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Scuffing resistance testing of piston ring materials for marine two-stroke diesel engines and mapping of the operating mechanisms

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Abstract

The incentive is strong for optimising sliding materials to reduce the risk for scuffing. In this study, scuffing tests were performed aiming towards finding new piston ring materials for greener marine diesel engines and also towards understanding scuffing mechanisms better. The tested ring materials were grey iron, Stellite 6, plasma sprayed cermet and high velocity oxy fuel (HVOF) cermet (both cermets with the same compounds: Cr-carbide, Ni, Cr, Mo). The Stellite 6 and HVOF cermet performed somewhat better than the other two materials. Microscopic and spectroscopic studies of failed sample surfaces revealed several characteristic features. It was clear that different mechanisms are active simultaneously, at different parts of the samples. Based on these results, we propose a hypothesis for a scuffing process involving several stages with distinctive mechanisms. Further studies are needed to strengthen this hypothesis and to relate these findings to actual deterioration mechanisms in the engine.

Keywords:

Scuffing, boundary lubrication, marine diesel engines, cast iron, cermet, Stellite

1. Introduction

The catastrophic nature of scuffing in marine engine cylinders implies a sudden shift from the normal, very low wear rate to a high one. After a scuffing failure, the cylinder liner has to be replaced, which is costly. The incentives are therefore strong for reducing the risk for scuffing, e.g. by optimising the sliding materials. This is especially true today, when development towards higher power output leads to higher risk for scuffing if no counteractions are made. There is also a strong concern for increased scuffing risks with the transition to cleaner fuels, which is one of the current actions taken to meet new emission legislations. According to experience, ships operating on low sulphur diesel suffer more frequent scuffing than ships operating on heavy fuel oil. The belief is that sulphur in the fuel has a beneficial tribological effect due to build up of a solid lubricating film and also due to promoting a beneficial mild corrosive wear. Some experimental studies also show that lubrication with high sulphur fuel provides a lower scuffing resistance [1, 2].

The present study is part of a project aiming towards greener marine transports by change of fuel from sulphur-rich heavy fuel oil to natural gas, totally free from sulphur. Despite this significant change, high reliability is immediately required for the new engine type, to make it able to compete with the current well-functioning, progressively refined engines. Use of piston ring coatings with higher scuffing resistance is one of the possibilities to make the reliability higher. The aim of this study was therefore to test the performance of piston ring materials and achieve a ranking of their scuffing resistance. To be more precise, we are focusing on the initial stages leading to severe scuffing. Once severe scuffing has taken place the surfaces are ruined by wear, and not much can be understood about the initiating mechanism.

The intention was further to study the sliding surfaces after test to achieve deepened knowledge about mechanisms and material behaviour during the initial stages of scuffing. This type of understanding is needed to analyse the critical mechanisms in actual engines and thereby enable validation of the relevance of specific scuffing tests. Some of the results were presented in earlier work [3], but are repeated here to simplify comparisons.

1.1 What is scuffing?

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*. The engine operator may experience this as a process where a well functioning system pass via micro-seizure (a pre-stage of scuffing) towards complete scuffing failure, or recovers to a well functioning system. Any problems with the lubrication would move the cylinder closer to a scuffing failure. Nonetheless ship operators report that using excessive amount of cylinder oil also can cause scuffing problems [3]. Many papers have reviewed the scuffing problem through the years, e.g. [4-6]. From these, it becomes clear that despite decades of research, there is no consensus among scientists, and the mechanisms of scuffing remain unclear. However, several mechanisms have been suggested. Some researchers focus on *how the lubricating film is destroyed*, for instance at a critical load or temperature [7]. 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 formation [4, 8]. Others still, view poor lubrication as a necessity for scuffing to be initiated, and *focus their model on the mechanisms of deformation occurring after lubrication has failed* [9]. In early literature, hard, etch-resistant layers were observed on scuffed surfaces (called white layers because of their white appearance in the light optical microscope after etching). Scuffing was described as the formation and spalling of this layer [5, 10, 11]. Damage accumulation and plastic fatigue are other explanations for initiation of scuffing [4, 12, 13]. More recently Ajayi et al. suggested that scuffing is due to adiabatic shear instability [9].

