

Research Article

Numerical Simulation of Wear Resistance of Ni-SiC Composite Coatings Deposited by Electrodeposition

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Abstract: In order to research effect of plating parameters on wear resistance of Ni-SiC composite coatings, Ni coatings and Ni-SiC composite coatings were synthesized on steel substrates by electrodeposition method. The results indicate that the contents of SiC particles increase with density of pulse current and on-duty ratio of pulse current increasing. The wear resistance of Ni-SiC composite coatings predicted using ANN model has the similar shapes with the measured curve and the maximum error is about 9.6%. The wear losses decrease when current density increases from 30 to 50 A/dm². SiC particles in Ni-SiC composite coating are much greater in number and are dispersed homogeneously in the deposit and the coating exhibited a dense structure.

Keywords: Electrodeposition, Ni-SiC, numerical simulation

INTRODUCTION

A advantage of electrodeposition is its ability to coat interior surface of pipes, valves, agricultural machineries and others parts, along with applicability on variety of metal materials, such as bearings, gears, plowshares and colters (Xia *et al.*, 2012; Zhou *et al.*, 2004; Baumann *et al.*, 2011; Jitputti *et al.*, 1995). A characteristic feature of this process is that colloidal particles suspended in a liquid medium migrate under the influence of an electric field (electrophoresis) and are deposited onto an electrode. All colloidal particles that can be used to form stable suspensions and that can carry a charge can be used in electrodeposition. This includes materials such as polymers, pigments, dyes, ceramics and metals (Feng *et al.*, 2005; Sen *et al.*, 2010; Heidari *et al.*, 2010; Aruna *et al.*, 2007; Low *et al.*, 2006).

This process is industrially used for applying coatings to metal fabricated products. It has been widely used to coat automobile bodies and parts, tractors and heavy equipment, electrical switch gear, appliances, metal furniture, beverage containers, fasteners and many other industrial products.

Electrodeposition processes are often applied for the fabrication of supported titanium dioxide (TiO₂) photocatalysts for water purification applications, using precursor powders which can be immobilized using electrodeposition methods onto various support materials. Thick films produced this way allow cheaper and more rapid synthesis relative to sol-gel thin-films, along with higher levels of photo-catalyst surface area.

Electrodeposition processes have a number of advantages which have made such methods widely used. And the advantages of electrodeposition processes are listed as follows:

- Complex fabricated objects can easily be coated, both inside cavities as well as on the outside surfaces
- The process applies coatings which generally have a very uniform coating thickness without porosity
- Relatively high purity
- Relatively high speed of coating
- Applicability to wide range of materials (metals, ceramics, polymers, etc.)
- Easy control of the coating composition
- The process is normally automated and requires less human labor than other coating processes
- Highly efficient utilization of the coating materials result in lower costs relative to other processes
- Modern electrodeposition products are significantly more environmentally friendly than many other painting technologies
- The aqueous process which is commonly used has less risk of fire relative to the solvent-borne coatings that they have replaced

Recent literatures on electrodeposition of metallic composite coatings containing nano-sized particles were investigated (Fustes *et al.*, 2008; Bund and Thiemig, 2007; Slimen *et al.*, 2011). C.R. Carpenter demonstrated that electrodeposits featuring codeposited CNTs exhibit

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finer mean matrix grain size, with the grain refinement increasing with increasing volume fraction of CNTs in the electrodeposition. Qiu amply reported that the hydroxyapatite/titania composite coating on NiTi was directly prepared by electrodeposition at low temperature. It found that addition of TiO_2 to the electrolyte changed the morphology of hydroxyapatite from thin flake-flower-like crystals to needle-flower-like crystals and the coating was much denser. K.H. Hou obtained the electroplating parameters for preparation of Ni-W/ Al_2O_3 composite coating with high tungsten content, high micro-hardness and excellent wear resistance by pulse plating procedure. It showed that the choice of electrodeposition parameters was very important in a pulse electrodeposition process since the physical, chemical and mechanical properties are changed accordingly. It is believed that the introducing superfine particles, such as SiC, CNTs, Al_2O_3 , TiO_2 and WC, into the coatings often resulting in grain refinement or in change in microstructure of the matrix.

SiC particles have a high hardness, high elastic modulus and better wear and corrosion resistance. Besides, the chemical stability of SiC particles is very excellent. Owing to the superiority of SiC particles, electrodeposit Ni-SiC composite coatings are becoming the focus of widespread research.

