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Investigation of piston ring – cylinder liner dry wear using a block-on-ring test rig

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Abstract: Characterization of the wear of piston rings and cylinder liner is an important aspect of large two stroke diesel engine design. Two major wear mechanisms exist; corrosive wear and mechanical wear. This paper deals with the most aggressive form of the latter, which is known as scuffing. Different material combinations for piston rings and cylinder liners are examined using a block-on-ring test rig. An accelerated wear test run without lubricant is used. Results show that the morphology of cast iron is an important parameter affecting the wear resistance of the material. It is also demonstrated that ceramic coating on the piston ring decreases the dry wear rate of both piston ring and liner, while the coefficient of friction is increased.

Key words: Cylinder liner, piston ring, dry wear, scuffing

1. INTRODUCTION

The majority of all goods are at some point transported by a ship directly propelled by a two stroke diesel engine. This engine type was first installed in a ship nearly a century ago, but is still the preferred propulsion method for large marine vessels due to proven service stability and flexibility with regard to suitable fuel. Because of its size, it is not feasible to machine the cylinder liner to an exact finish. Therefore, a different approach is currently used, by which plateau honing allows an accommodation to take place between cylinder liner and piston ring [1]. To further this, a soft run in coating is applied on top of a hard coating on the piston rings. As a part of the HERCULES-B project, the friction and wear between cylinder liner and piston ring is being investigated, with the objective of lowering both. This will improve the fuel efficiency, which in turn will result in decreased fuel cost as well as lower emissions. One aspect of this friction situation is the phenomena called scuffing, which is a disastrous severe wear situation.

2. SCUFFING

The cylinder liner surface is not smooth. Plateau honing after machining leaves a pattern of valleys with flat plateau hills while graphite porosities, which are intrinsic to the material, present an even distribution of cavities. Both features act as oil reservoirs and pathways, ensuring hydrodynamic lubrication, (a) in Figure 1. In some cases an otherwise stable and minimal wear situation of the piston ring and cylinder liner can escalate within a short period of time with severe accelerated wear and elevated component temperature as the result. When inspected afterwards, the cylinder liner surface is completely smooth and devoid of the original features. This event of accelerated wear is called scuffing and is commonly thought to be provoked by insufficient lubrication. In the case of oil starvation between piston ring and cylinder liner, the sequence of events leading to scuffing is thought to be [1]:

1. Lack of hydrodynamic lubrication causes micro welding and smoothing of the surface by plastic deformation of the surface layer and deposition of oxides shown as (b) and (c) in Figure 1.
2. After some time the oil reservoirs are closed off and most asperities have been removed, resulting in a large contact area between piston ring and cylinder liner.
3. At a critical level, the amount of available oil drops to a point where the smooth surfaces obtain metallic contact, causing adhesion and thereby severe wear.

2.1. Wear comparisons

Jensen et al [1] used a pin on disc test setup to simulate starved conditions, and found that scuffing was preceded by a detectable short period of increasing friction. The results indicated that oxidation resistance and hardness were important parameters for the scuffing resistance of the cylinder liner. Jang et al [2] used a Pin-on-Disk tester to find a relation between wear and soft and hard piston ring coatings. The results showed a temperature induced lubricating effect of oxides. Also, they found that the influence of surface roughness was stronger when the piston ring sample had a soft coating.

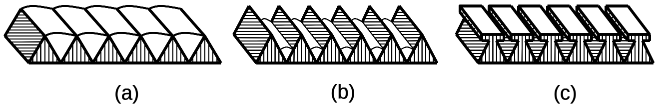
(a) (b) (c)

Figure 1. Cast iron cylinder liner surfaces. (a) hydrodynamic lubrication, (b) oil starved and (c) pre-scuffing. The jagged surface represents both the cavities presented by open graphite pores as well as the roughness left by machining and honing.

