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Substrate effect on the mechanical and tribological properties of arc plasma physical vapour deposition coatings

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Abstract

The present study describes and compares the mechanical and tribological properties of CrN coatings deposited by PVD/CAPD (Cathodic Arc Plasma Deposition) on three different substrates: steel, aluminium alloy and reinforced aluminium alloy. The coating-substrate interfaces were analysed by scanning electron microscopy (SEM). The ultra-microindentation technique was applied to measure coating hardness. Experiments using a tribometer (pin on disc configuration) under lubricated conditions have been performed in order to evaluate the friction and wear properties of the different systems.

The measured coating hardness depends on the indentation depth reached in the ultra-microindentation tests. In this study the coating-substrate system has been characterized, analyzing the hardness variation from the coating to the substrate by different indentation depths, and modelling the experimental curve with a universally approved mathematical model. The CrN–steel system exhibits the best performance, in which the system hardness is close to the CrN coating hardness. The CrN–AMC system performs better than CrN–aluminium but worse than CrN–steel system.

Keywords: PVD coatings; Aluminium alloys; Hardness; Tribology

1. Introduction

Physically vapour deposited coatings are used in several industrial applications like metal cutting, deep drawing or plastic injection moulding. In plastics manufacturing processes the surfaces of machine parts and moulds may be exposed to hostile environments due to abrasive action of fibres at elevated temperatures combined with the chemical attack by corrosive agents. The transition metals nitrides, such as chromium nitride-based coatings, have demonstrated to be wear resistant and also resistant to chemically aggressive environments [1,2]. CrN coatings possess sufficient thermal stability, as well as superior wear and corrosion resistance to improve the injection mould surfaces [2,3].

On the other hand, it is proposed that the steel moulds and tools used in the production of plastic components could be replaced with lightweight aluminium alloys coated with wear resistant coatings. This combination of aluminium alloys with specially designed coatings will permit a reduction in injection moulding cycle time and an increase in the life of the tools, as a result of the improvement in the thermal conductivity (aluminium vs. steel) and wear resistance of the PVD coatings. The low density of the aluminium will lead to significant advantages in manufacturing, assembly and maintenance of the mould. Furthermore, the good thermal conductivity of the aluminium (four times better than steel) allows the mould to tolerate a rapid and uniform heat distribution and dissipation, providing a better control of the temperature, thereby improving the quality of the product and reducing the cycle times of injection. However, light metals in general exhibit very poor

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tribological properties resulting in a severe wear. To correct this disadvantage the implementation of wear resistance coatings deposited by PVD is proposed.

The mechanical and tribological performance of the PVD coatings are strongly influenced by the substrates on which they are deposited [4]. The objective of the proposed work is to demonstrate the feasibility of depositing PVD coatings on aluminium and reinforced aluminium substrates and determine influence of the substrate on the mechanical and tribological behaviour of the system (coating + substrate).

2. Experimental details

In those study CrN coatings were deposited on three different substrates: 40CrMnNiMo steel (AISI P20), Al-7022 aluminium alloy and Al-6061 aluminium alloy reinforced with 22 vol% of Al_2O_3 particles (average size of 13.6 μm). All samples were polished to a mirror finish prior to coating deposition. CrN coatings (2.5–3.0 μm thick) were deposited onto the substrates using the Cathodic Arc Plasma Deposition process (PVD/CAPD).

The coating microstructure was examined in cross-section using a JEOL JSM-5600 scanning electron microscope (SEM). Backscattered electron images were obtained, and EDS analysis was conducted. Samples for SEM observations of the coatings were sectioned and prepared by standard metallographic techniques.

The coating hardness was studied using an ultra-microhardness testing system, capable of measuring force and displacement continuously, using a Vickers diamond indentor. For every sample the dynamic hardness measurements were carried out with a maximum applied load between 5 mN and 1000 mN. Each average value was calculated from 15 different measurements, discarding the anomalous values as consequences of the coating defects.

Tribological evaluation of coated substrates was performed using a Pin on disc tribometer, according to ASTM wear testing standard (G-99). Friction and wear properties were evaluated by sliding a WC-6%Co 6 mm diameter ball against the coated substrates. All tests were carried out at the same linear speed (0.10 m/s) under lubricated (Repsol 15W40 oil) conditions with an applied load of 40 N. The tests were performed at room temperature. When testing was completed, the amount of material loss was evaluated by measuring the cross sectional area of the wear tracks using a rugosimeter–profilometer. The wear volume and specific wear rate were calculated according to the classic wear theory [5]. The friction coefficient (μ = friction force/applied load) was plotted as a function of the number of laps in the test. At least three different tests were conducted for each test condition and material.

3. Results and discussion

3.1. SEM characterisation

SEM images of polished cross-sections of the CrN coatings deposited by PVD/CAPD on 40CrMnNiMo steel and Al-7022 substrates are shown in Fig. 1a and b, respectively. In these images it can be observed that CrN coating is dense and homogeneous and appear to exhibit a good continuity and adherence on both substrates.

Fig. 2 shows a SEM image of the polished cross-section of the CrN coating deposited by PVD/CAPD on the aluminium reinforced material. The A6061/(Al_2O_3)p substrate presents a homogeneous distribution of the alumina particles embedded in the aluminium matrix. The figure shows the presence of some cracked alumina particles, presumably due to the residual stresses caused by the aluminium matrix plastic deformation during the extrusion process.

As seen in Fig. 3a coating detachment problems over the crashed alumina particles were observed. A possible cause of the coating separation from the reinforced aluminium substrate can be the presence of residual tensions in the coating-substrate interface. In the composite material differences between the matrix and alumina reinforcements could modify the growth kinetics of the coatings. In some samples, zones could be detected where the coating is removed from the substrate surface (see Fig. 3b). This fact could be related to the gas present in the internal porosity of aluminium reinforced material, which comes out when the coating had already deposited. This material was extruded by Duralcan (extrusion conditions: T_{ingot} = 450 °C, T_{mould} = 400 °C and speed = 1 mm/min) and presents an average volume percentage of porosity around a 0.5%.

3.2. Indentation tests

In this study the coating-substrate system has been characterized, analyzing the variation of the hardness from the coating to the substrate by different indentation depths, and modelling the experimental curve with a universally approved mathematical model. Recently, a number of attempts have been made to develop a sufficiently general analysis of coated system indentation, based on the concept of work-of-indentations. The fundamental result obtained from this approach was that the response can be predicted accurately by equations [6–9]:

$$H_{sys} = H_{sub} + \frac{H_{coat} - H_{sub}}{1 + k\beta^{x}} \quad (1)$$

where H_{sys} is the apparent system hardness, H_{coat} is the intrinsic coating hardness, H_{sub} is the substrate hardness, k and x are dimensionless material parameters