Artificial neural network: The original appearance for the Artificial Neural Network came from examination of central nervous systems and their neurons, dendrites, axons and synapses, which constitute the processing elements of biological neural networks investigated by neuroscience. Artificial Neural Network (ANN) is the simple artificial nodes which connected together to form a network of nodes mimicking the biological neural networks. Currently, the ANN tends to refer mostly to neural network models employed in statistics, cognitive psychology and artificial intelligence. Figure 1 shows the framework of artificial neural network model and it is made up of input layer, hidden layer and output layer.

In modern software implementations of artificial neural networks, the approach inspired by biology has been largely abandoned for a more practical approach based on statistics and signal processing. In some of these systems, neural networks or parts of neural networks (such as artificial neurons) are used as components in larger systems that combine both adaptive and non-adaptive elements. While the more general approach of such adaptive systems is more suitable for real-world problem solving, it has far less to do with the traditional artificial intelligence connectionist models. What they do have in common, however, is the principle of non-linear, distributed, parallel and local processing and adaptation. Historically, the use of neural networks models marked a paradigm shift in the late eighties from high-level (symbolic) artificial intelligence, characterized by expert systems with knowledge embodied in if-then rules, to

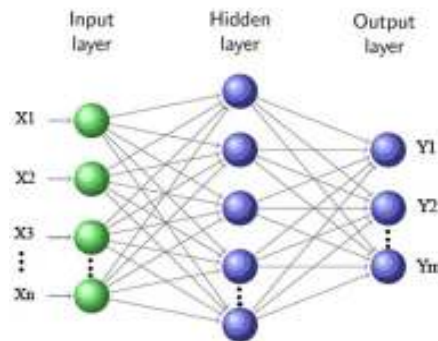


Fig. 1: Framework of artificial neural network model

low-level (sub-symbolic) machine learning, characterized by knowledge embodied in the parameters of a dynamical system.

An ANN is typically defined by three types of parameters:

- The interconnection pattern between different layers of neurons
- The learning process for updating the weights of the interconnections
- The activation function that converts a neuron's weighted input to its output activation

Mathematically, a neuron's network function is defined as a composition of other functions, which can further be defined as a composition of other functions. This can be conveniently represented as a network structure, with arrows depicting the dependencies between variables. A widely used type of composition is the nonlinear weighted sum, where, where (commonly referred to as the activation function) is some predefined function, such as the hyperbolic tangent. It will be convenient for the following to refer to a collection of functions as simply a vector.

The first view is the functional view: the input is transformed into a 3-dimensional vector, which is then transformed into a 2-dimensional vector, which is finally transformed into. This view is most commonly encountered in the context of optimization. The second view is the probabilistic view: the random variable depends upon the random variable, which depends upon, which depends upon the random variable. This view is most commonly encountered in the context of graphical models. The two views are largely equivalent. In either case, for this particular network architecture, the components of individual layers are independent of each other (e.g., the components of are independent of each other given their input). This naturally enables a degree of parallelism in the implementation.

The aim of this study is to obtain Ni-SiC composite coatings on steel substrates by electrodeposition process and to investigate and predict effects of preparation parameters on wear mass loss of Ni-SiC composite coatings.

