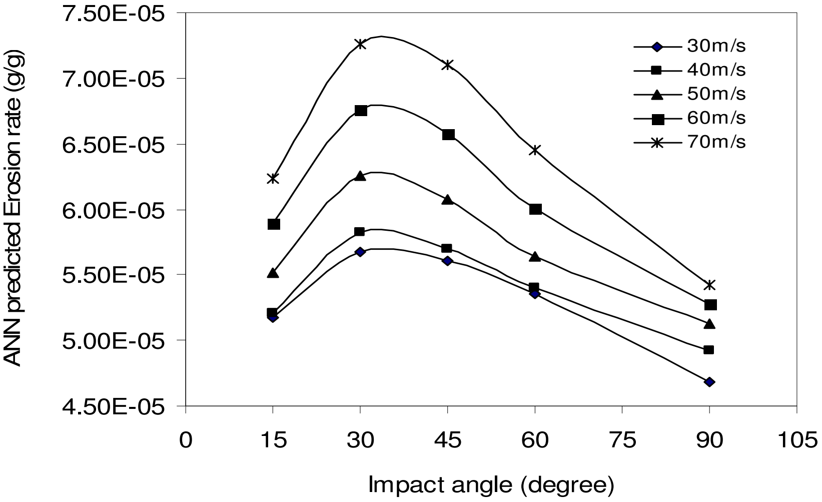
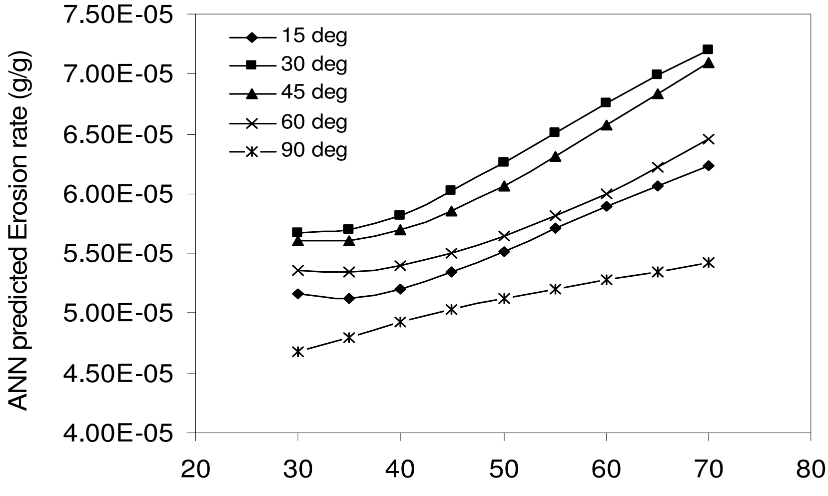


Fig.6 Predicted Erosion rate for different impact angles with impact velocity



It is interesting to note that the predictive results show good agreement with experimental sets realized after having generalizing the ANN structures. The optimized ANN structure further permits to study quantitatively the effect of the considered input impact angle and velocity. The range of the chosen parameter can be larger than the actual experimental limits, thus offering the possibility to use the generalization property of ANN in a large parameter space. In the present investigation, this possibility was explored by selecting the impact velocity in a range from 30 m/s to 70m/s, and a set of prediction for erosion wear rate is evolved. Fig.5 illustrates the predicted evolution of erosion wear rate of nickel aluminide coatings on mild steel substrate with impact angle at different velocities and fig.6 illustrates the predicted evolution of erosion wear rate with impact velocity at different impact angles.

As seen in fig. 5, the erosion wear rate for the different impact velocities shows a similar effect like first it is increases linearly from 15^o to 30^o, again it decreases. For the nickel-aluminide coating, the erosion wear rate at a 30^o impact angle was higher than at a 90^o impact angle. And in fig.6, the erosion rate presents a sigmoid-type evolution with the impact velocity. As the impact velocity increases, a remarkable increase of the erosion rate, the maximum mass loss moves at 30^o impact angle with the increase of the impact speed. Erosion rate is increasing linearly from 15^o to 30^o and it decreases linearly to 90^o with the increase of the impact speed. There fore the coating basically displays its erosion behavior as a ductile material.

CONCLUSIONS

For nickel-aluminide coatings, the erosion rate at 30^o impact angle was higher than at 90^o impact angle, thus suggesting the ductile behavior of the coating. In order to achieve certain values of erosion wear rate accurately and repeatedly, the influence parameters of the process have to be controlled accordingly. Neural computation can be gainfully employed as a tool for this purpose. The simulation can be extended to a parameter space larger than the domain of experimentation.

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