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A novel organoclay reinforced UHMWPE nanocomposite coating for tribological applications

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ABSTRACT

In the past few decades, there has been a growing demand for inert, wear-resistant, cost efficient, environmental friendly and low friction coatings. Polymer coatings are one of the best candidates to fulfill these demands due to their low density, anticorrosion properties, self-lubricity, low cost and ease of processing. However, some limiting factors such as low load bearing capacity restrict their applications. By keeping in view this limitation, polymer based nanocomposite coatings were developed in the present study by reinforcing ultra-high molecular polyethylene (UHMWPE) with different loadings of C15A nanoclay (0.5, 1.5 and 3 wt%) to improve the tribological performance of the polymer coating. A novel electrostatic powder spraying technique was used to deposit the coatings on an aluminum substrate. Tribological performance of pristine and C15A/UHMWPE nanocomposite coatings, with different loadings of C15A, was evaluated by using a ball-on-disk configuration with a counterface of 440C hardened stainless steel ball at room temperature under dry conditions. After the optimization of nanoclay loading, effect of linear sliding speed (such as 0.1, 0.2, and 0.3 m/s) on the tribological performance of the coating was also evaluated. X-ray diffraction, scanning electron microscopy and optical profilometry techniques were used to characterize the morphology and dispersion of nanoclay in the polymer matrix, evaluate the thickness and understand the wear mechanisms, respectively. It is observed from the results that 1.5 wt% C15A/UHMWPE nanocomposite coating did not fail even until ~100,000 cycles (sliding distance = 1.3 km) at a normal load of 9 N and a linear sliding speed of 0.1 m/s as compared to the pristine UHMWPE coating which failed early under same conditions. The improvement in the performance of 1.5 wt% C15A/UHMWPE nanocomposite coating is attributed to the resulting exfoliated morphology of the clay platelets in the polymer matrix due to its uniform dispersion that provides an efficient bridging effect, holding the polymer chains together and resisting their easy pull-out.

1. Introduction

Conservation of energy has become one of the most important goals of the present day research. To do so, researchers have been exploring various options such as replacing the conventional heavy metals like steel with lighter metals such as aluminum (Al), in most of the applications such as automobiles, gears, cams, shafts, bearing, and seals etc. In spite of their excellent properties such as high strength to weight ratio, light weight etc. Al suffers from poor tribological properties such as high friction and high wear which are major concerns in practically all the tribological applications. At present, about one third of energy resources are being wasted due to involvement of friction directly or indirectly [1]. Therefore, it is significantly important to develop alternative strategies which can minimize the losses of Al due to friction and wear. One of the approaches that the researchers have taken up to improve the tribological performance of Al, is by modifying its surface by efficient coatings. From literature, it is found that diamond-like carbon (DLC) coatings [2,3], molybdenum disulphide (MoS_2) coatings [4,5], metal carbide coatings (WC, CoCr), and other hard coatings (TiN, TiO_2, Al_2O_3) [6–9] have been developed to protect Al substrates against various counterface materials. However, there are some limitations associated with these hard coatings such as high thermal stresses in the coating, high friction, incompatibility with the lubricant, poor adhesion with the substrates and sensitivity to the environment and the possibility of the wear debris particles from these hard coatings damaging the entire tribological system adversely [10–13]. To overcome these limitations, few researchers have tried protecting the Aluminum surfaces with soft polymer/polymer composite coatings [14–16]. Polymer coatings are one of the best candidates to overcome the limitations of the hard coatings due to their low density, anticorrosion properties, self-lubricity, low cost and ease of processing [17]. However, there is always a need to further improve the properties such as load bearing

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capacity of these polymer coatings to pave the way for their usage in demanding tribological applications. Various researchers have tried this by reinforcing the polymer matrix with different novel nanofillers such as carbon nanotubes (CNTs) [16,18], graphene [19,20], metallic oxides (ZnO, WC, Al_2O_3) [21,22] and silica nanoparticles [23,24] etc.

Among polymers, ultra-high molecular weight polyethylene (UHMWPE) has a great combination of properties such as very low coefficient of friction (COF) of about 0.1–0.2, high abrasion resistance, self-lubricating, high impact resistance and durability which makes it an excellent candidate for coating purposes in tribological applications [25]. In spite of these excellent properties, UHMWPE still demands modifications to further enhance its load bearing capacity, tribological and thermal properties. To meet these demands researchers [16,18,20] have used different nanofillers (CNTs, graphene etc.) in UHMWPE matrix to fabricate UHMWPE nanocomposite coatings.

However, recent research has shown that nanoclays are also a very promising filler material due to their good barrier and mechanical properties, particle size, morphology, abundance and low cost. The most commonly used nanoclay is Montmorillonite (MMT), which is basically layered silicates having ~1 nm thick aluminosilicate layers stacked on each other. The first nanoclay reinforced polymer nanocomposite was made by a research group from Toyota in Japan which enhanced the properties of nylon 6 by reinforcing it with nanoclay [26]. Lately, a lot of development in polymer layered silicate nanocomposites has been attained [27]. Various studies have reported an improvement in the tribological properties of polymers (in bulk) by reinforcing them with different loadings of nanoclays such as 2 wt% in polypropylene [28], 5 wt% in Nylon 6 [29] and 1–2 wt% in polyvinylidene fluoride respectively [30]. Recently, Samad et al. [31,32] reported an improvement in the tribological performance of UHMWPE bulk nanocomposites reinforced with different concentrations of C15A organoclay. The results showed a significant improvement in tribological properties of UHMWPE bulk nanocomposites reinforced with 1.5 wt% nanoclay. This improvement was attributed to the uniform dispersion of the nanoclay platelets in the polymer matrix resulting in an exfoliated morphology and also to the formation of an adherent transfer film on the counterface ball.