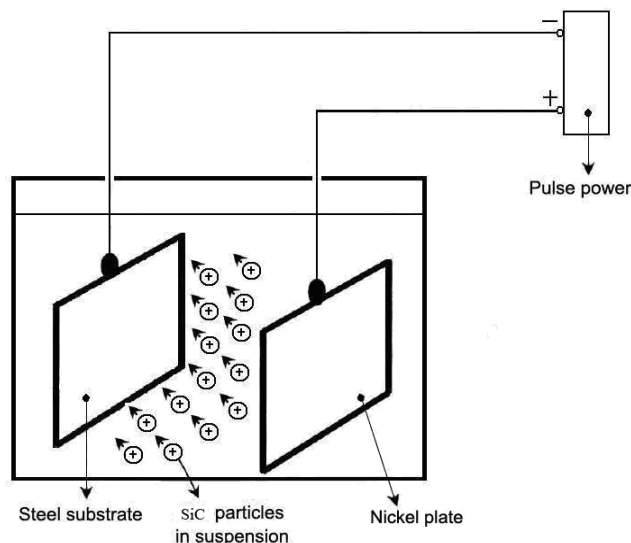


Fig. 2: Schematic diagram of the electrodeposition cell

EXPERIMENTAL METHODS

Nickel coatings and Ni-SiC composite coatings were fabricated by using electrodeposition process in this study. The schematic diagram of the basic electrodeposition cell is displayed in Fig. 2. The precursors used were SiC sols with purity above 99.99%. The SiC particles had an average primary particle size of ~40 nm. The SiC particle suspensions were prepared by ultrasonically mixing a given amount of particles (SiC particles: 4-10 g/L). The ultrasonic power was 150 and 200 W, respectively. After 10 min of ultrasonic mixing, the suspensions became clear and stable and therefore, suitable for the electrodeposition experiments.

Nickel plate with dimension of 30×20×2 mm was used as anode and steel substrates with dimension of 30×20×5 mm were used as cathode. The anode and cathode were separated at a distance of 40 mm. The electrodes were then placed in the colloidal suspension. The steel plates were polished with emery paper, chemically cleaned and etched and electroplated by electrodeposition. After plating, they were rinsed with distilled water and dried with ethyl alcohol prior to characterization. The frequency of the rectangular pulse electricity was 800 Hz, the occupational proportion was 20 to 80% and the amplitude of the current density was 30 to 60 A/dm².

During the electrodeposition experiments, the SiC particles in the sol were positively charged. Accordingly, the steel substrate to be coated was used as cathode and a nickel plate was used as anode. The deposition time was varied between 5 and 50 min to determine the optimum time for obtaining the desired coating thickness. The chemical composition of the electrolyte and the plating process parameters are listed in Table 1. After the electrodeposition coating process,

Table 1: The electrolyte composition and plating condition for preparation of pure Ni and Ni-SiC coatings

Chemicals	Content
NiSO ₄	200 g/L
NiCl ₂	50 g/L
H ₃ BO ₃	40 g/L
Octyl phenol	1 mg/L
CTAB	1 mg/L
SiC particles	4~10 g/L
Temperature	25~30°C
pH	4
Current density	30~60 A/dm ²
On-duty ratio	20~80%

the test samples were slowly dried in a humid atmosphere (~60% humidity). Scanning Electron Microscopy (SEM) (JSM-6460LV) and friction wear testing Machine (MRH-3) were used to examine the quality and morphology of the Ni-SiC composite coatings. The conditions for wear resistance of Ni-SiC are listed as follows: Load 10N, Friction pair 40Cr, Friction velocity 100 rpm and Time 10 min.

RESULTS AND ANALYSIS

Effect of SiC content on wear change: The metal nickel ions and SiC particles were directionally deposited on the surface of the cathode using a single-directional pulse current. Effect of SiC content on wear change of Ni-SiC composite coatings and predictive wear values predicted by artificial neural network are shown in Fig. 3.

It was seen from Fig. 3 that the contents of SiC particles increased with density of pulse current and on-duty ratio of pulse current increasing. It is because of that the cathode over-potential increases and the electric field intensifies with increasing average current density. Thus, the electrostatic gravitation between the cathode and Ni²⁺ ions becomes stronger and the deposition velocity of Ni²⁺ ions get faster, which enhances the

