VETOR

Effect of H-DLC coatings on direct acting cam-tappet friction forces

Efeito dos revestimentos H-DLC nas forças de atrito came-tucho de ação direta

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Abstract

In internal combustion engines, the valvetrain is responsible for up to 25% of the friction losses, at rotational frequencies below 2000 rpm. Important friction losses in valvetrain come from the contact between the cam and the tappet. Despite to manufacturer specifications for the engine lubricant, the lubricant viscosity can be changed under some conditions, affecting the cam-tappet contact forces. Also, the surface conditions of cam and tappet can affect these friction forces. This work presents a bench mono-valve experimental apparatus and results for frictional force investigations, using aged engine lubricant SN5W30, with viscosity modifications. The influence of a tappet crown coated with H-DLC is investigated, comparing to standard tappets. These experiments showed that, under specific experimental conditions, the friction forces between the cam and the tappet when H-DLC coating is applied are lower than standard applications, for all lubricant viscosity applications.

Keywords

H-DLC • Cam-tappet • Valvetrain

Resumo

Nos motores de combustão interna, o trem de válvulas é responsável por até 25% das perdas por atrito em frequências rotacionais abaixo de 2.000 rpm. Perdas importantes por atrito no trem de válvulas vêm do contato entre o came e o tucho. Apesar das especificações do fabricante para o lubrificante do motor, a viscosidade do lubrificante pode ser alterada em algumas condições, afetando as forças de contato came-tucho. Além disso, as condições da superfície do came e do tucho podem afetar essas forças de atrito. Este trabalho apresenta um aparato experimental de bancada monoválvula e resultados para investigações de força de atrito, utilizando lubrificante de motor envelhecido SN5W30, com modificações de viscosidade. A influência de uma coroa de tucho revestida com H-DLC é investigada, comparando com tucho padrão. Esses experimentos mostraram que, sob condições experimentais específicas, as forças de atrito entre o came e o tucho, quando o revestimento H-DLC é aplicado, são menores do que com o tucho padrão, para todas as viscosidades do lubrificante.

Palavras-chave

H-DLC • Came-tucho • Trem de válvulas

1 Introduction

Cars that nowadays operate primarily in cities are subjected to speed regimes over time that result in low engine speeds. In Brazil, these engines Otto cycle run on gasoline (with anhydrous ethanol content [1]) or hydrated ethanol only, or a mixture of both. They are called bi-fuel or flex-fuel engines. The efficiency of the ideal Otto cycle is a function of the compression ratio (CR), but increasing compression ratio is limited by the onset of knock, which can be prevented by increasing fuel octane number [2].

In terms of the vehicle energy efficiency, engines alone are responsible for a significant share of energy losses due to friction between their moving parts [3]. About 10% of the energy supplied by the fuel is lost in an internal combustion engine due to internal friction. This amount of energy loss corresponds to about 25% of the specific power at full load and is greater in partial loads. In idle, 100% of the indicated power is consumed by friction [4].

In an urban cycle situation, the losses are different from those presented at full load. Andersson [5] presented the energy distribution of burnt fuel for a medium-sized passenger vehicle during an urban cycle. Mechanical losses, in this case, represent about 15% of the power provided by the burning of fuel.

Even an 1% improvement in the fuel economy of a vehicle model has great economic and environmental relevance, as stated by Wong and Tung [6].

To promote a more favorable tribological condition in the cam-tappet systems and fuel consumption reduction, thin films can be used in the tappet crown [7]. Thin films are defined as a layer of material with thickness between nm and μm that is deposited on a material to change its surface properties. Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD) cover a series of deposition processes that can provide such films. The most popular carbon-based film is H-DLC, a micrometric layer of hydrogenated amorphous carbon, which effects are desirable for reducing friction and reducing wear [8]. In automotive applications, the H-DLC film is mostly applied with thickness between 2 and 5 μm. Ratamero and Ventura [9] calculated that the fuel economy benefits for a small passenger vehicle, equipped with an Otto I3 engine, is on the order of 0.5% with the use of H-DLC-coated tappets, compared to standard tappets.

Many authors have performed a series of experiments dedicated to determine the friction forces between cam and tappet. Dyson and Naylor [10], for example, carried out a series of experiments in laboratory, to determine the coefficient of friction (COF), with a variety of cams and tappets. The cams were made of steel and hardened superficially and the tappets in cast iron. Those authors used SAE 30 HVI base oil in their experiments, at 127°C.

Teodorescu et al. [11] showed that the COFs between the cam and the tappet are the largest around the nose of the cam in contact with the tappet.

