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REDUCED FRICTION LOSSES AND WEAR BY DLC COATING OF PISTON PINS

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ABSTRACT

A Diamond Like Carbon (DLC) coating is well known to offer superior wear and friction behaviour. This combination of properties makes DLC suitable for many different areas of tribology. This paper concerns itself with usage in the power cylinder environment of automotive diesel engines.

To estimate the potential of DLC coatings applied to piston pins in internal combustion engines, linearly reciprocating sliding wear examinations have been performed on uncoated and DLC coated component segments versus different counterpart materials as present in the power cylinder environment, including: piston (aluminium alloy), bushing (brass), piston pin (steel) and connecting rod (steel).

Evaluation criteria for the tests include friction and wear performance in dry and lubricated conditions. Test results show how the DLC coatings offer impressive wear reductions for each of the different counterpart materials used. Furthermore, special emphasis is given to the analysis of the friction behaviour. As expected, the coefficient of friction (COF) decreased for aluminium and steel counterparts when the piston pin segments were DLC coated. However, for the combination of DLC with brass the COF increased in the dry condition. This surprising outcome is explained with SEM and EDX investigations of the wear traces. The tests at elevated temperature with lubrication show an inverse relationship with respect to friction criteria when compared with the dry room temperature tests for the DLC with brass combination.

Examined engine tests confirm the results of the non-engine wear test rig, showing that DLC coatings applied on piston pins also exhibit properties and good potential to decrease frictional losses and fuel consumption in modern engines.

INTRODUCTION

Diamond Like Carbon (DLC) coatings have excellent properties such as high hardness, a smooth surface, high wear resistance and a low friction coefficient [1-3]. The combination of properties makes DLC suitable for many different tribological applications, such as machining or forming tools and other high-loaded components [1-4]. For automotive gasoline and diesel engine applications the present trends towards higher specific power output and increased efficiency provide good reason to believe that low wear and friction coatings applied to tribological systems will become increasingly more important and design critical in future. For automotive engines the development of increasingly greater combustion pressures provides higher loads and more demanding challenges on the power cylinder bearings. Specifically for this study the small end bearing is looked at, responsible for power transfer of the combustion load from the piston to the connecting rod through the piston pin. DLC coating of the piston pin provides good potential to solve inherent wear and galling issues in addition to providing a reduced friction bearing able to influence engine losses and fuel consumption.

The investigations looked at in the present work are divided into two main parts. Firstly, the tribological properties of DLC films were studied against different counterpart materials in the dry condition at room temperature. The second part of the investigation uses a lubricated condition at elevated temperature to better compensate for the physical engine environment. In addition, the lubricated analysis offers the opportunity to study the effects of diverse lubrication conditions. In all the tests particular attention is given to the wear and friction behaviour of the DLC coating against brass counterparts as little previous data has been published for this material combination. This elevated temperature work also allows comparison with previous DLC work reported in [1,3]. These authors reported the wear properties of DLC to decrease with increasing component or specimen temperature.

It is well known that DLC films have complex tribological behavioural characteristics with different counterpart materials [5,6]. DLC coatings show low coefficient of friction (COF) values in sliding against hard materials and easy-transfer soft materials [6]. However, in sliding against difficult-transfer soft metals like copper and brass, they show high COF values. The wear behaviour of DLC and slider materials strongly depends on the hardness of the counterpart. The harder the slider, the higher the wear rate of the DLC coating and the lower the wear rate of the counterpart [2,6].

EXPERIMENTAL PROCEDURE

DLC films were deposited on piston pins from series production. These pins were pretreated by lathing, case hardening and grinding. The pin bulk material is SAE 5515. Prior to the DLC coating process, the pins were cleaned by an aqueous alkaline detergent treatment. After loading into the deposition chamber a plasma etching follows in order to ensure precise cleaning and to activate the surface. Afterwards, a chromium layer, typically with a layer thickness of 0.1 to 0.3µm, is formed by sputtering to achieve bonding. Subsequently, for further adhesion improvement a transition layer of a tungsten containing hydrogenated amorphous carbon film is deposited within a thickness range of 0.3µm. The functional DLC top layer is produced by plasma enhanced chemical vapor deposition (PE-CVD) with ethyne C_2H_2 as a reaction gas. The plasma is generated by a high-frequency alternating electrical field. To prevent material changes in the substrate the reaction temperatures are below 200°C.

The produced DLC type is a hydrogenated amorphous carbon film containing a mixture of sp2 and sp3 bonds which was determined by raman spectroscopy. The total coating thickness including the bonding and adhesion layers is approximately 2.5µm.

Nanoindentation measurements were carried out on every specimen using a nanoindentation system with a Vickers indentor [7]. These measurements show that the hardness of the DLC coating was approximately 18.7GPa and the indentation modulus approximately 176.4GPa. The loads of the nanoindentation measurements were chosen in a way that the indentation depth was ten times smaller than the DLC top layer thickness. The surface roughness $R_z = 640$nm and $R_a = 58$nm was obtained by profiles using a standard roughness measurement system [8]. The adhesion of the DLC films was measured using the previously described procedure in [9], showing a good quality of HF = 2 at randomly chosen positions. The layer thickness of the top DLC film was approximately 2.1µm [10].

