INTERNATIONAL COUNCIL ON COMBUSTION ENGINES

03 | 2023

CIMAC Guideline

The causes of scuffing and actions to prevent scuffing in two-stroke engines

The first edition of this CIMAC Guideline was approved by the members of the CIMAC WG Lubricants at its meeting on February 23, 2023.

Content

1 Introduction

In 2020, IMO introduced a maximum 0.50% sulphur content limit in fuels for ships operating outside SOx-ECA, unless the ship is fitted with an abatement technology to clean the exhaust gas as per MARPOL Annex VI regulation 4, e.g., an exhaust gas scrubber. For the majority of vessels this meant a switch to operation on VLSFO (Very Low Sulphur Fuel Oil with ≤0.50% S content). However, this transition was not without its complications and several operators reported a higher frequency of main engine scuffing events compared to previous years.

When ships started using VLSFO in 2020 and reported scuffing incidents, CIMAC working group Lubricants prepared and sent questionnaires to ship owners/operators to gather operational feedback regarding these particular incidents. The questionnaires found that two thirds of respondents reported lubrication-related problems while operating on VLSFO, the majority of which related to scuffing incidents. (Figures 1-2).

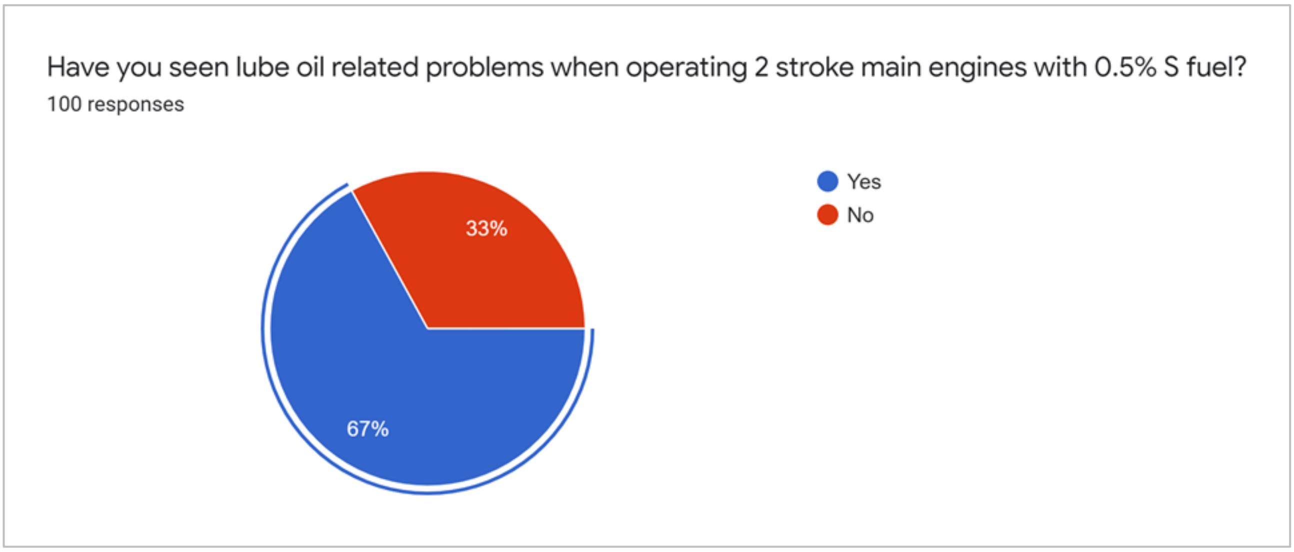

Figure 1: *Responses to CIMAC Questionnaire on VLSFO Operation (2020/21).*

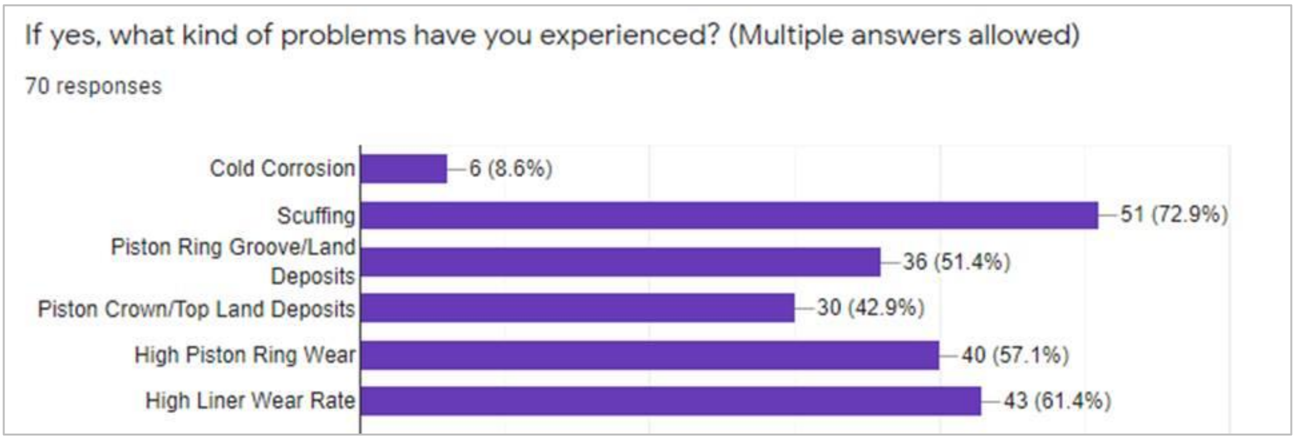

Figure 2: *Responses to CIMAC Questionnaire on VLSFO Operation (2020/21).*

While the root causes of these scuffing incidents remain a debated topic and subject of several investigations (see Section 3), this paper aims to provide guidance to understand known contributing factors, warning signs of scuffing and preventive/mitigating actions.

General guidance on lubrication of two-stroke engines can be found in [1].

The guidelines found within this document are general recommendations based on experience. Many engine specific conditions may influence the engine condition and CIMAC cannot be held accountable for any consequences when following these recommendations. Only the user will be able to assess the engine condition continually and therefore, the final responsibility lies with the user.

OEM's each have their own specific recommendations. For more information and specific guidelines for a particular engine, please consult the OEM websites, which include: www.man-es.com, www.wingd.com and www.j-eng.co.jp/en/index.html.

2 What is scuffing?

The term *scuffing* is used specifically to describe the extreme adhesive wear between lubricated surfaces which has arisen from the break down or failure of the lubricant film for whatever reason [2].

Figure 3 below, illustrates how adhesive wear occurs and the onset of scuffing.

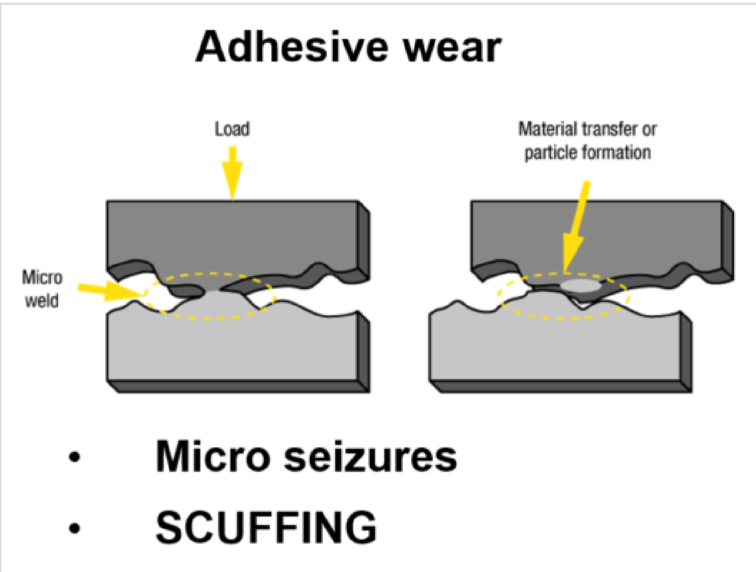

Figure 3: *Adhesive wear*

In the cylinder liner, scuffing begins when the oil film breaks down between the piston ring running surfaces and the liner wall causing adhesion between the surfaces, and micro welds to occur. As these micro welds increase in number, one or both of the running surfaces can be torn, dragged and roughened to the point where the surfaces break up and smooth running between the two surfaces is damaged. The effect of scuffing can also be seen with the rise in surface temperatures, for example at the cylinder liner wall.

Figures 4-5 show examples of scuffed surfaces.

