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The effects of surface texture in reciprocating contacts – An experimental study

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ABSTRACT

The effect of surface texture on friction has been investigated experimentally for a convergent-divergent bearing, operating under different lubrication regimes. This was achieved using recently developed test apparatus that closely simulates an automotive piston ring-liner contact, by sliding patterned plane fused silica surfaces against a convex steel pad. Textured patterns, consisting of pockets of varying shapes and orientations, were assessed on their ability to reduce frictional losses, and results compared with those from a reference smooth surface. These tests were performed under a range of lubricant viscosities and applied normal loads in order to vary lambda values (i.e. the ratio of minimum film thickness to composite roughness) and hence highlight the beneficial or detrimental effects of texture in boundary, mixed and full film regimes. In the boundary and mixed regimes – the regimes where surface texture was beneficial – grooves normal to the sliding direction were the most effective patterns among those investigated, reducing friction by up to 62%. The results suggest that pockets act to increase fluid entrainment and hence reduce any asperity contact that is present. However, pockets at reversal were shown to increase friction dramatically. In the full film regime, when a liquid film fully separates sliding surfaces, texture was shown to increase friction compared to the smooth case. In addition to this, the experimental setup allowed cavitation in the ring-liner pairing to be imaged. These results may suggest that the increase in full film friction due to surface texture may be due to the interaction of pockets with the cavitated region. Furthermore, imaging results confirm previous research in that the number of cavitation streamers increase as the film thickness decreases.

1. Introduction

In recent years, interest in reducing friction in internal combustion (IC) engines has grown significantly. This has mainly been due to stricter emission standards. For instance, in 2009, the European Union (EU) introduced an average CO_2 emission limit of 130 g/km for new models of passenger car, to be achieved by 2015 [1]. Furthermore, from 2020 onwards, EU regulations set a target of 95 g of CO_2/km as the average emissions for the new car fleet [2]. As a result, motor vehicle manufacturers have been increasing their investment in energy efficient technologies, to reduce fuel consumption and consequently CO_2 emissions. As part of the drive to meet these increasingly strict standards, there is now a heavy focus on the reduction of friction between the piston rings and cylinder liners.

According to Holmberg et al. in [3], IC engines exhibit considerable energy losses, with a significant proportion (11.5%) of the total dissipated fuel energy being due to engine friction. Furthermore, based on data gathered from various studies, Holmberg [3] concluded that the piston/cylinder system accounts for 45% of the IC engine friction loses, of which 40–45% come from the piston [4].

It is predominantly for these reasons that the concern of reducing friction in the piston ring-liner conjunction has received considerable attention in the academic literature, with key issues such as surface texture being extensively investigated. Although many studies have suggested that surface texturing can positively influence load support capabilities, friction and wear, the exact geometric parameters and operating conditions which enhance load carrying capacity or increase film thickness are yet to be demonstrated. To address this, the current paper describes research, using a newly developed experimental set-up, into textured bearings under reciprocating motion, simulating the contact between a piston ring and a cylinder liner. The impact of surface texture geometry on friction force is assessed for three distinct lubrication regimes: boundary, mixed and full film. Moreover, the study experimentally investigates the effects

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of cavitation in the ring-liner pairing, in order to assess the underlying mechanisms for textured and non-textured specimens.

2. Background

There has been widespread interest in the last half century in the study of microtexturing bearing surfaces. The concept that surface "micro-irregularities" may have an advantageous impact on friction between moving surfaces was introduced by Hamilton, Allen and co-workers in the mid 1960s [5,6]. They pointed out that the addition of "asperities and depressions" to one face of a parallel rotary-shaft face seal can improve the load support capabilities of the seal. Nevertheless, the vast majority of research investigating the performances of textured bearings was carried out in the last two decades. The study of micropockets was brought back in focus by Tonder [7,8] who primarily researched the effects of texture addition to both moving and stationary bearing surfaces. His research showed that the optimal positioning of the texture is in the vicinity of the bearing's inlet. Two phenomena were indicated as potential explanations. On the one hand, the texture reduces fluid leakage from the contact by creating resistance. On the other, a "virtual step" is created, similar to the abrupt change in film thickness used in Rayleigh step bearings.

Etsion and co-workers have several contributions to the field of laser applied microtexture. For almost a decade, they have experimented with, and theorised on, a wide variety of bearing geometries and rig settings [9–12]. Moreover, Etsion provided the academic community with a comprehensive review on the subject of laser surface texturing (LST) [13]. Experimenting with parallel bearings in reciprocating motion under pure sliding conditions, it was demonstrated that certain micropocket geometries can reduce friction by up to 40%. Particularly interesting was the behaviour of deep pockets, which showed poor performance, explained by the higher quantity of oil needed to maintain hydrodynamic film thickness at the onset of starvation.

