<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper published in *Wear*. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the original published paper (version of record):

Olander, P., Eskildsen, S S., Fogh, J W., Hollman, P., Jacobson, S. (2015)

Testing scuffing resistance of materials for marine 2-stroke engines: Difficulties with lab scale testing of a complex phenomenon.

Wear, 340-341: 9-18

<http://dx.doi.org/10.1016/j.wear.2015.06.015>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-265177>

Testing scuffing resistance of materials for marine 2-stroke engines – Difficulties with lab scale testing of a complex phenomenon

P. Olander^{1*}, S. S. Eskildsen², J. W. Fogh², P. Hollman¹, S. Jacobson¹

¹Ångström Tribomaterials group, Uppsala University, Box 534, 751 21 Uppsala, Sweden.

²MAN Diesel & Turbo, Teglholmsgade 41, DK-2450 Copenhagen SV, Denmark.

Abstract

Optimising sliding materials of marine two-stroke diesel engine cylinders for reduced risk of scuffing is imperative because of the high costs associated with replacing the cylinder liner. But how can a complex and poorly understood phenomenon such as scuffing be tested? This study investigates the potential of material selection based on lab tests. Experience from ship operation is combined with analysis of lab scale scuffing tests to evaluate the possibilities of gaining applicable knowledge from scuffing testing. Two piston ring materials, a grey cast iron and a plasma sprayed cermet coating, both currently used in engines, were tested. Each of the materials was tested with two surface characters, achieved by run-in in a real engine and by fine grinding respectively. The ranking of the two materials proved to differ between the two surface characters. In the tests, scuffing could only be detected when all oil had become removed from the contact by being adsorbed by agglomerated wear debris and scraped away. This and other critical mechanisms behind scuffing in the tests are thoroughly discussed and compared to possible mechanisms taking place in the engine.

Keywords: *Lubricated wear including scuffing; cylinder liner; piston ring; materials; marine two-stroke diesel engine*

*Corresponding author: Petra Olander (petra.olander@angstrom.uu.se)

1. INTRODUCTION

Is it possible to evaluate the scuffing resistance of a material in a lab test although scuffing is complex and poorly understood? The incentives for optimising the sliding materials, the lubrication technique and lubricating oil to reduce the risk for scuffing are strong. Development towards higher power output leads to higher risk for scuffing if no counteractions are made. There is also an anxiousness for increased scuffing risk with the transition to cleaner fuels, based on service experience from ships operating on low sulphur diesel, where scuffing takes place more frequently. The beneficial tribological effect is attributed to sulphur in the fuel building up a solid lubricating film and promoting a beneficial mild corrosive wear. There are also experimental studies showing that fuel with lower sulphur content give a lower scuffing resistance [1, 2]. The catastrophic nature of scuffing in engine cylinders implies a sudden shift from the normal low wear rate to a very high. Scuffed cylinder liners have to be replaced, which typically takes 18 hours and can cost up to 100.000 USD. Unplanned stops and expenses are never desirable, especially not in the shipping industry, where costs are essential for the competitiveness of a company. Preventing scuffing also has a safety aspect; when at sea, engine power must be fail-safe.

The present study is part of a project aiming towards greener marine transports by developing a new type of diesel engine that can operate on natural gas instead of on the sulphur-rich heavy fuel oil used today. This is a great challenge. Despite vast modifications, high

reliability is needed from start for the new engine type, to be able to compete with the current well-functioning, progressively refined engines. Piston ring materials with better scuffing resistance would be one way to achieve this. Field-testing is expensive and time consuming. Consequently, there is a need to investigate the possibilities of getting relevant knowledge from scuffing testing and the potential of enabling material selection from lab tests. Here, the literature on scuffing is reviewed and experiences from ship operation are presented. Lab-scale scuffing tests have been performed aiming towards simulating the initiation of scuffing. An interesting question is whether lab tests can be used to gain more valuable knowledge than that gained from engine experience.

1.1. What is scuffing?

The scuffing phenomenon has attracted some attention over the years and different definitions have been used. According to the ASTM Terminology standard G40, *Scuffing is a form of wear occurring in inadequately-lubricated tribosystems that is characterized by macroscopically observable changes in texture, with features related to the direction of motion*. However, there is still no agreement on the mechanisms behind scuffing.

Several papers have reviewed scuffing [3-5] and many mechanisms of scuffing have been suggested. Some suggested mechanisms consider how the lubricating film is destroyed, for instance at a critical load or temperature [6]. Others focus on the break down of solid lubricating films, such as oxide layers, which occurs if the wear rate is higher than the rate of film formation [3]. Still others view poor lubrication just as a necessity for scuffing to be initiated and focus on the mechanisms of deformation occurring after lubrication has failed [7]. In early literature, hard, etch-resistant layers were observed on scuffed surfaces (called white layers because of the white appearance when etched and viewed in light optical microscope). Scuffing has been described as the formation and spalling of this layer [4, 8]. Investigations have also focused on scuffing as an adhesive failure [9]. Damage accumulation and plastic fatigue are other explanations for initiation of scuffing [3, 10, 11]. A later suggestion by Ajayi et al. is that scuffing is explained by adiabatic shear instability [7]. According to this theory, scuffing occurs via adiabatic shear when the rate of thermal softening exceeds the rate of work hardening in the sliding contact. Wear particles also play a role in some of the suggested scuffing models [3, 12, 13].

