Experimental Study of Metallic Surfaces Exposed to Cavitation

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Abstract

Cylinder liners in heavy-duty truck engines are subjected to intense vibrations and may sustain damage from the cavitation of bubbles in the coolant liquid, with some risks of leakage and engine breakdown. An ultrasonic oscillating probe was used to simulate the pitting rates and behavior of samples extracted from cylinder liners, which are made of grey cast iron, with differences in surface roughness, glycol and inhibitor content in coolant, coolant temperature and graphite flake class; bainitic microstructures were also tested. Measurements consisted of mass losses under set intervals during experiments lasting 2.5 or 4 hours. Affected surfaces were later evaluated with scanning electron microscopy and confocal microscopy.

Results indicate higher cavitation damage with: lower concentrations of glycol and absence of corrosion/cavitation inhibitors in the coolant liquid, lower liquid temperatures between 76°C and 90°C, and presence of B-type graphite class in the microstructure. Results regarding surface roughness were inconclusive.

A sequence of surface damage mechanisms has been proposed, with corresponding microscope observations, to explain the mass loss trends and the associated microstructural changes over time.

Keywords: cavitation, cylinder liner, grey cast iron, erosion pitting, graphite class
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1 Introduction

Automobile engines are subjected to several kinds of degradation from their years-long service life with high energy outputs, and their parts are exposed to high temperatures, friction, vibration, mechanical stresses and impact from the pistons. Improvements to their performance and safety are a subject of continuous work at Scania and involve design and research.

Scania manufactures, among other products, trucks and heavy duty engines, and its cylinder liners may sustain cavitation damage from the engine coolant, as seen in Figure 1. Cavitation entails the appearance of small pits on moving or vibrating surfaces in contact with a liquid, and can be a serious problem in cylinder liners when they are perforated by the overgrown pits, allowing coolant liquid into the combustion chamber and causing engine breakdown.

Figure 1 – Cylinder liner with severe cavitation patterns on the body and on the upper O-ring groove [1]. Scale: 3:1.
This work aims to investigate cavitation attack from a Materials Science perspective, exploring the corresponding resistance and behavior of different phases, microstructures and surface features of grey cast iron – the material of which the liners are made. A better understanding of these properties will aid in the design and production of better engines and, at the same time, contribute to the scientific knowledge within Metallurgy.

1.1 Objective

To gather relevant data and knowledge about the effect of microstructural and surface features of grey cast irons on their resistance to cavitation erosion and associated damage mechanisms.

1.2 Motivation

It is the interest of Scania to acquire further information on the mechanisms of cavitation damage, which may cause serious failure and significant losses in maintenance to its cylinder liners, in order to enhance their service life and reliability. It is, however, often costly and time-consuming to perform complete engine or field tests to evaluate these damages. There are, however, shorter, cheaper tests in a laboratory setting which use a vibrating probe to induce bubbling in the liquid and simulate cavitating conditions in the engine coolant liquid, which are extremely useful in obtaining qualitative results about the behavior of materials in different cavitation conditions. The experiments performed gather data to integrate Scania’s database for current and future reference, as well as to provide insight, specifically about the erosion behavior of grey cast iron, relevant to the design and improvement of cylinder liners.

On the academic and scientific side, the results are an addition to the metallurgical knowledge. Grey cast irons have complex compositions and microstructures; the role and interactions of all of its microconstituents are not yet fully understood, whilst also being sometimes difficult to study. The findings of this work are thus aimed at contributing to such endeavor.
## 2 Background

### 2.1 Cylinder Liner

Cylinder liners are hollow, open-ended cylindrical parts inserted into the block of heavy-duty engines to protect it from direct exposure to the high temperatures and gases from the combustion chamber, as well as to guide the reciprocating movement of the piston. They must therefore withstand high temperatures, thrusting action, vibrations and friction. Their location in the block is shown in Figure 2:

![Figure 2 - Left: Perspective from the top of an engine block showing cylinder liners. Right: Schematic cross-section of an engine block highlighting the position of the cylinder liner. Courtesy of Scania.](image)

Cylinder liners are typically made of grey cast iron, and manufactured by sand mold casting or centrifugal casting, followed by inner and outer surface finishes; the production is inexpensive compared to that of other components [2, 3]. Because the inner surface is exposed to the piston and the combustion chamber, the requirements on its properties and performance are more stringent; it is honed, polished and lubricated [4]. The outer surface is in contact with
the recirculating engine coolant liquid, whose characteristics also play a role in the service life of the liner; specific to this work is the erosive damage named cavitation.

2.2 Cavitation

In Physics, the implosion of vapor bubbles due to a localized pressure increase is named cavitation [5, 6], and it has been found to be a cause of damage to surfaces in certain conditions. This erosive type of damage has also been called cavitation in engineering practices and in the associated literature [7, 8, 9, 10, 11, 12, 3, 13], and both meanings shall be used throughout this text - the latter being more frequent - and distinguishable by context.

The cavitation erosion of vibrating or moving solid surfaces exposed to a liquid is a well-known phenomenon and has been documented for over two hundred years [3]. It is a frequent problem for the producers and users of engines because, by principle, it cannot be avoided once the decision to use a liquid as coolant is made, as is the case in heavy-duty diesel engines; it can only be mitigated by design, operational and metallurgical factors.

Surfaces undergo cavitation when their movement creates pressure fluctuations in the surrounding liquid; bubbles form in its bulk and are then collapsed when a localized pressure increase occurs. The sudden volume contraction results in an energetic implosion accompanied by shock waves and high-velocity microjets, which impact the solid and damage it [11, 7, 3, 14]. The current work explores this effect on afflicted cylinder liners, one example of which was seen in Figure 1; the phenomenon is sketched below, Figure 3.

![Figure 3 - Schematic of cylinder liner pitting [13]. Bubbles in the cooling liquid collapse and erode the surface.](image-url)
2.3 Engine Coolant

The coolant liquid used in the heavy duty engines fabricated by Scania is a mixture of distilled water, ethylene glycol and additives. Glycol widens the liquid stability temperature interval of the mixture, thus acting both as an antifreeze, useful for cold climates, and as an ‘anti-boil’, allowing for higher operation temperatures. The additives may include corrosion inhibitors, lubricants, tracers for leakage and identifiers [15].