1.2 How is scuffing simulated in lab scale?

Lab scale scuffing tests are performed in different types of configurations as well as with different procedures. Configurations include pin-on-twin (one cylinder reciprocating on two) [14], ball-on-flat (reciprocating and rotating) [1, 15], cylinder-on-plate (pivoting) [16], pin-on-disc/block-on-ring (rotating) [9, 17]. Most test procedures include an increasing severity of the contact conditions, for example by increasing the speed [1], load [9, 15] or by starving the lubrication [17]. Some procedures do not include any severity increase [14, 16].

In most tests, scuffing is considered to occur when the coefficient of friction increases and reaches a specific limit. Qu et al. reported that the averaged friction coefficient normally obtained in reciprocating sliding tests was not sufficiently sensitive and instead used a concept where they analysed local friction changes [2]. Another approach is to use multiple criteria to rank scuffing performance, taking into account friction force, wear and resulting surface roughness[16].

Several different lubricating fluids (oils, fuels etc.) have been used, depending on the aim of the study and application targeted.

2. Materials and methods

Scuffing tests were performed using starved lubrication as a method to increase the severity of the contact situation. Four sample couples were tested, two comprising piston ring materials currently used in engines and two with new candidate materials. In all couples, the cylinder liner counter surface was an alloyed grey cast iron, commonly used in cylinder liners of engines. The materials are described in section 2.2.

The test parameters were chosen to simulate the boundary lubricated situation near the top dead centre, where scuffing normally is initiated:

- 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

The reciprocating motion in the test equipment is obtained from a servomotor connected via a crankshaft and a connecting rod to a linear bearing, holding the liner sample holder, see Figure 1. The normal load is applied with a spring. Both the normal force and the friction force are measured with strain gauges and continuously logged during the tests. Resistive heating is used to heat the lower (liner) sample from underneath and the temperature was measured and controlled using a feedback loop.

a) **Figure 1: Schematic view of the test configuration and photo of the rig. a) The (upper stationary) ring sample has a nominal contact area of 2x2 mm and slides against the (flat reciprocating) liner sample. b) The rig comprises two complete reciprocating sliding test set ups, driven by a common motor via a crankshaft. The stationary ring samples are spring loaded against the reciprocating liner samples.**

2.1 Test procedure

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

The actual scuffing test was performed with starved lubrication at 70 N load. To achieve a controlled thin oil film, the samples were first cleaned with hexane. Then a solution of oil and hexane was poured onto the vertically held sample. The oil-hexane-solution had a concentration of 7 wt% oil and 93 wt% hexane. This 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 then shaking helps 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. Verifying tests showed that the repeatability of the film thickness was within an error margin of maximum 10%.

In engines, a temperature increase (as measured in the circulating cooling water) can be observed before scuffing takes place. This temperature rise is caused by a friction force increase. Based on this fact, we selected an increased coefficient of friction as scuffing criterion in the present tests. The test was ended when a coefficient of friction of 0.35 was reached. 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 2: Typical friction curve from the tests. After keeping low and stable for thousands of cycles, the friction suddenly rises steeply, and never falls back to the low level. Passing a coefficient of friction of 0.25 was used as scuffing criterion.

2.2 Materials and surface preparations

The piston ring materials tested are presented in Table 1. The mating 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)

Table 1: Piston ring materials tested: grey iron, plasma sprayed (PS) cermet, high velocity oxy fuel (HVOF) cermet and Stellite 6. All ring samples were mating a liner sample of grey cast iron.

Ring material	Description	Comments
Grey iron	Pearlite matrix with graphite lamellas, cementite and small quantities of free ferrite	Used as piston ring material today. Also base material for some coated rings
PS Cermet	Plasma sprayed (PS) cermet coating with chromium carbides as ceramic phase and nickel, chromium and molybdenum as metallic phase. Porous because of coating technique	Used today on 1 st and 4 th ring of the largest engines.
HVOF Cermet	Same as above but sprayed with high velocity oxy fuel (HVOF) technique resulting in a denser coating with different structure	
Stellite 6	Co-based matrix with continuous network of chromium-tungsten carbides. Applied by welding, but can also be applied by spray coating.	Commonly used in tough sliding conditions (normally not oil lubricated) where it typically shows good performance (valves, etc.).