The tribological behaviour of the coatings was investigated using a linearly reciprocating ball-on-flat sliding wear test (Figure 1) using Cameron-Plint TE77 testing facility [11]. The flat specimen shown in Figure 1 was a section of a piston pin which was electrical discharge machined to the required dimensions (height was 4mm, length was 32mm, and width was 21mm) and cleaned in ethanol for 3 minutes. The samples were mounted in a way ensuring linear interaction of the counterpart curvature on the ridge of the piston pin sections.

This study was divided into two main parts. In the first section, the tests were carried out in a dry condition at room temperature. The counterpart was contacted to the layers with an applied normal force of 5N. The second part of the study evaluates friction and wear behaviour of the DLC coating in a lubricated condition at a temperature of 150°C. This temperature was chosen to avoid cracking of the oil and ensure no change of the lubrication conditions during the testing. The oil used was 0W-30 standard diesel engine oil. For the lubricated tests the slider was contacted to the films with an applied normal load of 200N.

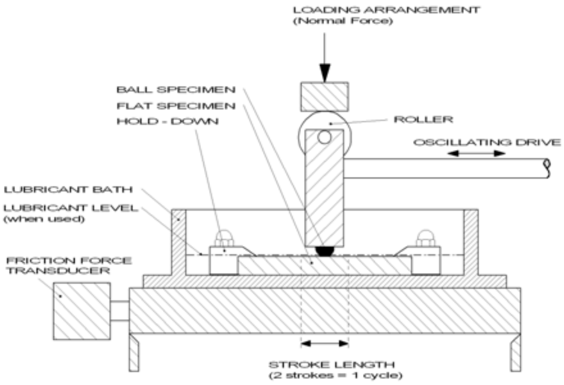

Figure 1. Scheme of Cameron-Plint TE77 testing facility [11].

For all tests the stroke was 4.6mm and the frequency was $20s^{-1}$. The tests were run up to a sliding distance of 2000m. The evaluation parameters were continuously data recorded throughout the entire test. The diameter of the counterparts was 10mm. The slider materials used in the present experiments are summarised in Table 1.

Table 1. Description of the slider materials

Material	Composition	Standard	Hardness
Steel	100Cr6	SAE 52100	62 HRC
Brass	CuZn31Si1	EN CW708R	130 HB
Aluminium	AlSi12CuNiMg	FM B2	155 HB

The volume loss of the specimen was assessed from linear profiles using a standard roughness measurement system and a subsequent fitting and calculation procedure. Some of the wear tracks were examined by light optical microscopy (LOM), scanning electron microscopy (SEM) and energy dispersive X-ray analysis (EDX) to identify the element composition of wear debris on the samples.

RESULTS AND DISCUSSION

Figure 2 summarises the friction behaviour as a function of sliding distance for the different combinations of piston pin to slider in the dry condition at room temperature. Figure 3 shows for the same mating materials the running-in stage of the test encompassing the initial 20m of sliding distance.

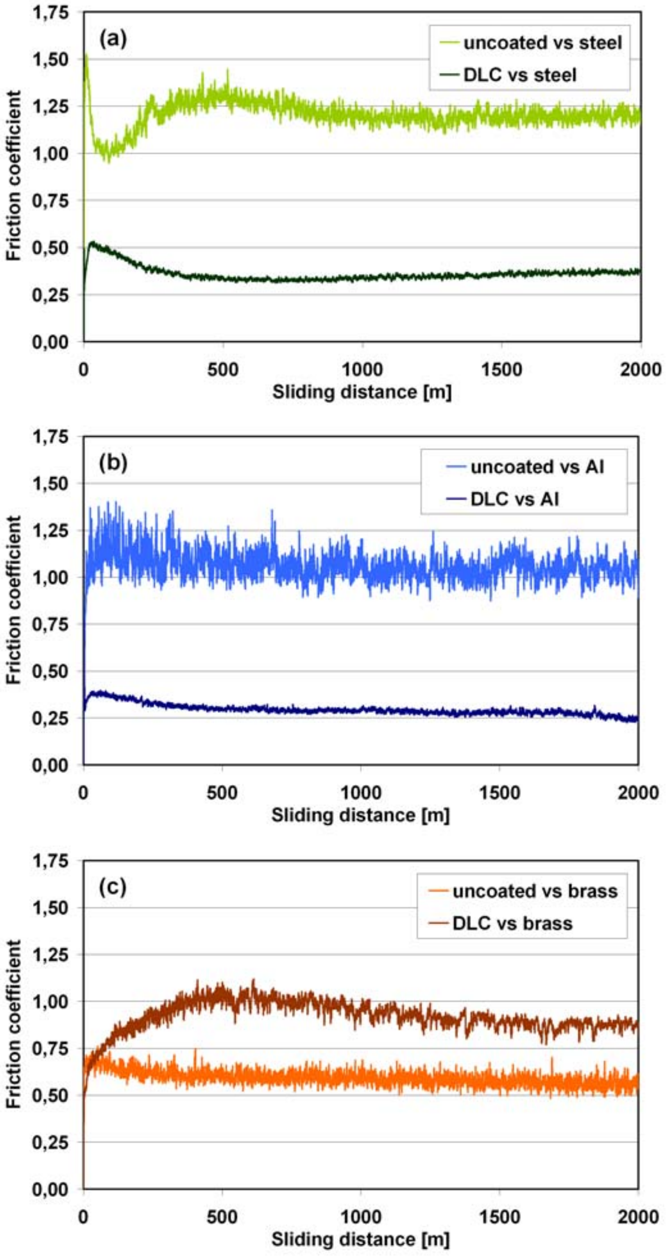

Figure 2. Friction behaviour of uncoated and DLC coated piston pin sections as a function of sliding distance for different counterpart materials in dry condition at room temperature. (a) Steel; (b) Aluminium; (c) Brass.

