



# Three-body wear performance of co-electrodeposited cermet coatings



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## ABSTRACT

In this paper, the three-body abrasive wear performance of co-electrodeposited nanostructured cermet coatings composed of two types of dispersed nanosized ceramic particles ( $\text{Al}_2\text{O}_3$  and  $\text{TiO}_2$ ) in nickel matrix is investigated using procedures and guidelines provided by ASTM G65-04 (Standard Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus). The main objective of this research was to evaluate three-body abrasive wear performance of co-electrodeposited cermet coatings that are designed to protect the surfaces of carbon steel pipes against moving sand grains in the transported bitumen production from some new unconventional oil production techniques such as steam assisted gravity drainage and also in-situ combustion. For this purpose, the effects of particle contents in the nickel matrix, applied current density and time of electrodeposition on the hardness and wear performance of coatings were studied. The microhardness values for coatings were measured using a microhardness Vickers tester equipped with a diamond pyramid indenter. For the three-body abrasive wear tests, the mass loss, surface roughness and depth profile of wear tracks were recorded and the surfaces of wear tracks were investigated using FE-SEM. The increase in microhardness of cermet coatings compared to the pure form of nickel was explained by the rule of mixture for composites and was correlated to grain refining and dispersion strengthening mechanisms which can take place during the co-electrodeposition of coatings. The results showed that the coatings with a greater quantity of  $\text{Al}_2\text{O}_3$  in the nickel matrix provide greater microhardness and therefore, an improved wear performance can be expected. Additionally, the wear surface analysis showed that rougher surfaces can be expected for coatings with lower microhardness compared to coatings with greater microhardness and this effect was explained using Archard's equation.

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## 1. Introduction

The main objective of this research is to produce wear resistance coatings that can be used to protect the surfaces of carbon steel pipes to be used in new unconventional oil production techniques (e.g. steam assisted gravity drainage and also in-situ combustion). Because of the presence of sand grains in the produced bitumen from these new techniques, the carbon steel pipes are subjected to wear and erosion by the movement of sand grains. Therefore, there is a need to produce low cost coatings which can withstand or reduce the wear on the surface of pipes used for oil production. Co-electrodeposition is one of the most common techniques for producing nanostructured cermet (ceramic–metallic) coatings. The nickel-based cermet coatings are widely used in the industry because of their superior mechanical and corrosion resistance properties as well as easiness of fabrication, lower production costs and competency for coating components of any geometrical feasibility [1]. However, the co-electrodeposited

cermet coatings do not have a better hardness or abrasive wear resistance compared to conventional microstructured thermal-sprayed coatings [2,3]. For measuring and comparing the wear performance of coatings produced in this research, ASTM G-65 standard for measuring abrasion performance of materials subjected to moving sand grains provides a practical approach and test method procedure which was used for evaluating wear performance of coatings.

The formation of cermet coatings consists of two separate electrochemical reactions that take place simultaneously on the surface of the cathode substrate during the co-electrodeposition process: (1) the electrocrystallization of nickel cations through the adsorption process from the electrolyte solution, and (2) electrophoresis of nanosized particles as a result of an excreted electric force from the electric field that exists between the cathode and the anode through the solution. Formation of cermet coatings has been extensively studied in the past through the work of Bockris et al. [4], Walsh et al. [5], and more recently the work of Thiemiig [6] and Stojak et al. [7].

Previously the two-body abrasive wear performance of these coatings was studied and it was found that wear mechanisms for these coatings are affected by the type of ceramic particles.

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For example, increasing the volume fraction of dispersed  $\text{Al}_2\text{O}_3$  particles in the nickel matrix improves the wear resistance of cermet coatings and this effect was correlated to greater hardness values of  $\text{Al}_2\text{O}_3$  (2000–2600 HV) compared to  $\text{TiO}_2$  (880–1121 HV). In addition, it was found that during the course sliding wear condition, changes in wear rate can happen and this effect was correlated to the changes in wear mechanism under different applied loads. The changes in wear mechanism were found to be correlated to the changes in the wear rate mechanism from abrasive to wear fatigue at lower loads and also to the effects of strain hardening under the heavier loads [8].

The improvement in hardness and wear performance of cermet coatings compared to pure or alloyed metallic coatings is believed to be affected by the hardness and volume fraction of deposited ceramic particles in the metallic matrix as well as the grain size of the metallic matrix. The increase in microhardness can be attributed to a combined effect of the dispersion strengthening (explained by the *Orowan* mechanism), and grain size refinement (explained by the *Hall–Petch* mechanism). Bund, Thieming and Sadighi et al. have shown that incorporation of nanosized ceramic particles at the deposition sites can affect the crystallization of the matrix by disturbing the normal growth of nickel crystals while forming new nucleation sites around the deposited particles [9–11]. In addition, Low et al. [12] have shown that the change in the crystalline growth of a metallic matrix increases the number of defects in the matrix crystal structure and therefore, it results in a greater microhardness for cermet coatings compared to pure metal coatings. Meanwhile, *Erb* has studied the changes in mechanical properties of nanocrystalline nickel and has shown that wear resistance and hardness for cermet materials can be significantly improved by grain refinement of the nickel matrix [13]. Although some of the above-mentioned recent progresses in understanding the formation and properties of cermet coatings have helped us to explore some of the potentials of cermet coatings for use in industrial applications, the full potential of these materials is still being challenged by fundamental concerns such as (a) nanostructure formation in the context of co-electrodeposition process, (b) frequency and size distribution of particles in the metallic matrix, (c) interactions between metallic matrix and nanoparticles, and (d) the relationship between the nanostructure of the coating and the mechanical properties of the coatings.

