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Fatigue assessment of multilayer coatings using lock-in thermography

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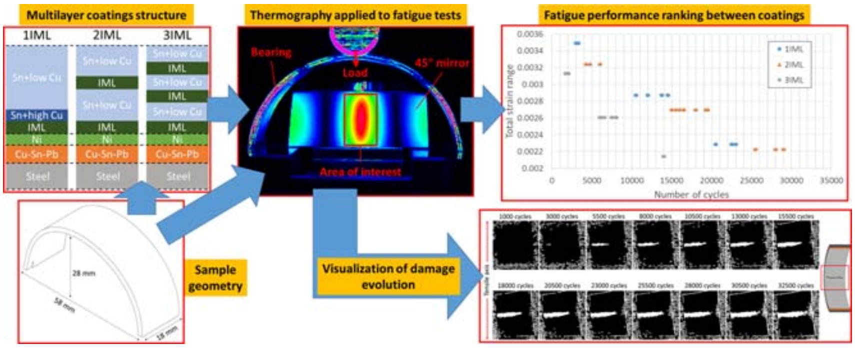
HIGHLIGHTS

- The use of Infrared Thermography allows ranking of the fatigue performance of multilayer coatings during fatigue tests.
- The new methodology detects damage earlier than other methodologies, facilitating far less conservative failure criteria.
- The coating with two intermetallic layers (2IML) shows better fatigue performance than the coatings with 1IML and 3IML.

GRAPHICAL ABSTRACT



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ABSTRACT

Plain bearings experience cyclic loading during operation, which may cause fatigue failure. In the bearings under study a steel backing has a leaded bronze interlayer, covered by a thin (20 μm) multilayer coating, which consists of several electroplated layers composed of Sn, Ni and Cu. Commercial performance assessments simulate the conditions of engines in a 'Pass or Fail' test. A new methodology is proposed to assess the fundamental fatigue behaviour for such complex layered bearings. Accelerated fatigue tests on half-shell bearings have been conducted under 3-point bend, whilst the coated side of the bearings are recorded with an infrared camera. Cyclic tests with strain gauges placed on the coating have been performed to evaluate the strains developing during loading. By combining these tests we can rank different coatings. A compliance based failure criterion is also compared with a failure criterion based on early damage revealed by infrared thermography, showing that the latter is far less conservative. Thus, this methodology allows detection of small scale fatigue cracks in the coatings significantly earlier, facilitating assessment and identification of possible mechanisms to explain the differences in fatigue performance between coatings. This provides valuable information to develop new coatings for future bearing designs.

1. Introduction

Plain bearings are a crucial part of internal combustion engines; typically comprising two half-shell bearings fitted together into a housing, supporting the crankshaft or the connecting rod. Multilayer coatings are used in such devices in order to reach a property compromise or balance between hard and soft materials, since a bearing needs to have high mechanical strength but also has to be able to embed foreign particles that could damage the crankshaft. The material system considered in this work comprises multilayer coatings made of Sn-Ni-Cu electrodeposited onto a leaded bronze interlayer bonded to a steel-backing (Fig. 1). In service, the engine loads are transferred to the bearing coating through a thin oil film, hydrodynamic pressure

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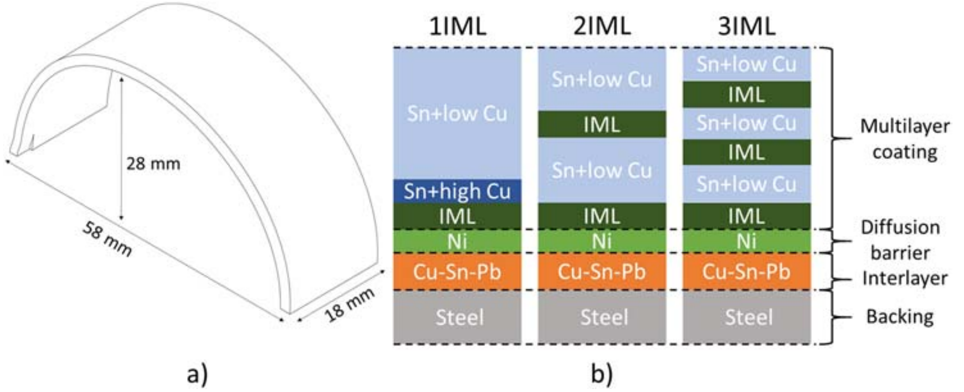

Fig. 1. Schematics of: a) a bearing and b) cross-sectional structures of the specimens (not to scale).

concentration variations of such oil films lead to dynamic stress fields, applying cyclic loading, which may then lead to cracking and spalling of these coatings [1].