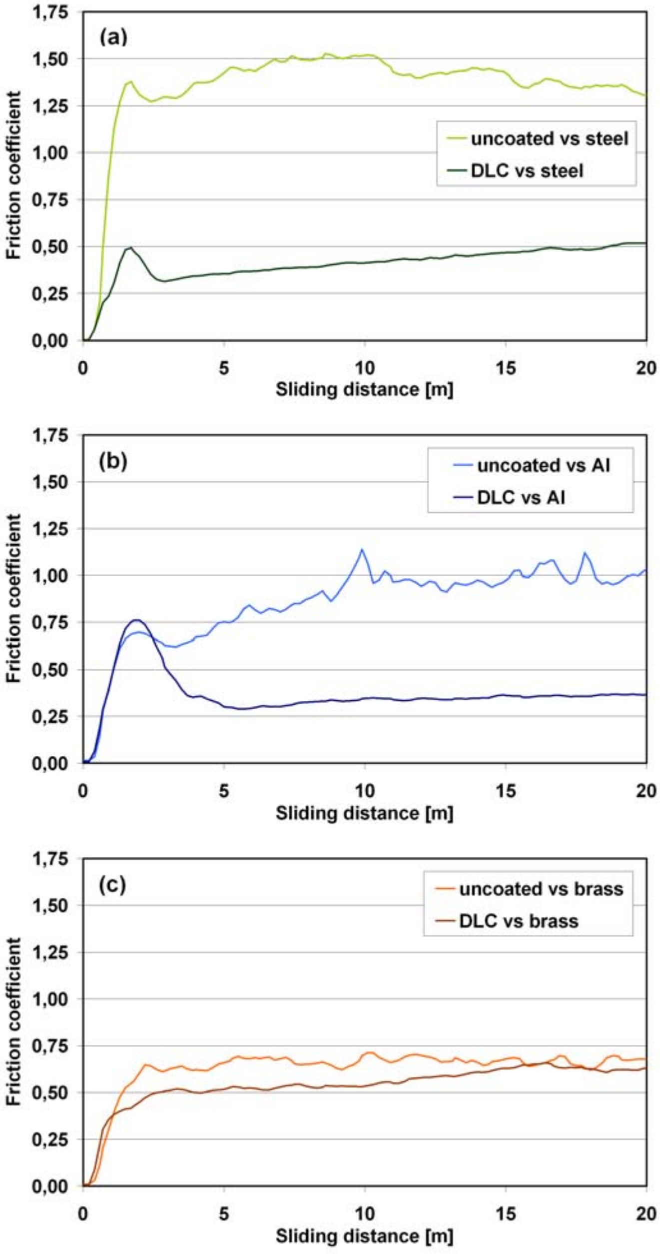

Figure 3. Running-in stage of the different mating materials from Figure 2. (a) Steel; (b) Aluminium; (c) Brass.

The friction coefficient of steel significantly decreased when the piston pin sections were coated with DLC films (Figure 2(a)). In general, the DLC layer undergoes a phase transformation from a diamond-like structure to an amorphous carbon that is transferred to the steel counterpart [6]. This behaviour was previously reported by Yamamoto [2]. A first layer is directly formed on the contact surface of the slider during the initial break-in stage. During this initial layer formation the COF reaches a running-in peak (Figure 3(a)) as the initial mixture of wear debris of the counterpart and the DLC film contains a small amount of carbon. A second layer is formed on the top of the first layer during the period of the break-in stage in which the friction coefficient continuously decreases (Figure 2(a)). This second layer mainly contains amorphous carbon which was transferred from the DLC coating changing the wear and friction behaviour in a way that galling or adhesive wear is reduced.

The friction behaviour of aluminium, shown in figures 2(b) and 3(b), provides comparable results to and confirmation with work reported by Luo [2]. In the initial running-in stage, the counterpart surface causes high plastic deformation due to high Hertzian point contact stress. Consequently, the aluminium alloy adheres to the DLC coating and reaches a peak coefficient of friction with a value similar to the uncoated test. After that, a smooth hardening, oxidized layer is formed, giving a good interface for reducing the coefficient of friction and improving the frictional behaviour [12, 13].The friction behaviour of brass in the dry contact condition, figures 2(c) and 3(c), is different to that of the tested steel and aluminium samples. The friction coefficient increases if DLC is applied to the piston pin segments, as previously reported by Liu [6]. In contrast to Liu, the SEM and EDX analysis in this work showed that after a full test the brass was transferred to the DLC film with high local concentrations in the piston pin machining marks, see Figure 4. The copper and the zinc peaks in the outer part of the wear track reveal the appearance of brass in the machining marks. However, brass as a slider material shows no typical break-in stage as is seen for steel or aluminium versus DLC. This is confirmed by SEM and EDX investigations of tests stopped after a sliding distance of 10m (Figure 5). The SEM image and the EDX spectrum show the first very thin brass marks transferred on the top of the DLC coating. Afterwards, the friction coefficient increased up to a peak at a sliding distance of approximately 500m. This can be explained with an increase of the wear track area and hence, an increased area of laid brass. Therefore, the high friction coefficient of the mating brass versus DLC is obtained by an adhesive mixture of DLC versus brass contact and a brass versus brass contact itself. After approximately 500m sliding distance the machining marks and the DLC coating of the piston pin segments begin to smoothen. In the period 500-2000m the fraction of transferred brass especially in centre parts of the wear track scales down. Therefore, the friction coefficient decreased due to a reduction of adhesive wear.