The (upper stationary) *ring samples* had a nominal contact area of 2x2 mm (see Figure 1) and were ground with SiC-paper (grit size 1000 followed by 4000). The last part of the grinding was performed with the sample positioned in the test rig to simplify alignment to the liner sample. Even surface pressure was ensured by the use of pressure sensitive film. SEM-micrographs of the ring sample surfaces are shown in Figure 3. The ring sample geometry were chosen to enable simple testing of new materials, since they can easily be cut out from piston rings or any block of material.

The lower samples, here called *liner samples*, were cut as a rectangular parallelepiped. The grinding was performed in the direction perpendicular to the sliding direction, using SiC-paper (up to grit size 4000).

Figure 1: Surface appearance of the materials as prepared for testing a) Grey iron with graphite lamellae (black) b) PS cermet showing different phases and some porosity, c) HVOF cermet, showing smaller grain sizes and less porosity than the PS cermet d) Stellite 6, showing the cobalt matrix and the carbide network. SEM (all same magnification)

2.3 Surface analysis

Light optical microscopy (LOM), scanning electron microscopy (SEM) and energy dispersive x-ray spectroscopy (EDS) was used to investigate sliding surfaces of three of the six samples of each material. Nital etchant was used on parts of the liner samples to reveal if white etching layers had been formed.

3. Results

3.1. Material performance

The candidate piston ring materials, HVOF cermet and Stellite 6 showed similar scuffing resistance (i.e. number of cycles before passing $\mu=0.25$). Both showed better results than the two materials currently used in engines, i.e. grey iron and PS cermet (see Figure 4). Worst scuffing resistance was obtained for PS cermet. However, the scatter was large compared to the difference in mean results between the materials. In Figure 5, the friction curves for the individual grey iron samples are shown as an example.

Figure 2 Mean values and standard deviations for number of cycles to scuffing, for the four ring materials. (Scuffing here defined as $\mu>0.25$.) The scuffing resistance is best for the HVOF cermet and Stellite 6 rings and worst for the PS cermet ring.

Figure 3 Example of scatter between individual friction curves from one single ring material, here the grey iron.

3.2 The various characteristic features of the surfaces after failure

After failure, the tribological surfaces exhibited a wide variation. Their characteristics varied between different locations on the same sample; between sample couples with the same ring material and naturally also between couples with different ring materials. However, some recurring characteristic features were distinguished, as presented in Table 2. SEM-micrographs exemplifying these characteristic features, using the letter denotation given in Table 2, are presented in Figure 6. Typically, the single worn samples exhibited several of these features, distributed over the surface. An example overview micrograph of a grey iron couple is presented in Figure 7. While only a few examples are presented here, the general concepts are based on observations from several couples of each material.

Table 2 Characteristic features distinguished on the tested ring sample surfaces and the corresponding liner samples (grey iron in all cases).

Characteristic feature			Ring material			
			Grey iron	PS cermet	HVOF cermet	Stellite 6
On ring and corresponding parts of liner sample	A	Tribofilm containing Fe, O, Ca, C, S	Yes	Yes	Yes	Yes
	B	Agglomerated wear debris. Can be larger debris or partially sintered fine debris. Consists of Fe and O, C, Ca and S. Sometimes only Fe and O.	Yes	Yes, but on liner sample only in and around graphite lamellas	Yes	Yes
	C	Roughened surfaces	Yes	No	No	Yes, partly or major parts. In ring sample, mainly in transferred iron rich layer
On ring sample	D	Transferred iron from the liner	Yes, in small patches (same appearance as on other ring materials)*	Yes, in small patches	Yes, in small patches	Yes, in small patches on two samples. On the rough ring it covers major parts
	E	Spalling of transferred material	Yes	No	No	Yes, revealing ring surface or transferred material
On liner sample	F	“White layer”, etch resistant because of fine-grained structure. In areas corresponding to transferred iron on ring (see E).	Yes	Yes	In small areas	Yes

*Impossible to detect with EDS, but the appearance is similar to that found on other ring materials, suggesting that there is transferred iron.

