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Comparison and analysis of protective tribofilms found on heavy duty exhaust valves from field service and made in a test rig

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ABSTRACT

Increasing demands from environmental legislations are changing the conditions that the valve system is exposed to in heavy duty engines. Increased pressures, higher temperatures and lower amounts of particulates which can build up a protective film are some of the increasing challenges which the system has to endure.

Thick protective tribofilms found on heavy duty exhaust valve surfaces have been analysed with SEM, TEM, EFTEM, STEM–EDS, Nano-indenter and XPS in order to get a better understanding for the tribofilms properties.

Two analysed samples are presented in this paper, from a field service truck and another from a test rig which uses vaporised engine oil to simulate the particle flow. The tribofilms are built up from several layers with varying compositions. Most of the material originates from oil additives, but also metallic oxides and other carbon compounds produced in the combustion system.

The similarities between the rig generated tribofilm and the tribofilm found on the field tested valve verify the test rig behaviour and opens up for realistic wear testing where the importance of the protective tribofilm can be investigated in detail that is not possible in motor tests.

1. Introduction

The exhaust valve system of combustion engines experiences a very complex contact situation of frequent impact involving micro-sliding, high and varying temperatures, complex exhaust gas chemistry and possible particulates, etc. The combustion pressure subjects the valves to high forces that deflect the valve disc. The deflection causes a small sliding movement in the sealing interface, which in turn causes wear [1,2].

The tribological conditions in the exhaust valve system are expected to become even more severe for engines that will follow the future emission regulations. Following such strict regulations will require enhanced combustion and cleaner fuels. These improvements are meant to result in less combustion residues. However, this improvement also results in a problem. The residues help to ease the very harsh contact conditions in the valve sealing interface, by forming protective tribofilms. This mechanism has been observed on several field tested modern exhaust valves in an earlier paper [3], but also reported for older engines [2].

Ashes constitute an important part of the particulate matter generated inside a heavy-duty diesel engine. These are typically a product of burned or vaporised engine oil. The ash particles have to pass through the exhaust valve interface when ventilating the cylinder and are therefore candidates for delivering material to the protective tribofilm. The ratio of ash in the total particulate matter generation is believed to increase in future engines as the combustion process is better controlled, decreasing the products from rich/lean mixture. Although the total particulate production in the cylinder is decreasing [4].

A test rig has been developed to test and evaluate the wear mechanism of the valve system sealing interface with different test parameters in a simple and cost effective way, as further presented in [5]. Bonuses of a simplified rig testing include that it enables the separation of parameters that are not possible to study separately in a combustion engine and furthermore the possibility to repeatedly interrupt the testing, analyse the surfaces and then continue again, in a time effective manner.

In previous work, a series of PVD-coated valves were tested with the aim to reduce the wear in the sealing interface in hot and dry conditions. Some of the coatings initially worked well showing a reduced wear rate, but they soon failed due to substrate fatigue under heavily loaded sliding conditions [5].

To further enhance the test rig to allow variations in particle flow, an oil inlet was added to a nozzle that streams hot air

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through the valve. This creates a flow of ash particles between the valve and the seat when the valve is open. When inserting the vaporised engine oil, a thick tribofilm was formed on the contact surface of the valve. This tribofilm proved to have protective wear properties and an elemental composition similar to tribofilms found in earlier work [3] when analysing the surfaces on varying field specimens.

In this paper, the tribofilms found on a representative field tested valve which has exhibited low wear rate (estimated recession of 50 μm) and the film found on a rig tested valve system have been deeply analysed and compared. The analysis aims towards gaining a better understanding of the composition and mechanisms formation of the tribofilm, and also to verify that test rig gives representative tribofilms. The similarities and differences are discussed with regard to friction and wear properties and the possibilities offered by the rig testing are analysed.

2. Experimental

Two exhaust valves have been investigated, one taken from a field tested truck with a service mileage of about 210,000 km (called *Field sample*) driven in city traffic with lots of start/stop actions, the other valve has been tested in an in-house built rig designed to simulate the contact situation (called *Rig sample*). The worn surfaces were investigated using Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Scanning Transmission Electron Microscopy–Energy Dispersive Spectroscopy (STEM–EDS), Energy Filtered Transmission Electron Microscopy (EFTEM) and X-ray Photoelectron Spectroscopy (XPS). Further, one of the valves was evaluated using a nano-indenter.

The contact surfaces of the valves were made of a welded Stellite F alloy, mainly consisting of Co, Cr and Ni. The counter surface of the valve seat insert of the *Field sample* has a Fe-based material alloyed with Co and Cu and the counter surface to the *Rig sample* had a Fe-based material alloyed with Mo and Cr.

