Brodogradnja/Shipbuilding/Open access Volume 70 Number 2, 2019

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http://dx.doi.org/10.21278/brod70208 ISSN 0007-215X
eISSN 1845-5859

PISTON RING MATERIAL IN A TWO-STROKE ENGINE WHICH SUSTAINS WEAR DUE TO CATALYST FINES

UDC 621.436.1:62-242:620.178.16
Original scientific paper

Summary

This research paper discusses preventive protection of the marine engine against abrasive effects of the catalyst fines in fuel. The relevant facts were gathered while analysing the performance of the slow-speed Wärtsilä RTA engine on an Aframax tanker. The analysis comprised fuel properties, regular and extraordinary examinations of the engine, including the control and replacement of piston rings and the measurement of the liner wear rate. The research particularly focused on the top compression ring as it withstands highest loads and fastest wear. On the other side, the research involved a chemical analysis of the piston rings with the purpose of establishing their chemical properties, structure, coating thickness and micro-hardness. In addition to a number of preventive measures that can be taken on board before injecting the fuel into the combustion chamber, the selection of a piston ring's material quality affects its wear rate to a large extent. The wear rate also depends on the catalyst fines in fuel. In practice, the piston ring of GGV type proved to be resistant to abrasive wear and its chemical properties were established through laboratory material testing.

Key words: *piston ring materials; abrasive wear; catalyst fines; marine diesel engine*

1. Introduction

Large marine engines use heavy fuel oil due to its low price. As a complex compound of various hydrocarbons, crude oil has a high content of carbons (83-87%). In petroleum refining, the process of cracking is used to break up heavy hydrocarbon molecules into lighter molecules containing less carbon atoms. The most efficient process is achieved by means of catalysts, i.e. solid compounds containing aluminium or silicon. These are very hard fines that cause abrasion of the engine liners and piston rings. The amount of catalytic fines in fuels is reduced in refineries and their content in fuel is prescribed.

There are a number of harmful effects of catalyst fines in the engine cylinders. Abrasion occurs on the cylinder liner walls if the impurities are thicker than the lubricating oil film. Impurities may get stuck between the piston ring and its groove and they may cut into a liner wall as well. Repair costs may be high and cause the ship's delay. For example, according to the report made on board a tanker [1], the repair costs that included spare parts, manhours, engagement of the technical superintendent and additional expenses excluding the charter-related losses, amounted to 500,000 $. Another example [2] of damage caused by catalytic fines refers to the cost of replacing the liner on the nine-liner two-stroke main engine, amounting to 420,000 $. The overall costs arising from the same cause in Sulzer 8RTA84T and MAN B&W 6S50MC engines are presented in Table 1 as the third example.

Table 1. Costs resulting from damage of marine engines due to catalyst fines [3]

Ship type	Tonnage	Engine type	Bore	Stroke	Cost
Tanker	302,986 DWT	Sulzer 8RTA84T	840 mm	3150 mm	900,000 $
Bulk carrier	54,000 DWT	MAN B&W 6S50MC-C	500 mm	2000 mm	1,500,000 $

According to the reports presented in the relevant literature [4], the rate of wear of the piston rings and the engine liners of the MAN 6S80ME-C was two times higher than expected, thus increasing maintenance and other related costs by 183,000 $. It should be noted that, due to harmful effects of catalytic fines, it may take just 100 running hours or slightly more than 4 days to reach the upper limit of the wear on all liners in a two-stroke slow-speed engine [5].

As the new international regulations on reduction of maximum allowed sulphur content in fuel are coming into force in 2020, thereby increasing the need for fuel cracking, it is assumed that the amount of fine catalyst residues acting as fuel impurities will be even larger.

Catalytic fines are easily capable of scratching and becoming embedded in steel surfaces. The abrasive property of the aluminium-silicon (Al+Si) fines results from their extreme hardness, measuring up to 8 on the Mohs scale (where diamond is 10) [6]. Marine residual fuels (RM) must meet ISO standard 8217: 2017 (Table 2). According to this standard, fuels that are commonly used in marine engines are allowed to contain maximum 60 mg/kg of catalytic impurities [7]. Engine makers prescribe the allowed maximum of catalytic impurities of 15 mg/kg before injecting the fuel into the engine cylinder.

Refineries are capable of producing fuels with 15 mg/kg of catalytic impurities, but this would make the fuel price considerably higher, so this is not practiced in real life [8].

