



Wear performance of co-electrodeposited cermet coatings

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ABSTRACT

In this paper, the wear behaviour of nanostructured cermet coatings composed of two types of dispersed nanosized ceramic particles (Al_2O_3 and TiO_2) in nickel matrix produced by co-electrodeposition is investigated. The effects of particle concentration in electrolyte solutions and current density on wear performance of coatings were studied using sliding wear tests. The increases in the wear depth versus sliding distance as a function of loads were recorded and wear track were investigated using SEM and microhardness. The analysis of element maps showed that the volume fraction of each type of dispersed particle in the nickel matrix corresponded to the concentration of that particle in the electrolyte solutions. The increase in hardness of cermet coatings compared to pure form of nickel was explained by the “rule of mixture” and was correlated to grain refining and dispersion strengthening mechanisms which can take place during electrodeposition. The results showed that the coatings with higher Al_2O_3 in the matrix provide greater hardness and as a result, an improved wear performance against sliding wear can be expected. In addition, changes in wear rate and wear mechanisms during the course of sliding were observed and correlated to the effects of surface strain hardening and fatigue wear under different applied loads.

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1. Introduction

Ceramic-metallic (cermet) composite materials are composed of a hard phase, such as metal carbides (WC, TiC) or metal oxides (Al_2O_3 , TiO_2 , Y_2O_3), and a binder phase, such as metals (Ni, Co, Cr) or alloys (NiCr, CoCr). These materials exhibit enhanced hardness and therefore better wear resistance as compared to uncoated steel or alloy substrates. The available industrial and scientific literature suggests that the degradation of surfaces through the processes of erosion, corrosion and abrasive wear cost industry considerable money in the replacement of parts and associated plant downtime [1]. The need for prevention of wear and degradation of components and parts in oil sands and wider petrochemical industries is paramount. The current solutions are overwhelmingly based on traditional surface heat treatment techniques using various alloyed steels to induce hard phase structures and thereby enhancing the wear properties of the base materials. Hard overlay coatings (such as plasma transferred arc welding technique or PTAW) are in use where components are subjected to severe wear by abrasive and erosive conditions and these are primarily based on WC–Ni cermet composites. The process follows fusion welding technique which requires complete melting of feedstock with the surface being coated. This not only significantly changes the surface of the steel being treated, but also causes complete dissolution of the hard WC reinforcement placed into the coating. Other methods for treating components do exist and the use of electrolytic chromium to treat rotors and stators

in a variety of pumps has been successful. However, the environmental concerns over both hexavalent and trivalent chromium have encouraged industries to switch to the use of alternative solutions. The use of plasma coatings and high velocity oxy-fuel (HVOF) coatings to protect hot sections of turbine engines is well known. The most common applications of commercially available HVOF coatings are for thermal barrier protection. Recent work has shown that microstructured WC–Co system provides one of the most wear resistant coatings when used at low temperatures and in erosive/abrasive environments [2]. HVOF thermal sprayed based WC- or WC–Co coatings have seen their use to replace hard chrome plating on aircraft landing gear in a landmark project executed through the cooperation among the US Department of Defence, the Canadian Department of National Defence, and Industry Canada [3]. A distinct limitation of HVOF is however its high flame temperature (usually above 2500 °C) which can easily melt the refractory powders such as WC and other ceramics. A hybrid cooling system is used to suppress it and maintain an under-cooling temperature during the spray of superfine powders; nevertheless, high thermal and residual stresses cannot be avoided. Secondly, HVOF is a ‘line-of-sight’ process, meaning its inability to coat highly irregular shapes and geometries, small inner surfaces, corners, elbows etc.

Electrodeposition process, which produces atomic bonding between the coating layer and the substrate, is widely used in industry because of its easiness of use and competency for coating components of any geometrical feasibility. However, the coatings produced by this method do not produce any better hardness and abrasive wear resistance than conventional microstructured thermal-sprayed WC-based coatings. Theoretical analysis and some experimental work published in the scientific

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literature have shown that as the grain size of a material is reduced from micron to the nanometer scale the size of the inherent defects is also reduced [4–6]. The micro-mechanisms of plastic deformation change and the presence of grain boundaries and triple junctions become very large compared to conventional microcrystalline materials. This has the effect of changing the mechanical properties of nanostructured materials by increasing the fracture toughness and strength of materials. Even though some remarkable progresses have been recorded the full potential of these materials is being challenged by fundamental questions such as: (a) nanostructure formation in the context of processing conditions and size distribution of start-up nanoparticles in the coatings, (b) interactions between substrate and nanoparticles and within nanoparticles, and (c) the relationship between the nanostructure and the mechanical properties of the coatings.

In this study, a modified co-electrodeposition method is used to develop nanostructured dual-oxide-ceramic dispersed metallic matrix coatings made from the dispersion of combined Al_2O_3 and TiO_2 nanosized particles in Ni matrix using electrolytic solutions. In General, nickel has a reliable corrosion resistance against many acidic or alkaline media found in heavy oil extraction process. When nickel is combined with hard dispersed nanosized metal oxide particles such as Al_2O_3 (2000–2600 HV) and TiO_2 (880–1121 HV), the produced composite shows higher hardness and improved wear resistance as compared to the pure or alloyed form of nickel [7–10]. The developed co-electrodeposition technique has distinct advantages over other deposition techniques: the robustness in coat-ability in parts/geometries, near room-temperature coat deposition, use of low energy and low investment in equipment and materials. In particular, the process is focused on developing cermet coatings by optimizing the co-electrodeposition process parameters such as applied current density and particle concentration in the electrolytic solutions that can ultimately contribute to the enhancement and controlling of the mechanical properties.