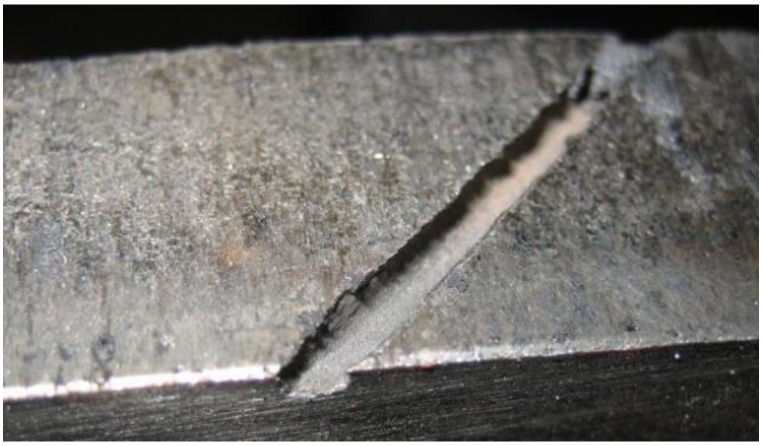

Figure 4: *Piston ring running surface after scuffing. (Source: MAN Energy Solutions).*

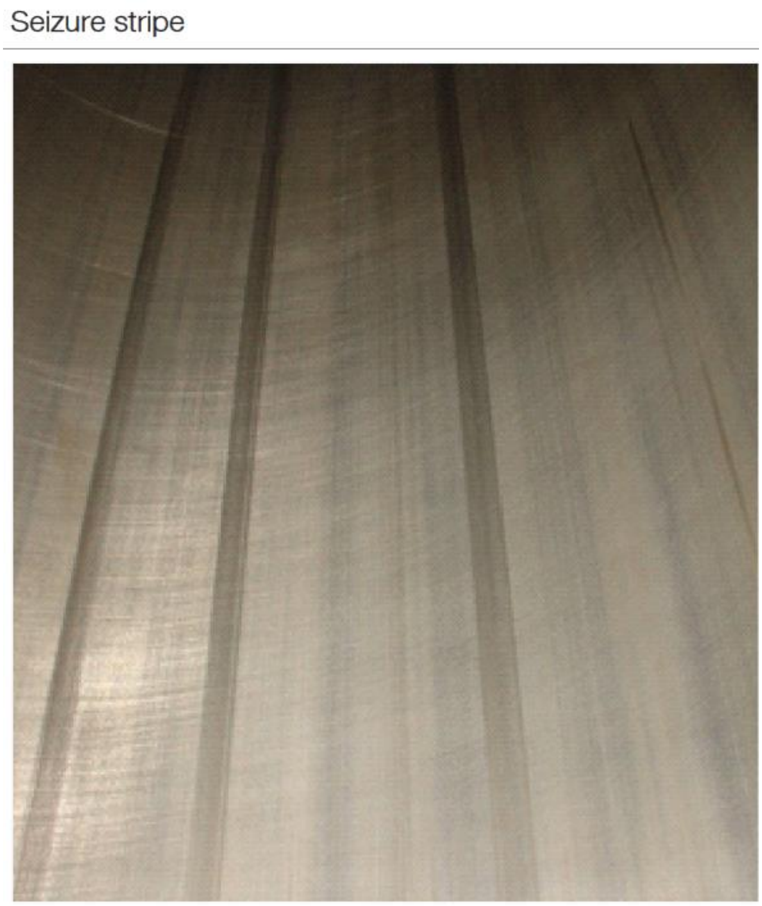

Figure 5: *Seizure stripe in liner wall. (Source: MAN Energy Solutions).*

3 Possible causes of scuffing

A well-maintained two-stroke engine will always be more efficient and better able to resist the challenges imposed. Scuffing usually occurs unexpectedly and can cause severe damage to the piston rings and liner. Scuffing can have several causes, of which some of the more common are described in Figure 6.

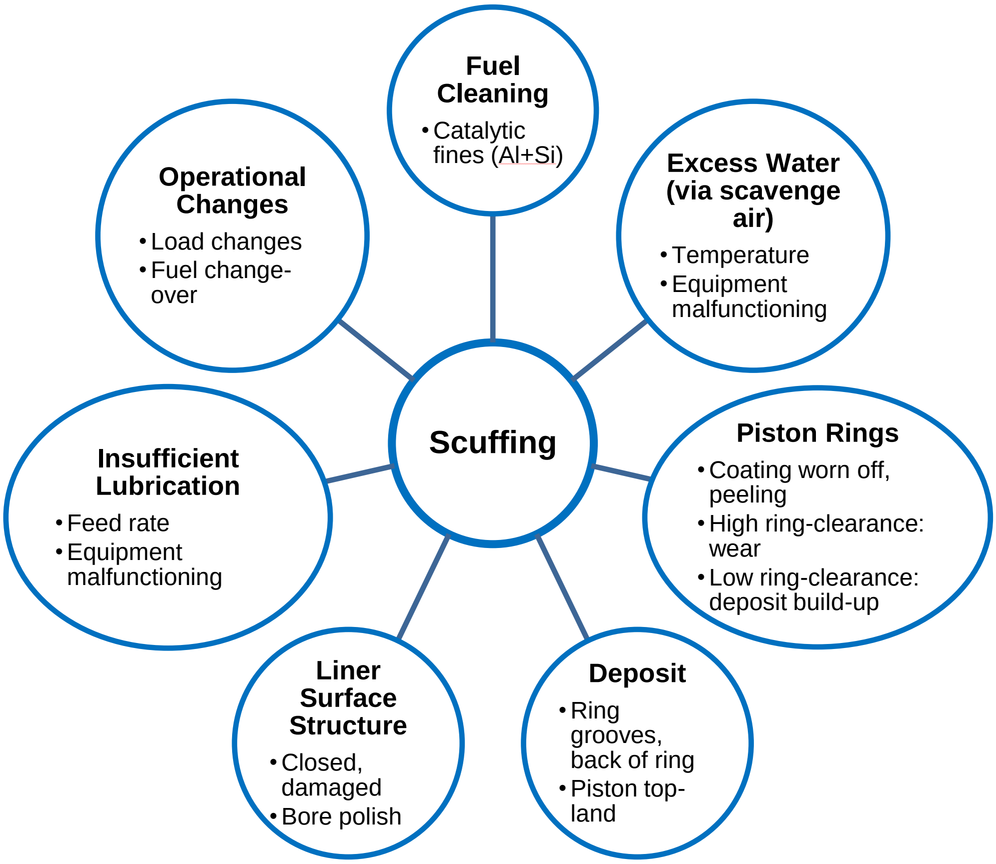

Figure 6: *Common possible causes of scuffing in two-stroke engines*

3.1 Liner surface condition is crucial

The condition of the liner surface plays a significant role with regards to scuffing. To ensure a proper oil film between the liner and piston rings, the liner surface structure needs to be sufficiently open (Figure 7). For a satisfactorily operated two-stroke engine, the liner surface is self-sustaining and does not require regular honing, as is typically the case on four-stroke engines. If a damaged liner surface is observed, possibly due to a scuffing event, machining or replacement of the liner is required.

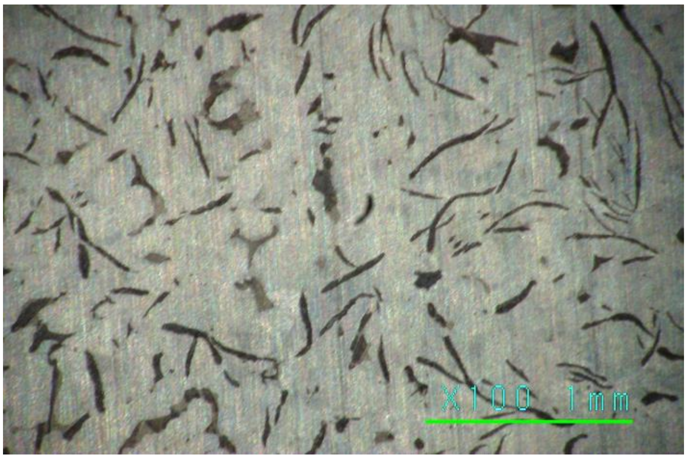

***Figure 7:** Micrograph of liner running surface showing normal graphite structure. The open graphite lamellas act as oil pockets (Source: Chevron)*

3.1.1 Bore polish

If excessive deposits accumulate on the piston top land, these deposits can polish the liner surface, and the running surface structure may over time become smooth like a mirror. As a result, the small cavities associated with the open graphite flakes may no longer retain the lubricating oil sufficiently and micro-seizures and possibly scuffing may occur. Examples can be found in Figures 8 A-C. Whilst, the bore polish-phenomena is rarely seen in modern engines, for older designs, it may still be an issue.

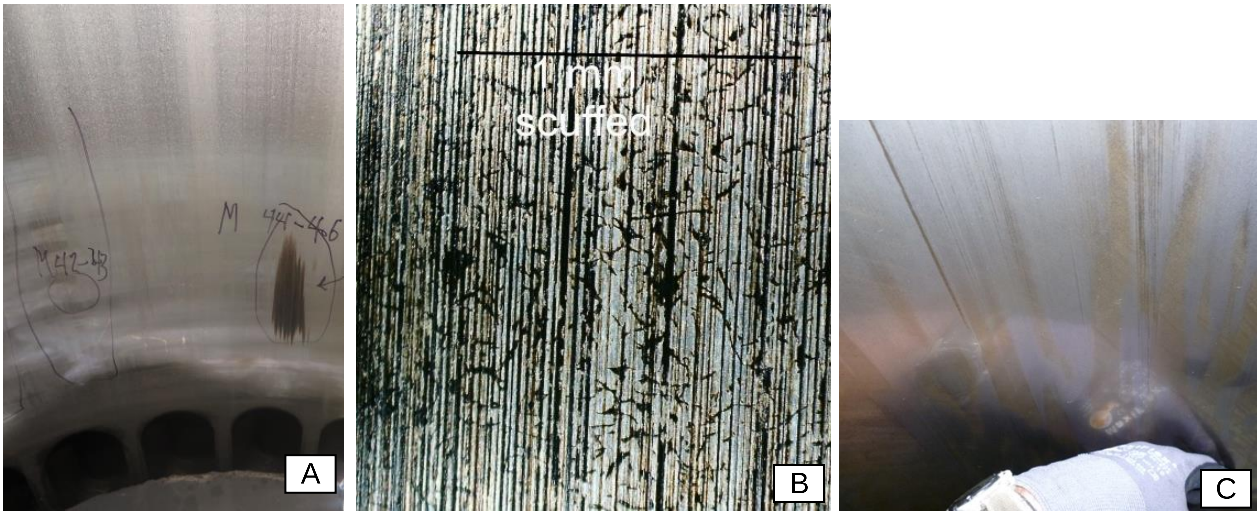

Figure 8: *A: Bore polished and scuffed areas; B: Micrograph of scuffed area in bore polished liner area from scuffed area in photo A; C: Different engine. Mirror-blank liner surface showing the glove and watch of the inspector.*

3.2 Piston rings – hard coating

Hard coated piston rings are recommended by most OEM's, especially when operating on fuels with less than 0.50%S.

