Wear 330-331 (2015) 193–198

Contents lists available at ScienceDirect

Wear

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

Formation and breakdown of oil residue tribofilms protecting the valves of diesel engines

R. Elo *, S. Jacobson

Ångström Tribomaterials Group, Department of Engineering Sciences, Uppsala University, Sweden

ARTICLE INFO

Article history:
Received 15 September 2014
Received in revised form
20 January 2015
Accepted 27 January 2015

Keywords:
Internal combustion engines
Valve
Wear protection
Lubricant additives
Tribofilm
Test rig

ABSTRACT

The contacting surfaces of modern valve systems experience a complex contact situation with repeated micro sliding at high temperatures and pressures. The wear rate of the surfaces has to be extremely low to fulfill the high demands on engine efficiency during its entire life-time—wear will cause valve recession and thus make the combustion less efficient. In addition to this, legislation requires reduced particulates in the emissions, which leads to aggravating conditions for the valves.

Studies of field samples from well-functioning engines have shown that a protective tribofilm is formed on the contacting surfaces of the valve. This tribofilm is primarily built up from combustion residues of the engine oil and fuel, making its composition sensitive to their additives.

Since the low wear rate is dependent on the formation of a tribofilm based on oil residues, while future legislation will demand even cleaner emissions, a deepened understanding about the formation and dynamics of these tribofilms is needed. How quickly are they formed, how quickly do they wear, do they require constant supply of “building material”, can they efficiently protect the surfaces also when substantially less building material is available?

In the present study, the formation and breakdown mechanisms of this type of protective tribofilms have been investigated in a specifically designed valve rig. This rig uses real engine components and allows controlled addition of oil mist (in the present case from a fully formulated engine oil) into a hot air stream, passing the operating valve.

Four phases were identified in the tribofilm dynamics. In the first—formation—phase, oil residue particles become trapped on the sealing surfaces of the valve, and then smeared out between the closing surfaces to form a covering tribofilm. In the second—equilibrium—phase, the tribofilm coverage is stable, meaning that the addition of new particles is balanced by wear of the film. Two types of films form, one thick carbon-based film and one thinner additive-based film. If the supply of oil is cut off, the third—breakdown—phase commences. Here the carbon-based film is quickly removed while the additive-based film keeps protecting the valve surface for numerous closing cycles. When also this film become worn through, the final phase—wear of exposed valve material—commences, involving severe wear and oxidization. Interestingly, it was found that the breakdown was slower if the equilibrium phase was longer, indicating that the additive-based tribofilm becomes more durable by being more worked.

1. Introduction

In four stroke engines, the intake valves open to let air flow into the combustion chamber and then close to facilitate the compression and combustion of the fuel and air mixture. The exhaust valves are closed during this phase, and then open to let the hot combustion products flow out of the chamber, after which they close and the process is repeated [1].

The contacting surfaces of the valve experience a complex and demanding contact situation. The closing of the valves involves a relatively high impact against the valve seat. The valve head then buckles somewhat when the pressure steeply increases in the combustion chamber. This shape change leads to micro sliding in the sealing interface, typically in the range of 5–10 μm [2]. This sliding motion has for long been considered one of the main causes of wear [3]. Further, being positioned right next to the combustion also means being subjected to high temperatures, especially so for the exhaust valve, which is repeatedly passed by the hot combustion residues. Wang et al. found that adhesive wear, abrasive wear, shear strain controlled wear and oxidation wear were predominant in a valve seat simulation test. They also found that the wear increased with

* Corresponding author. Tel.: +46 184717241.
E-mail address: robin.elo@angstrom.uu.se (R. Elo).

http://dx.doi.org/10.1016/j.wear.2015.01.066
0043-1648/

increased load and number of cycles but decreased with increasing temperature. This effect was acknowledged to be due to accelerated formation of oxide films, preventing direct metal to metal contact [4]. When investigating the dependence from cycle numbers on the wear of valves, Chun et al. found that wear occurred due to direct contact between the base metals. Continued wear was then prevented when a tribochemical reaction product layer formed by reaction between the base metals, air and combustion products [5].

To offer good performance during the entire lifetime of the engine, the wear rate of the valve surfaces has to be extremely low. The valve system is typically not exchanged, so it has to survive the full lifetime of the engine, which for heavy-duty diesel engines is in the range of millions of kilometers. This corresponds to approximately one billion closing cycles for the valve. In the worst case, local wear of the valve creates leakage from the combustion chamber. The leakage channel rapidly becomes overheated, which leads to catastrophic wear. But also an evenly distributed, slow wear of the valve surfaces is unacceptable if it leads to a recession of the sealing position. This changes the combustion volume and impairs the flow of gases through the valves. The recession makes the combustion less efficient, and therefore leads to increased fuel consumption. The negative effect of recession has been measured by Kent and Finnigan, showing that recessions of 1 and 2 mm reduces the power output by 3% and 10%, respectively [6].