2.4 Formation and Collapse of Bubbles

Pure substances occur in different phases depending on the temperature (T) and the pressure (P) at which they are. Phase diagrams, whose usual shape is shown in Figure 4, may be plotted to show the combinations of T and P for which each phase (solid, liquid, gas) is stable, forming stability regions.

![Phase diagram for a generic pure substance](image)

*Figure 4 – Phase diagram for a generic pure substance [16].*

Separating these regions are curves that represent an equilibrium state in which two of these phases are stable and may occur simultaneously. The point of intersection between the three regions is called a triple point; it is a unique combination of temperature and pressure particular to the substance for which all three phases – solid, liquid and gas – may coexist.

The melting and boiling points of a substance are the temperatures at which the solid-to-liquid and liquid-to-gas transformations happen at a pressure of 1 atm, respectively [17]. As shown by the arrows in the phase diagram in Figure 5, it is possible for a liquid to vaporize not only by a temperature increase, but also by a pressure drop.
Thus it is possible for vapor bubbles to form below the boiling point; likewise, an increase in pressure will revert the bubbles into liquid. This behavior can be generalized for liquid mixtures, such as the engine coolant fluid, and is the reason for the cavitation damage.

In the coolant fluid chambers of an engine, vaporization is undesirable but also unavoidable; the thrusting and receding actions of the piston on the cylinder liners impart cycles of low- and high-pressure onto the surrounding coolant [3, 7], inducing the formation and collapse of bubbles.

Because gases occupy much greater volumes (on the order of 1000 times) than their liquid counterparts, bubbles liquefy with a violent implosion; the freed volume is promptly filled by the surrounding liquid, with associated velocities so high as to be called a ‘jet’ (reaching hundreds of meters per second [10, 3]), as shown in Figure 6. High-pressure pulses accompany this event [18] and induce the disintegration of other bubbles, which, in turn, causes significant heat release due to the disappearance of interfacial area (release of interface energy) and to the phase change itself (release of vaporization enthalpy).
Different modes of collapse may occur depending on the proximity to the solid surface and the pressure changes involved.

Spherical collapse may happen when the pressure and temperature fields in the liquid, as well as inside the bubble, are homogeneous and the bubble is located away from a solid surface. It begins at maximum radius and, as the outer pressure increases and exceeds the inner pressure, the bubble implodes, sending a shock wave, as shown in Figure 7.

Nonspherical (or asymmetrical) collapse may occur when there is a solid surface nearby that interferes with thermal and convective fields, and it is the mechanism responsible for the damage to the material. Instabilities in the gas-liquid interface and pressure fluctuations allow the liquid to penetrate the bubble as a jet, impacting the solid, as represented in Figure 8:
Localized damage happens when the bubble center is located within about two times the maximum radius away from the solid [7]. The solid surface, when subjected to numerous of these small jets over time, sustains the damage called cavitation.

### 2.5 Cavitation Damage

Cavitation is mainly an erosive process that removes particles from the material. It may be thought of as consisting of an incubation period followed by an erosion process, whose characteristics may be studied in separation.

During incubation, the aggressive fluid motion causes the solid surface to deform plastically, with no removal of material, and form small pits. They may appear on spots of higher pressure amplitude or where surface defects (impurities, softer phases and boundaries, grooves and pores) are located, concentrating stresses. On particular pits, the deformation will be high enough to induce the appearance of microcracks.

Erosion ensues when these microcracks expand far enough to allow for the removal of a small particle by fluid motion. Once formed, a pit will favor the nucleation of more bubbles, as well as of cracks, therefore becoming a preferential pitting site. Erosion continues by chipping of the fractured boundaries, so that it tends to cluster around damaged centers [11].

Some studies [11, 20] have proposed a generalized pattern for the mass loss rates of ductile metallic samples, including steels and aluminum alloys, during rig cavitation experiments consisting of an exponential regime, in which the mass loss rate slowly increases over time, followed by a linear regime, in which mass loss rates are constant over time. These regimes tend to coincide with the aforementioned stages of incubation and developed pitting. These
insights shall be used as a basis for the explanation of the cavitation rates of grey cast irons in later chapters.

2.6 Material – Lamellar Grey Cast Iron

Lamellar grey cast iron, of which cylinder liners are typically made, is one of many iron-based (ferrous) metallic materials; these are usually composed of iron, carbon and other alloying (additive) elements [21, 22]. Carbon is present mainly due to the extractive processes that convert iron ore into metallic iron; other elements are also retained, but in smaller amounts [23]. During refining, alloying elements are added in controlled amounts to produce specific structure and property changes. Lamellar irons have outstanding vibration damping capabilities, good machining, fatigue and tribology properties, acceptable mechanical resistance and a low cost of manufacturing, being the material of choice for cylinder liners and offering desirable cost-benefit.

Ferrous alloys are often named according to their carbon content; steels are defined as those with %wt C < 2.1% (but in practice seldom exceed 1%), and irons are those with higher carbon levels (rarely exceeding 4%, which is approximately the amount remaining after the conversion of ore in blast furnaces). Because irons are very hard and brittle, thus difficult to conform, they have been, throughout history, cast in molds from the molten state into the final shape, and so are called cast irons.

The mechanical properties of metals depend on their microstructure, which may be explained as the disposition of its constituents – phases, phase combinations and defects, qualified with regards to morphology - on a microscopic scale, as revealed by an optical microscope at a magnification above 25x [24]. The organization of constituents and the interfaces between them influence, for example, dislocation movement and the corresponding plastic deformation of the material, as well as the accommodation of residual and applied stresses, crack propagation and fragilization effects. The microstructure is an order-dependent result of solidification, cooling and heating histories, and therefore provides information on them whilst also being a design factor for material performance.

One of the most useful tools to understand metallic materials and their microstructures is a phase diagram – a plot of the thermodynamic stability of different phases according to temperature (vertical axis) and the amount of a certain element (horizontal axis). These two
factors summarize the design (composition) and processing (temperature) concerns in fabricating of a piece from the materials perspective, and help estimate the microstructural features to be encountered.