Figure 7 shows the wear of the piston pin sections and counterparts decreased significantly when the piston pins were DLC coated. This can be explained with the formation of the different transfer layers discussed previously. These layers totally change the tribological properties of the investigated mating materials. As already mentioned, the wear behaviour of the DLC films and the slider materials strongly depends on the hardness of the counterpart. Therefore, brass shows the lowest volume loss of specimen, but the highest wear of the counterpart. The aluminium piston alloy causes a relatively high volume loss of the DLC coating due to silicon particles and intermetallic phases present in the microstructure. These particles and phases have a high hardness and cause wear of the piston pin section surface. The volume loss at the aluminium piston alloy itself is comparatively high as the aluminium matrix is quite soft. The wear values of the mating with steel have both the lowest volume loss of the piston pin segment and the slider material. This is due to the second transfer layer formed during the running-in stage which reduces the adhesive wear and the galling phenomena.

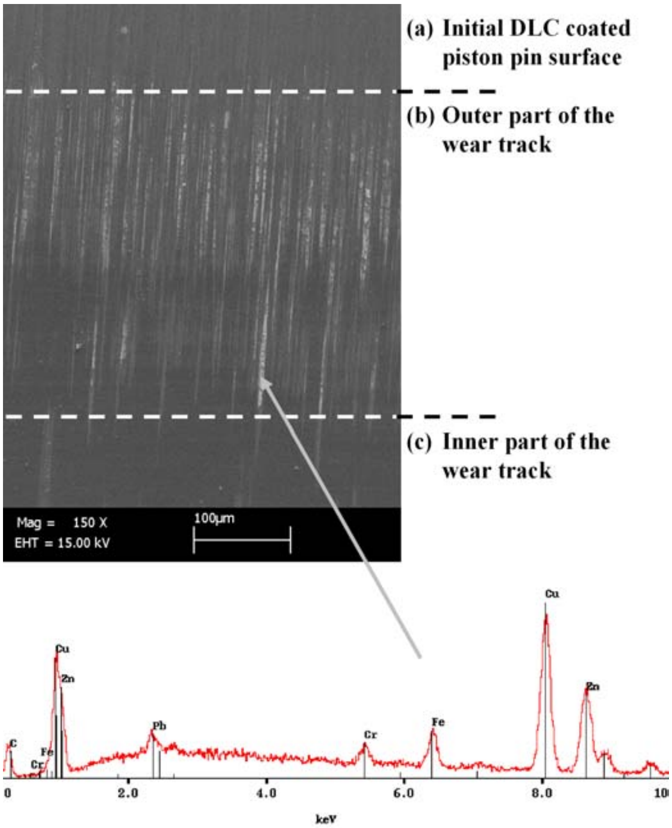

Figure 4. Part of a wear track of the DLC film after reciprocating ball-on-flat sliding wear in dry condition with brass as counterpart. Area (a) shows the untouched piston pin surface next to the wear track. In area (b) the transferred counterpart material could be assessed by EDX. Area (c) shows the inner part of the wear track, where the brass and the machining marks are totally removed.

Figure 8 summarises the friction behaviour as a function of sliding distance for the different piston pin to counterpart combinations in the lubricated condition at elevated temperature. Figure 9 shows the break-in stages up to 20m sliding distance for the same mating materials. As expected, the friction coefficient for the different systems is always lower than the coefficient of friction in dry sliding, although the applied load to the samples was significantly larger. For steel and aluminium the relations between uncoated and DLC coated piston pin segments are similar to the results in dry condition (figures 2(a) and 2(b)). The break-in stage of the DLC matings shows no significant running-in peaks in the lubricated tests. This suggests the transfer layers are not formed or the formation requires a longer period of time as the friction is mixed mode.

