Tribology International ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Development of valve train rig for assessment of cam/follower tribochemistry

MacDonald Ofune*, Paul Banks, Ardian Morina, Anne Neville

Institute of Functional Surfaces (IFS), University of Leeds, Leeds LS2 9JT, UK

ARTICLE INFO

Article history:
Received 11 October 2014
Received in revised form
18 February 2015
Accepted 20 February 2015

Keywords:
Single cam rig
Friction
Wear
Tribochemistry

ABSTRACT

Component bench tests are a crucial part of a tribology assessment experimental programme for most engines and subsystems. This is because they test the components under conditions simulating the operating characteristics of the system. These have become very important as they shed more light into the friction, wear, lubrication and importantly for this study, the tribochemistry of valve train systems. This work outlines the procedure for the development of a single cam rig (SCR) from a 1.25L FORD Zetec (SE) engine. Friction plots were used to validate the data obtained from the newly developed single cam rig with Mn–phosphate coated and polished follower against a cast iron camshaft. The tribofilm formed using normal and mid Sulphated Ash, Phosphorus and Sulphur (SAPS) 5W-30 oils were evaluated and correlated to the friction and wear properties of the tribopair.

Raman and FIB–SEM/EDX investigations of the tribochemical films showed that the normal SAPS oil produced patchy, thick (80–100 nm) and well dispersed tribofilm with better wear prevention capabilities. It was observed that Mid SAPS oil had lower wear prevention due to loosely dispersed and thin tribofilms. Absence of tribofilms at the centre of the insert with this oil also suggests that formation and removal processes are an integral part of the wear mechanisms in highly loaded cam follower systems.

1. Introduction

Environmental legislation calls for the use of engine lubricants with less impact on the environment in terms of exhaust emissions, while engine users demand more mileage per litre of fuel without any compromise on engine durability. From this standpoint, engine manufacturers require the optimum combination of materials, surface coatings and lubricant additive packages to minimize friction and wear in the piston, bearing and valve train components. The move from normal to mid and even ultra-low SAPS oils risks an increase in wear on engine tribocomponents. For this reason, there has been increased experimental work on the tribochemistry/tribology of 'low' SAPS containing oils against surface coatings, particularly DLC's and how they affect friction/wear of engine components-cam/follower tribopair.

It is estimated in the valve train, that the cam follower accounts for 80-85% friction losses while the remaining resistive losses are due to valve guide/valve stem, tappet/tappet bore, end bearings and other losses. These values are strongly influenced by speed which reflects urban and motorway drive cycles. friction losses [1,2]. Therefore, for improved engine efficiency, research into this tribopair is necessary. Accordingly, numerous authors have designed and used valve train rigs to study friction [3–7], wear [8–10], film thickness [11–14] and tribochemistry [15,16] at the cam tappet contact. Historically speaking, Dyson and Naylor [3] were perhaps the first to investigate friction at the cam follower interface using a push rod assembly where the tappets were held in place by a pair of flat springs, and the corresponding stresses measured by means of piezo electric gauges.

Ito et al. [8] studied the friction with the use of two strain gauges mounted on a push rod and shaft. Using both the deformation on the shaft and the force on the tappet, the friction coefficient was evaluated with a good degree of accuracy. The final apparatus was mounted on an engine for wear testing. A modern configuration of the cam/follower is the direct acting mechanical bucket type with a somewhat high sliding. Pieprzak et al. [4] used the configuration to develop a valve train rig for the evaluation of friction due to tappet/bore rotation. This was achieved by preventing the tappet/bore assembly from rotating with a rigid mechanical quill. High tappet/bore frictions of 13% were recorded at low speed with lower values at high speed. In our study, this approach was not ideal as tribofilms are affected by tappet/bore motion and lubricant entrainment velocity.

A vast majority of the cam follower studies involve the use of rigs with multiple cams. In these types of rigs, camshafts have lobes at 90° from each other thus making computation of torque

* Corresponding author. Tel.: +44 776 835 8068.
E-mail address: menmaof@leeds.ac.uk (M. Ofune).

http://dx.doi.org/10.1016/j.triboint.2015.02.026
0301-679X/

and relating it to a specific cam location more difficult. This is also coupled with system instabilities [17]. In order to understand different regions on the cam profile where significant friction and wear benefits can be achieved, it was pertinent to develop a single cam rig where the friction torque is investigated with respect to cam angle. Some aspect of this have been published in the literature [18,19]. The rig is also furnished with high data recording and control with 1 data point for as low as 0.2° of camshaft rotation (1800 data points for one rotation of the camlobes). This will provide a better understanding of the cyclic processes in the cam follower contact and give us the ability to link the friction/wear properties to the tribochemical films across the camlobes and inserts.

Conducting tribochemistry studies of engine valve train systems is a very difficult task due to sliding/rolling motion, film thickness variation, and high loads/stresses experienced at the contact of interacting asperities. These dynamic variations cause a significant distinction on the tribofilm formation and removal across the cam profile and on the inserts. According to reports by Liu and Kouame [18], tribofilm investigations at seven locations on the cam profile (±14°, ±10°, ±4° and cam nose-0° degree) showed that the tribofilms were different at each location and were made up of short and long chain polyphosphate films in which temperature had a significant effect on their tenacity. Long chain polyphosphates tribofilms were shown to have good antiwear characteristics [18]. The formation/or reaction kinetics of polyphosphate film are strongly influenced by temperature. It has been reported that the bulk of the films are composed of short chain with long chain at the topmost surface but this structure can be altered in fully formulated oils [20,21]. Similar findings with engine oil on metal surfaces have been reported to contain films composed of low concentrations of Zn, P, S with Ca and O as the topmost layer of the tribofilm [15]. These species have been reported to affect the antiwear properties of tribofilms [22,23]. Uy et al. [24] also investigated the tribofilms formed on tappets with Raman and observed Ca/Zn orthophosphate ($Zn_3(PO_4)_2$), $CaCO_3$, Fe_3O_4 with some undecomposed hydrocarbon on the surface.

