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Synthesis and properties of ceramic-based nanocomposite layer of aluminum carbide embedded with oriented carbon nanotubes

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Abstract

In the present work, carbon nanotubes (CNTs) were embedded in aluminum carbide coating in desired vertical/horizontal direction in order to fabricate a nanocomposite layer with unidirectional enhanced mechanical properties. A novel method based on monopolar pulsed plasma electrolysis under magnetic field was used for this purpose. Nanostructure of the obtained nanocomposite layer was examined with high precision figure analysis of SEM, AFM and TEM nanostructures. The mechanical and tribological properties of these coatings were investigated with respect to the direction of the embedded CNTs. The coefficient of friction was lowered from 0.2 to less than 0.1 in a pin-on-disc test against steel with dramatic affected coating wear rate by a decrease to near 400% with respect to raw substrate. The lower friction is attributed to more extensive creation of amorphous carbon on the counter surface and also in the coating wear track. As a conclusion, this method is appropriate for fabrication of hard coating on the surface of low-melting-point metals and light alloys.

Keywords: A. Films; B. Nanocomposites; C. Wear resistance; D. Carbides

1. Introduction

The composite plasma electrolysis (CPE) technique is a low-cost method suitable for fabrication of ceramic-based matrix composite coatings for such purposes as corrosion and abrasion resistance [1–4]. These coatings can contain hard particles such as WC, Al_2O_3 and ZrO_2 in a deposited matrix such as titania or titanium carbide. Recently, production of reinforcing hard powders with decreasing sizes has found industrial interest to fabricate new composites with better properties by applying of micro- and especially nanoparticles [5–7]. The term ‘‘size effect’’ for nanoparticles can describe the leading role of these nanocomposites [8]. Researchers have shown that nanocomposite coatings usually reveal enhanced mechanical, electrochemical and thermal properties as compared to pure ceramic coatings as well as microcomposite coatings [9]. The improvement of these characteristics depends mainly on the size, distribution and the amount of the embedded nanoparticles in the matrix [10–12].

One of these nanoparticles that has recently attracted the attention of many researchers for fabrication of nanocomposite coatings, is carbon nanotube (CNT). Carbon nanotubes have specific mechanical properties, which came from their unique structure (huge length to diameter ratio) [13–15]. They have recently been fabricated ceramic, metallic and polymeric based nanocomposite coatings. As these nanoparticles have different mechanical properties on their different orientations, some researchers have tried to fabricate nanocomposite coatings using oriented CNTs [16,17]. Also these materials have self-lubrication properties.

In the case of mechanical properties, however, the friction and wear resistance of nanocomposite coatings, modified by embedding some hard nanoparticles [18–20] but application of self-lubricant and oriented nanocomposite coatings can be of interest, especially for ceramic based nanocomposite coatings, which seems to have been studied less than other types of nanocomposite coatings. So in the present work, our main

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attempt was to fabricate of aluminum carbide matrix nanocomposite coatings containing carbon nanotubes (CNT) with an average diameter of 54 nm. The friction and wear performance of the fabricated coatings were analyzed in accordance to the direction of the embedded carbon nanotubes. Based on some empirical results and the mechanism of coating process, a model was developed for deposition of these kinds of coatings.

2. Experimental

Coin shaped (20 mm Ø × 2 mm) samples were machined from a 6082 aluminum alloy bar. The surfaces of samples were mechanically abraded by SiC paper (80 to 3000 #) and then polished on the surface of a soft cloth with the addition of appropriate abrasive solution. The preparation method and coating process are similar to our previous work [21]. In this study, multi-wall carbon nanotubes (MWCNTs) (received from Plasma Chem Company – Germany) were added to the electrolyte (10 g.l^{-1}). Figure 1 illustrates the SEM microstructure of the used CNTs. The average diameter of the CNTs was equal to 54 nm, which was calculated by the figure analysis of different SEM nanostructures and is not the reported data by its manufacturer. The electrolyte went under ultra sonic condition before usage for coating process. High magnetic fields were used in two modes for arranging the conductive nanoparticles in two directions with respect to the free surface of the substrate [16,22]. So, two kinds of nanocomposite layers were fabricated: Vertical oriented nanocomposite (VON) and horizontal oriented nanocomposite (HON). In order to measure the embedded CNTs in the nanocomposite layer, the weight of the used CNTs was measured before and after the coating process and ultra precision was applied for drying the electrolyte and collecting the nanoparticles. The coatings were characterized by scanning electro microscope (SEM, Philips XL-30), atomic force microscope (AFM, NanoScope II) and transmission electron microscope (TEM, CM-200 FEG Philips). Wear tests were done for the fabricated coatings according to the ASTM G-99 [23,24] pin-on-disc guidelines. WC-Co interfaces were used as pins and substrates were used as discs. Friction coefficient was monitored by this rig while mass loss data were measured by a Sartorius (CP324S) micro-balance. This micro-balance was also used for measuring the weight of the used CNTs before and after the coating process. The mechanical and tribological properties of these coatings were investigated with respect to the direction of the embedded nanoparticles. Some of the tests were done more than twice for ensuring the achieved data.