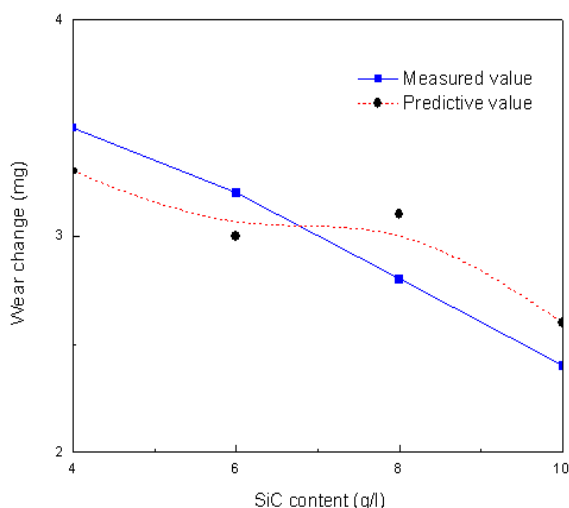


Fig. 3: Effect of SiC content on wear loss of coatings

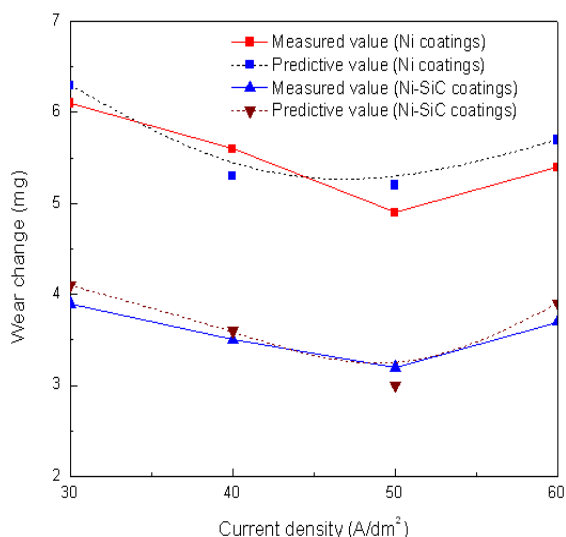


Fig. 4: Effect of current density on wear loss of coatings

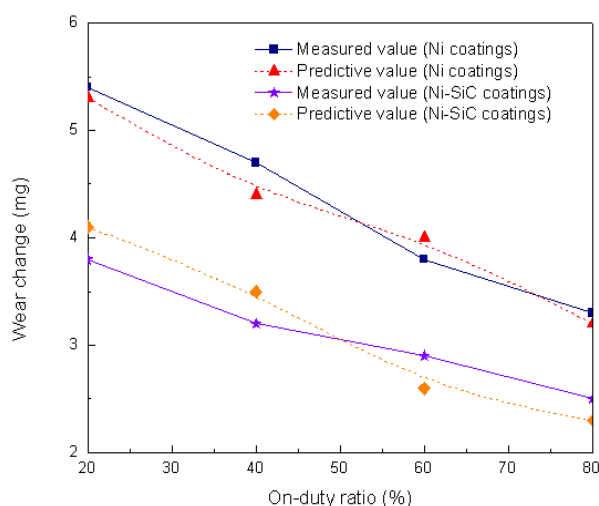


Fig. 5: Effect of on-duty ratio on wear loss of coatings

capability of Ni^{2+} to coat the SiC particles and increase the content of SiC particles in the plated coating. While SiC particles can enhance the wear resistance of Ni-SiC composite coating and then the wear losses of Ni-SiC coatings decrease with SiC particles content increasing. In addition, the predictive curves of wear losses predicted by ANN had the similar shapes with the measured curve and the maximum error was about 9.6%.

Effect of current density on wear change: Figure 4 indicated effect of current density on wear loss of Ni-SiC composite coatings. The solid lines showed wear loss of Ni coatings and Ni-SiC coatings and the dotted lines presented predictive loss of Ni coatings and Ni-SiC coatings forecasted by ANN.

It was seen from Fig. 4 that when the current density was between 30 and 50 A/dm^2 , the wear losses of Ni coatings and Ni-SiC coatings decreased with the increase of current density. While if the current density was above 50 A/dm^2 , the wear loss of coatings would increase. The reason is that when the current density increases, Ni^{2+} ions becomes stronger and the deposition velocity of Ni^{2+} ions get faster. However, there are lots of H_2 will occur in the surface of cathode, alerting oriented deposition of the SiC particles and thus decreasing the SiC particle content in coatings, then the wear loss increases.

It also presented that Ni-SiC coatings were better than the Ni coatings from the curve of the loss weight for abrasion. In the same plating conditions, the wear loss of Ni-SiC coating was only about 3/5 than that of Ni coating. The change rule of predictive mass losses was coordinated with that of measured values using ANN model and the maximum error for Ni coating and Ni-SiC coating was 6.1 and 7.8%, respectively.

Effect of on-duty ratio on wear change: Figure 5 presented effect of on-duty ratio on wear mass loss of Ni-SiC composite coatings. The solid lines showed wear mass loss of Ni coatings and Ni-SiC coatings and the dotted lines presented predictive mass losses of Ni coatings and Ni-SiC coatings forecasted by ANN.

