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Running-in and micropitting behaviour of steel surfaces under mixed lubrication conditions ☆

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ABSTRACT

The paper investigates the running-in of hardened steel surfaces under mixed lubrication conditions. Pairs of surfaces of both equal and differing hardness were loaded together under rolling/sliding conditions in a twin-disk rig, and the evolution of surface topography was investigated using in-situ profilometry. Evaluation of roughness parameters, height distributions and profile relocation showed that the running-in of these surfaces is a rapid process where the most prominent asperity tips undergo plastic deformation during the initial loading cycles. Finally, the pair of equal hardness disks, following further running in a separate series of experiments, was found to suffer from micro-pitting. This micropitting predominantly occurred along the tips of prominent asperities, and the potential link between running-in and surface failure is discussed.

1. Introduction

When freshly manufactured components are first loaded together in operation, they tend to undergo an initial settling period which is commonly termed 'running-in'. The running-in phenomenon is specified as a series of processes during which wear rates and friction for lubricated contacts stabilise [1]. These factors are governed by changes in the surface topography due to plastic deformation and mild wear and also chemical changes that may take place both in the lubricant and by tribo-film formation on the contacting surfaces.

It has been known for over a century that proper running-in can greatly lengthen the lifespan of engineering components, though this was not fully understood at the time. When real surfaces initially meet under a condition of no load they first contact at the tips of their asperities [2]. This causes the real area of contact to be far less than the apparent contact area. When load is applied, high pressures will be generated in the region of these micro-contacts and the asperity features will deform plastically until the increased bearing area is sufficient to support the applied load. Although the scenario described is one for dry contact it is also the case for mixed lubrication conditions where the film thickness is of a similar order of magnitude to the composite surface roughness, and aggressive asperities are in direct metallic contact.

The initial period of plastic deformation can modify the subsurface microstructure of the contacting materials, resulting in a degree of work-hardening [3]. However, most investigations have focussed on the geometric changes in the surface topography as this has the most immediate implications for the hydrodynamic performance of the interface.

The geometric change during the running-in of a surface is most frequently described by the use of the average roughness parameter (Ra). Though used liberally it does not provide any information regarding the shapes of the asperities [4]. Whitehouse and Archard [5] set out to quantify the surface roughness using various statistical parameters that had not been previously employed as descriptors of topography. They considered the mean radius of curvature of the asperity tips to be an important descriptor of a profile measurement. It was found that when subjected to loading, surface measurements show a rapid increase in radius of curvature of asperities as they deform [6]. When operating under elastohydrodynamic lubrication (EHL) conditions, this change allows for more effective lubrication as a result of the less severe pressure spikes experienced at each 'micro-contact' due to increased conformity as the asperities become more rounded.

Examples of the importance of considering running-in when commissioning new surfaces can be seen in the work of Østvik and Christensen [7] who showed that the load carrying capacity of an EHL contact was greatly improved by running-in and surfaces

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subsequently scuffed at higher loads. It was also found that as surfaces ran-in, asperity contacts became less frequent as the highest features were removed or flattened. Early experimental investigations into the running-in of lubricated surfaces tended to refer to the gradual reduction in roughness as a wear process and only hinted towards the plastic deformation of asperity contacts [8]. More recently, the improvement in hydrodynamic performance due to running-in has been demonstrated by the work of Lord and Larsson [9] using the electrical contact method on a variety of test surfaces, where all specimens showed reduced levels of metallic contact once run-in.

The work of Andersson [10] into the running-in of gears explained the flattening of asperities as a wear process. Running-in experiments showed that the lambda ratio, defined as the ratio of film thickness to composite surface roughness, is an important parameter in determining the extent to which the asperity features on engineering surfaces are loaded. Scanning Electron Microscope (SEM) imaging of gear tooth flank replicas showed surface asperity peaks which had been smoothed and flattened as a combined effect of surface yielding and wear, while the valley features remained unchanged, with no modification occurring in the region of the pitch point.

Bishop and Snidle published a number of papers describing their experimental test rig work using circumferentially ground steel disks [11,6,12]. Their experiments showed that as surfaces are loaded together under EHL conditions, asperity features become rapidly flattened in response to increasing load. The mean peak radius of curvature was also seen to increase significantly as more load was applied and the valley features, which were not subject to the same high contact pressures or degree of interaction, retained their shape [6]. Experiments performed to test the effect of surfaces plastically deforming and conforming to one another showed that a hard disk loaded against a less hard disk would leave an imprint of its micro-geometry on the counterface [12] and that the running-in process is essentially one where the micro-geometry of surfaces conform or accommodate each other via rapid plastic deformation. The important implications of conformity of micro-geometry could be seen much earlier in work by Tudor [13], where changing the relative position of two run-in surfaces reduced their hydrodynamic performance. These results suggest that running-in with engineering surfaces is not simply a general flattening of features but an accommodation process where the deformation of asperities is determined by the interaction with corresponding asperities on the counterface.