The dispersion content of particles in the metal matrix can be affected by several parameters: most notably, the composition of electrolyte, type and amount of nanosized particles in the electrolyte, and applied current density [11–14]. To the best of authors' knowledge, no studies have been conducted on the mechanical performance of nano-scale double-oxide ceramic dispersed cermet coatings developed by co-electrodeposition method. This research compares the Vickers microhardness and wear properties of the coatings composed of two types of nano-sized ceramic particles (Al_2O_3 and TiO_2) dispersed in a nickel matrix as variations of electrolytic composition and applied current density.

The main aim for this study is to understand how changes in electrodeposition parameters, such as types and concentrations of ceramic particles in the electrolyte solutions and applied current density can influence the wear mechanisms and consequently performance of the coatings subjected to applied loads. Another aim of this research is to provide an insight into wear mechanisms that can take place on the surface of coatings subjected to abrasive wear conditions under a range of loads and correlate the formation and transition of these wear mechanisms to mechanical, compositional and micro-structural changes caused by alternations in electrodeposition parameters during the production of cermet coatings.

2. Experimental procedure

2.1. Materials

This study used two types of nano-sized powders alumina ($\alpha\text{-Al}_2\text{O}_3$) and titania (TiO_2) purchased from M K Impex Corp. Ltd. The purity for TiO_2 was 98% (with traces of Al: 20 ppm, Ca: 75 ppm, Mg: 65 ppm, Nb: 119 ppm, S: 165 ppm and Si: 102 ppm). The purity for $\alpha\text{-Al}_2\text{O}_3$ was 99.95% (with traces of Na: 300 ppm, Si: 3.5 ppm, Ca: 1.6 ppm, Fe: 0.2 ppm, and Co: 0.8 ppm). The average grain size was 20 nm for Al_2O_3 and 50 nm for TiO_2 . The anode was made of a high purity nickel bar (99.9%). The substrate material was made from hot-rolled AISI-1018

carbon steel bars and specimens for co-electrodeposition were cut in a rectangular shape (length: 20 mm, width: 12.7 mm and thickness: 6.5 mm) using a saw band. The mill scale was removed by mechanical cleaning and the surface was prepared to a 600 grit finish. The surfaces were then cleaned in alkaline solutions (E-Kleen 102-E™ and E-Kleen 129-L™) and finally an acidic solution (acid pickling with 31% HCl) was used to remove any remaining grease or contaminates.

2.2. Co-electrodeposition

The standard formula for Watt's bath solutions were used as the electrolyte solution and the concentrations of metal-oxide powders in the electrolyte were obtained from previous research [15–17]. The pH of the electrolyte solutions was monitored and measured to be 4.0 to 4.2 and the temperature was kept between 50 to 55 °C. For naming convention, the co-electrodeposited coatings were divided into two groups; A1 and B1. The A1 group coatings were made in electrolyte solutions containing 0.5 M of ceramic particles with an equal ratio of both components, 0.25 M of Al_2O_3 (25.5 g/L) and 0.25 M of TiO_2 (20.0 g/L). The B1 group was also made in electrolyte solutions containing 0.5 M of ceramic particles but with a ratio of 0.375 M for Al_2O_3 (38.25 g/L) and 0.125 M (10.0 g/L) for TiO_2 . The chemicals used for electrolyte bath solutions are given in Table 1. The electrolytes containing the nanosized particles in the solution were agitated for 4 h prior to the electrodeposition process using magnetic stirring. The stirring velocity was between 300 and 320 rpm. A similar stirring velocity was also maintained during the electrodeposition.

The coatings were produced using DC co-electrodeposition method. The applied current densities used were 1, 2 and 3 A/dm². In order to maintain a constant thickness (40 μm) for coatings produced under different electrochemical parameters (electrolyte compositions and applied current densities), the electrodeposition time was set for 30, 60 and 90 min (for applied current densities of 3, 2 and 1 A/dm² respectively) following Faraday's Law. Scanning Electron Microscope (JOEL JXA-8200) was used to measure the average electroplated thickness. The produced average thickness for the micro-hardness and wear tests was set to be 40 ± 5 μm.

2.3. Vickers microhardness

Prior to microhardness tests, the surfaces of all specimens were prepared by using standard metallurgical surface preparation techniques with a final polish using 0.25 μm diamond paste. The micro-hardness tests were conducted on the cross-sections of the coating using a Leitz Miniload-2 micro-hardness Vickers indenter equipped with a diamond pyramid indenter operating under 25 g load. The test procedure follows ASTM E384-10 which requires a minimum of 10 indentations per coating. In this research for each specimen, twenty five indentations were made and an average hardness value was recorded using following equation:

$$Hv = 1854.4 \frac{P}{d^2} \quad (1)$$

Table 1
Chemical composition of electrolyte solutions.

Coating	Weight of suspended particles in the electrolyte solutions	Electrolyte composition
A1	Al_2O_3 : 25.5 g/L TiO_2 : 20.0 g/L	Nickel Sulphate Hexahydrate (1 M), Nickel Chloride Hexahydrate (0.2 M), and Boric acid (0.5 M) dissolved in distilled water
B1	Al_2O_3 : 38.25 g/L TiO_2 : 10.0 g/L	

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