The iron-carbon system is displayed below, Figure 9, zoomed in to its most important region of 0% to 7%wt carbon and 400⁰C to 1600⁰C [22]. It shows the phase transformations that happen during cooling from the molten state (casting) and also from possible heat treatments carried out below the melting temperatures.

![Figure 9 - Phase diagram for the iron-carbon binary system [25].](image)

All details and explanations of the diagram are beyond the scope of this report. Noteworthy for grey cast irons are the transformations of liquid ($L$) into $\gamma$ (austenite) and graphite ($C$), and the subsequent transformation of $\gamma$ into $\alpha$ (ferrite) and $Fe_3C$ (cementite) which occur in the 2.1% to 4.2% C range:

- **Eutectic solidification** $L \rightarrow \gamma + C_{graphite}$
- **Eutectoid decomposition** $\gamma \rightarrow \alpha + Fe_3C$
The liquid begins to solidify by first forming γ (the constituent being termed proeutectic austenite) as the matrix, then a cell-shaped eutectic mixture of austenite and graphite. When the system reaches 727°C, the remaining austenite (both proeutectic and in the eutectic) transforms into a lamellar eutectoid mixture of ferrite and cementite, and this constituent is termed pearlite. Further cooling to room temperature does not change the microstructure qualitatively and, in the end, it consists of graphite flakes dispersed in a pearlitic matrix. Some other constituents present in actual grey irons in smaller amounts include free ferrite, free cementite, iron-phosphorus eutectic (steadite), carbides and inclusions (oxides) [22].

The graphite profile in grey cast irons is usually described in terms of flake shape, size and size distribution; differences are a result of the solidification and cooling rates, chemical composition and heat treatments. Norms and standards such as EN ISO 945-1 [24] exist to aid in specifying a material of such complexity by comparing the microstructure of an unetched sample, observed under a light optical microscope at a magnification of 100x, with reference schematic images, as shown in Figure 11 Figure 12. Cast irons are then classified with a Roman numeral I-VI, a Latin letter A-E and an Arabic numeral 1-8.

Grey cast irons such as that used in the cylinder liners usually have graphite flakes, or lamellae, of Form I in Figure 10, and are called lamellar grey cast irons (LGI).

Figure 10 – Form classes of graphite particles. I: flake (lamellar); II: crab; III: compacted (vermicular); IV - VI: spheroidal (nodular) [26].
A detailed explanation of Forms II to VI is beyond the objective of this work, but it is worth mentioning they confer different properties such as ductility, malleability, machinability and toughness depending on the graphite morphology.

The lamellae of Form I may be distributed over the pearlitic matrix in five approximate configuration types as seen in Figure 11:

![Figure 11 - Classes of graphite distribution in lamellar grey cast iron.](image)

Type A: Uniform distribution, random orientation
Type B: Rosette groupings, random orientation
Type C: Superimposed flake sizes, random orientation
Type D: Interdendritic segregation, random orientation
Type E: Interdendritic segregation, preferred orientation [27].

Type A is the preferred microstructure for most applications in engine components subjected to vibrations, cavitation, high temperatures, fatigue and load bearing; it has higher toughness and ultimate tensile strength, therefore higher fatigue life and stress, probably due to the contiguity of the pearlitic matrix and the smaller number of stress-concentrating spots. It is obtained with inoculation and moderate cooling rates.
Type B occurs with near-eutectic compositions at low undercooling and a restricted availability of nuclei for solidification; as such, its groupings resemble, and may be confused with, eutectic cells.

Type C is typical of hypereutectic irons which solidify under small undercoolings; it is therefore not commonly seen on the most usual types of cast iron and is beyond the scope of this work.

Types D and E are characteristic of hypoeutectic irons and high cooling rates and undercooling; the graphite flakes precipitate in the interdendritic regions at the final solidification transients, and are detrimental to the mechanical properties of the material. Type E is typical of strongly hypoeutectic irons [24, 28].

Finally, the graphite flake size may also be specified according to Figure 12. Size distributions may be evaluated at a given region of the microstructure as percentages of the number of particles in each size (size count) or as percentages of the total area (volume fraction), each conveying different information about the processing history and mechanical properties of the material, and to be discussed later.

One interest of the current project is to study the influence of the graphite classes from Figure 11 on the cavitation erosion behavior of cylinder liner samples made of LGI. From the brief description provided about these graphite classes, it is expected that samples with higher fractions of A-type distribution be more resistant, and samples with higher amounts of B-type
distribution be less resistant to cavitation. In actual castings and cast pieces, it is hardly the case that only one of these distributions occur; more commonly, a combination of classes is the case, and less strict process control during manufacturing may yield undesirable amounts of classes B, D and E.

2.7 Previous Work

2.7.1 Cavitation in Cylinder Liners

Erosion pitting of engine parts due to cavitation is a well-documented phenomenon and has been studied for many decades [7, 11, 13, 14, 3], its causes and relevant operational parameters being well known; a summarized explanation of these is in place now.

The cause of the appearance and collapse of bubbles is the vibration of cylinder liners, which induces cycles of low and high pressure onto the surrounding liquid. Cylinder liner vibrations occur at their natural vibration frequencies – dependent on their geometry - and due to piston action. Higher vibration frequencies result in more low- and high-pressure instances and more bubble formation and implosion cycles, with more severe surface pitting. Higher vibration amplitudes lead to larger pressure drops and raises, making microjets more aggressive and causing more damage.

More energetic piston slaps primarily cause higher vibration amplitudes, therefore increasing cavitation erosion. Indeed, the regions of liners most prone to cavitation are the thrust side (TS) and anti-thrust side (ATS), as reported in the literature [7, 13, 3] as well as in inspections within the company [9, 12, 1]. Less clearance between piston and liner decreases liner vibration and deformation and reduces cavitation [7, 3], and larger coolant chambers at similar static pressures also decrease cavitation damage due to the lower probability of bubbles forming closer to the surface [3]. These factors, however, are important for other purposes such as power output, energy efficiency, engine dimensions, service life and production costs; their alteration for cavitation protection may not be possible.