It indicated from Fig. 5 that the wear mass losses of Ni coatings and Ni-SiC coatings decreased with the increase of on-duty ratio of pulse current. When the on-duty ratio was 20%, the wear losses of Ni coating and Ni-SiC coating was 5.5 and 3.7 mg, respectively. While the on-duty ratio was 80%, the wear losses of Ni coating and Ni-SiC coating was 3.4 and 2.5 mg, respectively. The reason is that when the on-duty ratio increases, Ni^{2+} ions and SiC particles become stronger and the deposition velocity of Ni^{2+} ions and SiC particles get faster and then the SiC content in Ni-SiC coatings increased. Owing to the high hardness of SiC particles, the properties of Ni-SiC composite coatings were enhanced.

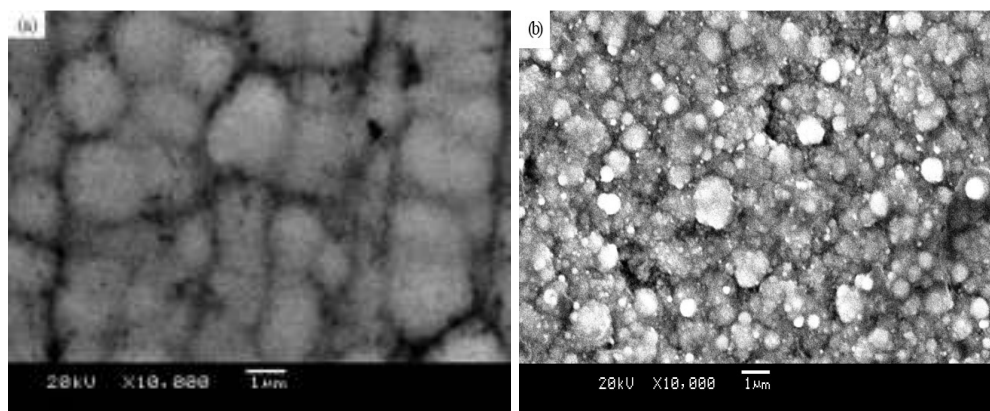


Fig. 6: Surface morphologies of coatings

It also illustrated that Ni-SiC coatings were better than the Ni coatings from the curve of the loss weight for abrasion. In the same plating conditions, the wear loss of Ni-SiC coating was only about 1/2 than that of Ni coating. The change rule of predictive mass losses was coordinated with that of measured values using ANN model and the maximum error for Ni coating and Ni-SiC coating was 6.3 and 8.7%, respectively.

Surface morphology analysis: The effects of plating parameters on the surface morphology of Ni coating and Ni-SiC composite coating were depicted in Fig. 6. Figure 6a and b show the SEM morphologies of Ni coating and Ni-SiC composite coating produced for current density of 50 A/dm², on-duty ratio of 60% and SiC content of 8 g/L at pH 5, respectively. It can be presented from Fig. 6a that Ni grains in Ni coating are much greater in number. However, the Ni-SiC composite coating exhibits a dense structure. Ni grains in the composite coating are small in number and SiC particles in coating exhibit slight aggregation.

CONCLUSION

Ni coatings and Ni-SiC composite coatings were prepared on steel substrates by electrodeposition process and numerical simulation for wear mass losses of coatings were forecasted using ANN model:

- The contents of SiC particles increased with density of pulse current and on-duty ratio of pulse current increasing. The predictive curves of wear losses predicted by ANN had the similar shapes with the measured curve and the maximum error was 9.6%.
- When the current density was between 30 and 50 A/dm², the wear losses of Ni coatings and Ni-SiC coatings decreased with the increase of current density. The change rule of predictive wear losses was coordinated with that of measured values using ANN model and the maximum error for Ni coating and Ni-SiC coating was 6.1 and 7.8%, respectively.

- When the on-duty ratio was 20%, the wear losses of Ni coating and Ni-SiC coating was 5.5 and 3.7 mg, respectively. While the on-duty ratio was 80%, the wear losses of Ni coating and Ni-SiC coating was 3.4 and 2.5 mg, respectively. The change rule of predictive mass losses was coordinated with that of measured values using ANN model and the maximum error for Ni coating and Ni-SiC coating was 6.3 and 8.7%, respectively.
- Ni-SiC composite coating exhibits a dense structure. Ni grains in the composite coating are small in number and SiC particles in coating exhibit slight aggregation.

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