Table 2. Limits of fuel contents to meet ISO standard 8217: 2017 [9]

Limits	Parameters (units)	RMA 10	RMB 30	RMD 80	RME 180	RMG 180 380 500 700	RMK 380 500 700
Max.	*Aluminium + Silicon (mg/kg)*	25	40		50	60	

Along with the efficient analyses of marine fuels, there are a number of other procedures and guidelines aimed at reducing fuel impurities, e.g. fuel bunker cleaning, equipment maintenance, crew training, high position of fuel intake from the tank, efficient fuel separation and filtering [10,6]. In addition, some companies perform fuel sampling immediately before and after the fuel separator in order to monitor its efficiency: according to the need or recommendation, another separator is cut in or the engine is switched from heavy fuel oil to diesel oil, as a prevention against the increased maintenance costs due to the wear of the piston rings and cylinder liners.

Another essential requirement for the long durability of the liners and rings is the efficient lubricating system, with the use of adequate lube oil and maintaining the engine loads within permitted limits. The purposes of lubricants are to protect against wear, reduce friction, separate moving parts, transfer heat (from combustion chamber and piston to liner) and power, reduce noise and vibration, seal for gases, prevent corrosion and carry away contaminants and debris [11]. To increase efficiency [12] to reduce pollution [13] and exhaust emissions [14] in marine two-stroke low-speed diesel engines, it is very important that, among other numerous engine components, that piston rings and cylinder liners have high-quality coatings, i.e. surfaces that generate ultra-low wear and friction between surfaces [15].

The ways of prolonging the durability of the liners and rings, i.e. the causes of shortening their life cycles, depends considerably on the material the piston rings are made of and its ability to withstand the effect of impurities that may appear in the combustion chamber through the scavenge air or fuel.

This paper presents an analysis of the effects of the piston ring material on its wear rate. Given the fact that the chemical composition is not known because the manufacturer cannot present its exact chemical composition and properties, laboratory testing of the ring materials was carried out for the purpose of the research.

2. Piston rings and their function

Piston rings in internal combustion engines have multiple functions. Apart from separating the combustion chamber from the scavenge air space, they ensure the heat transfer from the piston to the cylinder liner and prevent excessive oil to enter the combustion chamber from the crankcase. It is essential for the rings to ensure uniform film of lubricating oil across the cylinder walls. Piston rings include compression and oil control rings, their configuration being presented in Figure 1.

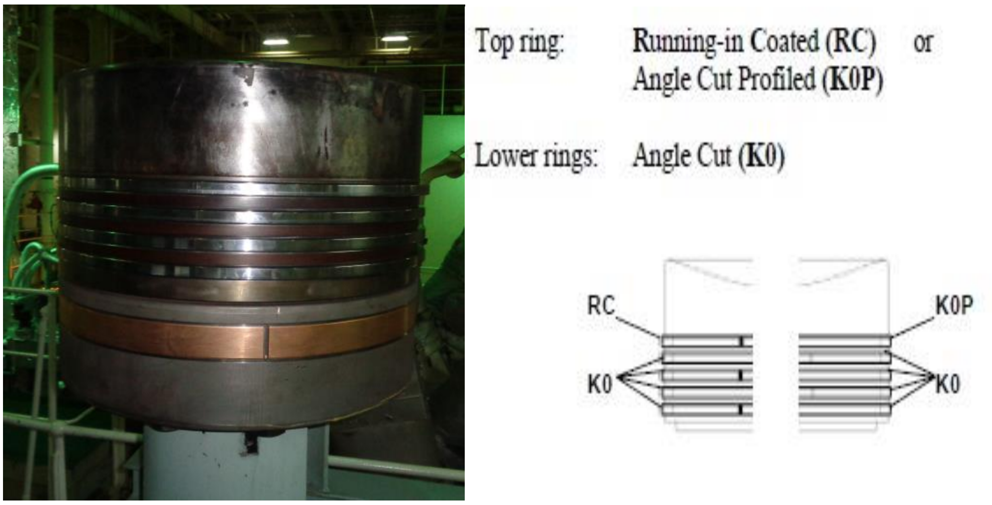


Figure 1. Design and configuration of the piston rings

2.1 Analysis of the recommended configuration of the piston rings and operation parameters in Wärtsilä RTA 58 marine engine

In this type of engine, the recommended configuration features the top compression piston ring of *Running in coated* (RC) type or the *Angle cut profiled* (K0P) type, its height being 16 mm [16,17]. The lower rings – not being that exposed to high pressure and temperature during the process of combustion – are of the K0 type and *Angle cut* type.