Many parameters can influence the friction forces between cam and tappet, such as cam and tappet geometries, lubricant viscous properties, and roughness of the surfaces in contact, among others. Lubricant contamination can also contribute for the friction behavior.

Hydrated ethanol, used as a fuel, can be mixed with the engine lubricant, changing its lubricating properties in some specific situations of vehicle use [12]. This phenomenon affects the friction between the cam and the tappet. The engine durability and energy efficiency can also be affected in these conditions.

This work aims to contribute to this subject, especially regarding to the effect of H-DLC thin film application.

2 Methods

Experiments with bench engine heads, measuring the resistant torques on the camshaft, require many mathematical calculations to extract information regarding friction between cam and tappet. Direct measurement of mechanical losses related to cam-tappet friction, in real engines, use electronic acquiring data devices that delivers electrical signals that are affected by intense electromagnetic interferences, restricting accurate acquisition of friction data [8, 10, 11, 13, 14].

Experiments with specially built devices for direct measurements of cam-tappet interactions usually do not use actual parts (tappets, valves, valve guides, valve springs, tappet guides and cams) of an internal combustion engine and may not present a constructive system equal to that of the engine.

Considering mechanical bucket tappets, an experimental bench apparatus was developed for the direct measurement of the contact forces between cam and tappet. This apparatus:

1 – uses actual parts of a combustion engine: cams, tappets, springs, valves, valve guides, and tappet guides, in an assembly identical to that in a given engine;

2 – allows easy substitution of the mentioned parts, or the whole valve system, without the necessity of significant changes in the peripheral mechanisms;

3 – directly measures the normal and tangential forces of cam-tappet contact, simultaneously and instantaneously;
4 – allows changes in the type of lubricating oil used;
5 – allows changes in lubricating oil temperature;

Figure 1 presents an overview of the apparatus.

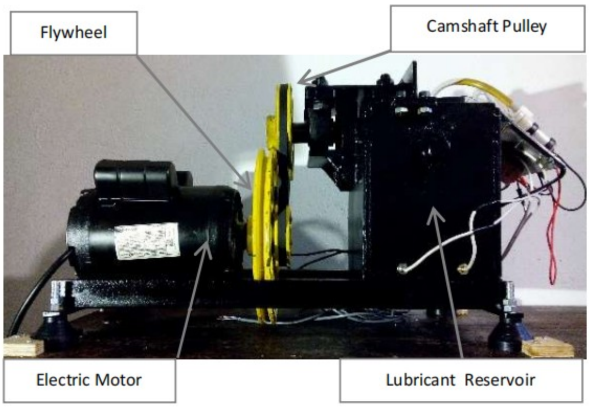

Figure 1: Direct Acting Mechanical Bucket Tappet Apparatus for Tribological Experiments.

A 2-hp AC HERCULES electric motor has a flywheel coupled to its shaft, as well as a pulley that transmits movement to the pulley of the camshaft.

In an attempt to reproduce the cam axle angular frequencies for a vehicle performing a city cycle (FTP75, first phase [14]), a rotational frequency of 1100 rpm was selected for the cam, by the choice of motor pulley and camshaft pulley diameters, according to the electric motor angular frequency.

The equipment has an electric oil heater, controlled by a device that monitors the oil temperature at the cam-tappet contact, using a thermocouple installed on lubricant source, as shown in Fig. 2. The device stabilizes the temperature at a desired value. An electric oil pump (DC 12V diaphragm electric pump, flow rate: 1.5 l/min) circulates the heated oil between the reservoir and the cam-tappet contact region. Typical variations on the pump flow are not expected to induce considerable change in the friction results.

The cam axle is supported by two bearings. The axle has the camshaft pulley at one end (Fig. 1), the two bearings near the ends of the shaft, and a bore threaded at the other end of the shaft, where the cam is attached, as shown in Fig. 2. The cam axle bearings are rigidly attached to the machine frame using screws.

The valve control system, including the cam-tappet pair, is placed within the lubricant reservoir. The valve system is mounted on a cell, which houses real engine parts, including tappet, valve, valve guide, valve spring, and valve seat. Therefore, the cell houses an entire real valve system. Figure 2 shows a detail of the cam-tappet and the cell.