Scuffing is a transition involving change of wear mechanisms and some of the mentioned theories involve transitions in several stages. Furthermore, scuffing on the local scale, which was called microscuffing by Ludema, could either advance into macroscuffing, i.e. catastrophic failure of the components, or it could be quenched and thereby heal [3]. This is in agreement with observations from marine 2-stroke engines, where a phenomenon called micro-seizure can appear on the surfaces (see section 2). Similar observations were also made in early studies on piston ring friction where “dull-looking” streaks (and sometimes “light” streaks) appeared randomly distributed over the liner surface before any roughening took place [14].

1.2. How is scuffing simulated in lab scale?

Lab scale scuffing tests have been performed using several configurations as well as with different procedures. Configurations include pin-on-twin (one cylinder reciprocating on two) [15], ball-on-flat (reciprocating and rotating)[1, 16], cylinder-on-plate (pivoting) [17], pin-on-disc/block-on-ring (rotating) [18, 7]. Most test procedures include an increase in the severity

of the sliding contacts, for example by increase of speed [1], load [16, 7] or by starved lubrication [18]. Some procedures do not include any increase in severity [15, 17].

In most tests, scuffing is considered to occur when the coefficient of friction increases and reaches a specific limit. Blau et al. [17] instead used a multiple criteria approach to rank scuffing performance taking into account friction force, wear and resulting surface roughness.

When it comes to lubrication, different fluids (oils, fuels etc.) have been used depending on the aim of the study and application targeted.

2. EXPERIENCE OF SCUFFING IN MARINE TWO-STROKE ENGINES

Over the last few decades of service experience with modern two-stroke diesel engines, scuffing failure of cylinder liners has been observed only quite seldom, typically less than one scuffing in the lifetime of an engine (~ 30 years). However, some years ago, the frequency of scuffing incidents increased on some of the largest engines from MAN Diesel & Turbo. This led to a very serious service situation where a twelve cylinder engine would experience a scuffing every second year [19].

During the mentioned incidents, the following observations were made:

- Using the same engine type, some ship-owners experienced scuffing incidents and some did not.
- Shorter stroke engines were more prone to scuffing.
- MAN Diesel & Turbo two-stroke engines are manufactured as licence production by several engine manufacturers, and one engine manufacturer seemed to produce engines that were more scuffing sensitive than similar engines from other manufacturers.

In spite of the increased amount of scuffing cases studied during this period and the improved statistical information being built up, the reasons for scuffing were still quite unclear, indicating and underlining the very complex and stochastic nature of the phenomenon.

Scuffing can easily be observed by a visual inspection of liner and piston rings through the scavenge ports (Figure 1). Often, something called micro-seizure can be seen before a scuffing incident, but not all micro-seizures lead to scuffing. Micro-seizure is probably the same phenomenon as that called microscuffing by other researchers (mentioned in section 1).

Figure 1: View of the 4 piston rings through the scavenge port. Micro-seizure, which could lead to a scuffing situation, is clearly seen on ring no. 4 (see inset).

Based on many years of service experience, it seems that at least the following 3 phenomena can lead to scuffing:

- Water droplets in the scavenge air will locally destroy the oil film on the cylinder liner surface if allowed to condense
- When the cylinder liner wear rate is low (diameter increase < 0.03 mm/1000 h), a situation can occur where the graphite flakes become closed, leading to less oil reservoirs on the liner
- Very smooth liner surfaces can occur typically in the middle and lower part of the liner (Figure 2), due to mechanical “bore polish” by a hard, calcium containing layer on the piston - the layer being formed when excessive dosage of cylinder oil is used. Introducing a piston scraper ring in the liner, which removes this layer, solved the problem with bore polishing. However, problems with increased risk for scuffing still occur when excessive dosage of cylinder oil is used.

Additionally, in cases of scuffing, a temperature rise of 1-1.5°C of the jacket cooling water (cooling the upper part of the liner) can be observed 10-20 hours before any visual scuffing signs on the rings and the liner can be seen. The wear rate during scuffing can easily be several mm/1000 h of the diameter as opposed to a normal liner wear rate of less than 0.1 mm/1000 h. The high wear rate following the scuffing initiation rapidly destroys the surfaces, which means that all traces of the initiating mechanisms are removed.

Introduction of a cermet coating (Ni, Cr, Cr-carbide, Mo) (same type as used in the present study) on the running surface of the piston rings seems to be a reliable countermeasure against scuffing [19].