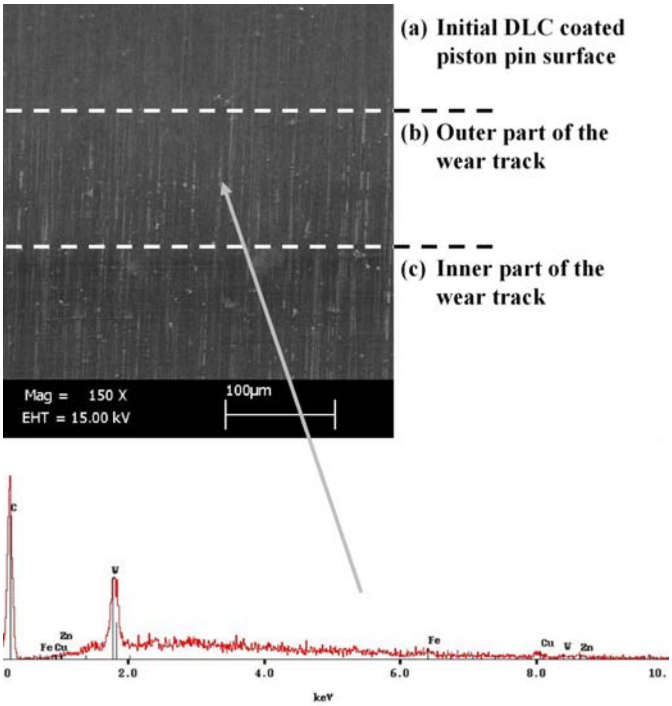

Figure 5. Wear track of the DLC film after reciprocating ball-on-flat sliding wear in dry condition with brass as counterpart. Stopped after a sliding distance of 10m. Area (a) shows the untouched piston pin surface next to the wear track. In area (b) the thin transferred brass marks could be poorly assessed by EDX. Area (c) shows the inner part of the wear track.

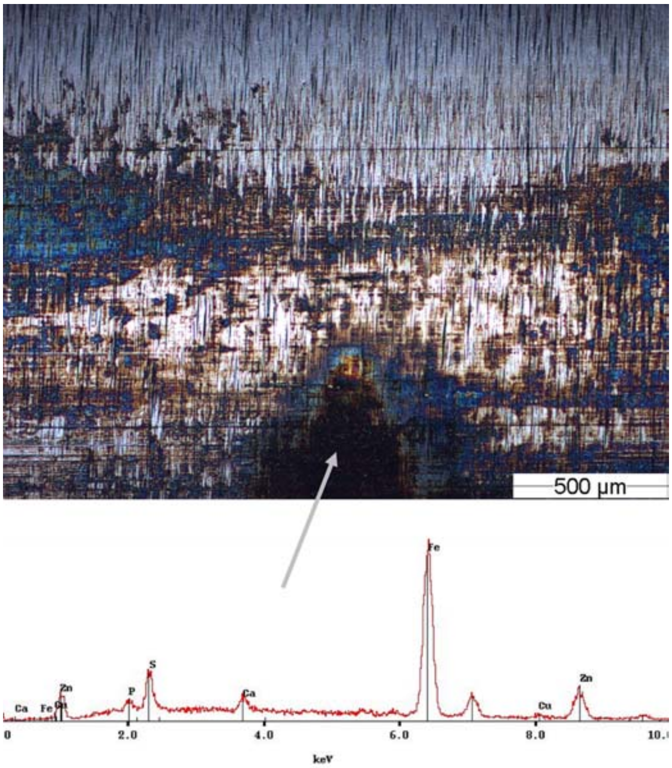

Figure 6. Part of a wear track of a piston pin segment after reciprocating ball-on-flat sliding wear in lubricated condition with brass as counterpart. At the top, the untouched piston pin surface next to the wear track is visible. In the inner part of the wear track the EDX spectrum with the largest copper and zinc peaks could be assessed.

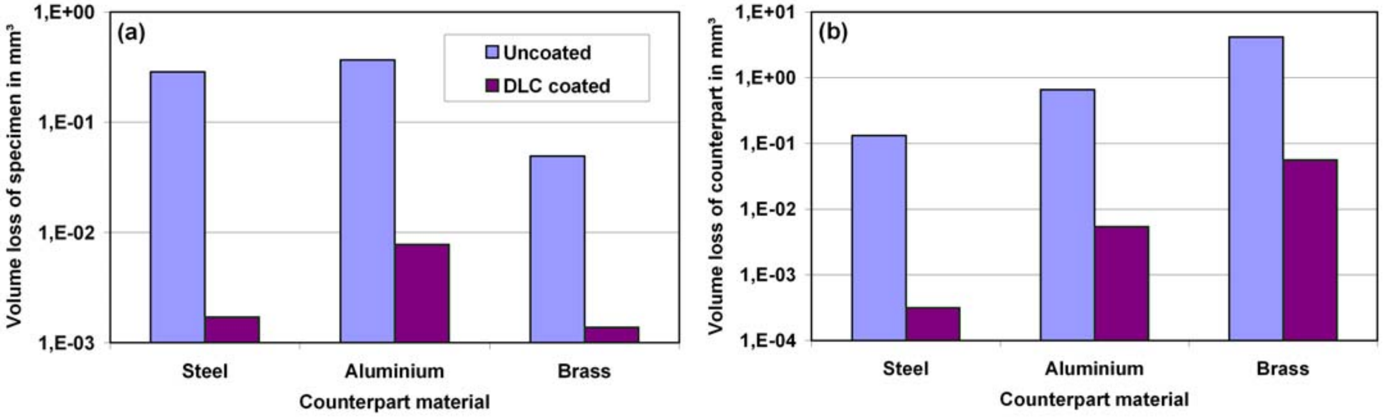

Figure 7. (a) Volume loss of piston pin sections of different mating materials. (b) Volume loss of the investigated counterpart materials after tests in dry condition.