Engine manufacturers are always trying to increase the power output, whilst decreasing the weight and size of new engines, thus increasing the loads that the plain bearings have to support. In response, coating architectures for bearings have become more and more complex in order to increase the fatigue lifetime under higher service loads. Such coating systems now comprise overlay bearings that consist of complex micrometre scale-multilayer structures (1–18 μm per layer) [2,3], that make the fatigue assessment process more complex, in particular detecting early damage in the coatings is challenging [4,5]. Previous methods have been based on detecting a compliance change in far thicker coatings.

In industry, accelerated test rigs are used to rank the fatigue performance of bearings by testing them to failure in an engine-like environment. One example is the Sapphire test machine [6], which simulates service loading by rotating an eccentric test shaft within the test bearing, where the dynamic load is applied as the result of oil film pressure between the bearing and the shaft due to the motion of the shaft. This is a useful pass-fail test to rank bearings in an engine-like environment; however, it does not offer insight into the fatigue mechanisms controlling the performance. Without a mechanistic understanding of what controls the fatigue performance of these layered systems, optimisation of bearing layer architectures and the microstructures of the various coatings is “black box” and can only be achieved empirically through trial and error.

In previous studies, simple bending tests have been used to test fatigue performance of coated systems [7–9]. This approach has also been adapted to test half-shell bearings, using a 3-point-bend configuration, in order to assess their fundamental fatigue performance. Several researchers have used such methodologies to assess relatively thick (400–180 μm) bilayer aluminium based coatings in plain journal bearings: M.C. Mwanza et al. [10] studied the different fatigue performance of aluminium based bilayer bearings with different lining compositions, Ali et al. [11] compared the fatigue performance of bearings produced by different manufacturing processes (HVOF versus roll bonding), and Joyce et al. [12] investigated the effect of environment by testing Al-Sn-Si bearing linings under oil, vacuum and air conditions. Each of these test methodologies involve simpler loading cases than the Sapphire rig, and hence allow the effect of changing the load levels, frequency, environment, etc., to be investigated. In addition, since the test configuration is simple, access to the lining surface of the sample is relatively easy, which allows monitoring techniques, such as strain gauging or different kinds of imaging (including replica approaches combined with optical microscopy) [13–20] to investigate the test in-situ during testing. A substantial increase in fatigue evolution observations becomes possible (e.g. crack initiation and growth) that helps us to understand what happens during the test. The simpler loading case also allows better control of the test conditions and the ability to link the effect of these more directly to the observed fatigue mechanisms.

The application of infrared thermography as a full-field, non-contact, non-destructive method to detect damage has been increasingly studied in the past years. Infra-red thermography has been successfully used for several applications related to damage detection such as monitoring civil structures [21–23], exploring plastic deformations [24] and evaluation of fatigue damage in materials [25–29]. For instance, Ummenhofer et al. [30] applied thermographic approaches to investigate localized damage occurring due to fatigue on welded structures during tests, showing the great potential of such techniques in detecting and studying the evolution of localized damage throughout lifetime.

Moreover, lock-in infrared thermography allows investigation of the temperature distribution on the surface of a cyclically loaded component by using the loading signal to filter out all temperature measurement that is not fluctuating and the same frequency as the test. This enables erroneous temperature changes to be disregarded, reduces significantly the measurement noise and allows for the detection of even smaller changes in temperature that are only related to the applied fatigue loading. Researchers have used this variant to successfully evaluate fatigue parameters and also evaluate the occurrence of fatigue damage in metals [25,31,32]. In this study we have introduced this observation approach to particularly investigate the fatigue performance of multilayer overlay bearing coatings and the detection of cracks.

The present work proposes a significant improvement to established fatigue evaluation methodologies [10–12] by using lock-in thermography approaches. This will enable the assessment of fatigue performance of thin coatings (where replication approaches are less successful in tracking fatigue initiation and growth processes on the very thin electroplated coatings), and the improvement of damage assessment location in post-mortem observations. Such improvements help elucidate the mechanisms leading to the fatigue and fracture of the coatings [33,34], making possible the optimization and informed design of new fatigue resistant bearings. This is in contrast to the empirical process followed by using industry standard approaches such as the Sapphire test. This methodology also offers opportunities to detect early damage in other coated structures and geometries, showing its wider applicability beyond the bearing domain.

2. Materials and methods

2.1. Specimens

The specimens tested are standard semi-circular bearings (Fig. 1a), consisting of a steel backing, a leaded bronze interlayer and the final multilayer coatings. Such coatings have thin nickel based and tin based layers applied to the bronze interlayer by proprietary electroplating approaches. Preceding the electroplating coating procedure, the substrate was degreased with an alkaline cleaner and etched