Pedersen et al [3] found that a ranking of cylinder liner materials with regard to dry wear was possible, and that the morphology of the cast iron was an important factor. To further investigate this, the same test rig has been used in the present work to perform new tests with a number of new cast iron cylinder liner materials, worn against piston ring surfaces with and without ceramic coating.

3. TEST SETUP

3.1. Block-on-Ring test rig

As part of the HERCULES-B project, a Block-On-Ring (BOR) test rig was constructed in 2008 at D.T.U. The schematic is shown in Figure 2.

3.2. Materials

MAN Diesel supplied 11 different cylinder liner test wheels, shown in Table 1.

Table 1. Cylinder liner test wheels.

Material	Cast iron type
A, B, C, L	Morphology 1 (M1)
D, E, F, G, H, I, J, K	Morphology 2 (M2)

Each wheel is machined from a unique cast with quantifiable differences in microstructure and chemical composition. Conventionally, M1 cast iron has been used for cylinder liners, but due to improved process control, new M2 liners can be cast. The fundamental difference between the two types of cast iron is the shape of the graphite inclusions, which gives M2 a higher tensile and fatigue strength. On the chemical level, M2 cast iron contains a higher amount of oxide forming elements compared to M1.

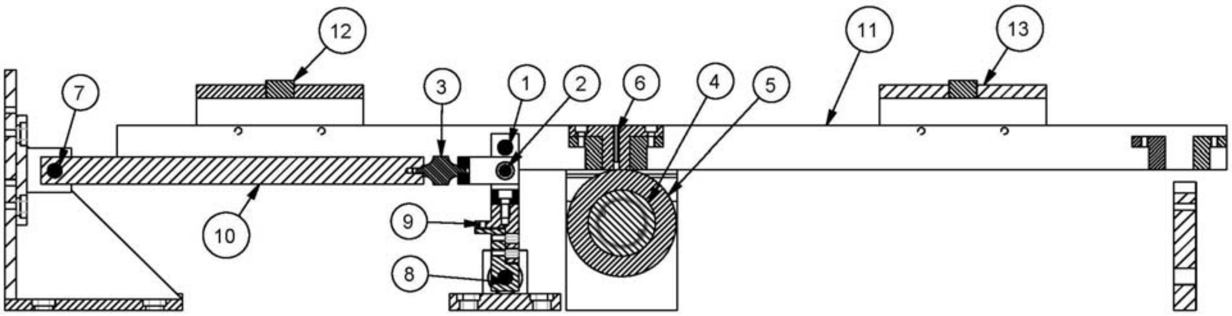

Figure 2. A schematic of the Block on Ring test rig.

Marker	Description
1	Bridge pivot point
2	Force transducer pivot point
3	Force transducer
4	Test wheel shaft
5	Test wheel
6	Hole for thermocouple
7	Pivot point
8	Pivot point
9	Bridge height adjustment screw
10	Force transducer connecting rod
11	Bridge
12	Counterweight load sled
13	Load sled

Piston ring segments with and without ceramic coating are available. Test wheels and piston ring segments are shown in Figure 3.

3.3. Experimental procedure

As scuffing is associated with lack of lubrication, the tests performed in this project have been performed under dry conditions in order to gauge the scuffing resistance. Step loaded tests as well as constant loaded tests have been performed, with the objective to establish a relation between scuffing resistance and intrinsic material properties, as well as formulate a fast and simple test method which can reveal the scuffing resistance of a given cylinder liner-piston ring combination. Step loaded tests were performed with an initial load of 40N which increased with 80N every 10 minutes until a load of 980N was reached (at 130 minutes) or the experiment terminated because of motor overload. In order to simplify the test procedure, constant load tests were performed with a load of 400N for fixed time of 90 minutes. Test wheels and piston ring segments were ground to a surface finish of R_a = 0.2μm – 0.5μm and cleaned with acetone before experiments.