As explained in earlier sections, bubbles may form when local pressure falls below a certain value; subjecting the coolant chamber to a higher hydrostatic pressure increases the mean value about which the local pressure fluctuates, thereby decreasing the probability of bubble formation and the maximum bubble radius [7].
A higher boiling point of the coolant means a higher stability of the liquid phase with respect to the vapor phase, reducing the probability of bubble formation. In this specific case, this is achieved with higher glycol concentrations; ethylene glycol itself has a higher boiling point than water [29] and its addition to water makes the mixture less volatile and less prone to cavitation.

Results from other studies [7, 10, 12, 13, 3] have shown that cavitation rates peak when the liquid is at intermediate temperatures between its freezing and boiling points.

Higher viscosity means more resistance to fluid flow; at similar energy levels, associated velocities are thus lower. Micro-jet velocities have been found by simulations [10] and experiments [10] to be smaller in higher-viscosity liquids, therefore causing less surface damage.

Higher liquid-vapor interfacial energies should, in principle, reduce the maximum bubble radius and result in less violent implosions, with an associated reduction in pitting; however, cavitation simulations in which liquid properties were varied independently have hinted that surface tensions have little effect [10]. It is noteworthy that these properties – viscosity, surface tension and boiling temperature, and especially the first two – are inherently correlated and depend on molecule size and shape as well as on complex intermolecular interactions between solvent and solute (s), and it is hardly possible to manipulate each separately and extensively in reality.

Coolants also have additions of corrosion and cavitation inhibitors; while various sources converge in that electrochemical corrosion and erosion-induced corrosion amount only to a small fraction of the damage under erosive conditions [13, 14, 3], it may well be that, due to their mechanism of action, corrosion inhibitors nevertheless protect the surface from mechanical pitting. Some tests under this work were therefore run with a mixture of glycol and water without inhibitors to understand whether the added resistance to pitting is due to the physical properties of glycol or to the chemical properties of the inhibitors.

2.7.2 Microstructure of Lamellar Irons

Detailed studies at Scania have correlated the microstructural features with the performance of lamellar grey cast irons on cylinder liners and other engine parts. It is accepted that the graphite morphology should be primarily of class A, see Figure 11, and a suitable size range,
for optimal fatigue and wear resistance; this also happens to be the preferred specification at the material surface for cavitation resistance. There is some tolerance to the presence of classes B, D and E; these classes will not necessarily fail to cavitation, but might increase the risk for it.
3 Experimental

3.1 Methodology

In accordance to the original project proposal, and following the interest of the Engine Development department at Scania, four varieties of graphite flake distribution in a pearlitic matrix were to be studied; an alternative to the material’s matrix constituent, bainite, was then included. Communication with other departments at Scania indicated their interest in the problem of cavitation of engine parts, which led to the incorporation of coolant properties and surface texture as variables in this study. The range of these variables was chosen to approximate actual engine operation conditions as found in internal technical reports and simulations [15, 12, 30, 1, 31, 32].

The variables isolated in each experiment set are summarized in Table 1 as follows:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Fixed Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant Composition, % mass glycol</td>
<td>0 (tap water)</td>
<td>T = 82°C</td>
</tr>
<tr>
<td></td>
<td>35, no inhibitors (35*)</td>
<td>Smooth surface</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>A+B/D/E</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50, stronger inhibitor (50+)</td>
<td></td>
</tr>
<tr>
<td>Coolant temperature, °C</td>
<td>75°C</td>
<td>Coolant: 35%</td>
</tr>
<tr>
<td></td>
<td>82°C</td>
<td>Smooth surface</td>
</tr>
<tr>
<td></td>
<td>90°C</td>
<td>A+B/D/E</td>
</tr>
<tr>
<td>Surface Finish</td>
<td>Smooth (ground w/ 600 grit)</td>
<td>T = 82°C</td>
</tr>
<tr>
<td></td>
<td>Rough (ground w/ 80 grit)</td>
<td>Coolant: 35%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A+B/D/E</td>
</tr>
<tr>
<td>Graphite Class and Microstructure</td>
<td>A</td>
<td>T = 82°C</td>
</tr>
<tr>
<td></td>
<td>A+B</td>
<td>Smooth surface</td>
</tr>
<tr>
<td></td>
<td>A+B/D/E</td>
<td>Coolant: 35%</td>
</tr>
<tr>
<td></td>
<td>B/D/E</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bainitic matrix</td>
<td></td>
</tr>
</tbody>
</table>

Coolant compositions were only specified in terms of the mass percent of ethylene glycol in the mixture; the balance corresponds to distilled or deionized water. The 35% and the 50% coolants are two of the usual compositions used and recommended by Scania, and were used in the experiments directly as supplied, that is, without any modifications. They are called, and shall be here referred to, as ‘ready-mixes’ or 35-65 and 50-50 mixes, respectively. Both also
have additives to inhibit corrosion and cavitation. A mixture of 35% glycol and 65% deionized water, without inhibitors, was also prepared for testing and will be referred to as $35^*$. Lastly, a 50% glycol mixture with more powerful cavitation inhibitors was added to the experiments; it will be shortened to ‘50+’.

Since the investigations aim at approximating the damage caused by cavitation and then evaluating its effects on the microstructure of grey cast iron, the experimental work consists of a testing stage and an analysis stage.

Cavitation was simulated by immersing a sample with a flat surface in a reservoir with coolant and making it oscillate at appropriate frequencies. This ensures that the liquid undergoes pressure variations to produce and implode bubbles, as well as providing an accelerated test which provides results quickly and at a lower cost compared to engine tests. This is a practice well described in literature and employed by researchers [7, 11, 12, 7] and was also the recommendation of Scania. Total damage was calculated in mass loss (instantaneous and accumulated). Because all samples have the same geometry, results may be compared directly.

Post-test analysis was carried out mainly using Confocal Microscopy (CM) and Scanning Electron Microscopy (SEM).

CM is useful in topological mapping and pit depth measurements, as well as being a fast and reliable method to view coarse, unpolished surfaces with appropriate detail levels without extensive prior preparation.

