



Fatigue behavior of a 316L stainless steel coated with a DLC film deposited by PVD magnetron sputter ion plating

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ABSTRACT

The present investigation has been conducted in order to evaluate the change in fatigue properties of a 316L stainless steel substrate when this material is coated with a hydrogenated, amorphous carbon (a-C:H) solid lubricant of approximately 2 μm in thickness, which has been developed in recent years and is known commercially as Dymon-iC™, a film deposited by means of physical vapor deposition (PVD) closed field unbalanced magnetron sputter ion plating (CFUBMSIP). The fatigue behavior of the uncoated and coated alloy has been evaluated under rotating-bending conditions at maximum alternating stresses in the range of 430–520 MPa, depending if testing was conducted in air or in a 3 wt.% NaCl solution. The results indicate that the presence of the coating provides a significant increase in fatigue properties, particularly under corrosive conditions, an outcome that is believed to be closely associated with the amorphous structure of the film, besides its elevated mechanical strength, a possible existence of a compressive residual stress state and good adhesion to the substrate. The fractographic analysis conducted both on the fracture surfaces of the tested specimens and along sections normal such surfaces clearly shows that fatigue cracks are nucleated on the surface of the coating and that propagate into the substrate once have crossed over the entire coating thickness.

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1. Introduction

Diamond-like carbon (DLC) coatings are widely employed as solid lubricants in contacting parts and components that rub against one another, due primarily to their outstanding tribological properties. Usually, DLC coatings have a mean hardness in the range of 20 GPa and lower friction characteristics than other more conventional coatings such as TiN and CrN, although their properties vary widely depending on their structure and amount of hydrogen present in their composition [1]. However, when such films are deposited onto alloyed steel substrates, they could exhibit high internal residual stresses, poor adhesion to the substrate and limited load-bearing capacity. Such disadvantages have been overcome by means of the addition of different metals, giving rise to

softer Me:C composite coatings with a better adhesion and toughness and reduced internal stresses [2,3].

Dymon-iC™ is a commercial carbon-based solid lubricant coating that has been developed in recent years. It is a hydrogenated, amorphous carbon material (a-C:H), characterized by its low friction properties, excellent tribological performance and high pressure-bearing capability [4,5]. It is deposited onto different materials by means of physical vapor deposition (PVD) techniques maintaining the substrate temperature below approximately 250 °C and employing a Cr interlayer to improve its adhesion to the substrate, which makes it a bi-layer coating.

As indicated by Baraguet et al. [6], deposition of thin ceramic coatings by means of PVD techniques generally leads to a significant improvement of the surface properties of the substrate. However, such an improvement may be achieved at the expenses of other important mechanical properties such as fatigue resistance, since cracks already present in the coating could be transfer to the substrate and decrease the fatigue life of the coated component. Thus, as new coatings are being developed and put into operation, the evaluation of their effect on mechanical properties

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other than tribological properties becomes an utmost important task.

In the past few years a number of investigations have been conducted regarding the evaluation of the fatigue performance of different metallic substrates coated with thin ceramic films deposited by PVD [6–12], which have allowed the general conclusion that this deposition technique gives rise to an improvement in the fatigue properties of the coated substrate. An example is the work conducted by Baragetti et al. [6], addressed to the evaluation of the effect of CrN coatings deposited by PVD, on the fatigue limit of different ferrous and non-ferrous substrates including 2205 duplex stainless steel, H11 tool steel and AA6082 aluminum alloy. According to these authors, the deposition of the film leads to an increase of about 15% in the fatigue limit of the steel substrates, but does not provide any improvement in the case of the aluminum alloy. For the latter substrate, overaging is expected to take place at the PVD deposition temperatures, which would impair the intrinsic properties of the alloy. These studies have been further extended to the analysis of fatigue behavior of PVD coated spur gears employed in the manufacture of gearboxes for automotive applications, by means of both experimental and numerical methods developed for the prediction of fatigue crack propagation [7].

Regarding the PVD coating of 316L stainless steel, the work earlier conducted by Berríos-Ortiz et al. [8,9] clearly indicates that if this material is coated with different understoichiometric TiN_x and ZrN_y films deposited by PVD closed field unbalanced magnetron sputtering, a significant increase in the fatigue properties of the substrate is observed, when testing is conducted both in air and under NaCl corrosive conditions. These results are in close agreement with those reported for the same substrate, but coated with a stoichiometric TiN film deposited by means of plasma assisted PVD (PAPVD) techniques [10]. In both cases, the increase in fatigue properties has been attributed to the elevated mechanical strength of these films, together with their very good adhesion to the substrate and high compressive residual stresses.