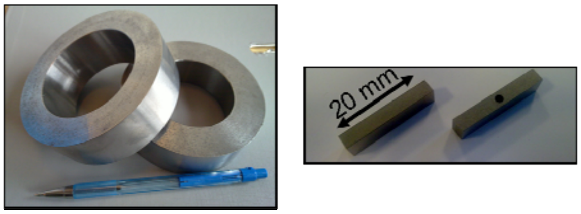

Figure 3. Cylinder liner test wheels and piston ring segments.

4. RESULTS

4.1. Step load

Earlier published testing covering Material A-E done by Pedersen et al [3] enables a comparison of results, as test method and equipment is identical. All step loaded experiments are gathered in Figure 4. For all materials the increase in load results in an increase in friction force. Even though the load is constant, the friction force steps have a positive slope towards the end of each experiment. Qualitatively, with the exceptions of material D and F, there is a clear correlation between type of cylinder liner and time before test termination. The M1 cast iron materials (A-C) all separate from the M2 materials with a test termination at 70 minutes. Aside from this obvious difference, step loading does not seem to differentiate the

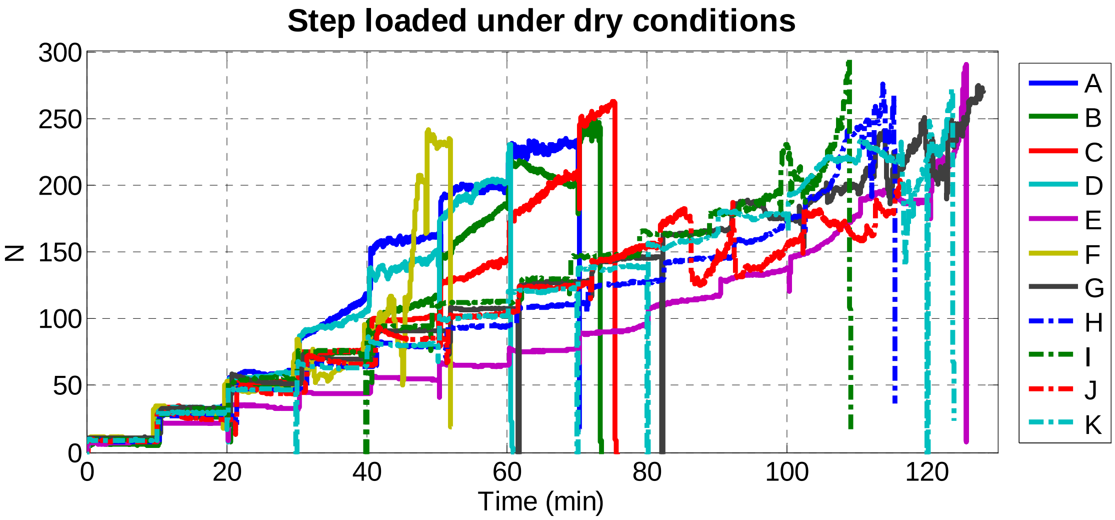

Figure 4. Step loaded experiments. There is a distinct difference between M1 cast iron (A-C) and M2 cast iron.

casts of M2, even though they are dissimilar in hardness and microstructure. A cross section of a piston ring segment after a dry test is shown in Figure 5. Plastic deformation has taken place to a depth of 100µm, effectively sealing the graphite pores.

4.2. Constant load

In order to investigate the longest lasting materials from the step loaded setup and to establish a new, simpler wear test, M2 materials F-K were put through a constant load test. As a reference, M1 material L was added. The constant load test is simpler and less time consuming than the step loaded test. Results are shown in Figure 6. As there is no step increase of the load, the gradual degradation of the surface is the only source for the increase in friction force. All test wheels converge on a friction coefficient of approximately 0.5. Material L reaches this terminal high friction level quicker than the remaining samples. The low friction level of material K appears to be due to experimental error. Disregarding K, the variation of the friction response of the M2 materials is small, suggesting that they all have something in common which gives them this behaviour.