SEM offers, with its adjustable voltage and detection settings, the possibility to investigate, among others, topology (Secondary Electrons detection), atomic weight differences (Backscattered Electrons detection) and chemical characterization (Energy-dispersive X-ray spectroscopy).
3.2 Cavitation Tests

The samples obtained from the cylinder liners are from both the inner and outer surfaces, as shown in Figure 13. A schematic top view is also shown, with dimensions in millimeters:

![Figure 13 - Left: Position of samples obtained from cylinder liner walls (inner and outer). Right: Schematic top view of test samples showing truncated sides for easier attachment to horn using a wrench.](image)

A photograph of the samples, set next to a pen for size comparison, is displayed in Figure 14.

![Figure 14 - Test samples used in the ultrasonic vibrating rig.](image)

The samples were screwed onto an ultrasonic vibrating probe and submerged in the desired coolant mixture contained in a beaker. This beaker was, in turn, placed inside another larger beaker filled with water to allow for better temperature control of the coolant liquid. The beakers were heated by a hot plate and the temperature was monitored by an electronic thermometer (whose probe was removed from the inner beaker before the probe was turned on). A schematic of the equipment to which the samples are attached is in Figure 15.
The whole test rig is shown in Figure 16, and the setup is similar to instructions in norm EN ISO 945-1 [33]. The most important adaptations made to the procedure specified in the norm include the use of different liquids than the recommended corrosive water and different temperatures of the test liquid, so as to allow for more realistic experiments. The circulating cooling bath was replaced by the two beakers for faster heating and temperature control, as well as to reduce coolant liquid consumption.

Prior to the testing of each sample the inner beaker was washed and the coolant was renewed; then, a stainless steel dummy sample was put to vibrate, in identical conditions, to stabilize the gas and bubble concentrations in the coolant. The following table summarizes all the procedure specifications and settings followed during the experiments:

Table 2 - Summary of specifications followed in the cavitation erosion experiments

<table>
<thead>
<tr>
<th>Factor [unit]</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample flat area [cm²]</td>
<td>2.7</td>
</tr>
<tr>
<td>Surface finish, smooth [grit]</td>
<td>600</td>
</tr>
<tr>
<td>Surface finish, rough [grit]</td>
<td>80</td>
</tr>
<tr>
<td>Sample screwing torque [Nm]</td>
<td>7.5 (12.5 for steel)</td>
</tr>
<tr>
<td>Horn amplitude [µm]</td>
<td>25</td>
</tr>
<tr>
<td>Horn frequency [kHz]</td>
<td>20</td>
</tr>
<tr>
<td>Sample depth into liquid [mm]</td>
<td>12</td>
</tr>
<tr>
<td>Coolant volume in beaker [mL]</td>
<td>100</td>
</tr>
</tbody>
</table>
Figure 16 - Photograph of test apparatus consisting of ultrasonic horn (A) holding sample submerged in coolant (B), whose temperature is held constant by the magnetic stirrer (C).
Testing consisted of running the samples on the test rig and recording the mass loss corresponding to each time interval. The time intervals used were 1, 3, 5, 7, 10, 15, 20, 30 min and every 30 minutes afterwards until the desired time (150 or 240 min, or whenever a sample was damaged due to unscrewing, in which situation the data points obtained formerly were preserved and the sample’s run was halted). Samples were rinsed with running water followed by ethanol and immediately blow-dried both before and after each run. Samples were chosen at random for each test to minimize experimental errors and bias.

Cavitation rate is also a concept used in the Results and Discussion chapters, and refers simply to the measured mass difference between two consecutive test time intervals. Cavitation rates may be compared directly, given the same time intervals, because the samples have the same surface area.

3.3 Scanning Electron Microscopy

Erosion pits, cracks and other surface features were investigated under a scanning electron microscope (SEM) for a better understanding of their order of their magnitude, morphology and chemistry. Samples were rinsed beforehand with ethanol in an ultrasonic bath. Micrographs were taken at magnifications of 100x, 200x, 1000x and, when relevant, 4200x. Other settings and specifications are included in Table 3:

<table>
<thead>
<tr>
<th>Table 3 - Scanning Electron Microscope settings.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model</strong></td>
</tr>
<tr>
<td><strong>Voltage</strong></td>
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3.4 Confocal Microscopy

The model used was a Sensofar Plµ 2300, aided by the accompanying software Sensomap. Focus was adjusted according to each sample, and brightness was adjusted automatically by the software. Measurements were made at 200x and 1000x magnifications. Data sets include isometric (full topography) measurements, contours (top view), histograms (height distributions) and profile (height over a line segment) of features of interest. Although all of these have provided important information for this study, most CM images used in this report are of contours due to their ease of interpretation and visualization on a printed document.
4 Results

4.1 Graphite Class and Microstructure

The resistance to cavitation erosion of samples under various operating conditions was examined by recording their mass changes at set intervals. The obtained data may be organized in plots of accumulated mass loss over the experiment time such as the one shown below, Figure 17, for the graphite microstructure assessment:

![Accumulated Mass Loss of Different Graphite Classes](image_url)

The general shape of the curves is of a rapid increase at lower times, followed by a somewhat linear region which lingers until the full four hours of experiment. This behavior has also been observed in the experiments regarding coolant composition, temperature and surface roughness. As shall be explained in further detail in the Discussions section, the first part of these curves is influenced by the removal of graphite from the affected surfaces, even before the matrix has sustained noticeable damage, and as such it does not depict correctly the resistance of a given material to cavitation erosion. This may be seen on the curve of the A+B/D/E microstructure on Figure 17; its mass loss is somewhat higher in the beginning but is phased out after t = 60 min, ending up with only the third highest values after 4h – an outcome which was expected according to former studies at Scania. Comparisons are, therefore, more reliably made from analyses of these curves after the initial graphite flake-off and damage.
incubation have ended, corresponding to 30 minutes of testing, and this is how the results shall be presented, such as in Figure 18. Early-stage data is more relevant for understanding mechanisms, whose discussion shall be postponed for now.