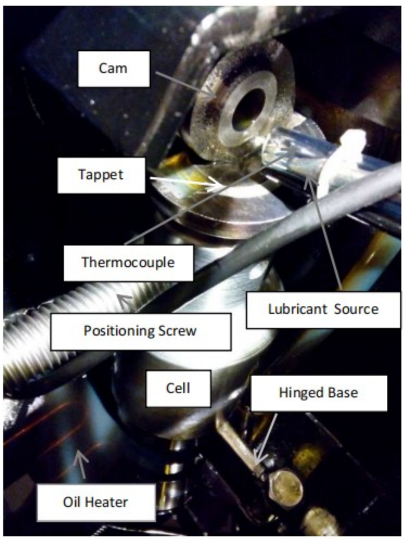

Figure 2: Inside the Oil Reservoir: Cam, Tappet and Cell.

The cell is supported by a Vertical Load Cell, VLC, which is supported on a hinged base, with two supports and with adjustable height, that restricts vertical movements of the assembly and allows rocking movements. The backward swing motion is restricted by a positioning screw (see Fig. 2) and the forward by a Horizontal Load Cell, HLC, Fig. 3. Thus, the forces between the cam and the tappet translate into a vertical force, on the VLC, and a horizontal force, on the HLC. The load cells have an electric full scale of 20 mV, with a sensitivity of 2 mV / V for a 10 V supply. The signals from the load cells are amplified and then viewed through an oscilloscope model Minipa GW Instek MO-2062, 600 MHz, 1G Sa/s.

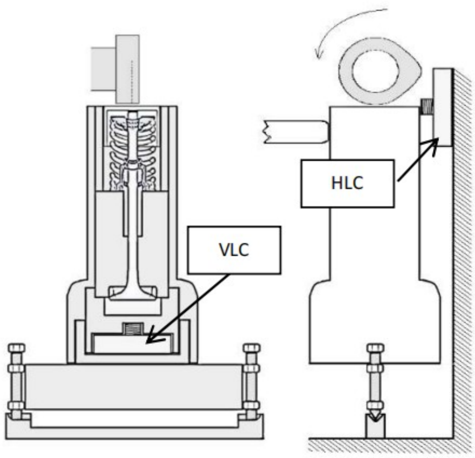

Figure 3: The Cell and it's Assembly.

In static or quasi-static tests, for determination of vertical forces, a Fluke 106 multi-meter was used to read the amplified voltages of the VLC cell, for various cam angles. The values of the amplified voltages from VLC and HLC and the applied loads are proportional to each other, as verified experimentally. A calibration procedure of the load cells was performed.

A small magnet was attached to a point at the outer diameter of the camshaft pulley and a small coil was attached to the apparatus structure, in order to detect the exact position of the cam when it promotes the biggest tappet lift. This assembly generated a trigger signal for oscilloscope reference.

In all experiments described in this work, the following compounds were obtained from a standard commercial Ford Fox 1.0 L engine: the cam, the tappet, the valve, the valve guide, the valve seat, and the spring.

An used SN5W30 commercial engine lubricant, aged for 10,000 km of vehicle running was applied. Used lubricant were selected to analyze a situation that better represents a situation closer to lubricant replacement, in which the additives effects are lower than new lubricant applications.

In the bench experiment, with the cam-tappet tribometer, portions of hydrated ethanol were added to the circulating lubricant in order to modify the lubricant viscosity. It was done directly and slowly, until a mixture percentage of about 25% (v/v) was obtained, considering the maximum possible in combustion engines internal flex-fuel, according to Costa and Spikes [16].

The experiments were performed considering the following steps, in chronological order:

1 - Mounting of cam on the shaft, and tappet in the cell, and checking the cam-tappet clearance;
2 - Addition of 1 L of lubricant in the reservoir and activation of the lubricant circulation-injection pump;
3 - Start of break-in;
4 - Observation of stabilization of electrical signals, end of the break-in, which occurred between 3.5 to 4.0 hours;
5 - Activation of the thermal circuit (controlled heating of the lubricant), temperature stabilization check, around 35 ^{0}C (trying to reproduce the cold phase of FTP-75);
6 - Start of data collection, with standard tappet;

Ten measurements of two voltage peaks were taken every 5 minutes, resulting in 20 measurements for each condition of percentage (%) of hydrated ethanol, which generated a point in a graph of Tension x ml Ethanol, or Friction Force x ml Ethanol, or COF per percentage (%) of Ethanol.

Each measurement cycle corresponds to an addition of hydrated ethanol, namely: initial (0 ml of ethanol) 100, 200, 300, and 400 ml of ethanol, which corresponds to 9.1%, 16.7%, 23.1%, and 28.6% of ethanol added to the lubricant. This process, in total, was conducted in about 30 minutes. Each section of 20 measurements took about 1min40s.