Figure 4 Examples of the characteristic features found on the sliding surfaces, presented in Table 2. Sliding direction is vertical in all micrographs. SEM at different magnifications

- A) Tribofilm (darker grey) containing Fe, O, Ca, C and S, here on liner sample mating PS cermet
- B) Agglomerated wear debris, here partially sintered fine debris on grey iron ring
- C) Roughened surface, here on a Stellite ring, the worst example
- D) Transferred iron (medium grey) from liner samples, here on a HVOF cermet ring
- E) Spalling of transferred material, in this case revealing (brighter) underlying Stellite ring surface
- F) “White layer”, etch resistant (thereby white when viewed in LOM) because of its fine-grained structure, found in areas corresponding to areas with transferred iron on the ring (see D). Here on liner sample mating grey iron ring.

Figure 5 Wear mark appearances on ring sample (upper) and mating liner sample (lower), here exemplified with a grey iron ring couple (sliding direction is vertical). The boxes frame examples of the different characteristic features described in Table 2 and exemplified in Figure 6. They also indicate that the features on the ring match those on the corresponding surface positions on the liner. The boxed areas are not the only areas where these features appear; they just illustrate the fact that every sample may include many different features. SEM

4. Discussion

4.1. Material performance

The two candidate ring materials, HVOF cermet and Stellite 6 both showed promising performance in the scuffing test, by sustaining low friction for longer sliding distances than the currently used grey iron and PS cermet. However, the wide scatter within a single material type compared to the relatively small differences in average between different materials is of course problematic. It shows that the effect of selecting between the tested materials is comparable to the effect of the sources of scatter in the tests. The possible sources of scatter were discussed in previous work [3].

4.2. How to ensure the relevance of a test?

The tribosystem of a lab test is rarely identical to that of the real application; the question is whether it is similar enough. Will the scuffing resistance ranking of materials be the same in the engine as in the test? Difficulties with evaluating the relevance of scuffing tests like the present were discussed in previous work [3]. For example, the ranking between ring samples of PS cermet and grey iron were reversed when testing with different surface preparation of the ring sample. Further, possible deviations in critical mechanisms between the test and application were discussed. In the tests, wear particles adsorbed a large fraction of the available oil, which led to removal of lubricant and thereby to an aggravated situation and an increased coefficient of friction. Very similar behaviour, where the large surface area of a relative small volume of fine wear debris adsorbs a significant fraction of the oil in a starved lubrication situation, was shown in [18]. Further, Holzhauser and Ling showed that this actually is a critical mechanism [19]. The question is whether this mechanism is relevant also in the engine. Clearly the critical mechanisms of scuffing in actual engines have to be better understood to ensure that the critical mechanisms in the test are relevant. To thoroughly study the mechanisms in situ in the engine would be ideal, but also impossible. A step towards this understanding is to closely study the mechanisms in the test, and consider their importance in the engine. This need motivated the present sample analysis using LOM, SEM and EDS.

4.3. Surface appearance after failure – Which are the relevant mechanisms?

The large modifications of the surface appearance are evident, but what can be said about the operating mechanisms? The various surface features present at the same sample (as exemplified in Figure 7), indicate that different mechanisms are simultaneously active, at different locations of the contact. If the scuffing process consists of several stages, different locations can be at different stages. From the observed characteristic features, we propose a hypothesis for the different stages and mechanisms of scuffing failure in the test. In the hypothesised course of events below, all the observed features are referred to using their letter designation from Table 2 and Figure 6.

Stages and mechanisms of a scuffing process – A hypothesis

1) *Tribofilm formation. Low wear rate*

An easily sheared tribofilm (A) containing Fe, O, Ca, C and S, is initially formed whenever lubricant is present. Further, adsorbed oil molecules will facilitate a low wear rate of asperity contacts, but occasionally direct contact or starved lubrication will occur as these molecules become scraped off and/or desorbed from the surfaces, due to high local pressures and high flash temperatures. This leads to mild adhesive wear forming fine wear debris at the asperities. The low wear rate of the tribofilm will be balanced by formation of new tribofilm, as long as lubricant is present.

