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

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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.

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 h 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*

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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) [7,18]. Most test procedures include an increase in the severity of the sliding contacts, for example by increase of speed [1], load [7,16] 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 lead 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 (Fig. 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).

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 (Fig. 2), due to mechanical "bore polish" by a hard, calcium containing layer on the piston. The layer is 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 h before any visual scuffing signs on the rings

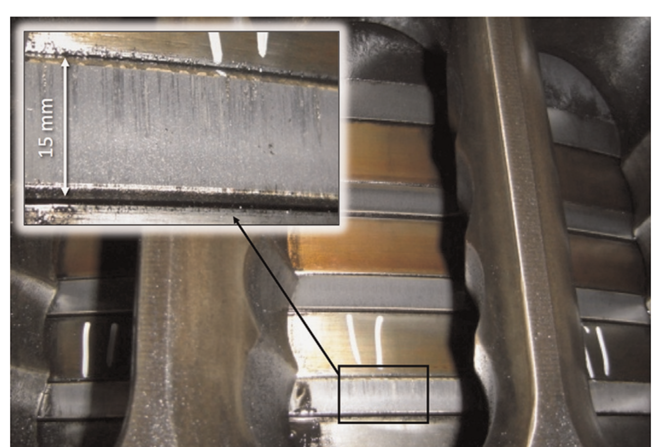

Fig. 1. View of the 4 piston rings through the scavenge port. Micro-seizure, which could lead to a scuffing situation, is clearly seen on ring no. 4 (see inset).