The major parts of the test rig are described in Fig. 1. A hot air supply was mounted to the inlet in which oil was added and vaporised before entering the inlet channel.

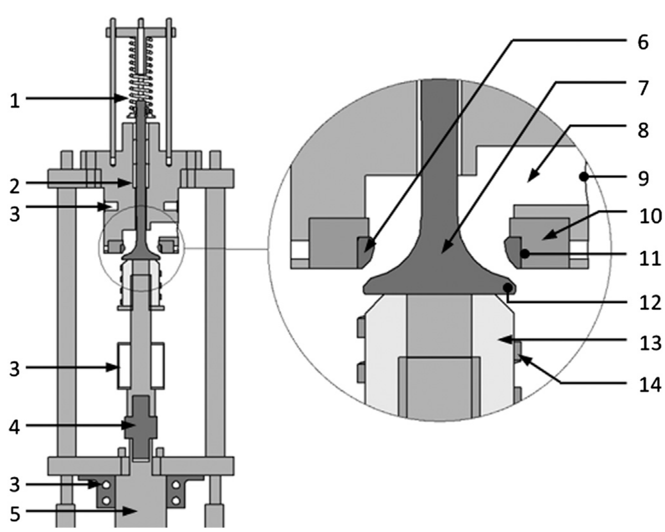

Fig. 1. Schematic cross section of test rig and its main parts. 1—Spring mechanism for valve–VSI separation; 2—Linear valve guide; 3—Water cooling channel; 4—Force measurement; 5—Hydraulic actuator; 6—Valve seat insert; 7—Valve; 8—Inlet/exhaust channel; 9—Inlet temperature measurement Ti; 10—VSI holder; 11—VSI temperature measurement; 12—Valve temperature measurement; 13—Heat and load transfer cylinder (outer shell in Cu and inner core in Stainless steel); and 14—Resistive heater.[5].

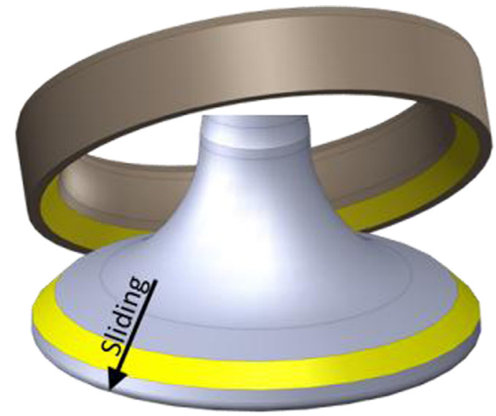

Fig. 2. View of the valve and valve seat inset geometry. The sealing interface is coloured yellow and sliding direction of the counter surface on the valve is marked. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2 shows the contact geometry of the mating surfaces. When the combustion pressure (or in the test rig applied force) is applied the valve will flex somewhat, yielding a small sliding in the contact interface (as marked in the figure) of about 5–10 μm. The valve is freely suspended, meaning that the valve is allowed to rotate and therefore the surfaces in contact will vary.

The Rig sample was tested for 500,000 cycles with short interruptions to allow wear measurement, after 1000, 8000, 30,000, 100,000, 200,000, 300,000, 400,000 and 500,000 cycles. These interruptions are shorter than the stops experienced by the *Field sample* which can be several hours or even days e.g. the truck is off during a week-end. The test duration of 500,000 cycles in the test rig is significantly shorter than the 210,000 km of the field tested sample due to the evaluation method which is based on the initial wear rather than the long-time recession measurements. With this method the test time is reduced to ~5 h instead of over 1000 h that would be required in an engine cell. The sealing force was 20 kN (equivalent to approximately 160 bar) and the frequency was 7 Hz. The rig operates at an elevated temperature to mimic typical temperatures of a real valve. The heater located beneath the valve was set to 750 °C and the air inlet was set to 600 °C. The oil flow of 0.3 ml/min was injected into the hot air stream which had a flow rate of 550 l/min.

2.1. Hardness

Nano-hardness measurements were performed on a polished cross section of the *Field sample* valve. A CSM Ultra Nano Hardness Tester with a Berkovich diamond tip was employed to make indentations in depth sensing mode to a depth of 200 nm. Seven indentation values were used for the tribofilm hardness and 10 for the substrate.

2.2. XPS

The chemical composition of the valve surfaces of the *Field sample* and the *Rig sample* was investigated using XPS. Surface high resolution depth profiles were acquired using a PHI Quantum 2000 system. The X-ray spot used to generate signal was 200 μm in diameter. A 4 kV Ar ion beam was scanned over a 1×1 mm^2 area, using 0.5, 2, 10, 40, 100, 110, 120 and 140 min sputtering times to acquire a sputter depth profile.