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The effects of magnetic field-enhanced thermal spraying on the friction and wear characteristics of poly(ether-ether-ketone) coatings

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ABSTRACT

It is demonstrated that the wear of poly(ether-ether-ketone) (PEEK) composite coatings can be improved by depositing them in the presence of a magnetic field. In this investigation, particles of PEEK were deposited on a low-carbon steel substrate by thermal spray coating under a magnetic field causing them to become aligned. Friction and wear behavior of the coatings, including crystallization level and hardness, were considered under different magnetic intensities, distances away from the substrate, and applied loads. The results showed that the degree of crystallinity and hardness of the coatings were not uniform across the distances away from the substrate. The maximum crystallinity and hardness were found at a distance of 100 μm from the substrate. The magnetic intensity had an effect on the PEEK coatings at distances of 50–150 μm from the substrate, the most pronounced effect being observed at 100 μm. The magnetic field was found to improve the coating properties of PEEK, resulting in reduced friction coefficient and increased wear resistance. Surprisingly, the specific wear rate of PEEK coatings decreased when the applied load was reduced from 25 N to 5 N. The application of a magnetic field could be successfully used in the thermal spray process for improving the friction and wear properties of PEEK coatings.

1. Introduction

Poly(ether-ether-ketone) (PEEK) is a high-performance polymer that has been used in various applications, such as, gears, sealing rings, bushings and bearings, due to its high mechanical and tribological properties [1–3]. Due to its high melting temperature, PEEK can be used as effective coatings on metallic substrates. Moreover, PEEK has been recently used for replacement of metallic substrates, including carbon steel, stainless steel, aluminum, magnesium, brass and bronze [4]. Several property-improving methods for PEEK have also been proposed in order to increase the industrial window of PEEK applications, these including hybrid PEEK bearing or bushing, outer and inner PEEK bearing, bolted joints, flexible couplings, and non-stick cookware. The designs of the chemical structure, material formulations and processing conditions are considered to be the basic methods for improving the properties of PEEK materials [5]. The addition of fillers, such as h-BN (hexagonal boron nitride), carbon fiber, graphene, WS_2 (tungsten disulfide) and CNT nanoparticles (carbon nanotubes), has been found to affect the overall properties of PEEK composites, especially tribological properties [2,3,6]. However, overuse of these fillers causes a drop in mechanical properties. Another method for enhancing the properties of PEEK coating is by inducing molecular chain alignment and/or molecular orientation [5,7–9]. This can be achieved by several processing methods, such as extrusion, injection molding, fiber spinning and film blowing [10,11,12].

In general polymer processing, a shear flow of the polymer melt can produce molecular chain orientation during the flow, and this will lead to the orientation-induced crystallization and higher mechanical properties of the polymer [2]. The electric and magnetic fields are also found to influence the orientation and crystallinity growth of the polymers [5,7–9]. In our previous work [9], PEEK coatings were applied by thermal spray technology under a magnetic field; it was found that the degree of crystallinity and hardness increased with increasing magnetic intensity as a result of molecular orientations of the molten PEEK [9]. The magnetic field-induced alignment or orientation of the molecular chains of polymeric materials has a significant impact on diamagnetic materials, such as, anisotropic polymers. The diamagnetic molecules of the polymer can interact with the magnetic field ($\vec{B}$). The extra energy related to the magnetic alignment is expressed by $E = -\chi\vec{B}^2$, where χ is the molecular diamagnetic susceptibility

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that is related to the molecular structure. The anisotropic molecular structure has an anisotropic diamagnetic susceptibility $\Delta\chi = \chi_{//} - \chi_{\perp}$. The amount of extra energy depends on the molecular orientation. The benzene molecule is an example of large anisotropy and for inducing current within the benzene ring [5,7].

Thermal spray coating for polymer is a process where polymer particles are melted and sprayed onto the surface of the substrate with high velocity, and the molten particles flow and spread. The shear stress is built up continuously and causes an alignment of the molecular chains of the molten polymer before entering the cooling process. Thus, the orientation-induced crystallization is finally initiated during the cooling. In this study, PEEK coatings were applied on a low-carbon steel substrate using a thermal spray coating process together with an electromagnetic field apparatus. The molten PEEK particles were coated under different magnetic intensities in order to determine the effect on improving the tribological properties of the PEEK coating. A ball-on-disc sliding wear testing method was used in order to imitate the ball bearing applications where the chromium steel ball was referred to as metal ball sliding in the PEEK housings. The degree of crystallinity and hardness were determined as a function of coating thickness, and these properties were used in relation to the tribological properties of the PEEK coatings.