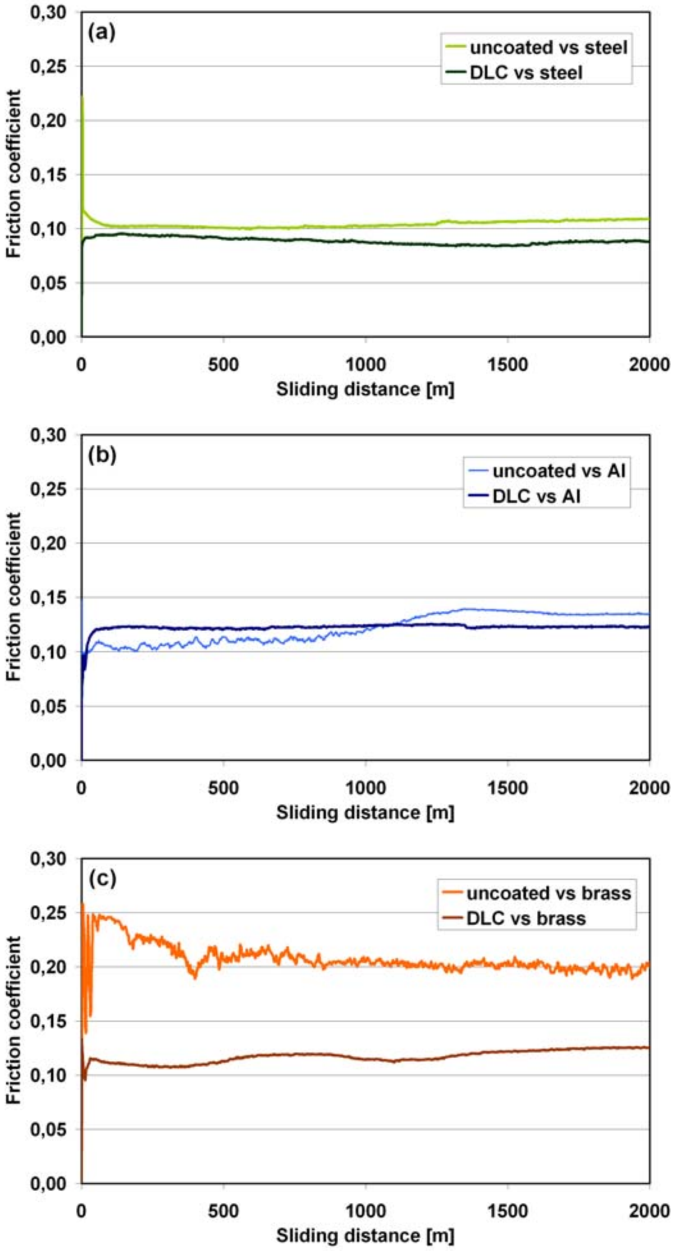

Figure 8. Friction behaviour of uncoated and DLC coated piston pin sections as a function of sliding distance for different counterpart materials in lubricated condition and at 150°C. (a) Steel; (b) Aluminium; (c) Brass.

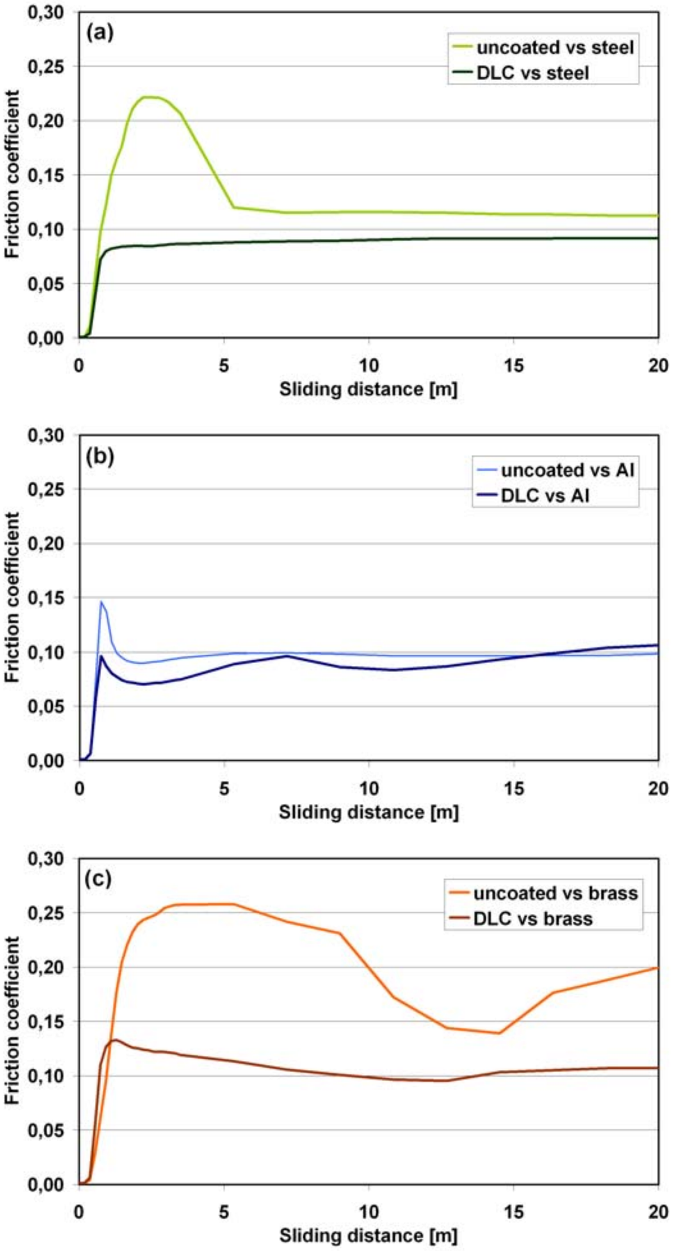

Figure 9. Running-in stage of the different mating materials from Figure 8. (a) Steel; (b) Aluminium; (c) Brass.