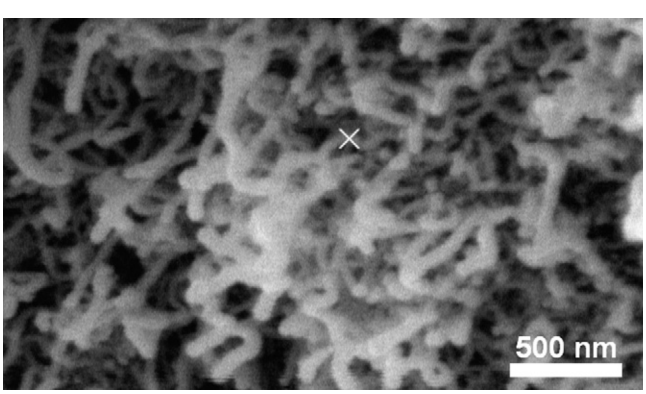

Figure 1. SEM microstructure of used CNT (average size 54 nm, indicated CNT has a diameter of 44 nm).

3. Results and discussion

3.1. Coating thickness, roughness and hardness

Figure 2 shows the variation of coating thickness with processing time for both of the fabricated nanocomposite layers. In plasma electrolytic saturation (PES) treatment, coating thickness will increase linearly with respect to the second root of the treatment time [25]. Though in some investigations, a linear increase has been reported for coating thickness, but it seems that in these papers long treatment times have not been studied [26]. Long coating times caused coating thickness to increase and hence the density of discharges became lower and lower. VON fabricated layers have lower deposition rate than HON layers.

Surface roughness of the coatings increased with the increase of treatment time (Figure 3). The roughness values of VON layers were higher than HON ones. This result was predictable due to the orientation of carbon nanotubes. Figure 4 shows the variations of surface microhardness for both VON and HON layers with respect to the processing time. VON layers showed a little higher surface hardness than HON layers; however, the error bars shown in Figure 4 interfere with each other. Increasing of coating time led to continuous increasing in the surface hardness, which is probably due to the fabrication of a thicker harder layer. As the hardness of substrate is very lower than that of the hard layer, it seems that thicker layers act as a support for performing microhardness test. Thinner coatings were cracked in the hardness tests because the relative soft substrate can not support the layer during the force loading in the hardness test [27–29]. As shown in Figure 4, the values of surface microhardness are approximately constant for the coatings thicker than 15 microns (4 h of coating process).

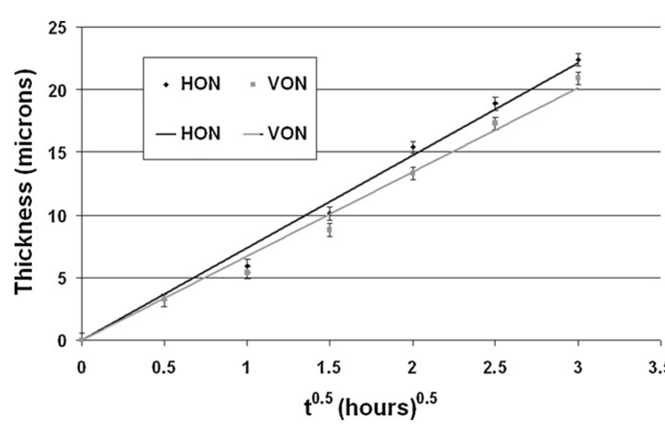

Figure 2. Variations of coating thickness with second root of processing time for both fabricated nanocomposite layers.