Figure 2: Initial stage of bore polishing in the lower part of a liner. Outside the white markings the liner surface has its normal appearance.

3. EXPERIMENTAL

The aim of the experimental work was to investigate tests for scuffing resistance of candidate piston ring materials for marine two-stroke diesel engines.

3.1. Scuffing tests

Scuffing tests were performed with either starved lubrication or step-wise load increase as methods to increase the severity of the contact situation. Two piston ring materials currently used in engines were tested, both mating the same cylinder liner material as used in engines. In the tests with starved lubrication, the two ring materials were each tested with two different types of surfaces. A summary of the performed tests is shown in Table 1 (details are described later in this section).

Table 1: Summary of the scuffing tests performed.

Test	Load (N)	Pressure* (MPa)	Run-in procedure	Ring samples
Starved lubrication	70	50	Yes	Finely ground
	70	40	Yes	Field worn
Step-wise load increase	100-1400	350	No	Finely ground

* Average nominal surface pressure in the end of the tests, as estimated from measuring the final areas of the wear marks.

The test parameters were chosen to simulate the situation near the top dead centre where there is boundary lubrication and scuffing generally is initiated. In all tests:

- Temperature: 180°C
- Stroke length: 30 mm
- Frequency: 5 cycles/s, corresponding to sliding speeds of 0-0.5 m/s during each stroke
- Lubricating oil: fully formulated cylinder oil commonly used in marine two-stroke diesel engines (Exxon Mobilguard 570, kinematic viscosity: 230 mm²/s at 40 °C, total base number: 71 mg KOH/g, inorganic constituents: Ca, Zn, Mg, Si, P, B, Fe, S, Al, Ba, Na, K, Ni, V, Cr, Cu, Pb, Sn)

The reciprocating motion in the test equipment is obtained from a servomotor connected with a crankshaft and connecting rod to a linear bearing holding the liner sample holder. The load is applied with a spring and the amplitude of the normal force as well as the friction force is measured with strain gauges and continuously logged during the tests. Resistive heating is used and the temperature was measured and controlled using a feedback loop.

In engines, an increased temperature can be observed before scuffing takes place (as described in section 2). This increase is caused by an increased friction force. A friction coefficient of 0.25 was selected as scuffing criterion, as exemplified in Figure 2, but since the friction increase rates were quite similar in all tests, the exact value selected was not critical for the resulting ranking or relative differences.

Figure 3: Typical friction curve from the scuffing tests. After keeping low and stable for thousands of cycles, the friction suddenly rises steeply, and never falls back to the low level. The passage of the coefficient of friction over 0.25 was used as scuffing criterion.

Starved lubrication

Prior to the tests with starved lubrication, a run-in period of 40,000 cycles at 100 N load and with one drop of oil was performed. This is enough oil to keep the contact surrounded by lubricant.

After this, the samples were cleaned with hexane. A thin oil film of about 1 μm was applied onto the liner sample by pouring a solution of oil and hexane on the vertically held sample. The oil-hexane-solution had a concentration of 7 wt% oil and 93 wt% hexane. The low-viscous solution forms a thin film on the surface, and when the hexane evaporates, a thin oil film is left. Holding the sample in a vertical position and shaking the sample afterwards help avoiding excessive solution held by surface tension along the sample edges. The oil film thickness was estimated to be about 1 μm , by measuring the weight increase of the sample after applying the oil film. Verifying tests showed that the repeatability of the film thickness gained, was within an error margin of maximum 10%.

Step-wise load increase

The tests with step-wise load increase were performed lubricated with several drops of oil. These tests were performed to find at what load scuffing would occur when flowing oil is surrounding the contact.

3.2. Materials and surface preparations

The two piston ring materials tested were:

- Grey cast iron with pearlitic matrix and primary cementite. Used for ring 2-4 in engines.
- Cermet coating (Ni, Cr, Cr-carbide, Mo). In larger engines, this thermally sprayed coating is used on ring 1 and 4 and it has been used successfully to counteract scuffing problems.

The (upper stationary) ring samples were cut from real piston rings and tested with different surface appearance (see Figure 4) and also different contact geometries (see Figure 5). The ring samples called *field worn* were cut from piston rings taken out from a well running engine. Thus, their surface appearance was just as when running in the engine and consequently the curvature from the radius of the ring was kept (400 mm). The *finely ground* samples were ground with SiC-paper (grit size 1000 followed by 4000). The last part of the grinding was performed in the test rig to simplify alignment to the liner sample. The scratches from running in the engine as well as those from the grinding were parallel to the sliding direction in the test. Pressure sensitive film (Fujifilm Prescale) was used to ensure that the ring sample was aligned to the liner sample. The paper was put on the liner sample, while the ring sample was pressed down gently. If an even colour was obtained on the paper, the test was carried out. If not, the mounting was adjusted until even pressure was achieved.