When high sulphur fuels are combusted in two-stroke engine, there is a level of (controlled) cold corrosion taking place which basically roughens up the liner surface helping the lubricant to 'stick' better to the surface and ensures piston rings are separated by lubricant film avoiding metal to metal contact.

However, when operating on lower sulphur fuels, lower amounts of acidic products are formed by the combustion, and the requirement on the cylinder oil to neutralise these acidic products reduces. This results in little or no corrosion on the liner surface, which may make the liner surface relatively smooth. This smooth surface makes it difficult for the lubricant to stay/stick on the liner surface to establish a consistent lubricant film separating the liner from the rings, and this may potentially cause metal to metal contact. In such case, the cast iron piston rings (without coating) and liner may experience localised welds (micro-seizures) between the two surfaces. This situation damages the liner surface and the rings where larger iron particles may be chipped off, and they may cause further damage.

The hard-coated rings provide better protection against micro seizures/scuffing due to the difference in the two mating materials and the hardness of the coating material over the liner material, minimising the risk of micro-seizures and eventual scuffing incidents.

3.3 Deposits

The free movement of the piston ring in the ring groove is crucial for engine efficiency, and there are different mechanisms in which this can be hampered due to deposits, leading to ring collapse, blow-by, increased wear and possible scuffing. Cylinder lube BN (Base Number), type and feed rate may have an influence on deposit build-up. See also Section 4.2 – Cylinder oil chemistry.

In Figure 9 A, deposits in the ring groove and back of the ring hinder the combustion gases to flow behind the ring and build up a sufficient pressure to push the ring out to the liner. This may result in loss of pressure in between the ring and liner. Hot combustion gases may then pass the ring and liner (usually called blow-by). This may lead to piston ring collapse, which is loss of tension for the piston ring. Alternatively, it may lead to disruption of the oil-film, and thereby metal-to-metal contact, which may lead to increased wear and possible scuffing.

In Figure 9 B, the deposit in the ring groove and back of the ring limits the ring's possibility to move. This may result in an unusual high pressure between ring and liner as the piston moves up and down in the non-cylindrical liner. The ring may push through the oil film and result in metal-to-metal contact, which could lead to increased wear and possible scuffing.

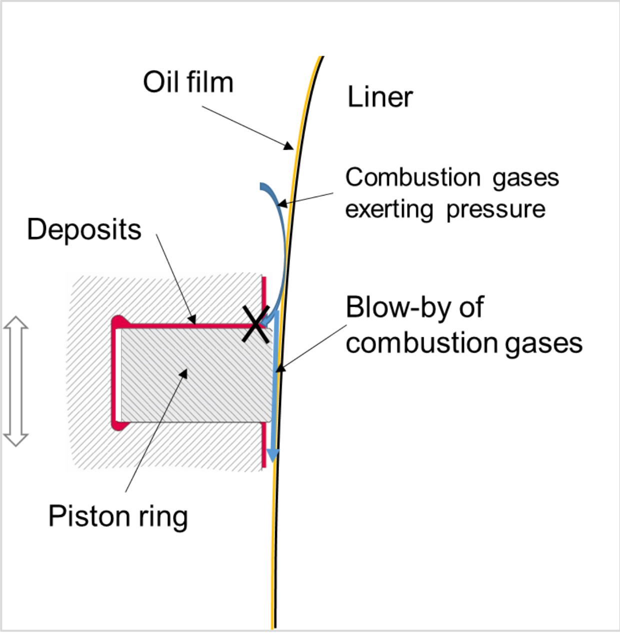

Figure 9A: *Deposits hinder combustion gases to flow into the groove, resulting in loss of pressure, collapsed ring and blow-by.*

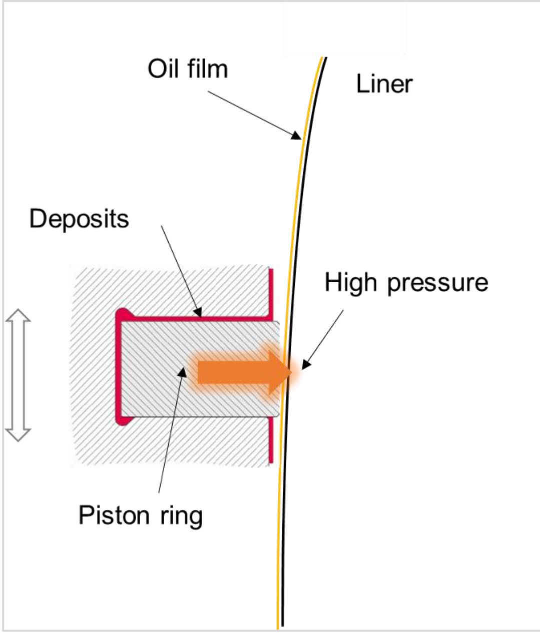

Figure 9B*: The piston ring is stuck in the groove due to deposits, which may result in an unusual high pressure between ring and liner.*

3.4 Lubrication system – equipment and operation

The lubrication system (e.g. lubricator) and cylinder oil feed rate are important parts for maintaining cylinder condition. To avoid scuffing, a hydrodynamic oil film is required to separate the metal surfaces of the rings and liner. Malfunction or insufficient oil supply may result in metal-to-metal contact and the initiation of micro seizures that can give rise to scuffing, if not detected in time.

The minimum feed rate is not the same for all engines and has to be determined for each engine installation by drain oil analysis and port inspections. See OEM guidance.

3.5 Excess water carry-over can disturb the oil film

The oil film can be disrupted by water droplets bombarding the liner surface and creating local lubrication disturbance at the liner. This typically happens when water droplets are insufficiently removed by the scavenging air cooler, due to damaged water shedding systems or too high scavenge air temperature.

The presence of water will also encourage the formation of sulphuric acid. This may cause cold corrosion where imbedded hard phase from the liner material could be released and three-body abrasion may initiate scuffing. More information can be found in CIMAC Guideline 11 (2017) Cold corrosion in marine two stroke engines [3].

3.6 Fuel properties: Catalytic fines (Al+Si)

Most marine residual fuels (HSFO, VLSFO and ULSFO) will contain catalytic fines. Catalytic fines contain Aluminum (Al) and Silicon (Si) components, and ISO 8217 includes limits for combined Aluminum and Silicon content. Catalytic fines are small hard particles that can cause 3-body abrasion which can lead to high rates of excessive wear, which in two-stroke engines can occur in the combustion chamber at cylinder liners, piston rings and ring grooves and may cause seizures and scuffing. The wear may be normalized if the influx of catalytic fines is stopped.

Fuel property requirements at the engine inlet are different to and stricter than those at delivery on board. This cleaner level of the fuel is achieved by the vessel's fuel cleaning systems. Primary functions of on-board fuel cleaning are to remove water and solids, e.g. catalytic fines, in order to reduce risk of excessive wear.

If scuffing is caused by catalytic fines, in principle, all cylinder units will be impacted, as all are supplied with the same fuel. Nevertheless, cylinder units in better operational condition may have a better resistance to scuffing.

Common reasons for catalytic fines issues are:

1. Insufficient cleaning of the fuel.
2. Abnormally high catalytic fine content beyond the capabilities of the fuel cleaning system can result in a high catalytic fines influx to the engine.
   a) High catalytic fine content can be due to high concentration at bunkering.
   b) Catalytic fines can collect in the bottom of tanks over a period of time. These can be disturbed and enter the fuel system in high concentrations. Factors such as vessel movement in heavy weather, the use of fuel additives and cleaning of residual tanks using diesel fuels can cause and contribute to issues in this regard.

More information can be found in CIMAC fuel cleaning guideline [4].

3.7 Operational changes

Scuffing occasionally occurs following significant changes to vessel operating conditions, such as sudden load changes, change-over in fuel types or compositions, operating in shallow water or heavy running etc. This can disturb the cylinder operating condition and cause failure of components in a borderline condition (e.g. worn piston rings etc.), and may lead to a scuffing event. Such scuffing cases can occur unexpectedly; in such cases follow the operational guidelines from your OEM and the recommendations for component replacement.

4 The role of the lubricant and lubrication challenges

The cylinder lubricating oils (CLOs) have several roles, some of them being critical to control wear and to prevent scuffing, such as:

- to form a stable oil film with good oil film thickness over the cylinder liner surface.
- to minimize deposit formation on piston and liner surfaces, and flush away particles formed during combustion as well as wear particles, and to prevent a build-up of deposits in sensitive areas such as the piston ring grooves to avoid the risk of ring sticking or breakage.
- to minimize corrosion by neutralizing sulfuric acid formed by the combustion of sulfur-containing fuel oil, and organic acids resulting from the combustion process or the lube oil degradation.