The fact that material K gave a completely different result made it clear that further examination of the variation of the results was needed. Therefore, the constant load test was repeated for material K twice, so three results were available. Also, two experiments using material K against ceramic coated piston ring segments were performed, one of which terminated early because of software error. All available constant load data for materials K and L are gathered in Figure 7, where a clear difference is apparent when the piston ring segment is

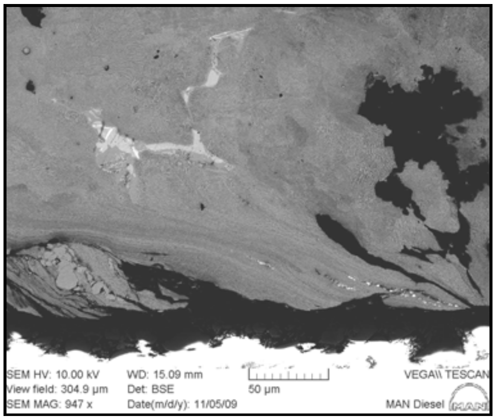

Figure 5. A cross section of a piston ring segment after dry testing. Surface facing down. Plastic deformation has taken place to a depth of 100 µm.

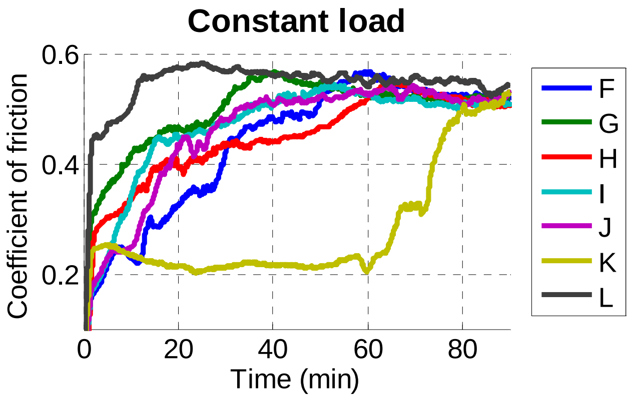

Figure 6. Constant load of 400 N under dry conditions. Test wheel L is made from M1 cast iron, the rest are M2. The result from K is a product of experimental error.

coated. The terminal friction level is higher, and LC reaches a maximum after 30 minutes with a coefficient of 0.7. The "C" postfix means a coated piston ring segment was used. Approximately the same value is reached by KC 25 minutes later. The repeated experiment with a coated piston ring segment against a K wheel terminated early, but the results up to test end are similar to the first KC experiment. After the initial maximum, the response falls somewhat and remains stable at 0.6 for both LC and KC.

The piston ring temperature development for material H subjected to step and constant load test is shown in Figure 8. For the step load, it increases continually, showing that no steady state is reached within each load step. For the constant load, the response is cyclic and generally higher, reaching temperatures of 150°C for short periods.

The cyclic temperature response of the constant load test suggests that removal of material is followed by a period with lowered material loss, which then leads to a new high wear period. This may be because removal of material releases graphite which acts as a lubricant. In order to quantify the material loss of the piston ring segment, it was weighed before and after testing.

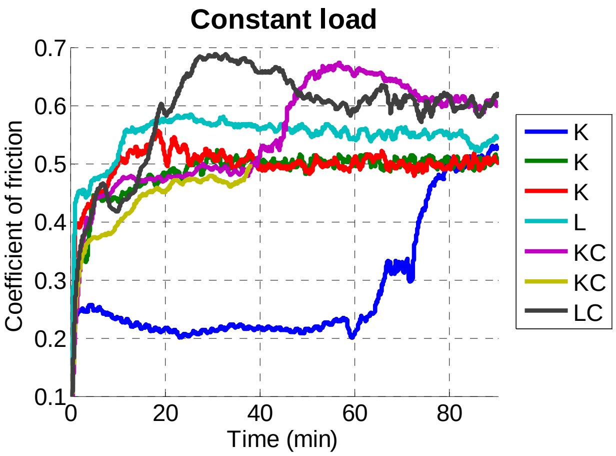

Figure 7. Experiments performed with coated piston ring segments have postfix "C".