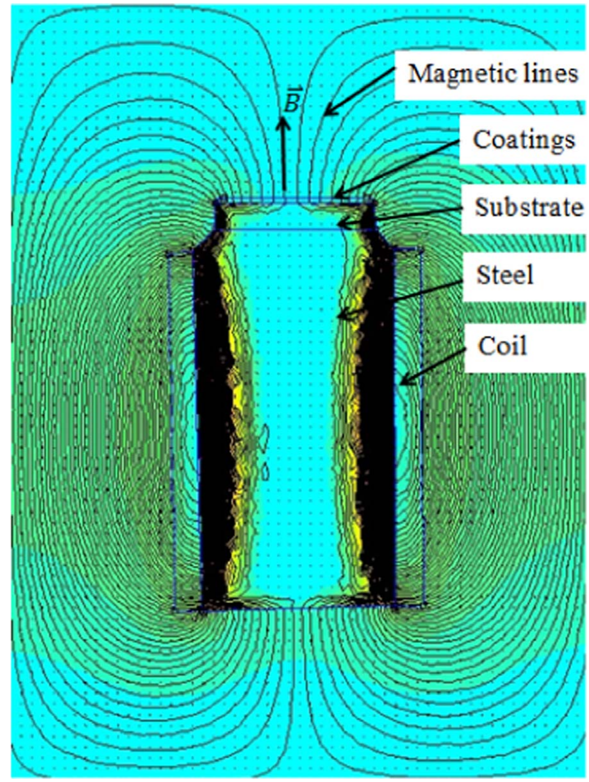

Fig. 2. Magnetic field directions applied into PEEK coating process.

2. Experimental

2.1. Materials and coating process parameters

Poly(ether-ether-ketone) (PEEK, grade 150PF; average particle size of 48 μm) was supplied by Victrex-MC (Tokyo, Japan). Low-carbon steel (AISI 1040) with a diameter of 25.4 mm and thickness of 5 mm was used as a substrate. PEEK powder was sprayed onto the low-carbon steel substrate by flame-spraying technique (DJ 1400; Sulzer, Winterthur, Switzerland). The flame spray coating system, equipped with a magnetic intensity controller, is shown in Fig. 1.

The magnetic field was generated by an electric current flowing into a copper coil; the direction of the magnetic field, as shown in Fig. 2, was simulated by the FEMM 4.2 program. The magnetic intensity was adjusted and controlled by varying the electric current supplied to the copper coil. The magnetic field intensity in this work was determined using a calibration curve (Fig. 3) for the linear relationship between the current supplied to the copper coil and the magnetic intensity.

The substrate was grit-blasted with Al_2O_3 powder and afterward cleaned with acetone prior to thermal spraying. It should be noted that the spraying parameters used in this work (Table 1) were experimentally determined by our previous work [9]. The temperature of molten PEEK before spraying was measured to be around 390–400 °C. Micrographs shown in Fig. 4 confirm that the spraying parameters used in this work were appropriate, as they physically gave good PEEK coatings showing a dense microstructure without pores on the substrate, both with and without a magnetic field. The differences in coating thicknesses with and

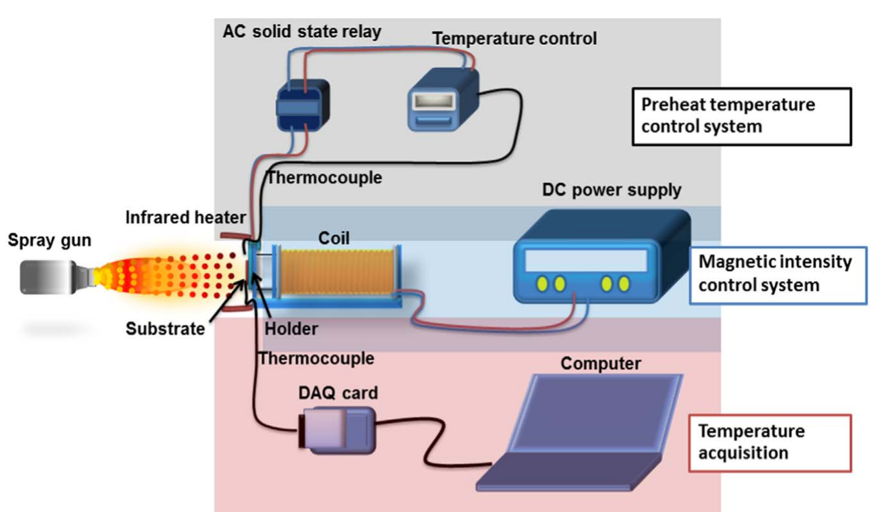

Fig. 1. The PEEK coating process with magnetic field.