**Figure 18 – Relative cumulative mass loss for different microstructures after 30 min of testing time.**

Linear fits to the above curves have been omitted, but reach correlation coefficients of about 0.99. A summary of the cumulative mass loss is plotted in Figure 19, taking only the final data from the above chart. The relative resistance of each microstructure is easily seen:

**Figure 19 – Summarized results for the relative resistance of several microstructures to cavitation erosion.**
The mass losses registered for each time interval also provide useful information and are directly related to the corresponding cavitation rates, such as in Figure 20:

![Relative Cavitation Rate to Graphite Class](image)

**Figure 20 - Comparison of relative cavitation rates of different microstructures.**

Samples whose graphite flakes are distributed in a mixture of A- and B-type classes, as summarized in Figure 11, labeled ‘A+B’, are the least resistant to cavitation; of the irons with pearlitic matrix, those with only A-type graphite are the most resistant. The best overall performance, however, was of the material with bainitic matrix.

Analysis of the data suggests that the B-type graphite is the main source of vulnerability to cavitation among the considered microstructures; samples with the highest occurrence of B-type graphite have mass losses up to three times higher than those of the A-type and bainitic ones. The difference is large enough to suggest that it is not so much that the A-type is desirable or beneficial, but that the B-type is deleterious.

Micrographs using confocal and scanning electron microscopy at a 200x magnification were produced for the samples after test completion (4h) and some are displayed below in Figure 21. They correspond to the least (A+B) and most resistant (A) graphite classes, and the most resistant of all microstructures (bainitic matrix) was also included. In the contour confocal micrographs, the brighter regions are undamaged, original surface, and the streaks come from their grinding in sandpaper prior to rig testing; the dark areas are pits and cracks. The SEM images showcase pit morphology and depth.
The damage is clearly more severe on the A+B microstructure, considering both pit area and pit depth; pits are also more connected to each other and many wide cracks may be seen. On the A-class graphite distribution, which is significantly more resistant to cavitation, pits are generally smaller and more shallow, and only a few large pits may be seen; cracks are also evident. Finally, on the bainitic sample, pits are more evenly sized and less connected to each other, and cracks are not so easily spotted.
4.2 Coolant Composition

A similar analysis was carried out for the coolant composition tests and the results are displayed below in Figure 22. The test times were shortened from 4h to 2.5h because no significant change in the data trends was observed after 2.5h.

![Figure 22 - Summarized results for the relative damage caused by several coolants.](image)

Tap water and 35%-mixture without inhibitors are much more aggressive liquids, with cavitation rates an order of magnitude higher than those of the other coolants. For better visualization, their data was excluded from the following plots and a comparison between the other, more viable, coolants becomes easier, as shown in Figure 23:

![Figure 23 – Enlarged view of Figure 22, showing the results for the three least aggressive coolants.](image)
Damage rates are about 20% higher for the 35% ready-mix coolant compared to the 50% ready-mix, and about 30% higher for the 50% ready-mix compared to the 50+, which has stronger inhibitors.

Electron micrographs for the samples exposed to different coolants were also produced after test completion, again at a 200x magnification; displayed in Figure 25 are images from secondary (left) and backscattered (right) electrons detection, the former indicating topography (darker for deeper areas) and the latter highlighting elemental differences (darker hues for lighter elements, i.e. carbon, and voids/cracks).

Starting with tap water, the surface looks almost completely eroded and irregular (as seen in the SE image), with very sparse spots of the preserved original surface (more evident in the BSE image); this is also quite true for the 35* series, but to smaller extents.

\[ \text{Figure 24 - Secondary electron (left) and backscattered electron (right) images of cavitated surfaces exposed to liquids without inhibitors after 2.5h of testing. SEM, 200x.} \]

A significant qualitative change is observed starting from the 35% ready-mix images, in which a much larger fraction of the original surface is still visible. Accordingly, the surface exposed
to the 50+ coolant is smoother and shows smaller, more shallow and more spread-out pits and other milder features.

Figure 25 - Secondary electron (left) and backscattered electron (right) images of cavitated surfaces exposed to different coolants with inhibitors after 2.5h of testing. SEM, 200x.

Cavitation erosion decreases with glycol concentration, as expected from literature and former work at Scania, and with the presence of cavitation inhibitors; the stronger inhibitor has also proved indeed more potent in these experiments.
4.3 Coolant Temperature

The results for the coolant temperature tests are plotted in Figure 26 and Figure 27:

![Figure 26 - Summarized results for the relative damage occurring at different coolant temperatures.](image)

Test samples lost approximately 29% more mass at 76°C, and 25% less mass at 90°C, compared to the reference temperature of 82°C.

The cavitation rate decreases as the coolant temperature increases between 76°C and 90°C, up to a factor of about 2 when comparing the rates at 76°C and 90°C, Figure 27:

![Figure 27 - Comparison of relative cavitation rates of different coolant temperatures.](image)

It should be stressed that this result is particular to the 35% Ready-mix coolant; the temperature of maximum aggressiveness may change with the liquid’s composition.
4.4 Surface Roughness

Considering only the aggregate mass loss after 2.5 hours of testing, rougher surfaces suffered approximately 21% more damage, as shown in Figure 28:

![Effect of Surface Finish, 2.5h](image)

*Figure 28 – Summary of relative accumulated mass loss of samples ground in 600-grit and 80-grit sandpaper.*

This particular result, however, cannot be taken as an unequivocal indication that rougher surfaces are more vulnerable to cavitation erosion. Figure 29 shows the relative cavitation rates for both types of surface texture; the curves cross over between 60 and 90 minutes. The pattern of constant mass loss after 30 minutes of testing does not hold for the samples ground in 80-grit paper, therefore no conclusions may be drawn from the present data. More experiments are needed to clarify the influence of surface texture.

![Relative Cavitation Rate to Different Surface Textures](image)

*Figure 29 - Comparison of relative cavitation rates of different surface finishes.*
4.5 Surface Evolution

A sequence of images at several stages of pitting, displayed below in Figure 30, was produced using confocal microscopy at a 200x magnification to give an overview of the progression of the surface damage to a sample under standard conditions.