Figure 11 summarises the wear results of the piston pin sections as well as the counterparts after the tests in the lubricated condition. For a better resolution of the outcomes the scales of the wear losses are different for each counterpart material. The diagrams in Figure 11 show the volume loss of the piston pin and slider materials greatly decreased when a DLC coating was applied to the specimens and the tests were carried out with steel or aluminium counterparts. This effect can be explained with the statements discussed previously concerning the fact that steel and aluminium matings build transfer layers. The differences between the uncoated and the DLC coated samples are smaller than in dry condition as the oil lubrication in general improves the friction and wear behaviour, but the relations are similar to tests without lubrication.

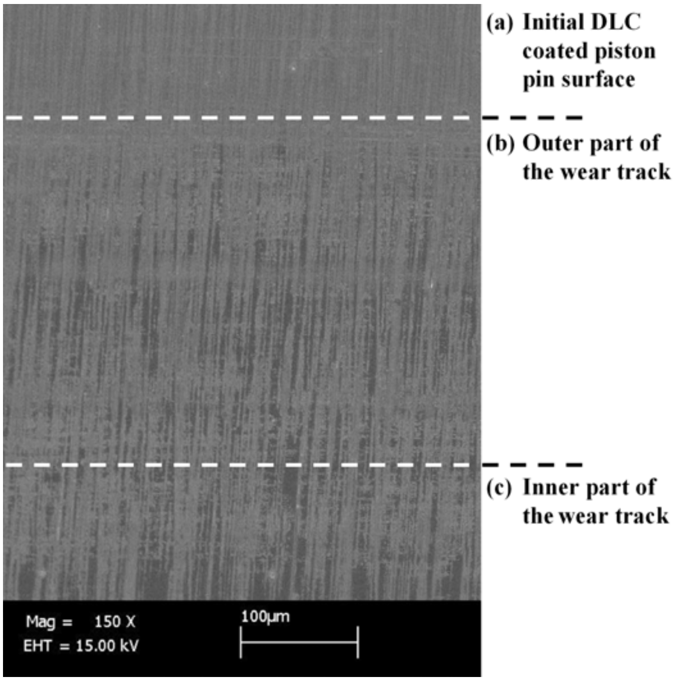

Figure 10. Part of a wear track of the DLC film after reciprocating ball-on-flat sliding wear in lubricated condition with brass as counterpart.

The volume loss of the tests with aluminium as counterpart was larger than the volume loss with steel sliders. Again, this is due to silicon particles and intermetallic phases in the aluminium alloy. These particles and phases have a high hardness and increase the wear of the specimens.

The wear of the brass matings is different, as already described a film of brass is transferred to the top of the uncoated piston pin sections (Figure 6). This transfer layer changes the wear behaviour from abrasive wear to adhesive wear and galling. Therefore, the friction coefficient and volume loss of the slider was extremely high. However, no volume loss of the specimen itself was observed. In spite of this, the transferred film could also be detected with the standard wear measurement procedure and calculation. These results are displayed in Figure 11 with a negative value. The mating DLC coated piston pin segment versus brass shows the lowest volume loss of specimen due to the low hardness of the slider.

The relation of the volume losses of the sliders is similar to the tests without oil lubrication. Brass, the material with the lowest hardness, shows the highest counterpart wear for the uncoated and the DLC coated samples, respectively. Compared to steel the volume loss of the aluminium slider is relatively large due to low hardness of the aluminium matrix.

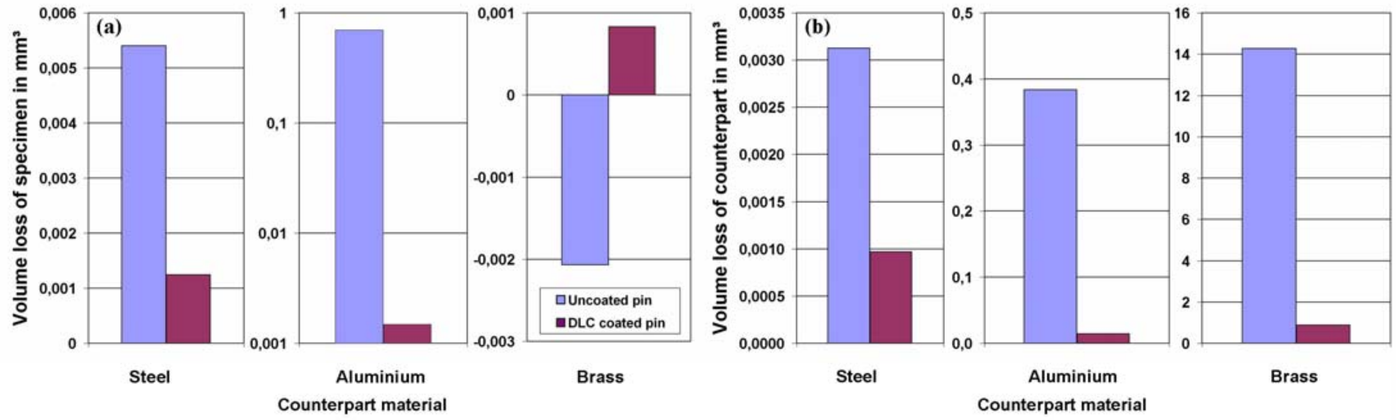

Figure 11. (a) Volume loss of piston pin sections of different mating materials. (b) Volume loss of the investigated counterpart materials after tests in lubricated conditions. Different scales used.

