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Looking into a laser textured piston ring-liner contact

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ABSTRACT

This paper presents an experimental study into the flow behaviour of lubricant in a reciprocating contact simulating a piston ring–cylinder liner pair. The aim was to understand the effects of cavitation, starvation and surface texture, as well as the interaction between these, in order to improve automotive engine performance. A custom-built test rig was used, in which a section of piston ring is loaded against a reciprocating, laser-textured, fused silica pad representing the liner. A fluorescence microscope focusses through the silica specimen onto the contact in order to image the distribution of dyed oil. Tests were performed using a range of texture geometries and orientations, under starved and fully-flooded lubrication conditions, with measurements being compared against those from a non-textured reference.

Under limited oil supply conditions, the non-textured reciprocating contact sweeps oil towards the reversal points (TDC and BDC), leading to starvation and increased friction. This issue is alleviated by the presence of surface texturing, with each pocket transferring oil from the inlet to the outlet of the contact as it passes; the result being 33% lower friction and oil distributed evenly over the liner surface. Even under fully flooded conditions, starvation is shown to occur following each reversal, as the change in sliding direction causes the cavitated outlet to become the oil-deprived inlet. This proof of cavitation-reversal-starvation, which occurs for up to the first 5% of the stroke length, depending on the lubricant's viscosity, corresponds to regions of high wear, measured in this study and on actual cylinder liners reported in the literature. This process is also counteracted by the presence of surface texture, with each pocket depositing oil into the cavitated region prior to reversal.

Fluorescence data also provides insights into other mechanisms with which different textures geometries control friction. Grooves oriented parallel to sliding direction increase friction as they appear to connect the high pressure inlet with the low pressure outlet, leading to oil film collapse. Grooves oriented transverse to sliding direction produce localised cavitation inside each pocket, which supports the theory that texture draws lubricant into the contact through the 'inlet suction' mechanism.

These findings can aid texture design by showing how pockets can be used in practice to simultaneously control oil consumption, and reduce friction and wear along the stroke. It should be noted that the lubricant transport mechanisms described above should also result from other types of depressions, such those produced by porous coatings (provided they are smaller than the contact area).

1. Background

1.1. Piston ring-liner lubrication

This research is concerned with understanding and improving the performance of automotive piston-cylinder liner contacts through the application of surface texturing. This contact serves four main functions; to *i*) make a dynamic seal between the combustion chamber and crankcase, *ii*) facilitate heat transfer from the ring to the liner, *iii*) produce a low friction sliding interface and iv) regulate the distribution of oil over the liner.

The main issues associated with piston ring performance that impact engine emissions are blow-by, oil consumption and friction.

Blow-by – *i.e.* the flow of combustion gases past ring-pack into the crankcase – reduces the pressure applied to the piston crown on the power stroke and therefore decreases the work done on rotating the

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crankshaft. Another undesirable effect of blow-by is that contaminant combustion products are introduced into the oil, which inhibit its effectiveness as a lubricant.

Oil consumption occurs due to oil flow between the crankcase and combustion chamber. This is undesirable since the loss of oil in the engine reservoir must be replaced, which costs money, while the increase in unburnt hydrocarbon exhaust emissions as the oils are vaporised and passed into the exhaust flow. Reducing oil consumption is also important to reduce oil in the exhaust gas that would otherwise clog the particulate filter and poison the catalytic converter [1].

Friction at the sliding piston ring interface consumes work directly from the thermodynamic cycle, and hence reduces the output work and efficiency of the engine. The amount of frictional dissipation depends on the sliding speed and lubrication regime that the contact is operating under. The latter is determined by the lubricant thickness, which in turn depends on the contact force, surface roughness and relative velocity between the piston ring and liner. However, other factors such as wear, starvation (*i.e.* the inadequate replenishment of lubricant caused by the multiple ring contacts and rapid reciprocating motion [2]), and presence of surface texturing also affect friction. It is important to reduce piston-liner friction since it is responsible for wasting a significant portion (~5% [3]) of a vehicle's total automotive fuel energy.

Modifying surface topography is a way of controlling *both* oil consumption and friction. However, few studies have looked at these two effects simultaneously (*i.e.* either surface topography's effect on oil consumption [4,5] *or* friction [6–11] have been studied). Their simultaneous investigation is necessary, since they are clearly interlinked.