One of the most important conclusions of Etsion's experiments is that a multitude of co-dependent parameters contribute to friction reduction in microtextured bearings. The interdependency of these variables was later extensively investigated by Fowell [14].

Despite its influential contribution, Etsion's numerical work [9–12] was limited by mass conserving considerations. Ausas et al. [15,16] and Fowell [17,18] refined his theoretical approach using a mass conserving cavitation algorithm, and demonstrated that load support had been over-predicted in Etsion's non-mass conserving approach, leading to exaggeratedly low values of friction coefficient.

Ryk et al. [19,20] made further extensive experimental contribution regarding the effect of textured surfaces in reciprocating piston ring/liner interfaces. Test rig experiments were conducted to evaluate the reduction in friction for non-textured versus textured and partially textured piston rings, when in contact with cylinder liner segments. The authors concluded that, by partially laser surface texturing the piston-rings at both axial ends, friction reduction of up to 25% can be achieved in comparison with the non-textured reference specimens.

Valuable experimental work on reducing frictional losses in IC engines by using laser-etched texture was also carried out by Rahnejat et al. [21]. The group used a single-cylinder test engine to study variations in torque for three cylinder liner configurations: a standard liner, a diamond-like carbon (DLC) coated liner and a laser-etched textured liner. Improvements of up to 4.5% could be observed when using the laser-etched textured liner, compared to the standard liner.

Subsequent experiments by Costa et al. [22] employed a capacitance technique to measure the minimum film thickness in a reciprocating contact with one surface containing a micro-textured pattern. Several pattern types were tested and it was concluded that for a given load the addition of specific texture patterns can increase the minimum film thickness in the reciprocating contact. However, this observation cannot be generalised, as situations where texturing can be disadvantageous to lubricant film formation were also demonstrated, particularly at very low loads. Experiments showed that the shape and orientation of patterns has a direct influence on film thickness, with chevron patterns pointing along the sliding direction being most effective configuration. Conversely, measurements using grooved textures gave the lowest fluid film thickness. Another noteworthy observation form their work was that features larger than the elastic contact width resulted in lower film thickness values when compared to smooth test samples.

More recently, dynamometer tests were carried out on a real IC engine, as described by Etsion et al. [23]. A naturally aspired 2,500 cm^3 Ford Transit engine was used to evaluate the effect on fuel consumption of laser surface texturing, being partially applied to the upper set of piston rings. Under these conditions, it was discovered that fuel consumption for partially LST chrome coated piston rings was up to 4% lower than in the case of corresponding non-textured conventional barrel-shaped piston rings. The effect of LST on the exhaust gas composition was also investigated; however, no significant difference between textured and non-textured piston rings was observed.

Other recent experimental work has been reported by Podgornik et al. [24], in which friction force in a lubricated contact was measured by using a piezoelectric friction transducer. Various patterned surfaces, comprising semi-circular grooves and dimples, were tested at different sliding speeds. It was observed that, given the correct geometric features of the pattern (pocket width and distance between pockets), reductions in the friction coefficient of between 20% and 40% can be achieved.

In conclusion, by reviewing the most relevant experimental results in the area of microtexturing bearing surfaces reported over the last half century, it becomes evident that the addition of texture can have both beneficial and detrimental effects on friction reduction. Greater load support and/or thicker lubricating film values were reported when testing bearing surfaces with specific micro textured patterns. Despite these achievements, most of the previous experimental work was limited by an exclusive focus on the impact of patterns on friction reduction, i.e. the shape of texture features and the geometric parameters of the pockets. In the process, the importance of, and interactions between, all the variables and operating conditions involved in the study of plain and micro-textured convergent-divergent contacts have so far been somewhat overlooked.

The current research attempts to addresses the aforementioned shortcoming to a large extent, by employing a reciprocating rig capable of measuring friction force and film thickness in situ and simultaneously, as well as cavitation in plain and textured contacts. Furthermore and perhaps most importantly, the tests are performed while accurately controlling all operating conditions at all times.

3. Description of experimental apparatus

A specially designed reciprocating optical test rig was developed to allow for the simultaneous measurement of friction, film thickness and cavitation behaviour in lubricated smooth and textured surfaces. The study investigates friction and cavitation behaviour associated with the contact between the liner and the piston's top ring, aiming to closely replicate the interaction between the two elements inside an engine. The most significant limitation is the use of a single ring, whereas pistons in IC engines commonly have three and in some cases more rings. Moreover, the piston skirt comes in direct contact with the liner in the real scenario [25]. In addition to this, the stroke length used in this study is 26.8 mm, which is