Operation parameters during the process of testing and the data referring to lubricating oil are presented in Tables 3 and 4. The six-cylinder RTA 58 engine used heavy fuel oil (HFO) type IFO350 whose viscosity at 50°C was 352.6 cSt, density 973.5 kg/m^3 at 15ºC, sulphur content 1.8% and amount of catalytic impurities 20 mg/kg [18].

Table 3. Information on the tested marine engine [19].

Maker	Engine type	Nominal / Service power (kW)	Nominal / Service speed (min^{-1})	Mean indicated pressure (bar)	Stroke (mm)
Wärtsilä	6RTA58-T	12000/10800	103 (92)	18.3	2416

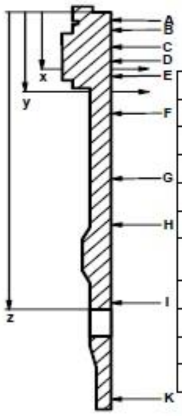
Table 4. Information on lubricating oil [19].

Cylinder oil	Consumption of cylinder oil (g/kWh)	Crankcase oil	Consumption of crankcase oil (l/day)
Talusia Universal/HR70	1.4	Elf Atlanta Marine 3005	100

During this engine type testing, the analysis involved two types of piston rings, specifically two types of the top rings that bear highest loads, with the code marks G17 SCP1RC16 and GGV SCP1CC16. There were engine problems that occurred while using the G17 RC piston ring due to the piston ring fracture (Figure 2) and the cylinder liner wear (Figure 3). The piston rings were replaced with the new chromium-plated rings of GGV CC type. The liner was replaced as well.

Figure 2. Damaged piston rings

Figure 3 presents the results of the worn-out cylinder liner testing. The liner's cross-section, with the reference points A – L as points of obligatory measurement, is on the left side. The inserted table shows the distance of the measurement points from the top of the liner. The second and third columns feature the measured values (in yellow colour), whereas the deviations from the boundary values are entered into the last two columns. The measurements revealed that the high rate of wear was observed only at the upper part of the liner, as shown in the diagram on the right side, which conforms to the manufacturer's guidelines in the manual WinGD for G17 SCP1RC16 and GGV SCP1CC16 piston rings [20].



	Distance from top	F / A	P / S	Wear [mm] F / A	Wear [mm] P / S
A	150	0.55	0.62	0	0
B	193	2.00	1.80	1.450	1.180
C	238	3.38	3.94	2.830	3.320
D	285	4.55	4.50	4.000	3.880
E	660	3.05	2.70	2.500	2.080
F	878	2.75	2.22	2.200	1.600
G	1424	0.50	0.51	-0.050	- 0.110
H	1970				
I	2275				
K	2760				
L					
Max. wear:		longitudinal:		mm/1000h	
		transverse:		mm/1000h	

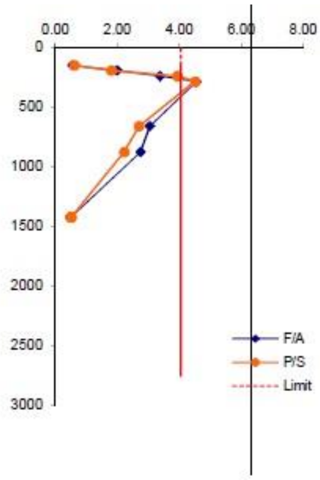


Figure 3. Measured wear of the cylinder liner

A suspicion of whether sudden liner and piston ring wear are caused by cat fines can be examined by taking a replica test of the liner surface (done together with Wartsila Switzerland Ltd. Technical services). The surface where was done replica test is shown in Figure 4 and microscope result in Figure 5.