For this study, the direct-current (DC) co-electrodeposition method was used to develop a group of novel nanostructured cermet coatings made from the dispersion of combined  $\text{Al}_2\text{O}_3$  and  $\text{TiO}_2$  nanosized particles in a nickel matrix using *Watt's* electrolyte solutions. When nickel is combined with hard dispersed nanosized metal oxide particles such as  $\text{Al}_2\text{O}_3$  (2000–2600 HV) and  $\text{TiO}_2$  (880–1121 HV), the produced composite shows greater hardness and improved wear resistance as compared to the pure or alloyed form of nickel [14–17]. The developed co-electrodeposition technique has several advantages over other coating deposition techniques: the robustness in coat-ability in materials, near room-temperature processing, low energy input and low investment in equipment. In particular, co-electrodeposition provides flexibility to design and achieves desired mechanical properties for the coating by optimizing the co-electrodeposition process parameters such as applied current density and particles concentration in the electrolytic solutions that can ultimately contribute to the enhancement and controlling of mechanical properties for the coatings. The dispersion particle content in the matrix is a function of several parameters including the chemical composition of the electrolyte solution, type and volume fraction of nanosized particles in the electrolyte solution, and applied current density to the cathode [18–21]. To the best of this authors' knowledge, no studies have been conducted on the three-body wear performance

of co-electrodeposited cermet coatings composed of both  $\text{Al}_2\text{O}_3$  and  $\text{TiO}_2$  particles dispersed in a nickel matrix. A variety of test conditions exist to produce either two-body (grooving) or three-body (rolling) abrasive wear mechanisms. They can be mainly categorized as 'free ball' and 'fixed ball' mechanisms [22]. In the 'fixed ball' mechanics, which allows more accurate control of the normal load (to an accuracy of  $\pm 0.01$  N), the ball (or the wheel) is driven positively by a shaft and the specimen is loaded against the ball with the desired normal force by a lever arm arrangement.

In this study, the three-body abrasion resistance of coatings was evaluated using a rubber wheel abrasion test system corresponding to ASTM Standard G 65-04 (*a combination of procedures C and D*) [2,23]. The schematic diagram of the apparatus and details of test procedures are provided in ASTM Standard G 65-04. Pressure was applied against a rubber wheel by using static normal force of 45 N. The wheel revolution was 100 spins (providing a lineal abrasion sliding distance of 71.8 m). The abrasive sand for this test was rounded quartz particles with average size of 212–300  $\mu\text{m}$ , and the sand mass flow was 325 g/min. The wear performance was determined by the mass loss. Sand was continuously supplied between the sample and the rotating rubber lined wheel. No recycling of the abrasive took place and all tests were performed dry. The tests were performed for a set number of revolutions of the rubber wheel (depending on the abrasive media and load), with the coatings being weighed before and then after each set of revolutions. The tests were continued until the coating wore through to the substrate. The wear depth, roughness and surface profile for all coating materials were measured and compared. The worn coatings were examined by FE-SEM on the top surface and also on cross-sections through the middle of the wear scars along the direction of flow of the abrading medium.

## 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 ( $\text{TiO}_2$ ) purchased from M K Impex Corp. Ltd. The purity for  $\text{TiO}_2$  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 for  $\text{Al}_2\text{O}_3$  was 20 nm and for  $\text{TiO}_2$ , 50 nm. Originally the size distribution of as-received powders ( $\text{Al}_2\text{O}_3$  and  $\text{TiO}_2$ ) was investigated using TEM, and it was found that the as-received powders are composed of large clusters to a few microns when dissolved in solution used for TEM imaging purposes. To prevent agglomeration of powders in the electrolyte and to minimize the deposition of large powder clusters in the nickel matrix, 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 TEM imaging on the stirred solution and powder mixture showed that the large clusters of powders that were seen in unstirred solution were separated into much smaller clusters (to a few or less than 100 nm). The individual grains to a size of 20–50 nm were also found in the TEM images of stirred solutions. The anode was made of a high purity nickel bar (99.9%). The substrate material (cathode) was made from AISI-1018 carbon steel bars (hot-rolled) and specimens for co-electrodeposition were cut in a rectangular shape (length: 76.2 mm, width: 25.4 mm and thickness: 12.7 mm) using a saw

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