![Figure 30 - Evolution of cavitation damage on a grey cast iron surface with A+B/D/E graphite distribution exposed to a 35%-Ready Mix at 82°C. CM, contour, 200x.](image-url)
Cavitation erosion on grey cast iron surfaces may be described with the following series of events:

- graphite flake removal and plastic deformation of the matrix (incubation period);
- nucleation of cracks on (former) graphite flake tips and on plastically deformed sites on the matrix; formation of small, deep pits in grooves, scratches or graphite veins;
- crack propagation;
- cracks meet other cracks and pits and locally fragilize the material. End of incubation period;
- material removal when enough cracks have joined at a certain area or volume, leaving behind large pits and holes;
- crack formation and propagation continue and are favored by existing pits and rough edges; cracks create new pits, enlarge the existing ones and connect them; tunnels between pits are formed.

Matrix deformation and pitting may be seen on the image corresponding to 1 min test time in Figure 30-b, and has also been observed with the aid of the SEM, Figure 31. These features have not been observed in untested samples.

Figure 31 - SEM image of a cavitated surface after 1 minute of testing, magnified at 1000x. Already some graphite flakes have been chipped off.
The most easily found features related to cavitation at this stage are pits with exposed graphite and little damage to the surrounding matrix, as seen in Figure 32.

![Figure 32 - Enlarged view of a chipped graphite flake. SEM, 4200x.](image)

A confocal image of a similar event is displayed below, Figure 33. The more resistant matrix is still largely unaffected, but some yet shallow pitting has begun on a few flake tips:

![Figure 33 - Onset of pitting at flake tips after 1 minute of testing. CM, contour, 1000x.](image)

Another recurring, though less frequent, feature found is shown in Figure 34. Elemental analysis has shown no composition discrepancies with the matrix, and confocal microscopy has not indicated significant height differences with the surrounding undamaged material. It
is thus believed that this is a site in which plastic deformation has just begun, however there is not enough information to associate any deformation mechanism to it yet.

![Figure 34 - Enlarged view of a crater-like feature found in surfaces after 1 min of testing. Possibly a site of mild plastic deformation. SEM, 4200x.](image)

The following, Figure 35, is a pit formed in the matrix, away from any graphite flakes. Its rounded, slightly elevated borders and depressed center hint at direct erosive action from the liquid.

![Figure 35 - Enlarged view of an early-stage pit formed in the matrix. The surrounding rings are likely to have resulted from shockwaves following bubble implosions. SEM, 4200x.](image)

Topological measurements made using confocal microscopy show the depth profiles of these features, such as in Figure 36:
Nucleation and propagation of cracks at flake tips and pits has also been observed in samples analyzed after 30 minutes (Figure 30-c) and indicated with arrows on the enlarged image below, taken at 1000x magnification, Figure 37:
Deep pits along a scratch or a flake have also been found, Figure 38:

Stress concentration at graphite flake tips, crack tips and plastically deformed sites in the matrix favors crack propagation and pitting of the matrix ensues, as shown on Figure 39. No
graphite is present in the surface; the cracks seen will go on to coalesce and remove even more material.

Figure 39 - Cavitation pits growing in the pearlitic matrix after 30 minutes of testing. CM, contour, 1000x.

Past this point, pits also start to expand and coalesce; the mass loss rates increase up to a certain value and from there remain constant throughout the experiment; this means a linear growth in the accumulated mass loss values very evident for times larger than 1h of testing.

As the damage becomes more widespread, distinctive features such as the ones described so far become clouded by the coarseness of the eroded area, and corresponding microscopy at magnifications higher than 200x has not provided further relevant insight.

What is seen, then, at magnifications of 200x and lower, is a collection of holes and pits growing at the expense of the matrix as time passes, as seen in images d, e and f of Figure 30.

At 1.5h of testing, there are a few large pits and many small ones, and several not fully developed cracks and graphite flake voids are seen. The latter two are not easily seen in the last image, corresponding to the full 4h of testing, in which the pits have a more even size distribution.

A possible connection between the observations made with the aid of microscopy and the mass loss behavior of the samples shall be presented in the following Discussion section.
5 Discussion

5.1 Microscopy and Characterization of Surfaces

Elemental analyses were performed on the SEM for the pits and their surroundings at different magnifications – namely, 1000x and 4200x – and little to no signs of corrosion products or oxidation were found, as would otherwise be evidenced by the presence of oxygen-characteristic peaks in the acquired spectra. Only iron, carbon and, on rare occasions, other trace elements such as Si, Al, Cr and Ca were detected (these are, however, part of the alloys’ compositions and most likely have not come from the coolant). An oxidized sample was also analyzed for comparison, and the elemental spectra of its oxide spots did include oxygen peaks, showing that the other samples were not oxidized.

Topological measurements of untested samples on the CM showed that graphite flakes have a slightly positive height relative to the basal (matrix) plane, whereas cavitated samples (at any test time) had negative heights on corresponding positions, indicating that the graphite flakes had been removed, at least partly, during the experiments.

Round pits of early stages of cavitation, such as the one from Figure 35, are distinctively deep, and its borders project slightly upward. The small pits found along grooves and voids of Figure 38 are, in comparison, much deeper and their borders are on level with the adjacent material.

5.2 Cavitation Rig and Mass Loss Experiments

During the ultrasonic rig experiments, a few observations were made which may be taken as additional evidence of the general damage sequence hypothesized in the Results section (and which shall be revised later on). The coolant becomes smoky after about one hour of testing, and after 1 to 1.5 hour of testing, very fine aggregates can be seen retained by the magnetic stirring bar and oriented parallel to its magnetic field lines; both events hint toward the removal of magnetic α-iron from the surface, but no specific chemical analyses were carried out on the aggregates, nor on the liquid. Changes in the chemical composition of used coolants may be used to understand the action of inhibitors.

No mass loss was detected from brushing and rinsing the test samples.

As per the scope of the project, the combined effects of two or more variables have not been investigated. Some effects may have a very discernible impact at certain conditions and
become indistinguishable in different settings; therefore the test conditions should be
controlled and specified, and comparisons should be made with care.