Among the factors affecting scuffing, the oil film thickness and the lubricant chemistry to avoid deposit build up are the most critical.

4.1 Oil film thickness

The oil film thickness is determined by the amount of available oil, the temperature, oil viscometrics (viscosity and viscosity index: change in viscosity with temperature) and the load applied to the surfaces in motion, and these parameters lead to different lubrication regimes as shown in Figure 10. The three types of lubrication depicted are:

- Boundary lubrication, characterized by a high friction coefficient and some contact of the sliding solid surface asperities, resulting in wear.
- Mixed lubrication and elastohydrodynamic lubrication, characterized by a low friction coefficient and low wear.
- Hydrodynamic lubrication, characterized by relatively low friction and virtually no wear as the solid surface asperities are kept fully apart.

The main objective of lubrication is to reduce wear to a low level, thus components and the lubricant need to be matched to achieve this goal. This is for example achieved by ensuring adequate bearing surface area for the load conditions and adequate lubricant viscosity to allow at least boundary lubrication conditions to be achieved on all interacting moving surfaces.

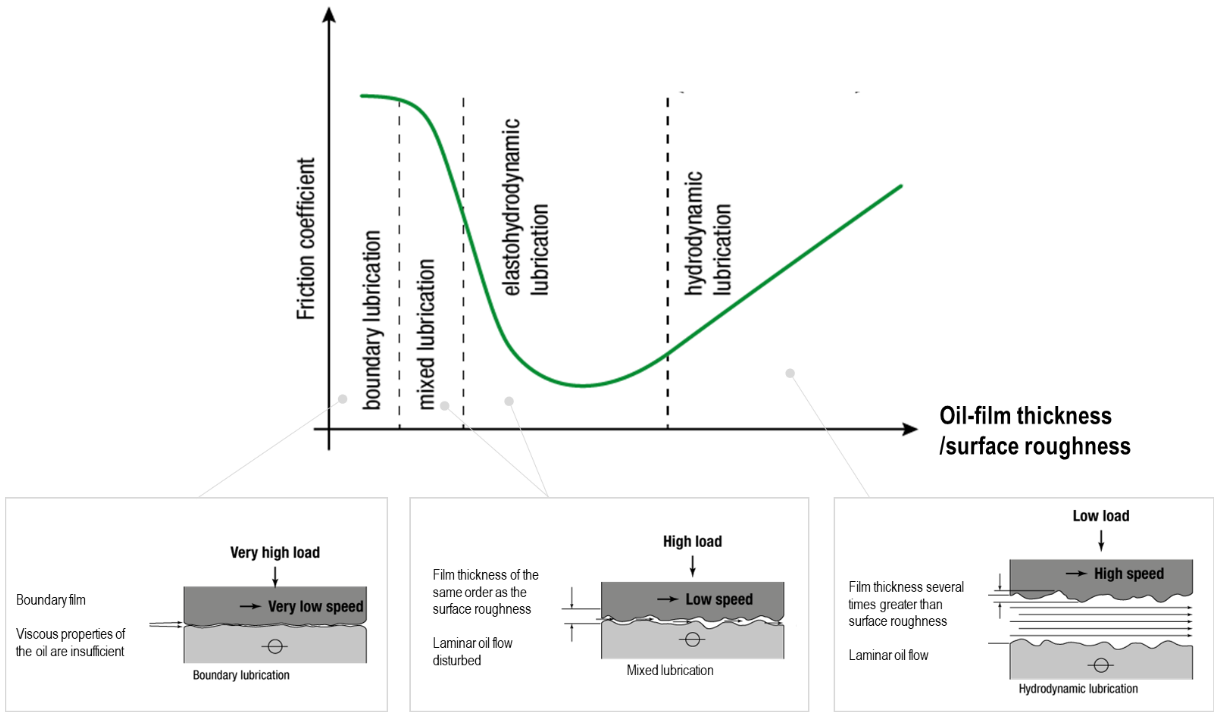

Figure 10: *Lubrication regimes with Stribeck curve on top [1].*

This is why the two-stroke engine OEMs recommend using CLO with a viscosity expected to provide a sufficiently thick oil film to prevent contact between the surfaces, so as to minimize wear and prevent scuffing.

However, even though critical, the CLO viscosity alone is not enough to prevent scuffing. It is necessary to properly adjust the CLO feed rate to ensure that lubrication of the engine matches the operating condition. In view of this, it is fundamental to follow the lubrication guidelines provided by the OEMs for each engine type and to apply the right lubricating oil feed rate and CLO type (see also Figure 11).

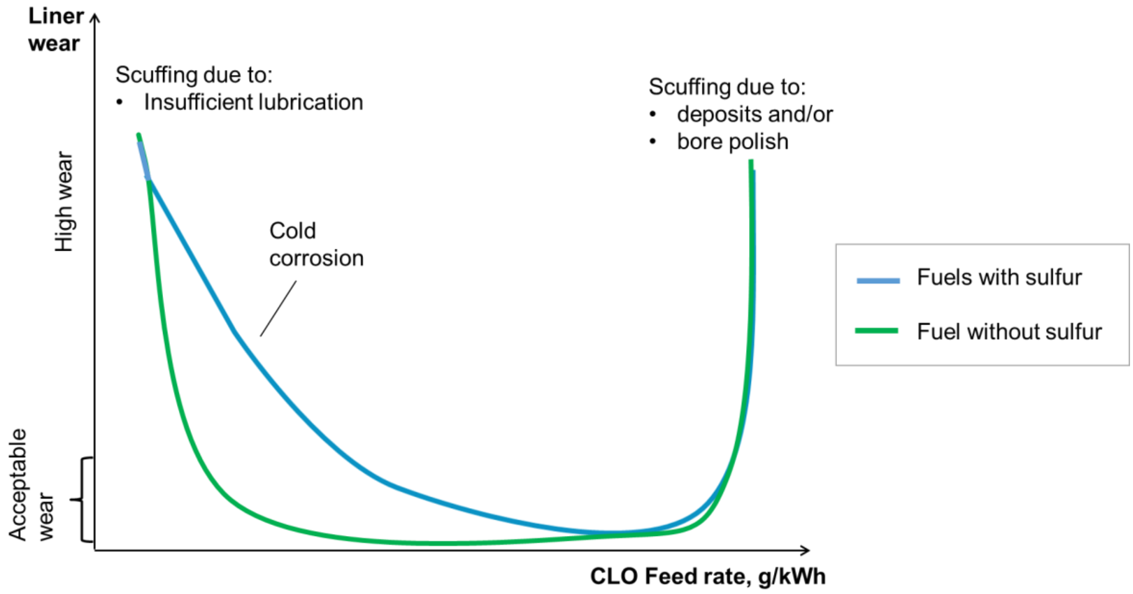

Figure 11: *Impact of CLO feed rate on wear.*

If the feed rate is too low, too little cylinder oil is supplied, so the oil film will be too thin to prevent adhesive wear and possible scuffing. Since the CLO also cools the rubbing surfaces of the rings and cylinder wall, too little lubricant may allow these surfaces to overheat and scuff. For operation on fuels with sulfur, too little CLO (or the BN in the CLO is too low) will increase the risk of corrosion that results in corrosive wear, which can cause severe wear (cold corrosion) [3].

If the feed rate is too high, or the BN is too high, or the CLO is not able to keep the engine clean, the accumulated deposits can result in ring and ring groove deposits that can cause ring sticking, and lead to scuffing. See also Section 3.3 - Deposits.

4.2 Cylinder oil chemistry

The CLO is designed with selected additives and base-oils to control the lube oil film thickness and the deposit formation. Some of the additives are used to prevent deposit formation or to wash the deposit-forming materials away in the scavenge drain oil. This keeps the piston lands, piston rings and grooves clean, so the piston and its rings can move freely. If the cylinder oil chemistry has inadequate cleaning ability, piston rings may stick, overheat and collapse. See also Section 3.3 - Deposits. Reduced engine efficiency, ring breakage and a scuffed liner are then possible outcomes.

Modern cylinder oils can also include a mix of dispersants, anti-oxidant and anti-wear chemistry that when combined with detergents provide the necessary deposit and wear protection performance for effective engine operation.

The selection of cylinder oil is dependent on both the fuel or the mix of fuels in use, as well as the engine type and running conditions. The fuel mainly drives the Base Number (BN) selection that is, in general, adapted to the sulfur content of the fuel in use. However, some low BN CLOs may suffer from insufficient cleaning ability and may not be suitable to some engine technologies and running conditions. To minimise the risk of operational issues related to the cylinder oil, operators must ensure that they are using the latest cylinder oil formulations with full validation and acceptance from the OEM, and should follow OEM guidelines on lubrication settings and engine maintenance.

5 Operational recommendations

This section includes actions in case of scuffing and also some general operational recommendations. OEM operational guidelines provide up to date guidelines to causes for scuffing, actions to prevent scuffing, and recommendations for action in case scuffing occurs. Please refer to OEM guidelines for specific details and recommendations.

5.1 Actions in case of scuffing

In case of scuffing, see general guidance on actions in the text box below. Always follow OEM recommendations.