Figure 4: Difference in appearance between the two types of ring surface preparations. Grey iron on top and cermet below. For the grey iron, the largest difference is that the finely ground rings (a) show graphite all the way up to the surface in the lamellas, whereas in the field worn (b) some graphite has become removed, leaving open cavities. For the cermet, the finely ground surface (c) is more even than the field worn (d) in which the hard phase lies higher than the softer metallic phase. Pores are visible in both cermet surfaces, but the field worn is rougher. SEM (same magnification)

The lower samples, here called *liner samples*, were cut from a cylinder liner of a marine two-stroke diesel engine, made of alloyed grey cast iron with pearlitic matrix and primary hard phase (cementite and steadite). The samples were ground flat, since rings normally have a larger diameter than the corresponding cylinders, which ruins the possibilities to achieve a good alignment with even pressure distribution. The grinding was performed in the direction perpendicular to the sliding direction using SiC-paper (up to grit size 4000).

Figure 5: Schematic views of the test configuration and sample shapes for the different sample types. The (upper stationary) ring sample slides against the (flat reciprocating) liner sample. a) Ring sample with the finely ground surface and nominal contact area 2x2 mm to the left and b) with original field worn surface and curvature kept (radius 400 mm) to the right.

3.3. Surface analysis

With the objective to collect clues about critical mechanisms for scuffing initiation, light optical microscopy (LOM), scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) was used to analyse the surfaces before and after scuffing tests. Ideally, the lab-tested surfaces should be compared with samples taken from engines that have experienced scuffing. It is, however, very difficult to get hold of such samples of high quality. Normally, both rings and liners become completely destroyed after scuffing has occurred, thereby ruining the traces of the problem initiation.

4. RESULTS

4.1. Coefficient of friction during run-in

The starved lubrication tests were preceded by a 40,000 cycles run-in period in flowing oil, to allow the surfaces to adapt to each other. During this period stable friction was obtained (Figure 6). From these results we can see that the coefficient of friction is lower for the grey iron samples.

Figure 6: Friction curves for the field worn cermet and grey iron samples during run-in with ample supply of oil. The friction is lower for the grey iron.

4.2. Starved lubrication and finely ground rings

The grey iron showed a better scuffing resistance (i.e. more cycles before passing $\mu=0.25$) than the cermet in the test with finely ground rings (Figure 7). The scatter was large compared to the difference in mean result between the materials.

Figure 7: *Scuffing resistance in tests with starved lubrication and finely ground rings. Friction curves shown in upper part; mean values and standard deviations for number of cycles to pass the scuffing criterion $\mu = 0.25$ in lower part.*

4.3. Starved lubrication and field worn rings

In the starved lubrication tests with field worn rings, the cermet showed the better scuffing resistance (Figure 8) Hence, the ranking is reversed, but again the scatter is large compared to the difference in mean result between the materials. The field worn rings generally gave more rapid scuffing than the finely ground. Note that the results cannot be directly compared because of the different contact geometries (Figure 5).

Figure 8: *Scuffing resistance in tests with starved lubrication and field worn rings. Friction curves shown in upper part; mean values and standard deviations for number of cycles to pass $\mu = 0.25$ in lower part.*

4.4. Step-wise increased load

It was found impossible to reach the scuffing criterion by increasing the load up to the maximum possible (1400 N) of the present experimental set-up, as long as there was cylinder oil surrounding the contact. This load corresponds to nominal surface pressure of 350 MPa, which is much higher than the 5 MPa in engines. Only a small number of samples were tested using this procedure, since it was regarded fruitless. In some of these, sudden increases in friction and roughened surfaces were obtained. In these, it was consistently observed that wear debris was accumulated around the wear mark and had adsorbed the oil, thereby leaving the wear mark dry.

4.5. Observations of worn surfaces from scuffing tests

Valuable observations demonstrating critical mechanisms taking place in the scuffing tests are presented in the following micrographs. In all, the reciprocating sliding direction has been vertical in the micrograph.

Wear debris

After the starved lubrication tests, wear debris was found scraped off at the turning points on the liner sample and on the sliding surfaces (see Figure 9). Sometimes, the debris has the appearance of small wear debris that has sintered together. In other cases it has the appearance of relatively large wear particles agglomerated with finer debris and oil. The latter type was found more abundantly on field worn rings.

Figure 9: a) Scraped off wear debris at turning point of wear mark on a liner sample run against a field worn cermet ring. The wear mark itself has no visible signs of oil. LOM. b) Example of agglomerated wear debris. Here, a mixture of small and relatively large wear particles fills pores and cavities of a field worn cermet ring. This wear debris originates mainly from the mating grey iron. SEM, EDS used to confirm elements

Grey iron ring

After the starved lubrication tests, the worn surfaces of field worn and finely ground grey iron had similar appearances, although on the field worn rings, larger parts of the surfaces were roughened. Examples are shown in Figure 10.