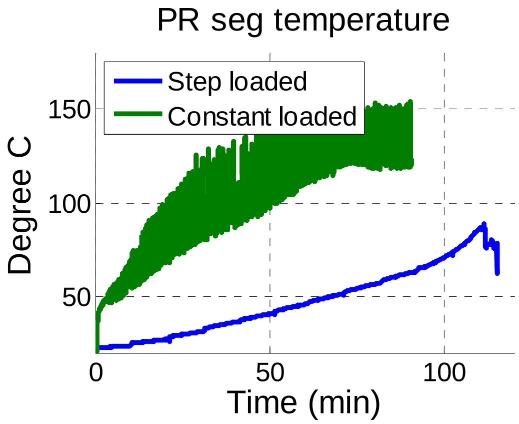

Figure 8. Piston ring segment temperature when sliding against material H. The constant load test causes a cyclic temperature response, with a running average up to 50°C higher than that produced by the step loaded test.

This was not possible with the test wheels, as they were too heavy.

Therefore a method which uses profile measurements to quantify the amount of material removed was developed, as shown in Figure 9. The segmented line indicates the unworn surface, and the full line is the measured profile after testing. The wear is then quantified as the area below the dashed line. Using this method, Figure 10 presents the wear for ring segments and test wheels for the constant load experiments.

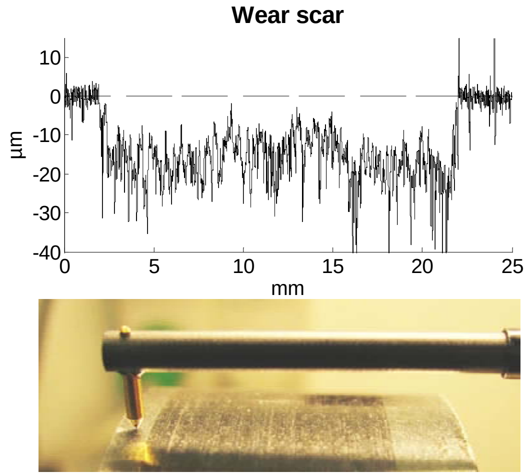

Figure 9. The wear of the test wheels was measured by performing a profile measurement across the wear scar and summing up the lost area.

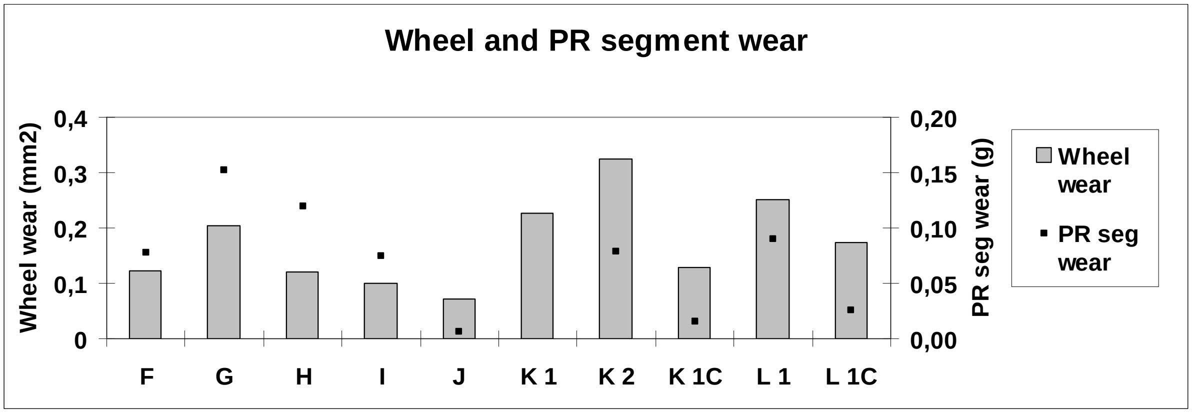

Figure 10. Piston ring segment wear for K 1 is omitted because of experimental error. Likewise K2C was terminated early because of a software error.