Actions in case of scuffing:

1. Increase lubrication oil feed rate according to lubrication system or OEM guidelines. See Section 4.1 and 5.3.
2. Reduce pressure on the cylinder.
    a. If possible, reduce mean effective pressure (MEP) and maximum combustion pressure (Pmax). See Section 5.8.
3. Overhaul the cylinder as soon as possible.
    a. Exchange damaged components, e.g. piston rings and liners. See Section 5.4 and 5.8.
4. In case catalytic fines in the fuel is suspected to be the failure cause, take a sample of the fuel in use before engine inlet (after the filter) to support further assessment of the failure cause. See Section 5.11 and 3.6.

5.2 General recommendations for operation

All engines are different and must be treated individually, however some general advice for best practice operation can be given. See text box below.

General recommendations for operation

Each OEM has their own specific recommendations. However, a well-maintained engine will always be more efficient and better able to resist challenges.

- Install piston rings with the appropriate design and coating in accordance with OEM advice for your specific engine.
- Follow the OEM lubrication guidelines
- Keep the engine, fuel pumps and fuel system well-maintained.
- Make a maintenance and monitoring strategy. Follow OEM advice, and include e.g.
    - Regular Scavenge port inspections (visual inspections)
    - Measurements of piston ring coating thickness and ring groove clearance.
    - Drain oil sampling, analysis and action on the result.
- Use well established operating procedures
- Verify functioning of the lubricator.

➢ Healthy cylinder condition
  ✓ Well lubricated surfaces
  ✓ Liners, piston, and rings in good condition

5.3 Ensure sufficient lube oil at liner surface

Insufficient lubrication oil or the breakdown of the lube oil film thickness may lead to scuffing of piston rings and cylinder liner. The sliding surfaces need to be separated by an oil film, which prevents adhesion of piston ring and liner material. Scuffing can occur within short periods of insufficient lubrication. It is therefore important that lubrication oil gets evenly distributed over the cylinder liner surface. It is especially important that the lube oil lubricates the upper part of the liner, where the pressures, temperatures and wear are highest.

The minimum feed rate is not the same for all engines and has to be determined for each engine installation. It is important to follow the OEM lubrication guidelines to optimize the lube oil feed rate.

The lubricators must be checked and maintained, and it must be ensured that all pumps are working.

5.4 Replace or recondition components in case of scuffing

When scuffing has occurred, the microstructure of piston ring and liner surface has altered to a very hard and brittle layer (the white layer). See figure 12. This layer must be removed to restore a satisfactory cylinder condition. Therefore, it is generally recommended to replace the scuffed piston rings with new rings, and to replace cylinder liner with a new or fully reconditioned liner.

Figure 12: *Microstructure of cross-section of scuffed piston ring/liner, showing the martensitic white layer, which is very hard and brittle, and must be removed before satisfactory cylinder condition can be restored.*

In addition, if scuffing occurs due to a fuel with a high concentration of catalytic fines, it is essential to check and (if necessary) replace: Fuel injection nozzle, fuel oil pump plunger/barrel, piston stuffing box ring, piston rod, turbocharger turbine blade, etc.

Always refer to OEM guideline for details and updates.

5.5 Use hard-coated piston rings

Most modern low speed engines are equipped with hard coated piston rings, which provide enhanced protection against scuffing. It has been observed that some of the scuffing incidents reported (Section 1) did involve ships which were not using hard coated rings. Maintaining sufficient coating thickness is vital, and in order to reduce the risk of sudden scuffing incidents, overhauls should be scheduled based on remaining coating thickness. See OEM recommendations.

It is important to note that merely changing the piston rings to hard coated ones may not necessarily solve the problem if the liner surface is also damaged. The liners may need to be machined (e.g. honing, wave cutting etc.) or replaced, and an assessment may be needed from engine designers to make that decision. See also Section 5.4.

5.5.1 Thickness measurement of piston ring coating

Piston ring coatings, such as cermet-coating, chrome ceramic coating, etc., are widely applied on recent two-stroke marine diesel engines and generally recommended for operation on low-sulphur fuels.

It is recommended to measure thickness of the coating periodically and to estimate the remaining lifetime of the coating using the thickness and wear rate over time. When the coating thickness is 50-100 µm, the crew should plan the overhaul of the piston and replace the piston ring pack. When the thickness is less than 50 µm, overhaul at the earliest opportunity is recommended. Refer to OEM guideline for details.

5.6 Checking piston ring wear

One OEM recommends that piston ring wear also can roughly be estimated on rings without coating by means of piston ring gap without having to dismantle the piston.

Piston ring wear (Δt) is calculated with the following formula:

$$\Delta\text{t (Ring wear)} = \frac{L\,(Ring\ gap) - L_0(Ring\ gap\ [new])}{2\pi}$$

where *L* represents measured piston ring gap and *Lo* represents initial/new piston ring gap when fitted. Refer to actual OEM manual for wear limit of the piston ring.

5.7 Scavenge port inspection

Scavenge port inspections should be carried out in accordance with the OEM recommended maintenance schedule and enable the general condition of the engine to be assessed. They should also take place if there are any changes in drain oil analysis results (see Section 5.9).

A visual inspection can identify/confirm the presence of scuffing and/or abrasion to liners and piston skirts, as well as the amount of deposits and free movement on the piston rings in the grooves. An inspection can also identify broken, collapsed or abnormally worn piston rings, water leakages, injector fuel leakage, etc. Overview of piston ring conditions and actions can be found in Section 5.8.

5.8 Overview of piston ring conditions and actions

There are various damage propagation mechanisms to the piston rings of large two-stroke engines. The challenge is to correctly and swiftly identify the issue and then take appropriate corrective action to support a healthy cylinder condition and avoid a complete breakdown scenario. This section provides a few visuals (Figures 13-16) of different scenarios and corresponding actions, which have been derived from OEM's field experiences. It is important to note that the actions described against each scenario were not only based on condition of the piston rings, but also other operating conditions, as different conditions may require different mitigating actions.

Additionally, when diagnosing these issues, consideration should be given to the guidance provided in section 5.9 Scavenge drain oil analysis.

Figure 13: *Normal operation - good main engine condition and well lubricated piston rings. (Source: WinGD [5]).*

Figure 14: *Action required - Piston rings are scuffed and overhaul is needed to obtain normal conditions. (Source: WinGD [5]).*

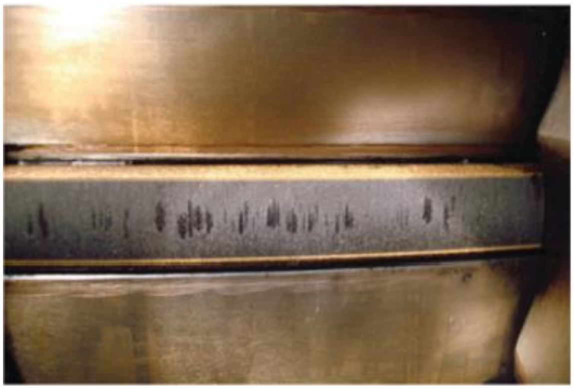

Figure 15: *Action required – Marks of micro-seizures on the piston ring, and lubrication oil feed rate should be increased. (Source: MAN Energy Solutions).*

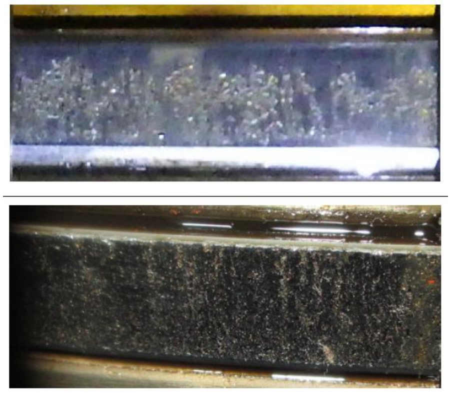

Figure 16: *Action required – Scuffing. Early stage of adhesive wear followed by a case where adhesive wear has occurred and piston rings should be changed. (Source: Japan Engine Corporation).*

5.9 Scavenge drain oil analysis

Cylinder oil scavenge drain analysis is a useful tool that can assist in evaluating and monitoring the cylinder condition. On two-stroke engines, during normal operation, fresh cylinder lube oil is injected into the cylinder and the used oil is drained from the bottom of the cylinder liner and discharged (once-through principle). See Figure 17.

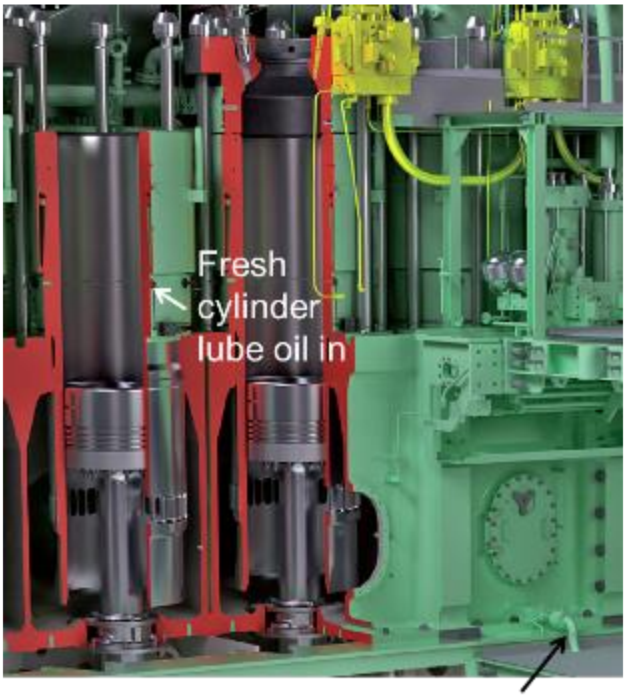

Figure 17: Fresh cylinder lube oil is injected, and scrape down drain oil comes out

The used cylinder lube oil (also called “scavenge” drain oil, piston underside drain oil, drip oil or scrape down oil) can be sampled from the engine through the scavenge bottom drain. A procedure for sampling the scrape down oil can be found in Appendix III.