Figure 10: Surface appearance of scuffing tested grey iron ring samples. SEM, EDS used to confirm elements.

a) Finely ground ring. Here some of the graphite has been removed from the lamellas during the test, thereby achieving an appearance similar to the initial appearance of the field worn samples (cp. Figure 4, upper right). Some lamellas are filled with agglomerated wear debris

b) Field worn ring, overview across the whole wear mark. The boxes are magnified in c and d.

c) To the left the surface is worn rough while to the right the graphite lamellas have become closed and agglomerated wear debris have been smeared out.

d) To the left, the surface is covered by smeared agglomerated wear debris and to the right the tribofilm formed during the preceding run-in period is still present. For more information about the tribofilm formed with this oil, see previous work. [20]

Cermet ring

The cermet ring surfaces resulting from the scuffing tests with starved lubrication were also similar, regardless of starting from the field worn or finely ground appearance. However, also in this case, more roughening was observed on the field worn rings. Examples are shown in Figure 11.

Figure 11: Scuffing tested surfaces of ring samples. SEM, EDS used to confirm elements.

- a) Overview of the whole wear mark of a field worn ring sample, where the middle section is covered by agglomerated wear debris that fills the cavities. Along the edges, the wear mark has a darker appearance caused by oil contained in the wear debris agglomerate (as shown in Figure 9). In this example, no surface damage of the rings surface can be seen.***
- b) Dark agglomerates of wear debris and oil to the left, lighter agglomerates of fine wear debris filling cavities to the right.***
- c) Iron transferred from the liner covers parts of the smooth areas.***
- d) Some of the field worn rings are partly roughened, generally in the middle of the wear scar. Here, coating splats have become completely removed or fragmented.***

Liner

The liner samples generally did not show as much wear and plastic deformation as the ring samples. This is due to the shorter, intermittent sliding distance experienced by the liner. Analogously, no closing of graphite lamellas was observed. An example of a worn liner sample is seen in Figure 12.

Figure 12: Part of wear mark on a liner sample. The darker bands to the left consist of tribofilm. The band to the right is partially covered by smeared out agglomerated wear debris and roughened. SEM, EDS used to confirm elements.

Step-wise increased load

In tests with step-wise load increase where the test was stopped before the oil was depleted, the ring samples kept smooth up to the highest loads, and the graphite lamellas became closed (Figure 13). However, no agglomerated wear debris or transfer of iron from liner or roughening of the samples had occurred, as was the case with samples from starved lubrication tests.

Figure 13: Example of the smooth surface of a grey iron ring after test with final load of 1400 N and oil surrounding the contact. The darker areas are covered by a tribofilm (described in [20]). The graphite lamellas were closed over the whole wear mark, but neither roughening of sliding surfaces nor increased coefficient of friction was obtained. SEM, EDS used to confirm elements.

5. DISCUSSION

The fact that the two surface preparations employed (field worn and finely ground) give different ranking for the same set of materials emphasizes a general challenge; how do we decide which ranking is relevant for scuffing resistance in the engine? Further, the surface preparation combined with sample geometry has a stronger influence than has the material itself (compare Figs. 7 and 8). The importance of considering the relevance of scuffing tests was also demonstrated by Han et al. [16], who showed that unidirectional sliding and reciprocating sliding gave opposite scuffing performance ranking for grey cast iron and steel. Although scuffing testing is not unique in this respect, the complex nature of scuffing and the limited understanding of the scuffing process occurring in ship engines does make it particularly demanding. Clearly, the phenomenon of scuffing is more complex than indicated by most papers on the subject. In this discussion, we therefore try to discuss the mechanisms found in the tests in the light of what we know from experience from marine engines.

From ship engines we know that the friction force increases before scuffing becomes evident. This is clear from the temperature increase of the cooling water preceding visual signs of scuffing. Only macro scale friction changes would lead to a substantial heat increase, but micro-scale effects might be the initiating problem. Is the increased friction the cause for scuffing initiation or is some other mechanism initiating the scuffing process and the high friction? Either way, there are two possibilities for a higher friction force according to the classic law by Amonton, a higher coefficient of friction or a higher normal load. These two possibilities will be discussed in section 5.1 and 5.2, with regards to possible causes. A mind map organising these causes is presented in Figure 14.

Figure 14: Mind map organising possible causes for high friction, based on the fact that the friction force becomes higher before visual scuffing can be observed.

5.1. Higher friction due to higher coefficient of friction

A higher average coefficient of friction during the stroke could either be due to a larger part of the stroke running in boundary lubrication (or even partly dry friction) and/or a higher coefficient of friction within the different lubrication regimes. In boundary lubrication, the coefficient of friction can be divided into one adhesive and one abrasive part. With these aspects in mind, we can consider the different possibilities for increased coefficient of friction.