COMPARISON TO ENGINE TESTS

As part of FMs internal product development several internal engine tests were carried out on a modern high powered diesel LVD architecture to assess the effects of the DLC coated pistons pins on friction and wear behaviour. The tests implemented to assess product performance and provide validation with co-ordinated rig test work. Tests were carried out on gravity die cast aluminium alloy pistons with and without brass bushings. Additionally the connecting rod component was similarly tested with and without brass pin bore bushings in the small end bearing region co-incident with the piston pin. The engine variant results are separately illustrated in the Tables 2-5. Due to concealed restriction the detailed values of the component volume loss are not presently available for publication. The wear is however benchmarked with a grading system. The symbol (++) means the component was in excellent condition. The evaluation (+) stands for good condition, (○) for satisfied condition, (-) for sufficient condition and (--) for unsatisfied condition. For a better understanding and an improved comparison to the non-engine tests the materials used in the tests are again referred to the engine components. The steel counterpart stands for the con rod, the brass for the bushings and the aluminium for the piston material.

Table 2 shows the volume losses of the parts after different engine tests with bushings in the piston and the con rod. Both the uncoated as well as the DLC coated piston pin was in direct contact with the brass counterparts. Especially, the results from Figure 7 could be verified. The volume loss of the piston pin enormously decreases if a DLC coating was applied.

Table 2. Wear documentation of separated components from engine tests with bushings in the piston and the con rod

	Piston pin	Con rod	Piston
Uncoated pin	-	-	-
DLC coated pin	++	+	+

Table 3 summarises the evaluation of the components after various engine tests with bushings in the piston and without bushings in the con rod. Therefore, the counterpart materials of the piston pin were steel and brass. The mating steel versus DLC shows the best performance in the engine. This can again be explained with the formation of a transfer layer to the steel bulk material. The engine tests without DLC coating on the piston pin and bushingless con rod caused after a short testing time a huge amount of adhesive wear. As no tribological layer is formed, the materials start to gall. This has initiated a failure and significantly reduced the lifetime of the whole engine.

Table 3. Wear documentation of separated components from engine tests with bushings in the piston and without bushings in the con rod

	Piston pin	Con rod	Piston
Uncoated pin	--	--	-
DLC coated pin	++	○	+

The results shown in Table 4 summarise the wear documentation of the parts after different engine tests without any bushings in the piston and with bushings in the con rod. Hence, the counterpart materials for these engine tests were aluminium and brass. The outcome of these tests helps confirming the investigation of the non-engine rig work, in that the decrease of wear for the mating DLC with aluminium due to the formed transfer layer on the top of the aluminium surface.

Table 4. Wear documentation of separated components from engine tests without bushings in the piston and with bushings in the con rod

	Piston pin	Con rod	Piston
Uncoated pin	○	-	-
DLC coated pin	+	+	○

Table 5 summarises the volume losses of the components after various engine tests without any bushings in the piston and con rod. The uncoated and DLC coated piston pin was in direct contact with steel and aluminium counterparts. This system shows a significant advance in wear on the different parts due to the reasons discussed previously. Hence, a DLC film gives a beneficial solution to avoid bushings in the piston as well as the con rod and helps to fulfil the requirements of high specific output diesel engines.

Table 5. Wear documentation of separated components from engine tests without bushings in the piston and the con rod

	Piston pin	Con rod	Piston
Uncoated pin	+	--	-
DLC coated pin	++	○	○

In summary, the internal combustion engine tests generally agree with and confirm the outcomes of the reciprocating ball-on-flat sliding wear tests. The investigated components show a large decrease in wear when a DLC coating is applied to the piston pin.

Furthermore, friction measurements were carried out in a diesel engine with DLC coated piston pins, bushingless pistons and con rods with bushings. The measurements showed a drag torque reduction for various rotational speeds and oil temperatures in a non-fired engine. DLC films applied on piston pins also exhibit properties and good potential to decrease frictional losses and fuel consumption in modern engines. Therefore, Federal-Mogul has used DLC coatings for two customers in series production since 2007.

SUMMARY

In this study uncoated and DLC coated piston pin sections were investigated to assess wear and friction behaviour using different slider materials under reciprocating ball-on-flat sliding wear tests with and without oil lubrication and temperature. In the dry conditions the analysis of friction shows excellent potential for DLC films to decrease the friction in sliding against steel and aluminium. The increase of friction for the DLC coated specimen versus brass has also be explained with transferred material onto the top surface of the piston pin section which could be proved by SEM and EDX investigations. In addition, SEM and EDX analysis also verify the contradictory results for the brass matings in the lubricated condition showing that the coefficient of friction increases for the uncoated piston pin samples.

The volume losses for all tests state that a DLC coating applied on the piston pin segments can significantly decrease the wear of each component.

Furthermore, examined internal combustion engine tests confirmed the results of the non-engine wear rig work. Engine tests also suggest that the specific engine output and the fuel consumption can be positively influenced if DLC coatings are applied to the piston pins.

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