Analysis of the scrape down oil can show whether the cylinder condition is within the normal range or whether action must be taken. Such actions could be adjusting the cylinder lube oil feed rate or changing cylinder oil type. In the case of scuffing, the actions should be to increase the cylinder lube feed rate and reduce the pressure on the cylinder.

Generally, the analysis of the scrape down oil is indicative of the cylinder condition mainly through the BN-value and the iron-content (Fe). The evaluation should be based on the combination of both BN and Fe in order to determine proper actions. Once readings have been obtained, the OEM lubrication guidelines should be consulted to ensure the engine is operating in the recommended range or if any change to feed rate or cylinder oil type is required. General advice can be found in [1].

In case of scuffing, the analysis of the drain oil will show very high values for iron (Fe). The remaining BN will generally not be affected by the scuffing event, and it can be anything from high to low. See Figure 18. Iron levels can also be very high due to catalytic fines in the fuel, or during running in of liner or piston rings or in case of high corrosive wear.

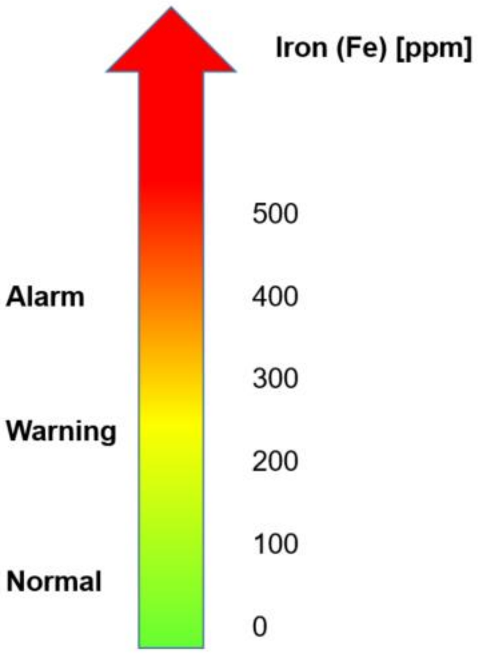

Figure 18: Scavenge drain oil analysis interpretation for total Iron (Fe). In case of scuffing, Iron results will be high, and remaining BN can be from high to low.

5.9.1 Sample intervals

Scavenge drain oil samples should be taken at certain intervals, and guidance is given in the text box below.

General guidance regarding drain oil sampling:

Sample intervals:

- 200-300 running hours for on board testing
- 500-1000 running hours for lab testing
- More frequent sampling, if suspicion on issues or changes in operation (e.g., running in, change to new cylinder oil, or fuel type or batch, load changes, etc.)

Operational and environmental parameters influence the wear of engine components, and on-board equipment can therefore be of great value in the continuous process of protecting the engine and optimising the cylinder lube oil feed rate. However, on-board measurement cannot be solely relied on. It is recommended that samples are sent for laboratory testing regularly to ensure adequate correlation between the two types of measurements. More information on testing methods can be found in Appendix II – Description of measuring methods for drain oil analysis and in [6].

5.9.2 Example of scuffing showed in drain oil

The following Figures 19-20 show a scuffing incident on a two-stroke engine where unit #3 failed, whilst other five units were in satisfactory operational condition. A steep rise in total iron (Fe) content in unit #3 was observed. An additional PQ (Particle Quantifier) index test, which shows level of ferrous magnetic debris in the lube samples, showed good correlation with the total iron content, which indicated progression of scuffing wear incident. More information on measuring methods can be found in Appendix II.

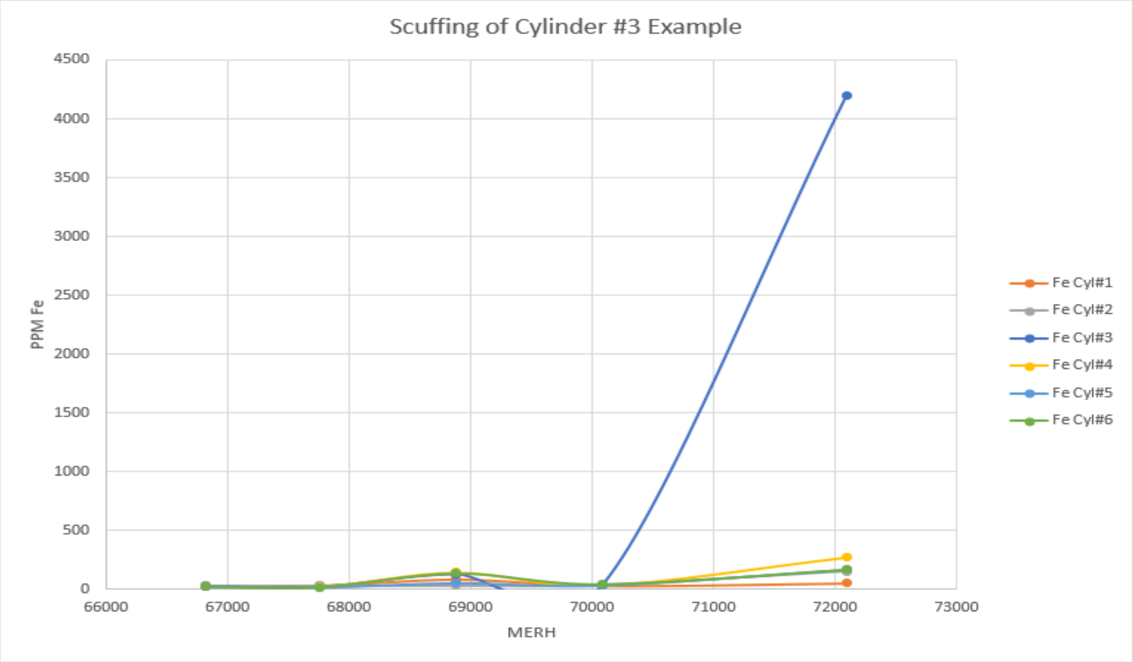

Figure 19: *Unit #3 scuffing incident indicated by the steep rise in (total) iron content (ICP method)*

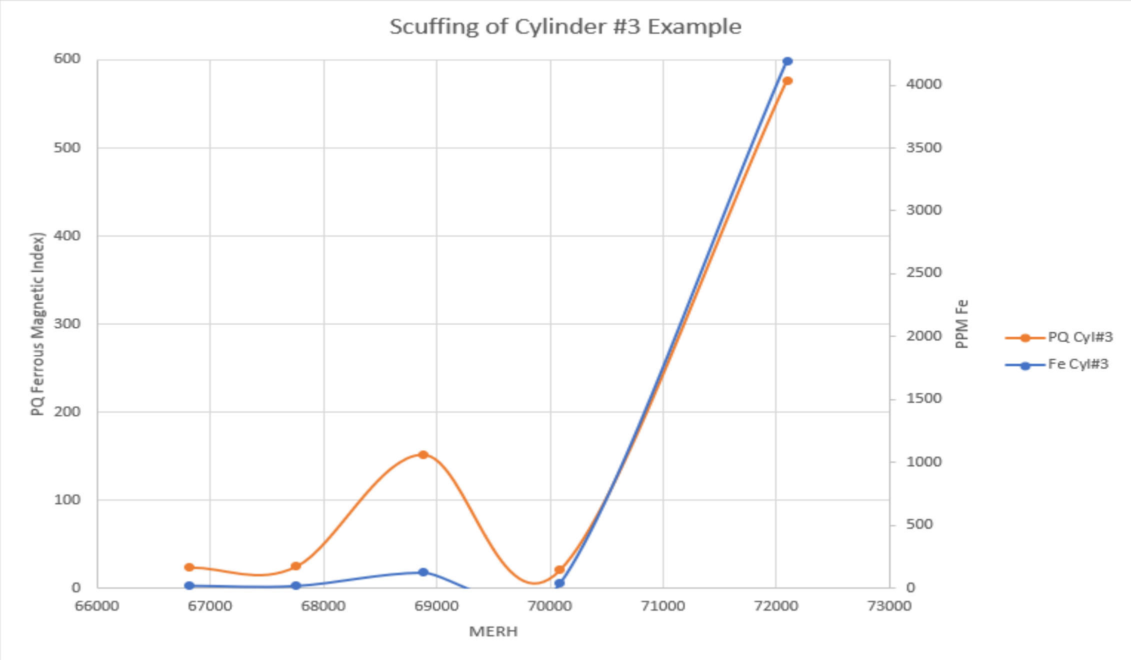

Figure 20: *Graph showing rise of PQ index is proportional to the total iron during scuffing incident*

5.10 Cylinder liner wall temperature monitoring

Cylinder liner wall temperature monitoring is another useful aid for monitoring piston running and cylinder liner performance. This can provide an early indication of a possible scuffing incident. An increase in temperature can be due to friction between piston rings and liners, which can lead to abnormal wear. Early warning signs require urgent mitigating action.