However, a very limited work has been reported on polymeric coatings reinforced with nanoclays for the improvement in tribological properties. Golgoon et al. [33] enhanced the wear resistance of plain carbon steel by depositing 5 wt% clay-polyester nanocomposite coating. Bellisario et al. [34] evaluated the effect of different concentrations of modified MMT and mixing time on the tribological properties of polyester coatings and found optimized results at low filler contents and mixing times.

It is to be noted that there are no studies whereby nanoclay was used as reinforcement in UHMWPE polymer matrix to develop low friction and wear resistant coatings on metallic substrates. Hence, the focus of this study is to evaluate the feasibility of using nanoclay as reinforcement in UHMWPE to develop nanocomposite coatings to protect Al substrates for bearing applications. Electrostatic powder spray coating method was used for the deposition of pristine UHMWPE and UHMWPE nanocomposite coatings reinforced with three different clay loadings (0.5, 1.5, 3 wt%) on Al substrates to evaluate their tribological and mechanical properties.

2. Experimental details

2.1. Materials

UHMWPE powder with a particle size of 80–90 μm and density 0.94 g/cm^3 was used in this study which was procured from Good Fellow Corp in Cambridge, UK. Cloisite® C15A organically modified nanoclay (platelet size in the range of 8–15 μm and a specific gravity between 1.7 to 1.9) modified with quaternary dimethyl dihydrogenated ammonium was used as reinforcement. It was procured from Southern Clay Product, USA.

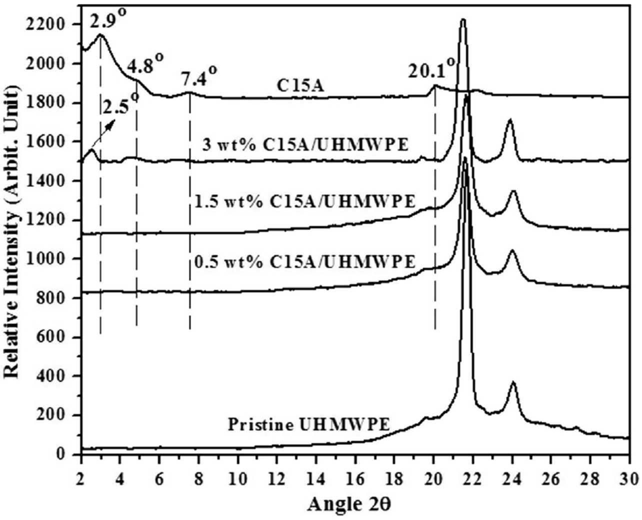

Fig. 1. XRD patterns of pristine UHMWPE, C15A organoclay and C15A reinforced UHMWPE nanocomposite with different loadings of clay.

2.2. Preparation of nanocomposite powders

Sonication method along with magnetic stirring was used to prepare C15A/UHMWPE nanocomposite powders. Different concentrations of nanoclay (0.5, 1.5 and 3 by wt.%) were used to make nanocomposite powders. Required amount of nanoclay was sonicated for 10 min in ethanol (50 ml) with the help of a probe sonicator at an amplitude of 30% and a cycle on/off time of 20/5 s to disperse it uniformly. This was followed by magnetic stirring of the mixture at 1000 rpm for 2 min for further dispersion. The required amount of UHMWPE powder was then added slowly to this mixture which was further magnetically stirred for another 1 h. Eventually, the nanocomposite powder was dried in a furnace at 80 °C for 24 h to make sure of the complete evaporation of the solvent.

2.3. Substrate preparation

Aluminum alloy (Si = 0.17%, Fe = 0.15%, Mn = 0.5%, Ni = 0.3%, Mg = 0.6%, Cr = 0.1%, and balance = Al), with a sample size of 25 × 25 mm × 6 mm, was used as a substrate. Samples were grinded to a roughness (R_a) of 0.45 ± 0.05 μm. After grinding, samples were cleaned with acetone by using ultrasonic cleaning method for 15 min followed by drying with the help of an air blower. The air dried samples were then subjected to plasma treatment with a radio-frequency power of 30 W by using Harrick Plasma equipment for 10 min. It has been observed in a previous study that plasma treatment helps in cleaning the substrate and increasing its surface free energy leading to an improved adhesion between the coating and the substrate [35].

2.4. Coating procedure

Electrostatic spray gun (Model no 17288, Craftsman®) was used for depositing the powders on the substrate. The electrostatic powder spray coating method is expeditious, environment friendly and relatively more energy efficient as compared to other conventional methods. Furthermore, it has no requirement of using particular solvent for a specific polymer and results in less wastage of coating material. The basic principle of electrostatic spray gun is that negatively charged powder particles are deposited on positively charged sample. Cleaned and plasma treated substrates were preheated at 180 °C for 5 min, followed by spraying of the powder with a particular composition. Finally, the powder coated samples were cured on the heating plate at 180 °C