1.2. Surface texture

Applying texture – *i.e.* features such as dimples or pockets – to the surface of engineering components is an obvious way to modify friction and has been investigated since the 1960s [12]. Surface texture is particularly suited to reducing friction in piston-liner type contacts, since the relatively low contact pressures preclude stress concentration and fatigue issues, which arise in components involving counter-formal contact such as gears. The impact of this approach can be significant, with friction reductions of over 50% being demonstrated in laboratory controlled tests [13], and some evidence suggests that this translates to measurable improvements in overall engine performance [14]. Compared to other energy saving solutions, surface texture is relatively cheap and simple to implement. It does not require components to be redesigned and can be incorporated easily into existing and future technologies. These reasons have led to an exponential increase in the number of technical publications of the subject, as noticed by Gropper and Wang [15].

The most widespread means of creating surface patterns in engineering components has been Laser Surface Texturing (LST) due to its ability to create micron sized features, using short, often femtosecond, laser pulses. This approach can be applied to a wide range of materials including metals [16], polymers [17], ceramics [18]. However, due to the limitations related to production times and manufacturing costs, other innovative production methods are being explored – these, along with their advantages over LST, have recently been reviewed by Costa and Hutchings [19].

Many of these studies have shown that surface patterns can improve friction, wear and load carrying capacity in fluid film bearings. In the earliest work on micro-texture (1966), Hamilton et al. [12] observed that surface texture can improve the load carrying capacity of a mechanical face seal, while later work (1968–1969) by Anno et al. [20,21] demonstrated a reduction in friction coefficient when using surface texturing. The wear debris entrapment properties of surface texture were later emphasised by Suh *et al.* [22] who concluded in 1994 that the ploughing component of friction in a non-lubricated bearing can be reduced through surface texturing. Following this, major work was later carried out by Etsion and co-workers, as summarised in [23,24].

A number of mechanisms have been suggested to explain how texture can reduce friction, however none have been proved; these include: i) pockets acting as micro-wedge [20] or step bearings [25], ii) pockets increasing the volume of lubricant entrained at the inlet [26], iii) pockets pressurising lubricant due to elastic deformation [27], iv) pockets pressurising lubricant due to cavitation ("inlet suction") [28,29], v) pockets trapping debris [30], vi) pockets feeding oil into the cavitated region to prevent starvation [13]. In order to apply texture effectively in practice, it is vitally important to understand which combinations of these mechanisms occur and under which conditions.

Recent work at Imperial College [13,31–37] has investigated a variety of surface texture geometries in a contact closely replicating an automotive piston ring-cylinder liner pair. The relationship between the friction reduction capability of surface texture and lubrication regime was characterised in [13] for a variety of textured shapes, while in [35,37,38] rules for the optimum pocket width, depth and spacing was established for the best performing shape determined previously (*i.e.* rectangular pockets orient normal to the direction of sliding, so as to be completely entrapped inside the contact). To help understand the mechanisms leading to the observed friction reductions of textured surfaces, film thicknesses were measured for the first time in a textured reciprocating contact operating in mixed lubrication regimes [31]. This showed that pockets act to increase the oil film thickness by 10 s of nanometres, causing a reduction in asperity contact and hence significant reductions in friction due to the steepness of the Stribeck curve in the mixed regime. The transient behaviour of individual pockets passing through the contact was studied in [32], where it was shown that pocket entrainment frequency is more important than physical spacing between pockets. In the most recent study [33], a close correlation was found between the amount of wear in the vicinity of the reversal point and the volume of oil within the pockets. This current study sheds light on the mechanisms behind these observations, in particular for cavitated and starved reciprocating contacts.

1.3. Cavitation

The phenomenon of cavitation is prevalent around piston ring-liner interfaces due to the converging diverging geometry of the contact and the lubricant's inability to sustain sub-ambient pressures [39], which leads to its transition from a liquid to a gas-liquid mixture. Cavitation manifests itself as gas pockets that form inside the lubricant at the rear or the contact. We suggest that the presence of cavitation is important as it can cause lubricant starvation due to the reciprocating nature of the contact. Fortunately, it has been suggested that such cavitation induced starvation may be alleviated by the supply of oil provided by surface pockets [13].

The first to suggest the film rupture boundary condition was Gümbel (1921) [40], while the multiple cavitated regions were first formulated mathematically by Swift (1931) [41] and Stieber (1933) [42]. Since this first suggestion of film rupture, considerable efforts have been made to investigate cavitation behaviour in various types of bearings, both numerically and experimentally. With regard to the theoretical investigation, a sequence of papers by Jacobson and Floberg [43], Olsson [44] and Floberg [45,46] were published between 1957 and 1974, proposing what is collectively referred to as the JFO theory boundary conditions. This theory was the first attempt at defining the reformation boundary conditions necessary to express closed cavities and the related change in expected load-carrying capacity.

Various experimental contributions to the understanding of film rupture and pressure variation in the cavitated region were made by Dowson *et al.* [47,48] and Etsion and Ludwig [49], both groups relying on photography techniques and pressure measurements. Arcoumanis