5.11 Operation recommendations for fuel cleaning

On board fuel treatment is extremely important to ensure fuel going into the engine remains within the OEM provided limits. Following fuel parameters are considered important at the engine inlet:

- Abrasive catalytic fines.
  - Generally, a maximum level of 15 ppm is acceptable for a short period of time, but the normal level must be kept lower.
- Water in the fuel.
  - Water in the fuel should be low, and free water is not acceptable.
- Level of ash content.
  - Ash level should be low for the components that can be removed by fuel cleaning, e.g. Catalytic fines (see above), dirt etc.
- Correct injection fuel viscosity.

Specific to the direct impact on the piston ring/liner tribology, a high concentration of catalytic fines in the fuel at engine inlet can be damaging by causing excessive wear of cylinder components. Hence, it is important to ensure that fuel separators are operated under optimum conditions of flow and temperature to minimise the possibility of higher catalytic fines and water going into the engine. More information can be found in CIMAC guideline for fuel cleaning [4].

6 Appendix I – Wear mechanisms

Wear of large engine running components (cylinder liner and piston rings) is generally attributable to three primary mechanisms:

- Abrasive wear
- Adhesive wear (micro-seizures and scuffing)
- Corrosive wear (Cold corrosion)

6.1 Abrasive wear

Abrasive wear can be caused by hard asperities in the components rubbing against each other or by hard particles from contaminants such as catalyst fines (catalytic fines) from fuel oil. These hard particles embed themselves into the piston ring and/or liner surface and breach the oil film, thus abrading the surfaces and wearing them down at high speed. Asperity contact can occur when asperity or hard particle sizes exceeds the thickness of the lubricating oil film.

6.2 Adhesive wear

Adhesive wear is due to a loss of oil film between piston ring and liner. This leads to metal to metal contact and thereby friction and high temperature which may lead to localised bonding between the two mating surfaces (micro-welding) and subsequently may lead to scuffing (macro-seizures) of the surface.

When the micro-welding (micro-seizures) is broken, the surfaces are roughened, and they may continue to penetrate the oil film during the contact. When micro-seizures are observed, it is a common practice to increase lube oil feed rate and thereby reduce the pressure between the mating surfaces (reducing engine load). If not treated, the wear may evolve into macro-seizures (scuffing), causing momentarily high wear of the mating parts. If scuffing has occurred in the combustion chamber between piston ring and liner, the components must be exchanged or machined to remove the damaged layers.

6.3 Corrosive wear (Cold Corrosion)

Corrosive wear occurs when there is a combination of a wear situation (abrasive or adhesive) and a corrosive environment. The rate of material loss can be very high; much higher than the sum of the individual contribution of wear and corrosion. This is because loose corrosion products are easily removed by wear to continually reveal fresh metal beneath, which in turn can corrode quickly. Likewise, stable oxide films that would normally limit corrosion (in the absence of wear) are instantly worn away. Corrosive wear may be found on the cylinder liner and piston ring running surface and is commonly referred to as “cold corrosion”. More information could be found in CIMAC cold corrosion guideline [3].

7 Appendix II - Description of measuring methods for drain oil analysis

The iron concentration in the drain oil will reflect the wear of the piston rings and liners. A high number indicates high wear and a low number could indicate low wear.

Different analysis methods detect different wear types (see Table 1). Some measure total iron while others measure the iron formed by adhesive or abrasive wear. This could be wear derived from "normal wear" mechanisms, from catalytic fines in the fuel, from micro-seizures and/or scuffing. These iron wear-particles are magnetic and can therefore be measured by devices using the magnetic flux technique.

Wear particles from cold corrosion are iron oxides, which are non-magnetic. On-board detection methods for corrosive wear-forms are based on chemical reactions. Results from both the ferro-magnetic iron and the corroded iron should be combined to provide the total iron reading. These methods are not described further in this document.

Wear types	**Wear mechanism**	**Measuring method**		
		Magnetic iron	**Corrosive iron products**	**Total Iron**
Normal wear Catalytic fines Micro-seizures Scuffing	Abrasive or adhesive wear	A	-	A+B
Cold corrosion	Corrosive wear	-	B	

Table 1: *Correlation between wear type and mechanism and different iron measuring methods.*

On shore laboratories typically use ICP techniques to determine the total iron. These techniques look at smaller particles, however, they are able to measure both corrosive and adhesive / abrasive iron particles depending on the technique and sample preparation method used. OEM recommendations are based on these methods.

X-ray techniques determine the total iron. Such systems can be used on board and in the lab and allow larger particles to be measured. However, proper homogenizing of the sample is important. Some of the chemical reacting on-board test kits are less accurate and require dedicated sample handling.

The chart in figure 21 displays the Fe detection methods relative efficiency (vertical axis), and size of particles best measured with the corresponding Fe detection method.

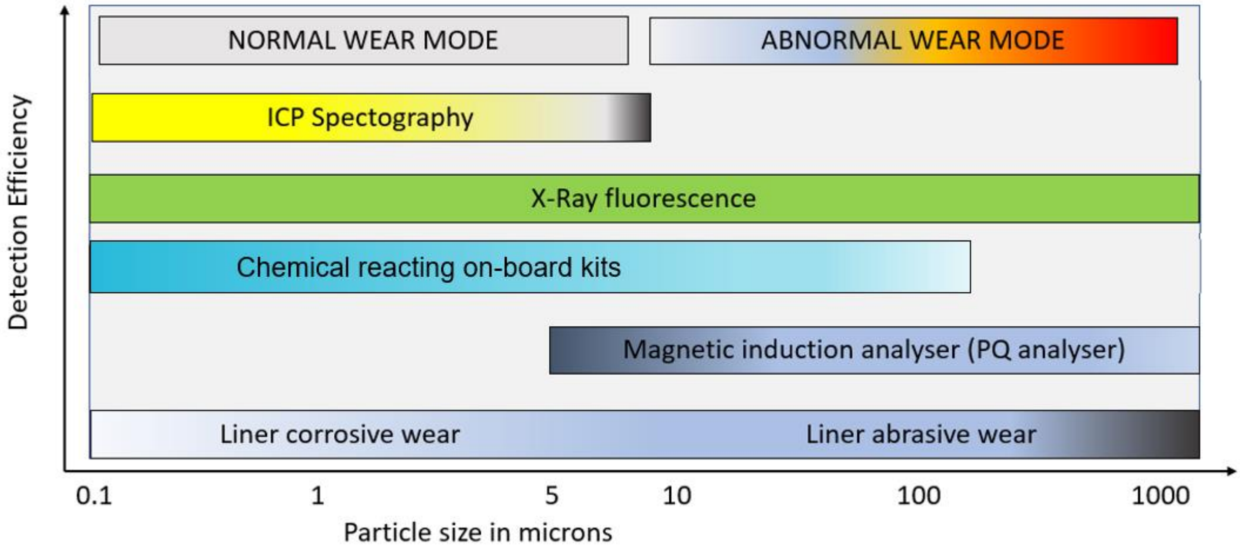

Figure 21: *Different iron detection methods have different measurement performance.*

8 Appendix III – Procedure for sampling of scrape down oil

This appendix offers guidance on collecting scrape down oil samples properly.

Challenge:

Maintaining an optimal cylinder oil feed rate for an engine requires continually up-dated information. This information must be collected properly to ensure a correct basis for decisions.

Solution:
Collecting the scrape down oil samples correctly, ensures valid samples. This entails appropriate collecting, handling and labelling of the oil samples.

8.1 Introduction

Scrape down sample analysis is an important tool, along with port inspections to determine cylinder liner and piston ring condition and to optimise cylinder oil consumption. It is very important that all information required is provided and that the sampling is carried out correctly, to ensure the best possible basis for decision making regarding feed rate or cylinder oil BN.

It is important to optimise the cylinder oil consumption, to avoid over-lubrication and oil waste. Scavange drain oil analysis is a useful tool to reach the optimum.

8.2 Overview of the scrape down oil analysis process

The process in Figure 22 should be followed when sampling scrape down oil. The individual steps are described in detail in the following sections.

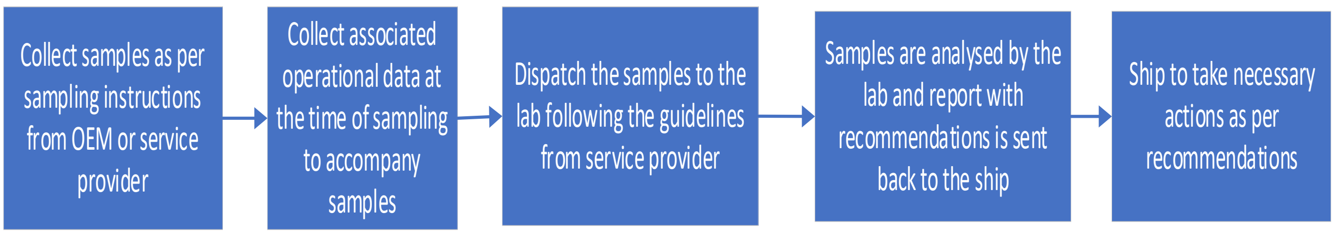

Figure 22: *Overview of the scrape down oil analysis process.*

8.3 Prerequisites

Prior to collecting the samples, please go through the following steps:

1. The scavenge air box and drains must be thoroughly cleaned, as numerous samples have to be taken within a relatively short time frame, with no room for mistakes. This should be done approximately 24 hours before the samples are to be taken.