More recently, similar studies have been conducted with high strength steels substrates of the type SAE Q&T 4340 coated with TiCN films deposited by PAPVD techniques [11]. These investigations have also shown that the presence of the ceramic film provides a significant increase in fatigue life, in the range of 140–180% when the coated substrate is tested in air, and moderate increases of the order of 25% when tested in a NaCl solution. As in previous investigations, fatigue cracks were observed to nucleate at the surface of the coating and propagate normal to the substrate-coating interface after traversing the entire coating thickness.

One of the few examples in which PVD deposition of ceramic films impairs the fatigue properties of the substrate is that of the aluminum alloy AA7075-T6 coated with a ZrN film [12], in agreement with the earlier findings of Baragetti et al. [6]. In this case, it was observed that the deposition process of the ZrN coating gave rise to a significant decrease in fatigue properties, which cannot be fully compensated for by the presence of the film. As in the case of the AA6082 alloy, it is believed that this decrease in fatigue properties can be attributed to the overaging of the material and loss of the T6 condition, achieved after aging at about 120 °C. However, an interesting aspect of the study was that at maximum alternating stresses below 220 MPa and in the presence of a corrosive NaCl solution, the behavior of the coated alloy approached that of the uncoated material, which highlights the good corrosion resistance of the ZrN coating and its ability to protect the substrate if no delamination of the film occurs.

The fatigue behavior of metallic substrates coated with DLC films has been much less investigated than that of the nitride coatings. Among the few studies addressed to the analysis of this subject, it is important to point out the recent works conducted by Sundaram [13] and by Golden et al. [14].

Sundaram [13] carried out an investigation addressed to the replacement of hard chromium plating by means of DLC coatings, employing a Si interlayer as intermediate bonding between the film and the substrate. The axial fatigue experiments ($R = 0.1$) conducted in air by this author on samples of 4340 M steel indicate that the DLC coating, of approximately 5 and 10 μm in thickness and compressive residual stresses in the range of 1 GPa, gives rise to a slight improvement of the fatigue properties of the steel substrate, in comparison with those of the Cr plated specimens, which is more remarkable for the 5 μm thick coating.

On the other hand, Golden et al. [14] carried out an investigation of the performance of fretting fatigue of Ti-6 Al-4 V alloy with several coatings (including two different DLC films of 1.5 and 5 μm in thickness) and surface treatments. As part of the investigation axial fatigue tests ($R = 0.1$) were also carried out on samples coated with the DLC films at maximum stresses in the range of 690–965 MPa. The limited data reported by these authors indicate that the DLC coatings could give rise to reduction in fatigue life by a factor of 4 or less, under some experimental conditions.

Therefore, given the fact that most fatigue studies carried out with PVD coated materials have involved mainly the deposition of nitrides and carbonitride films and that limited information can be found in the current literature regarding the fatigue behavior of substrate-coating systems involving the deposition of amorphous DLC films, the present investigation has been conducted in order to evaluate the change in fatigue life, both in air and in a corrosive NaCl solution, as well as the change in fatigue limit in air of a 316L stainless steel substrate coated with a commercial DLC coating (Dymon-iC™) also deposited by PVD techniques.

2. Experimental techniques

2.1. Sample preparation

The present investigation has been conducted with samples of a commercial 316L stainless steel of the following composition (wt.%): 0.03 C, 2.0 Mn, 1.0 Si, 17 Cr, 12 Ni, 2.5 Mo, 0.045 P, 0.03 S and Fe bal. The alloy was provided in the form of bars of 12.7 mm in diameter and 6.1 m in length. From this material, 10 tensile and 130 fatigue specimens were machined, according to the ASTM A 370 and ASTM E 606 standards, respectively. Additionally, a number of parallelepiped samples of AISI D2 tool steel (20 mm $\times$ 12.7 mm $\times$ 5 mm) were employed for the purpose of characterizing both the thickness and absolute hardness of the DLC coating deposited onto some of the tensile and fatigue specimens in the same batch. Fig. 1 illustrates the sketches of the tensile and fatigue specimens.

Machining of the samples was conducted with utmost care in order to avoid the introduction of undesirable residual stresses. The turning operation was carried out employing a horizontal turret lathe at low speeds, which allowed the continuous reduction of the depth of cut of the material. SiC papers grit 400–2000 were further employed for the elimination of the remaining circumferential notches and imparting a “mirror-like” finish to the machined specimens. The mean roughness of the as-polished samples was of $\sim 0.05 \mu\text{m}$ and that of the coated specimens was of $\sim 0.063 \mu\text{m}$. Such a slight increase in roughness could be due to the presence of some unreacted particles typical of most of the PVD deposition processes.

2.2. Coating deposition and characterization

Five tensile, 60 fatigue and all the characterization D2 tool steel samples were sent to Teer Coating Ltd., Hartlebury, Worcestershire, UK, where these were coated inside an industrial reactor by closed

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