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The wear and lubrication performance of liquid–solid self-lubricated coatings

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ABSTRACT

The use of solid lubricants (MoS_2, PTFE, graphite, etc.) embedded in coatings has been largely employed in different industries, especially in those applications where liquid lubricants cannot be used. Although the use of liquid lubricants is desirable whenever it is possible, limited research has been addressed towards the development of self lubricated coatings containing liquid lubricants. One of the main reasons for this is due to the complexity of embedding lubricant reservoirs inside the coatings. This work focuses on the production of liquid lubricant filled capsules that will be used as reservoirs in thermally sprayed coatings. The capsules were used and injected in a conventional thermal spray process for obtaining the self lubricated coatings. The obtained coatings consist of embedded liquid lubricant filled capsules in a polymeric matrix. The lubricant contained in the capsules is released to the system whenever the coating is worn out, promoting the breakage of the capsules.

Coatings obtained with different spraying parameters have been tested in this work. The characterization has been performed by optical microscopy and Scanning Electron Microscopy (SEM) techniques and the tribological properties (i.e.: self lubricating function and lubricant release) have been investigated by reciprocating ball-on-plate tests using a stainless steel ball as counterpart. The wear tracks have been investigated using SEM.

It was found that the coatings provided a good lubrication performance as long as the matrix material was not remelted after spraying using capsules with thin wall. For the non-remelted coatings, the coefficient of friction remained below 0.2 and the material loss varied depending on the normal load and on the spraying parameters. The coatings obtained with thick wall capsules resisted better the thermal input, but the lower amount of lubricant was insufficient to keep low friction under certain loading conditions.

1. Introduction

Most of the industrial and mechanical processes need lubrication to work properly. Lubricants reduce friction and protect against wear as long as a lubricant film separates the moving parts involved in the process. Modern technologies require the application of dry coatings. Lubrication of dynamic surfaces by fluids adds indeed complexity, weight and cost to the system and therefore limits its performance. Therefore there is a need to improve the lubrication systems of dynamic surfaces. This can be done by using smart materials (e.g. self-healing materials) or by modifying the surfaces of components.

Materials that heal themselves have been a major topic of research due to the savings associated to maintenance costs that might represent. Maintenance operations are not only costly to the companies but they are also risky since 15–20% of accidents are related to maintenance operations [1]. In 2001 the first autonomic self healing material (a material able to heal itself without the human intervention) was developed at the University of Illinois, USA [2]. The self-healing material was based on a polymer matrix reinforced with catalyst and microcapsules filled with healing agents. The healing concept was based on the crack propagation inside the material, when the tip of the crack hits a microcapsule the healing agent is released and reacts with the catalyst agent, thus restoring the initial properties of the material. This concept has been further developed and it is being used in paints and other polymer-based materials [3–7].

Machine elements such as bearings and hydraulic systems need to maintain low wear rates and full film lubrication. This is a challenge where self-healing materials can find an important new field of application. As mentioned above, most self-healing coatings have developed for use as paints, which is not an optimal technology for mechanical components in machine elements. Therefore, other coating technologies producing coatings with a better mechanical stability are needed to develop the next generation of self-healing materials for components with high mechanical demand. These coatings should provide machine elements with a reservoir of liquid lubricant in the material that can be released when starving conditions occur in the system. This concept has been developed by electrodeposition [8] and thermal spray [9] recently. In the first case, the main limitation is the materials that can be used for the matrix, which have to be only metals. This is a disadvantage in many

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mechanical components, since metal–metal contact can lead to galling and severe failure of machines. In the second case, this limitation is overcome since thermal spray can produce a variety of matrix materials (polymers, metals and ceramics) however the healing material needs to be pre-processed and optimized prior to the deposition process due to the high deposition speeds and temperatures achieved in thermal spraying.

The self-lubricating thermally sprayed coatings developed for the first time consisted of a polymer matrix [9,10] containing liquid lubricant filled capsules. The main challenge for producing liquid containing self-healing coatings by thermal spray is to avoid any damage of the capsules during the production process since the temperature of the flame can damage the capsule material and thus burn the liquid lubricant, which is normally an oil. A new flame spray system modified for spraying lubricant filled microcapsules together with the matrix material of the coating has been developed recently [10]. Polyurea microcapsules were produced by miniemulsion polymerization [11]. The miniemulsion process is based on a stable oil-in-water emulsion where all the ingredients in the dispersed phase (e.g. monomer and lubricant) are mixed. Interfacial polymerization at the droplet interface is used for shell formation around the liquid core (i.e. lubricant) by adding a second monomer to the emulsion. In this way the amount and type of lubricant can be modified and tuned to the desired amount. The capsules produced by the miniemulsion process were kept in a water-based solution in order to protect them during the thermal spraying process. As a result a coating with homogenously distributed capsules was obtained [9].

In the present work this first family of liquid–solid self-lubricating thermal spray coatings are analyzed in terms of lubrication and wear performance. Nylon-11 matrix coatings containing polymeric capsules filled with a synthetic oil (polyalphaolefin, PAO) have been prepared by flame spray. Coatings obtained with different spraying conditions are tested (spraying distances, and powder feeding systems). In addition, the effect of post-treatments will be also analysed. Two different types of capsules (high and low liquid contents) will be also studied.