7 - Shutting down the machine, purging the lubricant with hydrated ethanol and washing the systems with solvent;

8 - Using the same cam, the same machine setting, and a new 1 L portion of the same aged lubricant, the tappet was replaced by a tappet coated with H-DLC;

9 - Repeat steps 1 to 7;

In the tests, new 16MnCr5, carburized and tempered tappets, new nodular cast iron cams with Mn, and other 1.0 l Fox Ford engine parts were used. The commercial thin-film taped H-DLC had a base layer of chromium nitride (CrN) and a functional layer of DLC type a-C: H (courtesy HEF-Durferrit).

3 Results and Discussion

Figure 4 shows the captured signal during tests performed according to the described experimental methods. These signals came from the HLC, with linear amplification.

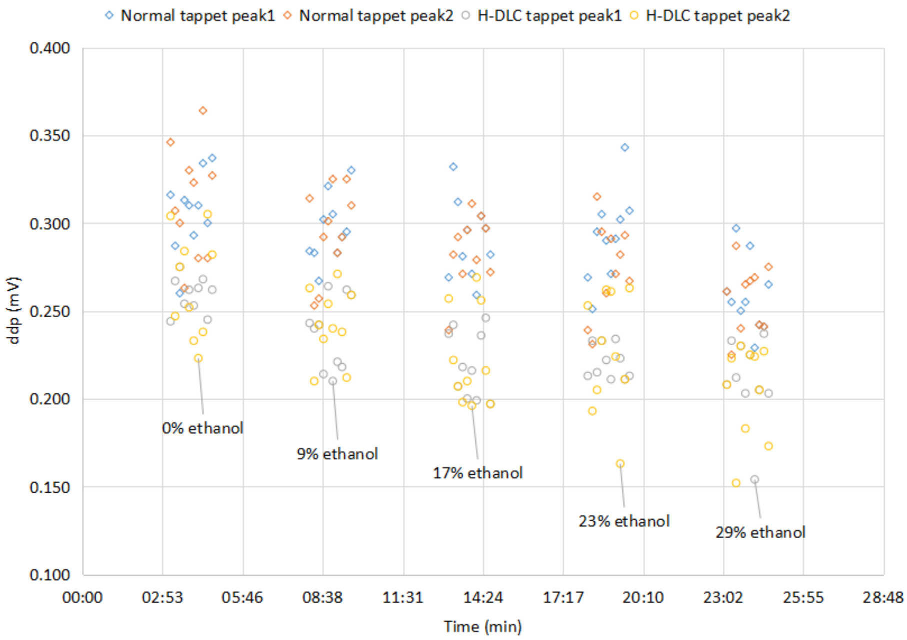

Figure 4: Electric signals of forces from mono-cam bench with hydrated ethanol additions.

According to Fig. 4, some noisy electrical signal data was observed, with a clear trend for different values depending on the fraction of added hydrated ethanol. As can be seen, there is a trend of decrease in the electrical signal obtained. Additionally, is it possible to observe a different behavior comparing the signals from the normal tappet use and the H-DLC tappet use. Due to the noisy electrical signal, it was necessary to analyse each group of data and it was possible to make a standard deviation and average calculus, allowing to extract some clear trend.

In terms of friction forces, the data from Fig. 4 can be summarized as seen in Fig. 5. Each point is an average of peak1 and peak2 ddp values, converted for friction forces. The bar errors came from the standard deviation of each group of data and error propagation.