2) *Wear and agglomeration of wear debris during local starved lubrication aggravates the situation*

The amount of oil in the contact interface will decrease because it becomes adsorbed onto wear particles that form agglomerates and is scraped away. Due to this, the oil starvation will locally increase and result in even more fine wear debris, further aggravating the oil starvation. This constitutes a negative spiral resulting in the formation of agglomerated wear debris (B). Initially, it will contain Fe, O, Ca, C and S that originate from the tribofilm and perhaps also lubricant mixed with these particles. At later stages, the wear particles will increasingly consist of Fe and O. These debris could either be due to wear of an already oxidised iron surface or due to metallic adhesive wear forming iron wear particles that subsequently become oxidized. As wear progresses and more of these agglomerates are formed, the friction will escalate due to the aggravated oil starvation, which leads to more adhesion and more wear particles in the sliding interface. These wear particles will plough and indent the surfaces and also form

a growing volume, which becomes plastically deformed in the interface and becomes sintered. The resulting friction rise will increase the temperature.

3) *Transfer of iron from the liner sample and formation of white layer*

Eventually, when all tribofilm has been worn off along a region of the liner (a line of contact, see Figure 7) and with no oil present, strong adhesion will lead to transfer of iron from the liner to the ring sample (*D*). The transferred patches show different sizes (compare *D* and *E*). The transferred material is corresponded by smooth, fine-grained areas on the liner. These areas are etch-resistant and thereby viewed as a “white layer” in the LOM. In the SEM the fine-grained structure is observable both with and without etching (*F*). The exact grain sizes may differ from area to area.

4) *Spalling of transferred material, roughening and formation of large wear particles*

When the situation is aggravated even further due to the negative spiral, larger areas of the sliding surfaces adhere to each other, spalling of transferred material starts to occur (*E*) and the surfaces become roughened (*C*). This will also lead to formation of larger wear debris. At this stage friction is high, vibration levels become high and as a consequence new oil might migrate into the contact, and agglomerates of oil and larger wear debris will be formed (*B*).

The present work has offered some new understanding about the intricate behaviour of sliding surfaces during starved lubrication.

- Small surface variations may lead to large changes in local performance
- The scuffing process involves many stages with different operating mechanisms
- These stages can occur simultaneously at different locations.

Previously, among other factors, wear of solid lubricating films [8], wear particles aggravating lubrication [4, 19] and white layer formation [10] have been linked to failed boundary lubrication and scuffing. However, often focus seems to be on one single aspect and not on the whole complex process. If scuffing is a process containing many important stages and mechanisms, this explains the large number of scuffing theories presented. Further, perhaps more than one course of events can lead to the macroscopically observable phenomenon called scuffing.

Many questions remain unanswered and further studies are needed to understand how the present findings from a small-scale lab test, focusing on the initial stages of scuffing, are related to the scuffing process in an actual operating engine. Are some aspects of the scuffing process more important and how can we relate these aspects to material performance? How is the fine-grained “white layer” formed and which role does it have? How is the spalling and roughening observed in the present tests related to scuffing theories such as adiabatic shear instability [9] and subsurface plastic fatigue [4, 12]? To find some answers, further studies could include tests that are interrupted at different stages, microscopy investigations of the sub surface in cross sections, and analysis of field samples showing signs of micro-seizure or scuffing.

One could argue whether the events occurring in these tests really are representative of scuffing in the engine, since the tests do not always involve roughening of the surfaces. According to the ASTM definition (see section 1.1), macroscopic changes of the surface are characteristic of scuffing. However, this study is focused on starved lubrication, which often is assumed to be part of the scuffing problem. Further studies with continued tests at high coefficients of friction could give more information about later stages of the process.

5. Conclusion

Scuffing tests were performed with starved lubrication and parameters aiming to simulate scuffing in marine diesel engines. From the test results and analyses of sample surfaces, the following conclusions were made:

- The HVOF cermet coating and Stellite 6 coating showed somewhat better scuffing performance than grey iron and the plasma sprayed cermet coating.
- Several characteristic features were observed on the surfaces after scuffing failure. From these observations we propose that the scuffing process consists of several stages with distinctive mechanisms and that different stages can be active at different locations simultaneously. Local starved lubrication starts a process that works as a negative spiral. Hence, small local surface variations may lead to large differences in local performance.
- Further studies are needed to strengthen the proposed hypothesis, to get further understanding about the significance of each stage and to better relate the proposed mechanisms to other published scuffing theories, as well as to scuffing in engines.

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