2. Please ensure that there are enough sample bottles on board. The required amount is:
   - 1 for clean system oil;
   - 1 for used system oil;
   - 1 for fresh cylinder lubrication oil;
   - 1 per cylinder (for a 12 cylinder engine: 12 sample bottles)
   - 1 fuel sample. See also Section 8.5.
3. Filling in an information form for common information such as engine load, speed, fuel oil properties (kin. visc, %S, catalytic fines, etc.), cylinder oil type (BN), feed rate (per cylinder), engine and component running hours etc. This only needs to be done once.
4. Engine load should be stable and outside maneuvering load (normally above 25% load).

- Perform the test in good weather and sea conditions.
- Wait min. 12-24 hours (or as long as possible given vessel schedule) after a load change before collecting any samples. Consult OEM recommendations.

8.4 Collecting and labelling the samples

When collecting scrape down oil samples follow the steps below. Please see Figures 23-24 for examples of the valve placements mentioned below.

Please note that in order to collect scrape down or drain oil per cylinder, each cylinder must have its own drain valve. Some engines do not have individual drain valves. If there is only one common drain outlet, only one sample needs to be taken, i.e., steps 1-12 only need to be performed once.

Process for collecting and labelling the scrape down oil sample:
1. Close the 3-way valve or the shut-off valve. See Figures 23-24;
2. Open the drain valve momentarily to blow out oil and sludge in the drainpipe;
3. Repeat from step 1 for all cylinders;
4. Wait until sufficient drain oil has accumulated in the drainpipe. This time may vary and depend on engine design, load, cylinder oil feed rate etc. Usually about 30 to 120 minutes, but please use your own experience to assess the time needed;
5. Open the drain valve and drain the accumulated oil completely for disposal;
6. Refill the drainpipe according to step 4;
7. Open the drain valve and fill the sample bottle to the neck;
8. Close the drain valve;
9. Seal the sample bottle;
10. Open the 3-way valve or the shut-off valve;
11. Fill in the information required on each sample;
12. Label the bottle with relevant information, e.g. bar sticker from lube oil analysis partner, or cylinder no., date, time, IMO no. etc.
13. Repeat from step 5 for all cylinders.

Process for collecting and labelling the other samples:

1. Clean system oil
    a. Take 1 sample from the clean system oil tank.
    b. Label the bottle with relevant information, e.g., bar sticker from lube oil analysis partner, or “Clean system oil”, date, time, IMO no. etc.
2. Used system oil
    a. Take 1 sample from the system oil circulating system.
    b. Label the bottle with relevant information, e.g., bar sticker from lube oil analysis partner, or “Used system oil”, date, time, IMO no. etc.
3. Fresh cylinder lubrication oil
    a. Take 1 sample from the cylinder oil day tank. Make sure to take the sample from the cylinder oil in use when taking the scrape down samples.
    b. Label the bottle with relevant information, e.g., bar sticker from lube oil analysis partner, or “Fresh cylinder oil”, date, time, IMO no. etc.
4. Fuel
    a. A fuel sample is recommended to include for full analysis, but it is not always necessary, as information is usually available from the bunkering sample. Please note that this information is for the fuel before fuel cleaning, and e.g., catalytic fines may be removed during fuel cleaning.
        i. In case a fuel sample is not included, relevant information from the fuel analysis should be included when sending the samples. E.g., fuel-sulfur, kin. viscosity, catalytic fines, and preferably the full ISO 8217 analysis.
        ii. In case a fuel sample is included, it is most relevant to take the sample just before the engine inlet, after the filter.
    b. In case of scuffing, a fuel sample should be taken just before the engine inlet, after the filter.

Please note!

Be careful in handling the bottles:

- Make sure the bottles are not contaminated in any way before, during or after the oil sample is collected.
- Be sure to label the bottles correctly and fill in all the required information in the information form.

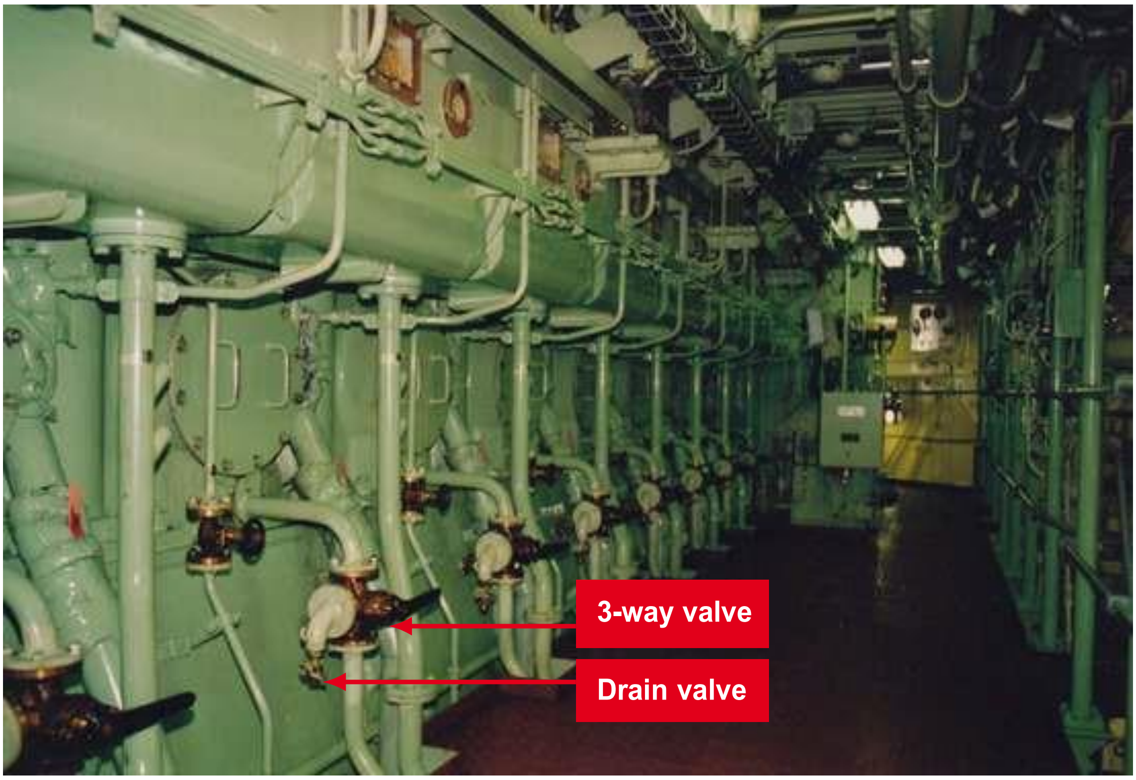

Figure 23: *Example of scrape down/drain oil sampling on a MAN ES engine (S50MC).*

Figure 24: *Example of scrape down/drain oil sampling on a WinGD engine (RTA84CU).*

8.5 Sending the samples

After all the samples have been taken, all the bottles labelled correctly and the information form has been properly filled in, please return all samples via courier to your oil analysis partner.

Please note!

The oil samples may degrade over time. Likewise, the value of the information gained from an scrape down oil analysis will diminish over time. Please ship the samples as soon as possible after sampling to obtain the most accurate current cylinder condition reports.

8.6 Analysis of the samples

The oil analysis partner will analyse the oil samples and will often provide guidance on the quality of the oil and which actions to take. See also Section 5.9.

9 Acronyms and Abbreviations

BN	Base Number
Catalytic fines	Abrasive particles of Aluminium and Silicon found in residual fuels
CLO	Cylinder Lubricating Oil
ECA	Emission Control Area, as defined by IMO
Fe	Iron Content (Ferrous)
HSFO	High Sulphur Fuel Oil (>0.50%S)
ICP	Inductively Coupled Plasma (Test method for elemental analysis)
IMO	International Maritime Organisation, part of the United Nations
ISO	International Standards Organisation
OEM	Original Equipment Manufacturer
PQ	Particle Quantifier
SOx	Oxides of Sulphur
ULSFO	Ultra Low Sulphur Fuel Oil (≤ 0.10%S)
VLSFO	Very Low Sulphur Fuel Oil (≤ 0.50%S)

10 References

[1] CIMAC Recommendation 31 (05-2017): The lubrication of two-stroke crosshead diesel engines. (www.cimac.com)

[2] J.A. Williams, Engineering Tribology, Oxford Science Publication, 2000 (p 176)

[3] CIMAC Guideline (11-2017): Cold corrosion in marine two stroke engines. (www.cimac.com)

[4] CIMAC Guideline (2023): Guideline for design and operation of fuel cleaning system for diesel engines. (www.cimac.com)

[5] Guide for judging condition of relevant piston-running components Version 5 April 2021 WinGD

[6] CIMAC guideline (02-2023): Used engine oil analysis. (www.cimac.com)

11 Acknowledgement

This document was made by the CIMAC Working Group Lubricants. At the time of this document's publication, the following companies are a member of the CIMAC Working Group Lubricants. For clarity, the companies are listed by their generically known names rather than their legal entities.

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- Exponent International
- ExxonMobil
- Gulf Oil Marine
- Hans Jensen Lubricators
- Hug Engineering
- Infineum
- INNIO Group
- IPAC
- Japan Engine Corporation
- Lloyds Register
- London Offshore Consultants
- Lubrizol
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CIMAC e. V.
Lyoner Strasse 18
60528 Frankfurt
Germany

President: Prof. Dr. Donghan, Jin
Secretary General: Peter Müller-Baum

Phone +49 69 6603-1567
E-mail: info@cimac.com

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