...caused by insufficient supply of lubricant

The oil that is sprayed onto the piston is moved up and down by the movement of the piston and becomes depleted by drainage in the lower part of the cylinder and by being burned during combustion. Insufficient supply of new lubricant will consequently lead to starved lubrication and a higher coefficient of friction. The most intriguing experience from service is that the risk for scuffing seems to increase also when too much lubricant is injected. This means that also other factors must be important.

In the lab experiments with starved lubrication, there is intentionally too low supply of lubricant, used as a way of accelerating the wear situation. The mechanisms resulting in oil depletion in the test, and possibly also relevant in the engine, is discussed in the following section.

...caused by impaired lubrication

A high coefficient of friction can be caused by an insufficient effect of the lubricant. This could be due to too high temperature and thereby too low viscosity of the oil, or by water droplets from the scavenge air condensing on the cylinder wall, as was reported in Section 2. Similar mechanisms are not possible causes in the lab test. Instead, accumulation of wear debris seems to be the critical mechanism leading to oil depletion. In the tests with step-wise load increase starting with ample amount of oil, the oil became dark and thick because of wear debris, until eventually it was too thick to flow back into the contact. Only then, the friction increased. Thus, these tests were also transformed to a starved lubrication situation before failing. It seems reasonable that the same mechanism is critical also in the tests with thin initial oil films, as indicated by the observed agglomerated wear debris sometimes containing high amounts of oil (see Figure 9). In supplemental experiments (unpublished data) initiated with dry sliding, high unstable friction and severe roughening of the surfaces, we could see that as soon as oil was added to the contact, the coefficient of friction decreased and reached the same levels as during running-in (see Figure 6). Hence, as long as there were ample amounts of lubricant surrounding the contact, the coefficient of friction stayed low.

Holzhauser and Ling showed that removal of oil is a critical mechanism [21]. They examined boundary lubrication in situ using an SEM with modified vacuum system and observed that oil became adsorbed on wear particles that agglomerated and became removed from the surface. Thereafter, severe wear occurred. Similar behaviour, where the large surface area of a relatively small volume of fine wear debris adsorbs oil, thus aggravating the starved lubrication situation, was also shown by Pettersson and Jacobson [22].

Another variant for involvement of wear debris in scuffing initiation was suggested by Enthoven and Spike [12]. By visual observation through a sapphire disk in contact with a rotating ball, they showed that scuffing was preceded by build up of fine wear debris in the inlet of a sliding contact. The debris agglomerate prevented the oil from coming into the contact, thereby causing starvation. Li et al. [13] recently performed a similar test, but with stationary ball and rotating sapphire disk. They observed that it was rather the entrapment of agglomerated wear debris drawn into the contact that was the initiating factor. Plastic flow appeared where the agglomerated debris was entrapped, which was suggested to be due to concentration of the load, leading to local high friction. This latter approach is similar to the

model suggested by Ludema [3] in which wear debris agglomerates to form larger particles, which eventually carry high loads and thereby cause high stresses.

The relation between wear debris and initiation of a high wear and high friction situation in different scuffing tests seems to be clear. Is it also an important mechanism for initiation of scuffing in the cylinder? In other words, are these tests simulating scuffing in real applications? It seems reasonable to assume that wear debris typically will be removed with the cylinder oil, which is injected into the cylinder every 1-20 strokes. This is especially true in a well functioning cylinder with low wear rate. But if the wear rate or the retainment of wear debris in the contact increases for some reason, this might be a mechanism for initiation of scuffing. This could also explain why using more lubricant increases the risk for scuffing. We know that it leads to problems with calcium-containing layers forming on the piston. Such a layer has a negative effect by polishing the liner surface, but even when a piston scraper ring is used to scrape it off, the scuffing risk remains higher. We could speculate that this is due to wear particles from the scraped layer, which could lead to ruined lubrication in the same way as in the lab experiments [22].

The coefficient of friction could also increase due to impairment of a solid lubricating film. Such an effect could appear if lubricant additives are no longer present or cannot work properly. Also, the beneficial effect of sulphur in the fuel is commonly attributed to the propensity to build up a solid lubricating film [2, 1]. Hence the solid lubrication could become worse due to a change of fuel and this would be especially critical when lubrication is impaired due to other reasons.

...caused by changes in surface appearance

Too smooth surfaces, either due to a too low wear rate or due to bore polishing by a hard calcium-containing layer on the piston, is related to scuffing. In both cases, the graphite lamellas become closed and can no longer work as oil reservoirs on the liner. It is commonly assumed to be an advantage to use materials with an ability to contain oil in reservoirs such as pores and cavities. This has also been shown experimentally for instance by Pettersson and Jacobson [22]. Furthermore, if the entrapment of wear debris is an important factor for scuffing initiation (as discussed), wear debris could become trapped in the cavities rather than between the sliding surfaces. Thereby the initiation process would be delayed and the chance for healing increased.