The valves used today manage to keep the required, extremely low, wear rate partly due to the formation of a protective tribofilm on the contacting surfaces. The tribofilm is primarily built up by residues from the engine oil and fuel [7]. A test rig specifically designed to perform fundamental studies on real valve components, has been employed in previous studies [8–10]. In its latest version, it has proven capable of reproducing the type of tribofilms found on field samples [9,10].

Since the tribofilms are built up from combustion residues from the engine oil and the fuel, their composition and structure are sensitive to the amount and type of additives in oil and fuel. This has been evident from samples run in the valve test rig [10] as well as from field samples [11].

The demands for cleaner emissions with less particulate matter are escalating. Within the European Union, the legislation is according to the euro classification of heavy-duty vehicles [12]. To fulfill these demands, the engine oil and fuel should preferably include less additives, since these often are not fully combusted, but form particles. A byproduct of such an improvement is that the supply of building material for the protective tribofilms decreases, which may lead to a reduced protection of the sealing surfaces and therefore an intensified wear and possibly premature engine failure. These changes constitute a great challenge for engine developers and valve producers. How shall the current, extremely low wear rates be kept when the supply of primary building blocks of the tribofilm becomes strongly reduced?

In previous studies by the present authors, the valve surfaces have been studied either when the tribofilms have been fully formed or when the valve couple has started to wear—indicating that the tribofilms have been removed. This has provided a lot of valuable information but limited insights into the dynamics of the formation and breakdown of the tribofilms. To achieve such insights, the current study also includes tests simulating the initial processes, when the tribofilm is first formed, and conditions where established films are expected to wear off or break down.

2. Materials and methods

2.1. Materials

A test rig based around exhaust valves, valve seat inserts (VSI) and a valve guiding system from a truck engine have been used to create a contact situation similar to that of real engines. In the present investigation the valve seat inserts are made of an iron based material while the valves have a steel base with a Stellite F hard facing on the closing surface, according to the compositions presented in Table 1. The closing surfaces are tilted 45° relative to the direction of the closing force. An intentional small mismatch between the valve and valve seat insert angles make sure that the outer rim of the closing surfaces comes into contact first. In the real engine, this is to avoid any opening force resulting from the combustion pressure. The mismatch angle results in an initial thin contact ring along the outer rim, which broadens towards the center, as the components adapt to each other during running in.

The oil used in the tests is a fully formulated, commercially available engine oil for heavy diesel engines, Scania LDF2 10W-40.

2.2. Methods

The valves and valve seat inserts were run in the valve test rig detailed in [8], with the changes made to allow addition of oil mist into the gas flow according to [10], see Fig. 1. In short, the valve and valve seat insert is mounted in the rig with a spring pushing the valve down into an open position. A pushrod closes the valve with a force of 20 kN at a frequency of 6 Hz. The system is heated by two sources, one resistive heater mounted around the pushrod (operating temperature 750 °C) and one hot air gun delivering about 500 l/min of air with a temperature of 600 °C. A spray nozzle allows controlled feeds of oil into the stream of hot air [10]. The temperature, closing force and frequency were selected to represent typical conditions in the engine.

To study the initial stages of tribofilm formation, tests were run for 10; 100; 1000; 10,000 and 100,000 closing/opening cycles with the addition of 0.5 ml/min engine oil into the hot air stream. To also study the tribofilm breakdown dynamics, samples were first run for 10,000 or 100,000 cycles with the addition of engine oil mist, followed by another 1000 or 10,000 cycles, without the addition of oil. The intention of this test scheme was to investigate how well a newly formed tribofilm can protect the surfaces once the supply of tribofilm forming elements is cut off. In a real engine, the valves are not intentionally lubricated, but get access to oil residue particles as engine oil is pushed up into the combustion chamber by the piston rings or leaks down through the valve guiding system. This creates a situation where the access to oil residue particles varies depending on driving style, fit between components and other parameters such as temperature of the oil. The variation might not be as definite as on or off,

Table 1
Composition of the contacting surfaces of the valve and VSI. Elements included, but in small percentages, are marked with X [wt%].

	Cr	Ni	Fe	Co	C	Si	W	Mn	Mo	V
Valve	25	22	X	Bal.	X	X	15			
VSI	7		Bal.			X		X	12	4

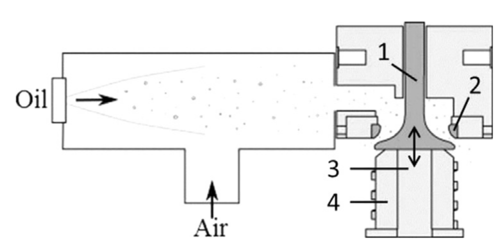

Fig. 1. Schematic view of the set-up showing the oil delivery system and position of the valve (1), the valve seat insert (2), the pushrod (3) and the resistive heater (4). The arrow indicates the movement of the valve. [10].