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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 where 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.

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 counter-actions 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 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 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 characterised 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

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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 Fig. 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.

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.

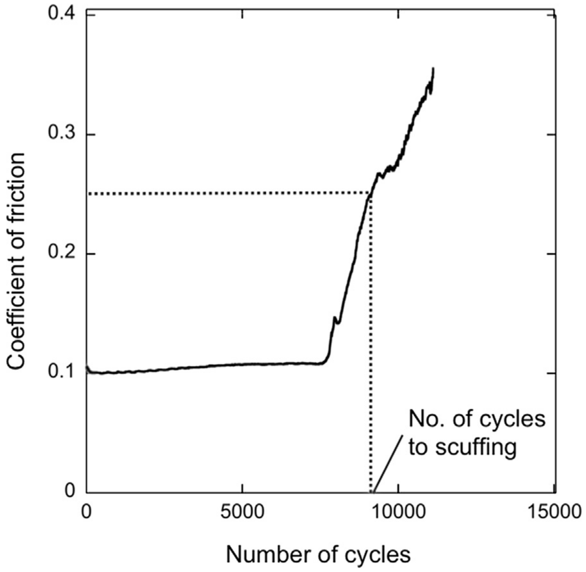

Fig. 2. Typical friction curve from the tests. After keeping low and stable for thousands of cycles, the friction suddenly rises steeply, and never falls back to the low level. Passing a coefficient of friction of 0.25 was used as scuffing criterion.

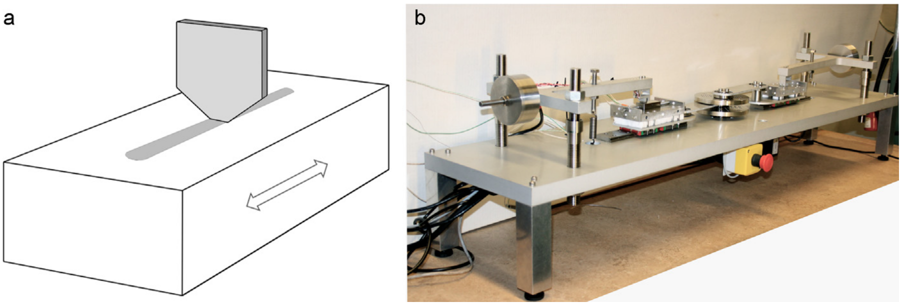

Fig. 1. Schematic view of the test configuration and photo of the rig. (a) The (upper stationary) ring sample has a nominal contact area of 2 × 2 mm^2 and slides against the (flat reciprocating) liner sample. (b) The rig comprises two complete reciprocating sliding test set ups, driven by a common motor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