5.2. Higher friction due to higher normal forces

A higher normal force between the ring and the liner will lead to a higher friction force directly, but also indirectly because a larger part of the stroke will be within the boundary lubrication regime, which would lead to a higher average coefficient of friction and a higher risk for dry sliding. The maximum nominal pressure between the rings and the liner is typically 5 MPa, shortly after the combustion moment. The normal force is higher for higher power outputs and could locally become higher if uneven temperature distorts the ring shape and/or the liner shape. Also, if agglomerated wear debris enters part of the sliding contact (as was discussed in 5.1), this would lead to a local increase in normal force.

The highest surface pressure in the lab test with ample amount of oil was 70 times higher than the typical surface pressures in engines. This load by itself was not enough to cause severe surface damage and scuffing (see Figure 13). The coefficient of friction did not increase until the oil had become removed from the contact. Results where scuffing is obtained even in the presence of lubricant have been published by other researchers. Ayaji et al. [1] tested scuffing resistance with fully immersed contacts, but performed their tests in diesel fuel oils, which are not as lubricious as the fully formulated cylinder oil used in the present study. Scuffing tests have also been performed using polyalphaolefin (PAO) [16, 7], and hexadecane [1]. Qu et al.

[15] performed scuffing tests in diesel fuel as well as in jet fuel and could detect initial scuffing by monitoring the progressive changes of the local friction along the strokes. They considered the averaged coefficient of friction to be too insensitive for tests of scuffing resistant materials.

5.3. Result scatter

The wide scatter within a single material compared to the differences in average between different materials shows that the sources of scatter are comparable to the actual variations in material performance. Several factors could affect the scatter. The initial amount of oil added and the initial distribution could vary slightly, which will lead to scatter. So will the pressure distribution and definition of the contact area; the ring sample shapes were chosen to enable simple production, but sample alignment during mounting proved to be difficult. Even surface pressure of the ring sample was ensured by the use of pressure sensitive film. The paper was put on the liner sample, while the ring sample was pressed down gently. However, the paper has a thickness in itself implying that even when pressure appeared to be evenly spread, sometimes the wear mark showed only on parts of the ring.

Controlling all parameters carefully is of course crucial to minimize the scatter. Nonetheless, if wear debris is the most critical factor, a somewhat stochastic behaviour should be expected. Agglomerations of wear debris are not stable, but will be formed and collapse repeatedly; this was observed by Li et al. [13]. Consequently, a large number of repeated tests would be necessary to achieve statistically reliable ranking of the candidate materials.

The comparatively well controlled lab tests giving such a wide scatter proposes an interesting question: How wide is the scatter in the much less controlled and much more variable world of real engines, and how many scuffing failures would it take to become statistically sure that one ring material actually has a better scuffing behaviour than the other? We know from the serious service situation mentioned in Section 2 that engine type, ship owner and manufacturer all play a role for the number of scuffing incidents. The field data is also characterised by another type of uncertainty. Typically it does not include details on loads, speeds, fuel quality, possible lubrication malfunctions, deviations of the ring material quality, possible corrosion, etc. Clearly, many parameters other than ring material are important for the occurrence of scuffing. It seems reasonable to expect a wider relative scatter of occurrence of scuffing in real engines than in the lab.

5.4. Summarising discussion

The focus in this paper is on the possibility to test if one material is better than the other at preventing scuffing failure. Some of the possible causes for scuffing initiation are material dependent while some are not. Material properties such as wear rate, nature of wear debris, ability to form solid lubricating tribofilms, heat conductivity and amount of cavities could all have a role in initiating scuffing. These will also most likely influence each other, for instance, ability to form lubricating films or holding oil will lead to a lower wear rate. Scuffing is a catastrophic type of failure due to several feedback factors. For instance, an increased friction force leads to a temperature increase, which leads to lower viscosity of the oil as well as uneven temperature distorting the rings, which leads to local high loads. The wear rate will accordingly increase, leading to removal of lubricating tribofilms as well as more wear debris. It seems logical that most material properties previously mentioned should affect either the initiation or the progression of scuffing and also the possibility for healing.

The important aspect is that the material dependent mechanisms in the test must be similar to those in the engine. The wear particles seem to play a large role in different scuffing tests, while it is more uncertain if they are important in the engine. If they are not part of the critical mechanism in the engine, tests should be designed so that wear particles are not accumulating.

Obviously, the mechanisms for scuffing in the engine has to be better understood to enable design of proper scuffing tests. Such an understanding could be gained by further systematic testing, accompanied by systematic studies of field experience and field samples (for instance on micro seized piston rings), enabling comparison of decisive mechanisms.