The accumulated mass became strongly linear after 1h and so remained afterwards, for all
samples and variables, as was observed from linear fits of the corresponding data points in
the plots. It should be noted that linear fitting is only one of many possible numerical
approximations to the collected data; for example, a second-degree polynomial fit also
achieves correlation coefficients very close to unity; this is, in part, due to the mass losses
being very small (on the order of $10^{-4}$ to $10^{-3}$) fractions of the samples’ total mass. This is,
however, a relevant result because it agrees directly with the predictions and observations
found in the associated literature, namely in Haosheng et. al. [20] and Beregovenko et. al. [8].

These authors also discuss an exponential-like behavior of the mass loss in the beginning of
the experiments, for several steel grades, for times of about 15 minutes or less, and attribute
to it the incubation stage which, as reported in the Literature Study section, involves plastic
deformation of the matrix without much material removal.

The early-stage data obtained for this work, however, shows a seemingly different behavior;
for all cast iron samples, mass loss increases rapidly until about 3 minutes, after which it
becomes very small; it then increases steadily until 30 minutes, after which it remains rather
constant until the completion of the experiment.

This trend may be simply the combination of two ‘exponential + linear’ responses of two
distinct constituents – namely, graphite and pearlite. Graphite, being much softer and easily
sheared, has a very short incubation period – shorter than 1 minute – and is readily removed
from the surface, reaching the linear stages long before the pearlitic matrix has sustained
appreciable damage. Pearlite (and bainite), harder and more resistant, must absorb some
energy in plastic deformation and crack propagation before being eroded, the result of this
being a longer incubation period. Deformation and removal of the matrix is accelerated by the
appearance of the small, deep pits observed along grooves (recall Figure 38) and graphite flake
voids, and by stress concentration on flake tips.

For $t \leq 30$min, the measured mass losses should reflect, in order: surface graphite removal;
underlying graphite removal & flake tip pitting; end of incubation stage in matrix.
After about 30 minutes, the matrix reaches a stage of constant mass loss. Figure 37 and Figure 39 have shown coalesced cracks, and this is the most likely mechanism of chipping. Material removal leaves behind a pit, but it consumes the cracks which caused it; when the matrix reaches the linear regime, crack density may have reached a steady state, the removal of cracks by pitting being balanced out by the formation of cracks induced by cavitation energy input.

The lower cavitation rates of the incubation period may also be explained with a similar reasoning; undamaged material has a much lower crack density and average length, and cracks must nucleate and grow prior to coalescing. The end of the incubation stage happens when cracks are numerous and long enough so that any appreciable propagation will result in material removal – but the regions surrounding a pit are already weakened enough to easily nucleate new cracks.

A simplified illustration of this, considering a homogeneous, ductile matrix, is shown below for early stages (top) with little material damage and for late stages (bottom) of significant pitting. Blue arrows indicate cracks.

![Figure 40 - Schematic illustration of cracking mechanisms and corresponding mass loss curves for incubation (top) and developed (bottom) stages of cavitation of a homogenous, ductile matrix.](image-url)
5.3 Environmental Protection

The investigations performed and the conclusions obtained from this study have a greater goal of extending the service life of cylinder liners and of heavy-duty diesel engines in general. Improving service life entails a lower consumption of raw materials and delays the maintenance, replacement and disposal of parts, a result of which is the amelioration of associated environmental impacts.

The testing method used, an ultrasonic rig operating in a laboratory, provides important qualitative results using a fraction of the time and the resources (electricity, coolant mixtures etc) of an engine test, which may run for weeks whilst continuously demanding fuels, much like the actual vehicle they are utilized in. Therefore not only the results of this study, but also its experimental apparatus, contributes to a reduction in environmental damage of the activities of Scania. It is not expected that the rig experiments replace engine tests completely, but that they help in deciding which variables and factors should be prioritized in these tests and which can be eliminated altogether.
6 Conclusion

The resistance to cavitation damage of grey cast irons used in cylinder liners of heavy-duty engines was investigated. An ultrasonic rig was used to vibrate material samples under varying engine coolant compositions and temperatures, surface roughness and graphite flake distribution in the microstructure. Erosion rates were calculated by recording the mass lost by test samples; following the experiments, Scanning Electron Microscopy and Confocal Microscopy were used to analyze pits and crack morphology.

It has been found that:

- Cavitation rates decrease with increasing concentration of glycol, and with the use of cavitation inhibitors. The effect of inhibitors is more significant than that of glycol concentration.
- Cavitation rates on different microstructures decrease on this order: A+B, B/D/E, A+B/D/E, A, bainitic. Among these, the presence of B-type class is the main source of vulnerability.
- Cavitation rates decrease with increasing temperature between 76 °C and 90 °C.
- The effects of surface texture on cavitation rates were inconclusive and should be studied more closely in the future.
- The parameters with the highest impact on cavitation resistance, within the investigated ranges, are: presence of cavitation inhibitors in the coolant, glycol concentration in the coolant and presence of B-type graphite clusters on the microstructure.
- Ultrasound rig testing is useful method for differentiating design and operational parameters involved in cavitation.

The effects of coolant composition, coolant temperature and graphite distribution agree qualitatively with literature studies and former experiments performed at Scania.

A mechanism of the evolution of surface damage has also been proposed consisting of graphite removal, pitting on graphite flake tips, crack propagation and pit expansion.
7 Future Work

- More experiments may be performed with the specific aim of better understanding the incubation stage of cavitation erosion and associated damage mechanisms. Analyses may include pit size and depth, roughness and hardness measurements. Mathematical modelling of cavitation rates and stages may be of use if associated to a framework for comparing damage between laboratory- and field-tested samples.
- Chemical analyses of coolants after use may provide insight on the extent of inhibitor consumption and of possible protection mechanisms.
- Chemical analyses of high depth sensitivity may provide insight on surface deposits and oxide layers of surfaces subjected to cavitation.
- Experiments may be shortened from 4 hours to 2.5 or 2 hours when faster, qualitative results are needed.
- A larger number of experiments should be run to improve statistical confidence in the results.
- Interactions between variables can be investigated by varying two or more parameters in the same experiment. This shall add to the existing knowledge about cavitation damage and aid decisions in design and product selection.
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9 References