2. Experimental procedure

The samples tested in this work are thermal spray coatings with a matrix of polyamide 11 (Nylon-11) filled with lubricant capsules. The coatings were deposited on carbon steel by powder flame spraying (FS-Powder) method. The details of the different components of the coatings and the coating process are described below.

2.1. Liquid lubricant filled capsules

Lubricant-filled microcapsules of polyurea were synthesized by miniemulsion polymerization [11]. This method consists in the interfacial polymerization at the lubricant droplet interface, which forms a shell around the liquid core. In this work an oil-in-water miniemulsions was prepared by emulsifying an oil-phase (20% v/v) in an aqueous phase by means of an ultrasonifier (Labsonic 2000) in small-scale experiments and a homogenizer (15MR-8TA, APV GAULIN Inc.) in large-scale experiments. The oil-phase consisted of isophorone diisocyanate and lubricant in two different ratios (30 and 70 vol.%) and the water aqueous phase consisted of a 10 g/l polyvinylalcohol (Celvol 523) stabilizer solution. Guanidine carbonate (NCO/NH_2) was used on the aqueous phase to complete the polymerization. By varying the isophoren diisocyanate to lubricant ratio in the oil-phase the wall thickness of the capsules can be controlled and thus the total amount of lubricant inside the capsules. The amount of lubricant in the capsules and the thickness of the wall are important parameters to evaluate the lubricating properties of the produced coatings. The liquid lubricant used was a fully formulated polyalphaolefin (PAO) since this is a typical synthetic oil used in gear and bearing systems [12].

2.2. Thermal spray process and coatings

The substrate material was ST-52 carbon steel (S355M according to EN 10113-3), which was degreased and grit blasted using corundum grade 24 just before the spraying process. The roughness (Ra) of the substrates was about 3 μm. A commercial Nylon-11 powder (ET-11 E + C Evertuff, polyamide-11 hereafter called Nylon, particle size > 100 μm) and the capsule suspensions were sprayed using a flame spray system with a Eutectic Terodyn 3500 gun (Eutectic Castolin). Using this spraying system and the Nylon, the particles temperature in-flight expected is about 120–350 °C [13]. In all cases the number of passes and the powder feed rate was kept constant.

Since the flame spray equipment does not allow introducing the capsule suspension in the feeding system a set-up for co-spraying the nylon powder (matrix material) and the capsules was designed. The suspension containing the capsules was fed into the flame using two different feeder systems located close to the nozzle of the gun allowing the control of the total amount of capsules, injection angle and position. The first system introduces the capsules by injection radial to the flame and the second system introduces the capsules by atomization axial to the flame (Fig. 1). The main goal of these systems was to avoid the degradation of the capsule shell material during the spraying process and assuring that the aqueous solution was completely evaporated during the thermal spray process.

Table 1 shows the different coatings produced and the spraying parameters that were selected for each one. These parameters were chosen in order to study their influence on the lubrication performance. One coating was post-treated by a remelting process with the flame of the gun (no powder or capsule injection). The lubricant amount expressed in vol.% presented in the table refers to the volume percentage ratio of lubricant and shell material in a single capsule. The nylon/capsules ratio column refers to the feedstock material (relative amount of Nylon powder and capsule slurry) injected in the flame.

Different properties and characteristics of the coatings were measured and/or assessed. Due to the heterogeneous nature of these coatings, there are some properties that cannot be measured properly for example, the hardness and porosity, which are important parameters in thermal spray. Therefore these two properties have been only estimated according to the observations after production of the coatings. Indeed, once an indentation is performed in the coating and a capsule is reached, the lubricant is released and therefore the hardness values recorded cannot be taken as valid. Erratic results with a large statistical error were obtained due to this fact. Regarding the porosity and due to the polymer nature of the matrix and the temperature of the spraying process (above the melting temperature of Nylon-11, 175-191 °C [14]), it has been found to be negligible in all coatings (a cross-section analysis was performed, but it will not be displayed in this paper). The thickness of the coatings was measured using a magnetic induction device (Elcometer 256FN, USA) due to the fact that the substrate is magnetic. The results are shown in Section 3.2.

2.3. Lubricating properties of the coatings

The lubricating properties of the coatings were studied using a reciprocating tribometer (Resmat, Canada). The tests consisted of measuring the coefficient of friction (COF) of a 4.76 mm in diameter AISI 316 steel ball rubbing against the coatings in a 10 mm stroke, an average sliding velocity of 10 mm/s and at normal loads of 5, 10 and 20 N during 30 min in dry conditions. All the coatings listed in Table 1 were tested. Two tests for each coating were performed in order to check the repeatability of the results.

The initial mechanical conditions of the contact have been calculated using Hertz contact theory in order to have an estimation of the mechanical conditions of the coating at the beginning of the wear tests [12]. It is worth noticing that Hertz contact theory applied to