Lohner et al. [14] investigated the running-in of lubricated line contacts in both gear and disk machine tests. They quantified the effects of lubricant specification on changes in surface roughness parameters and actual surface micro-geometry using profile relocation techniques and, like others, found that the surface modification during running-in was limited to asperity tips.

Recent interest has been directed towards the long term implications of the effect that plastic deformation of asperities has on surface fatigue life. Finite element modelling work conducted by Bryant et al. [15] investigating the plastic deformation of rough surface line contacts draws attention to residual tensile stresses around asperities introduced by plastic deformation. Bryant also demonstrated that the residual rough surface deformation only affects the asperity peaks and does not extend to the valley features.

This paper presents the results of an investigation into running-in under mixed lubrication conditions in a series of disk machine tests. It is shown that under the conditions examined, running-in is essentially a process of plastic deformation where asperities on contacting surfaces rapidly conform to each other. Furthermore, the effects of asperity plastic deformation on the long term fatigue performance of the surface is considered.

2. Power recirculating twin disk test rig

The running-in tests shown here were undertaken using a twin-disk machine, where power is recirculated between the EHL contact and a gear pair, such that the drive motor only has to overcome frictional and other losses in the system. Fig. 1 shows the main components of the test rig.

The test disks are 76.2 mm in diameter and are crowned with a radius of 304.8 mm, giving a self-aligning elliptical point contact with a nominal aspect ratio of 4:1, with the major axis parallel to the shaft. The disks are case hardened to a surface hardness of 800–840 Hv, and are made from a typical alloy gear steel to Rolls-Royce specification 6010. Importantly, the crown is produced using an axial grinding process which gives a surface with directionality similar to that of ground gear teeth in relation to the surface kinematics. The as manufactured surface finish has an average roughness (Ra) between 0.3 and 0.4 μm. The shafts on which the disks are mounted are gear connected, giving a rolling/sliding contact with a slide/roll ratio which depends on the chosen gear ratio. The work presented here used slide/roll ratios of 0.25 and 0.5. The fast shaft rotational speed is steplessly adjustable between 200 and 3000 rpm, and is driven by a 5.5 kW electric motor controlled by a variable frequency drive.

The disks are loaded together hydraulically, allowing the generation of Hertzian maximum contact pressures of up to 2.1 GPa. The contact between the disks is lubricated by jets at both inlet and outlet of the contact, with OEP-80 naval gear lubricant which is a mineral oil with EP additives. OEP-80 is a performance specification, and as such the properties of lubricants meeting that specification can vary, but Oila [16] carried out detailed measurements and found the viscosity at ambient pressure to vary from 0.113 Pa s at 40 °C to 0.031 Pa s at 100 °C, with the pressure-viscosity coefficient (obtained from an empirical viscosity correlation) falling from 2.58×10^{-8} Pa^{-1} to 2.03×10^{-8} Pa^{-1} over the same temperature range.

Traction at the contact is measured via a strain-gauged quill shaft between the drive gearing and the slow shaft. This allows the torque in this shaft to be measured and recorded throughout the experiment. A separate series of runs of the test rig was carried out with the fast shaft disconnected from the power recirculation gears so that the disks ran in a pure rolling configuration. In this means of operation two identical pairs of shaft support bearings provide the frictional resistance to rotation. This can thus be

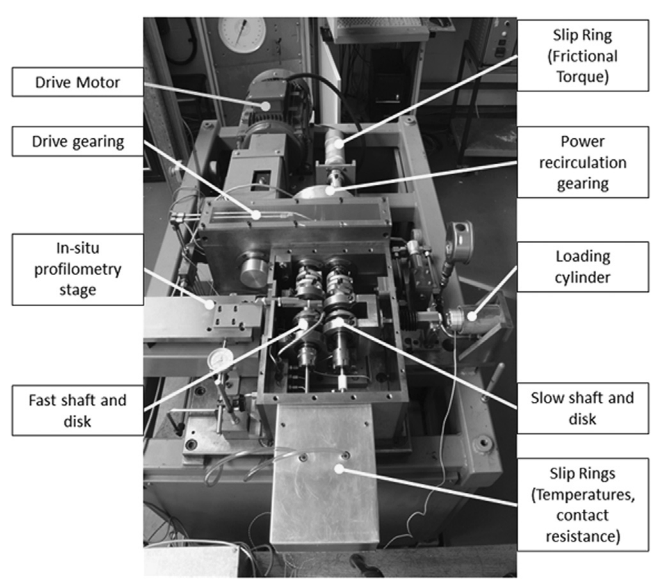

Fig. 1. View of test rig.