6. CONCLUSIONS

Based on the presented service experience and the experimental study, the following conclusions can be drawn:

- In the tests, scuffing (as defined by the friction criterion) only occurred after all oil had become removed from the contact.
- In the tests, oil was removed by being adsorbed by agglomerated wear debris and then scraped away from the sliding contact.
- The initial surface character of the ring proved to be important for the scuffing resistance in the tests; the two tested surface characters gave reversed ranking of the two tested materials.
- Further, the present results indicate that the importance of the surface character may differ between different materials.
- The high scatter necessitates many repetitions of the scuffing tests to give statistically reliable results.
- In spite of the difficulties associated with scuffing testing, further development of test procedures is valuable. This is because of the high costs and uncertainties associated with full-scale testing.
- To ensure that the material ranking can be reliably transferred from lab tests to engine performance, it is important to consider which mechanisms that are critical in the engine and test respectively. To enable this, the critical mechanisms of scuffing in engines have to be better understood.

7. ACKNOWLEDGEMENT

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2011) under grant agreement no. 265861 (Helios).

8. REFERENCES

1. O. O. Ajayi, M. F. Alzoubi, A. Erdemir and G. R. Fenske, Effect of carbon coating on scuffing performance in diesel fuels. *Tribology Transactions* 44(2) (2001) 298-304
2. J. Qu, J. J. Truhan, P. J. Blau and H. M. Meyer III, Scuffing transition diagrams for heavy duty diesel fuel injector materials in ultra low-sulfur fuel-lubricated environment. *Wear* 259 (2005) 1031-1040
3. K. C. Ludema, A review of scuffing and running-in of lubricated surfaces, with asperities and oxides in perspective. *Wear* 100 (1984) 315-331
4. D. Scott, A. I. Smith, J. Tait and G. R. Tremain, Materials and metallurgical aspects of piston ring scuffing - Literature survey. *Wear* 33 (1975) 293-315
5. W. F. Bowman and G. W. Stachowiak, A review of scuffing models. *Tribology Letters* 2 (1996) 113-131
6. H. Czichos, Failure criteria in thin film lubrication: Investigation of the different stages of film failure. *Wear* 36 (1976) 13-17
7. O. O. Ajayi, J. G. Hersberger, J. Zhang, H. Yoon and G. R. Fenske, Microstructural evolution during scuffing of hardened 4340 steel - Implication for scuffing mechanism. *Tribology International* 38 (2005) 277-282
8. M. D. Rogers, Mechanism of scuffing in diesel engines. *Wear* 15 (1970) 105-116
9. D. Markov and D. Kelly, Mechanisms of adhesion-initiated catastrophic wear: pure sliding. *Wear* 239(2) (2000) 189-210
10. T. Sheiretov, H. Yoon and C. Cusano, Scuffing under dry sliding conditions—Part II: Theoretical studies. *Tribology Transactions* 41(4) (1998) 447-458
11. Y. Z. Lee and B. J. Kim, The influence of the boundary lubricating conditions of three different fluids on the plastic fatigue related mechanisms of wear and scuffing. *Wear* 232 (1999) 116-121
12. J. Enthoven and H. A. Spikes, Infrared and visual study of the mechanisms of scuffing. *Tribology Transactions* 39(2) (1996) 441-447

13. H. Li, K. Yagi, J. Sugimura, S. Kajita and T. Shinyoshi, Role of particles in scuffing initiation. *Tribology online* 8(5) (2013) 285-294
14. H. W. Tishbein, The friction of piston rings (translated from german). National advisory committee for aeronautics NACA TM 1069 (1940) 25-26
15. J. Qu, J. J. Truhan and P. J. Blau, Investigation of the scuffing characteristics of candidate materials for heavy duty diesel fuel injectors. *Tribology International* 38 (2005) 381-390
16. J. M. Han, R. Zhang, O. O. Ajayi, G. C. Barber, Q. Zou, L. Guessous, D. Schall and S. Alnabulsi, Scuffing behavior of gray iron and 1080 steel in reciprocating and rotational sliding. *Wear* 271 (2011) 1854-1861
17. P. J. Blau, M. Yao, J. Qu and J. Wu, Use of multiple criteria to map the high-temperature scuffing behavior of Co-based superalloys. *Wear* 267 (2009) 374-379
18. H. Yoon, J. Zhang and F. Kelley, Scuffing characteristics of SAE 50B38 steel under lubricated conditions. *Tribology Transactions* 45(2) (2002) 246-252
19. J. W. Fogh and C. L. Felter, Cylinder condition analysis in relation to large bore engines, paper no. 147. *Proceedings of CIMAC Congress Bergen* (2010)
20. P. Olander, P. Hollman and S. Jacobson, Piston ring and cylinder liner wear aggravation caused by transition to greener ship transports - Comparison of samples from test rig and field. *Wear* 302 (2013) 1345-1350
21. W. Holzhauser and F. F. Ling, In situ SEM study of boundary lubricated contacts. *Tribology Transactions* 31(3) (1987) 359-368
22. U. Pettersson and S. Jacobson, Influence of surface texture on boundary lubricated sliding contacts. *Tribology International* 36 (2003) 857-864