The wheel wear of materials F-J is moderate, while K and L both have a high level of wheel wear when an uncoated piston ring segment is used. Material J has one of the lowest levels of piston ring segment wear. For the coated experiments, both material K and L experience a lower level of material loss, most pronounced for material K.

5. DISCUSSION

Both the step loaded and the constant load test agree that there is a distinct difference between the behaviour of M1 and M2 cast iron.

5.1. Step load or constant load

The step load test was initially formulated to find the dry wear limit for the cylinder liner materials. This is done by adding weight until the motor overloads or the load reaches 980N. Measured temperature during experiments shows that it is increasing steadily throughout the test. Therefore it is unclear whether the test termination is a feature of the load or of the increasing temperature, which would have occured even if the load was not increased. With the load change every ten minutes and a long test time of over 2 hours, it is also time consuming to perform. These issues are not present with the constant load test, and since it produces the same qualitative relationship between M1 and M2 cast iron, the constant load test is considered the better choice of the two.

5.2. Run in

There is a longer period before a constant level of friction is reached for the M2 cast iron in the constant load tests. Material L breaks down faster than material K when the piston ring segment has a ceramic coating. This suggests that the initial oxide film on M2 cast iron is thicker and more durable, which can be explained with a higher content of oxide forming elements.

5.3. Self-lubrication

The only available lubrication is the graphite contained in the materials themselves. Graphite is a good lubricant, and there is no doubt it plays an active role in the experiments, as the surface of the wheels becomes black shortly after test initiation. Hard coating on the piston ring segments removes one contributor of graphite, which can explain the higher terminal friction coefficient in the coated experiments.

5.4. Wear progression

Focusing on the wear behaviour of an M2 type wheel in a constant load test using a coated piston ring segment, a sequence of events can be theorized. Initially, the oxide film of the test wheel is being worn down, resulting in an increasing friction force. This is slowed down to some extent by graphite which is drawn out of pores and onto the surface, acting as lubricant and colouring the surface black. When the oxide film and available graphite is worn off, metal on metal contact causes micro welding, which plastically deforms and hardens the microstructure of the test wheel, resulting in closed graphite pores. As the hard coating on the piston ring segment is considerably harder than the cast iron, the test wheel surface is worn off, exposing a rougher surface and releasing graphite. This causes the friction force to drop somewhat and a cyclic stable pattern is reached, in which material removal and graphite release is alternated with metal on metal contact. This theory is supported by the observed cyclic change in temperature. The fact that the terminal friction is lower than the maximum friction suggests that the high temperature influences the wear. The coating on the piston ring segment is worn smooth, and presents less of a grating action than an uncoated piston ring segment which contains hard particles and is prone to present a jagged surface upon wear. This may explain the decrease in material loss for both surfaces when the piston ring segment is coated.

6. CONCLUSION

The tribological situation in the two stroke diesel engine is complex and difficult to recreate under laboratory conditions. This is however necessary as full scale testing is prohibitively expensive. Earlier experimental comparisons of cylinder liner materials have included lubrication in their experimental setup. This is inherently difficult, as the amount and state of any lubrication will be based on an educated guess on what the actual situation is in an engine. In the present tests, lubrication has been left out all together. This makes it possible to perform a very conservative comparison between materials, as it can be assumed that good dry wear properties will also correspond to a good scuffing resistance.

The performed experiments promote closing of surface cavities which is associated with scuffing.

For both test methods examined, the results agree that there is a fundamental difference between the dry wear behaviour of M1 and M2 cast iron, with the latter having a longer run in period before severe wear occurs. This is largely thought to be explained by a higher content of oxide forming elements, causing a thicker layer of oxide.

Furthermore the results show that having a hard coating on the piston ring results in lower material loss for both surfaces but a higher terminal coefficient of friction.

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