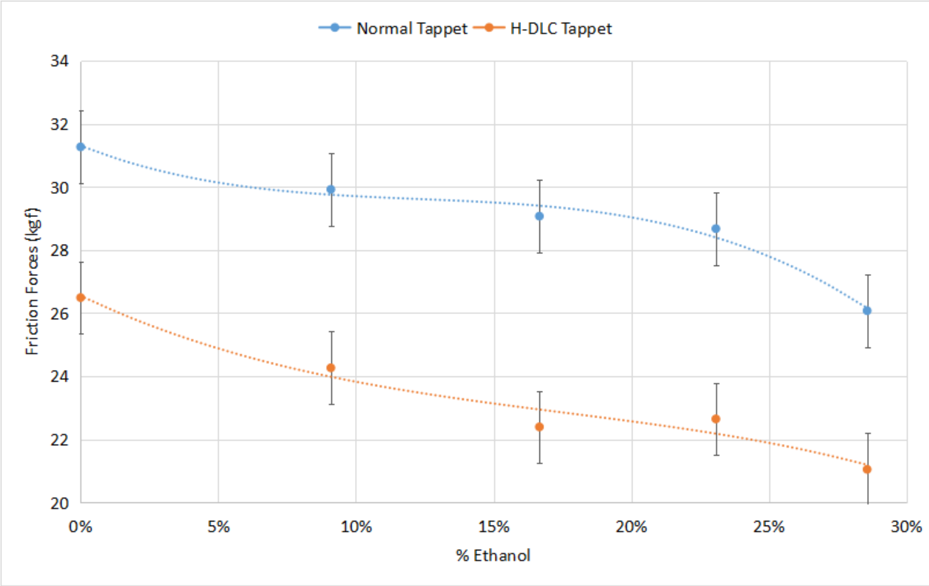

Figure 5: Friction forces from mono-cam bench with hydrated ethanol additions.

These summarized results from Fig. 5 indicates that really there's a clear trend decrease of friction forces with the addition of hydrated ethanol, and clearly indicates that the use of H-DLC tappets promotes a general decrease in friction forces.

In terms of friction coefficients (COF), the data from Fig. 5 can be summarized as seen in Fig. 6. COF is calculated by Eq. (1), for nose-cam and tappet contact:

$$COF = \textit{force from HLC}/\textit{force from VLC}. \quad (1)$$

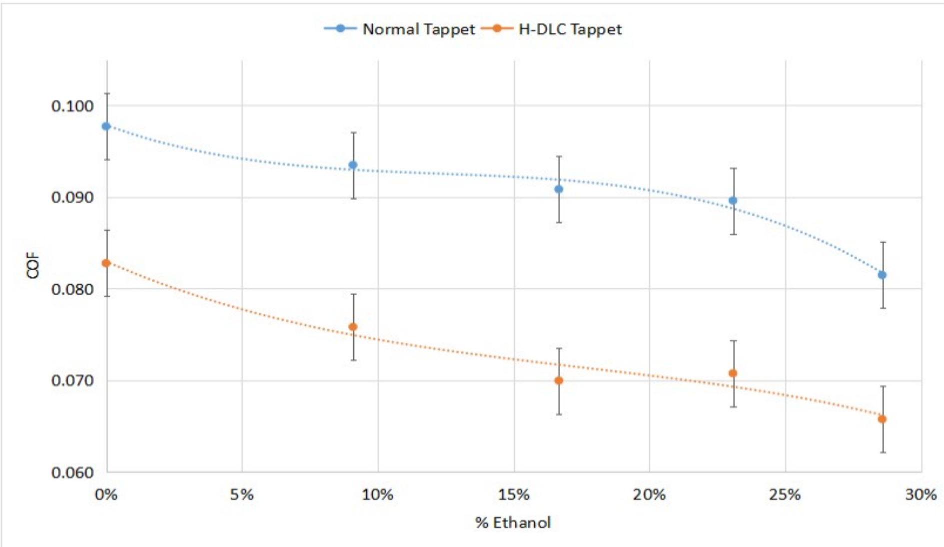

Figure 6: Friction coefficients from mono-cam bench with hydrated ethanol additions.

Regarding the general decrease of friction forces (and COFs) due to H-DLC coating on the tappet crown, it is possible to consider that all boundary cam-tappet contact friction forces are reduced, compared to the use of non-coated tappet crown [7].

4 Conclusions

The presented experimental apparatus combines favorable characteristics of several already developed and built devices for cam-tappet tribological experiments, with the difference of housing a real system of an internal combustion engine valve assembly, driven by a real cam.

Based on the experimental results it was possible to evaluate that, under the applied conditions:

- Dyson and Naylor obtained results of reliable COFs for the nose region of the cam in contact with the tappet. Those authors obtained a COF value of approximately 0.10 [10], which is a value comparable to those obtained in this work, considering experiments for standard tappets without hydrated ethanol addition;
- The use of electronic filters in these experiments was not mandatory;
- The cam-tappet friction forces decrease due to hydrated ethanol additions, under the specific test conditions;
- The H-DLC coated tappet crown promotes a general decrease of friction coefficients of about 20%, compared to the standard tappet crown results, for any hydrated ethanol content.

So, it´s possible to conclude that:

The presented apparatus can be useful for cam-tappet friction force studies.

The experimental results obtained in this work showed that the addition of hydrated ethanol implies in the reduction of total friction forces (and COFs) between cam nose and tappet, under the specific experimental conditions.

The use of H-DLC coating on tappet crown implies in a systematic reduction of friction forces (and COFs), for all contents of hydrated ethanol added.

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