Currently, coatings/surface treatments are finding increased application in valve train systems. For instance, super finishing before deposition of TiN achieved 40% reduction in friction torque with 1–2% achievements in fuel consumption [5]. Similar results were obtained in a motored cam rig by super carburizing inserts to R_a of 0.09 μm [6]. The utmost in the use of coating architectures, is the sporadic increase in the use of DLC's in the improvement of cam follower friction/wear. DLCs have been touted for their low friction and wear-resistant properties in boundary/mixed lubrication. Friction coefficients as low as 0.006 have been reported in additivated oils [25]. However, due to vast DLC surface finishes available, these results are not general. DLC tribo properties are influenced by dopant elements, the quality of the oil, the submicron interlayers, and the need for adhesion of coating [26]. There is also a difference in their behaviour according to the interaction with oil additives which have conventionally been designed for ferrous surfaces [15,27,28].

It will be noteworthy to mention that the tribofilm removal rate, formation and stability are of utmost importance in highly loaded boundary/mixed tribological systems and so also in cam/followers. Gangopadhyay and coworkers [15] observed significant abrasive marks on DLC coated tappet in motored tests. This indicates a cyclic film removal process. There was also evidence in the tests performed on mixed sliding/rolling contacts by Haque et al. [17] on motored multiple valve train rig and MTM. SEM/XPS micrographs of the H-DLC coating revealed irregular polishing with the centre of the inserts showing high atomic species of the Cr interlayer while regions further from the centre revealed lower Cr in a ratio of 16.5:1. This indicates a high wear towards the centre of the inserts. Polishing can be very detrimental to engine components as the surfaces may lack the retention of engine lubricant necessary for the optimal operation. This heterogeneous polishing could be because the centre of the insert is in direct contact with the cam, flank, shoulder and ramp positions of the cam while further from the centre, contact is more predominant with the nose. Also, huge contact pressures lead to coating damage and peeling. Similar results have been reported by Kodai [29] on non-metal doped DLC coating deposited by RF plasma.

Furthermore, in commercial applications, DLC coatings have been tested in fired engine conditions to ascertain their performance in realistic operating conditions. In a recent paper by Durham and Kidson [10], fired engine tests were performed for 300 h on four different DLC coated tappets where they reduce camlobe wear by as much as 50–75 folds in the inlet/exhaust camshafts when compared with standard steel. However, it was observed that only one of the coatings tested (HHS) showed resistance to polishing, spallation and pitting wear. A similar approach has been employed on motored tests by Haque et al. [17]. Using a different deposition process (unbalanced magnetron sputtering) from [10] in the production of W-DLC [29], no spallation or peeling was observed but the coating was worn from the surface in motorcycle stand tests.

Component bench rigs examine the tribopair under practice oriented engineering structures, thus better simulating the operating characteristics of the engine [30]. For instance, the friction characteristics of the inlet camlobe in a motored single cam rig, though, not identical with the conditions in an engine, have been reported to mirror those of the fired engine [31]. Consequently, bench/motored cam follower tribometers have become vital as they shed more light into the friction, wear, lubrication and more importantly, the tribochemistry of valve train systems.

This study outlines the development of a single cam follower rig for the study of tribochemistry on the inserts in boundary/mixed lubrication regime. It is the objective of this study to investigate the composition and thickness of the tribofilm and correlate this to friction and wear on the inserts. Mapping of tribofilm across the inserts has not been widely investigated. This study has shown that the thickness and composition of the tribofilm vary significantly, particularly at the centre of the insert. This is highly influenced by the oil type and temperature. Assessment of surface interactions with normal and mid SAPS oils on Mn–phosphate coated and polished inserts are discussed, as a means of validating the data obtained from the newly developed rig.

2. Rig developmental procedure

2.1. Modification of engine cylinder head

Fig. 1a shows a slice which was produced from a 1.25L Ford Fiesta Zetec (SE) engine with a double overhead camshaft (DOHC) and flat faced removable inserts in bucket arrangement. This was used in a non-fired mode and driven by a 2.2 kW ABB motor. The camshaft was slightly modified to accommodate the design configuration of the rig. This was achieved by sectioning the inlet camshaft into four bits in sets of 2 cam lobes each. At the ends of the new camshafts, holes were made to fasten them to stud shafts. The modified camshaft assembly is shown in Fig. 1b. The clearance between the follower and base circle of the camlobes was maintained at 0.21–0.25 mm. This was achieved by using standard production inserts with slightly greater thickness from 2.60 to 2.70 mm. The centre of the camlobe was also slightly offset from the centre of the inserts to allow for some bucket/tappet rotation and reduce friction torque.

This shaft was then connected to a high sensitivity torque transducer by means of flexible couplings to account for any misalignment. The plain bearings at the centre between the camlobes were ground off to prevent any contact and eliminate friction at this