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Combined friction and wear reduction in a reciprocating contact through laser surface texturing

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ABSTRACT

The aim of this study is to gain insights into the interactions between laser-textured surface pockets and friction and wear behaviour of an automotive piston-liner pairing. To do this, a recently developed, reciprocating, test apparatus was used to conduct wear tests under highly loaded conditions. Fused silica specimens with a range of pocket geometries were rubbed against a convex steel pad and the resulting friction and wear data were compared with those from a non-textured specimen. Contact conditions were set to remove the influence of initial surface roughness on texture behaviour. These tests showed that, as the specimen become worn and surface roughness increases, the contact progresses further into the mixed and boundary regime. This leads to a significant improvement in the relative performance of the textured specimens, showing reductions in friction of up to 70%, compared with the non-texture case. This is consistent with previous results that have shown texture to have the effect of boosting film thickness in the mixed lubrication regime. Surface texture was also shown to reduce the volume of wear, by up to 69% (corresponding to a change in wear coefficient from 2.67e−4 to 0.81e−4 [mm^3/N m]). Another, important, finding is that both friction and wear reduce monotonically as the sum of the pocket volumes along the stroke increases. This may aid texture design, since it means that individual pocket width and depth values can largely be ignored, so long as the overall volume is maximised. The only exception to this trend is when the pockets are larger than the contact area. In this case, friction increases due to a collapse of the lubricant film, while wear reduction remains unaffected – a discrepancy which may suggest that pockets reduce wear and friction via separate mechanisms.

1. Introduction

Surface texture has been investigated as a means of controlling friction and wear in sliding contacts for approximately fifty years [1], since it is relatively simple to implement and may be used in conjunction with other lubrication approaches. Currently, surface texture is receiving increased attention due to the need to improve the energy efficiency of automotive contacts [2], which, in turn, is driven by stricter CO_2 emission limits [3], and the pressing issues of climate change. It is also the case that methods of producing texture are becoming cheaper and more accurate [4]. Despite all this, there is still a lack of firm evidence regarding the mechanisms by which surface texture affects tribological performance and this is limiting its development and application.

Investigations into how surface texture functions can typically be divided between those that relate to friction and those that relate to wear. The majority of early texture friction experiments were performed under full film hydrodynamic and elastohydrodynamic conditions [5–15]. Under these regimes, no conclusive improvement due to surface texture was demonstrated (with different studies showed the effectiveness of texture as being beneficial [13], detrimental [14], negligible [15]). Recently, however, more attention has been paid to measuring texture performance under mixed and boundary conditions, where several studies [16–21], have shown how pockets can lead to friction reductions of more than 50%. Furthermore, such conditions of mixed and boundary lubrication have become increasingly prevalent due to the recent trend towards lower viscosity lubricants aimed at reducing hydrodynamic losses [22].

The main explanations of how surface texture affects friction can be summarised as follows. In 1966 Hamilton and Allen [1,23], introduced the concept of “micro-irregularities” and suggested that surface texture can create resistance that acts to prevent fluid from escaping the contact. Following this, Tønder proposed that surface patterns generate a “virtual step”, within the contact that

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resembles the discontinuous change in film thickness associated with a Rayleigh step bearing [24,25]. Later, when studying the behaviour of transverse roughness in EHL lubricated contacts, Morales-Espejel [26] and Greenwood [27] suggested that each asperity peak entering contact zone behaves as a flow exciter that closes and opens the inlet to allow varying amounts of fluid to enter. Years later, Morales-Espejel, Tripp and co-workers [28] observed that, under EHL lubrication conditions, oil is released from the pocket under pressure, as a result of elastic deformation of the material in the contact area, and this could increase load support and hence film thickness. In 2006, the concept of “inlet suction” was identified in Olver and Fowell's work [29,30], whereby the reduction in pressure afforded by cavitation as lubricant expands into a pocket at the contact inlet leads to an increase in lubricant entrainment and hence film thickness. Very few of these mechanisms have been proved experimentally. In terms of experimental evidence, what is known so far is that pockets boost film thickness in the mixed and boundary regime [31], typically by a few tens of nanometres, which, due to the slope of the Stribeck curve in this lubrication regime, has a significant effect on friction [32]. Furthermore, a single pocket entrainment causes only a temporary increase in film thickness, which must be sustained by the entrainment of subsequent pockets otherwise it will become squeezed from the contact [32].

Studies into the effects of surface texture on wear have uncovered two main mechanisms, namely those of “lubricant replenishment” and “wear debris trapping”. The first of these relates to starvation – i.e. the reduction in film thickness due to an inadequate volume of lubricant present at the inlet [33], which is a believed to be an issue in automotive piston-liner contacts, caused by the rapid reciprocating motion of the contact and the fact that the oil must lubricate multiple rig contacts [34]. Starvation occurs when lubricant is pushed aside during one pass of the contact and does not flow back in time for the next pass [33]. In such situations, pockets on component surface can act as “micro-reservoirs” and increase the flow of lubricant back to the contact – a process known as lubricant replenishment [35]. Several studies have investigated this mechanism. Blatter et al. [36] ran pin-on-disc tests on specimens with varying groove geometries, showing reductions in friction coefficient and wear rate, coupled with the increased wear life that were attributed to the grooves' ability to store lubricant and replenish the track. In a more recent study, Borghi et al. [37] examined the chemical composition of textured and non-textured surfaces using Energy Dispersive Spectroscopy (EDS). This revealed significant quantities of Mg and Ca inside the dimples, thus demonstrating the retention of lubricant as the means by which the textured surfaces reduced friction and wear. Krupka et al. [38] also concluded that pockets can act as oil reservoirs capable of supplying lubricant into the contact region to overcome starvation. Their tests, carried out under EHL and mixed lubrication conditions, showed micro-dimpled surfaces overcame starvation and increased film thickness, which resulted in a measurable reduction in abrasive wear. Further important work suggesting that pockets reduce friction by acting as reservoirs for lubricants, and hence aiding a “micro-wedge” effect, has been provided by Rahnejat and co-workers [39,40]. Finally, the current authors observed that pockets carried lubricant into the cavitated region, and suggested that this could reduce starvation in reciprocating contacts, in which the cavitated region would otherwise be ingested by the inlet following reversal [16].

The second mechanism proposed to explain texture induced wear reduction is that of “debris trapping” whereby pockets remove particles, which would otherwise remain in the contact and accelerate surface damage. One of the first studies into this was carried out by Varenberg et al. using a flat-on-flat sliding contact under dry fretting conditions [41]. They showed wear debris being removed from the contact area and accumulating in the micro-textured pockets. Following this, they showed schematically how the pocket filling takes place: starting at the rim, followed by the centre and finally the base. In addition to this, Pettersson and Jacobson investigated the influence of surface texture on wear under starved and lubricated boundary conditions [18,19] and concluded that recesses can remove debris from the contact zone and hence delay or decelerate wear [19]. They used a reciprocating ball-on-plate tribometer and observed that grooves and squares parallel to the sliding direction reduced wear to negligible levels compared to an untextured surface. Further confirmation of pockets acting as debris traps has been obtained through the use of relatively recent techniques, such as SEM, that allow the morphology and chemistry of textured surfaces to be captured immediately after performing tribological tests. The first of these studies was carried out by Zum Gahr et. al [42] on plain and micro-textured steel/oxide-ceramic and self-mated oxide-ceramics sliding pairs. They noticed that instantaneous spikes in the friction force signal were present after 50 m of sliding for the untextured specimens but did not appear until after 400 m of sliding for the dimpled textured specimens. SEM micrographs of the worn surfaces obtained after the test showed that both fresh and partially compacted debris from the contact area had accumulated in the micro-dimples. Their conclusion was that the friction spikes observed early on in the untextured specimens sliding tests were due to particle entrapment, whereas the eventual spikes in the texture surface tests were due to the detachment of layers, or groups, of wear particles which had accumulated in the micro-dimples.

As described above, the majority of investigations into surface texture have, so far, focussed on either friction or wear but not both simultaneously. Since texture is most effective in reducing friction under mixed and boundary conditions, where appreciable surface contact and wear occurs, it seems likely that the effects of pockets on friction and wear are interlinked. The aim of the simple experiments described in this study is to explore the relationship between these three parameters. We hope that this will provide fundamental insights which will inform how deliberately applied surface texture can improve the lubrication of piston/cylinder contacts, since these account for 45% of the frictional energy dissipated in a typical automobile (frictional losses in turn make up 11.5% of the total fuel energy [2]). Furthermore, for the reasons mentioned above, it is believed that contacts in these components experience starvation and may therefore benefit from texture-enhanced lubricant replenishment. That being said, our findings may also be applied to other vehicle components, such as crankshaft bearings (which consume around 19% of a vehicle's fuel energy [43]), as well as other conformal contacts in application such as compressors.

2. Experimental procedure

2.1. Test rig description

This study used a custom-built reciprocating test rig capable of measuring friction force under conditions that partially replicate those found in an automotive piston liner pairing, as detailed in [16]. The reciprocating rig's main structural features are presented in detail in Fig. 1. This comprises a linear contact between a stationary convex AISI 52100 steel pad and a fused silica plate that slides along two linear bearings with a controlled amplitude of 28.6 mm and nearly sinusoidal velocity profile by means of a cam mechanism. Dead weights are attached to the silica pad specimen holder in order to generate an operating normal load, while a system composed of a heating circulator and two pumps allows