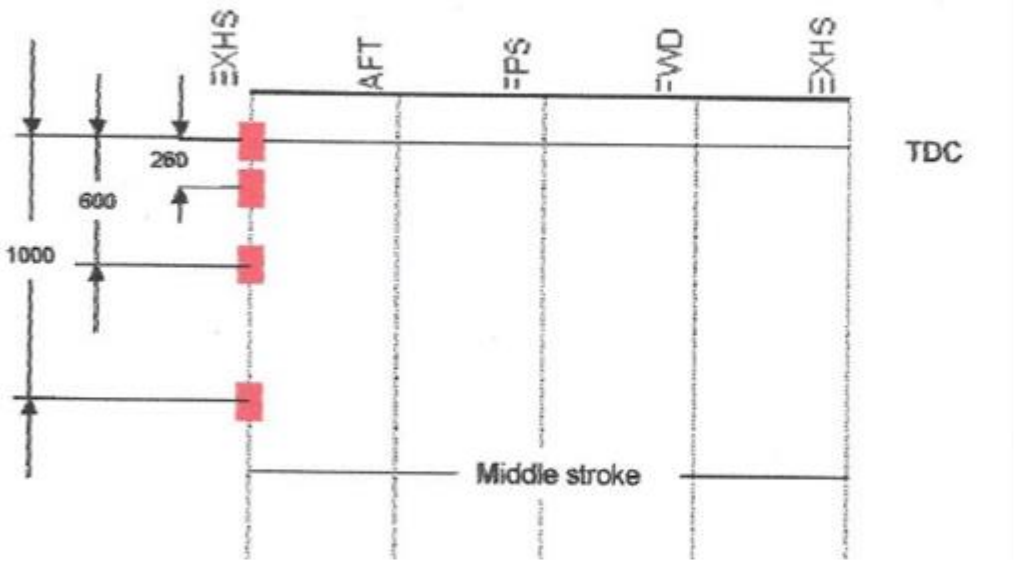
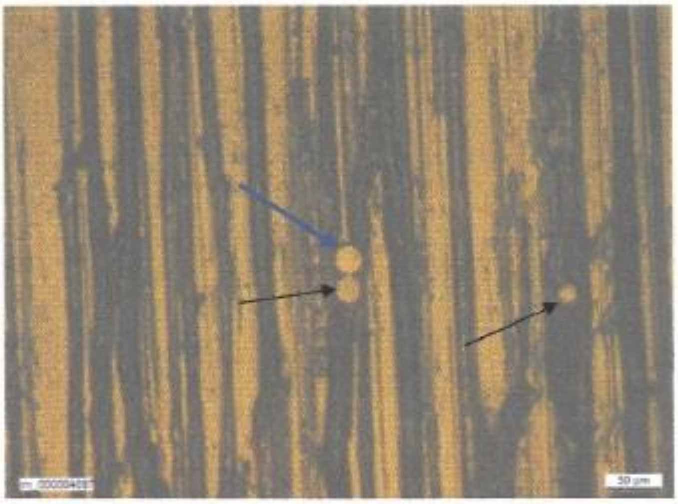


Figure 4. Replica location done at the cylinder liner

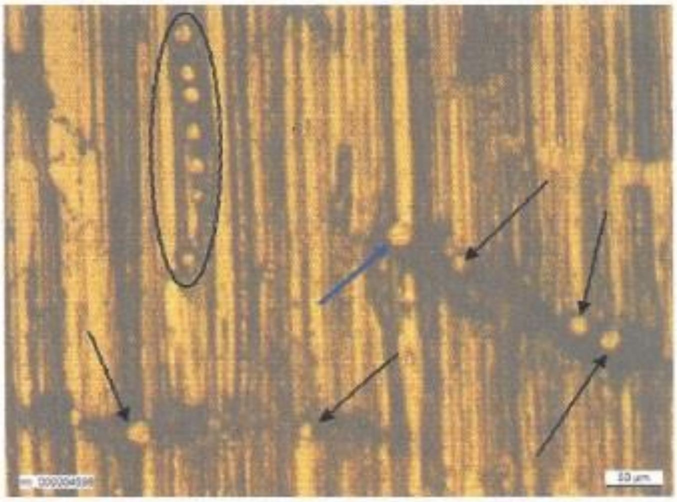


Comment:
Abrasive wear, broken Hard Phase, embedded catfines - biggest visible r = 14 µm.

Scale: 200:1

Unit: 4

Position: EXH-600 mm from TDC



Comment:
Abrasive wear, damaged Hard Phase, embedded catfines - biggest visible r = 10 µm.

Scale: 200:1

Unit: 4

Position: EXH-600 mm from TDC

Figure 5. Catfines in the cylinder liner examined under microscope and comments

3. Methodology applied in analysing the chemical composition of the base and layers of the piston rings

The analysis of the chemical composition of the piston rings' base and layers included the methods shown in Figure 6. The samples were gathered by the author during the onboard service in the capacity of the chief engineer.

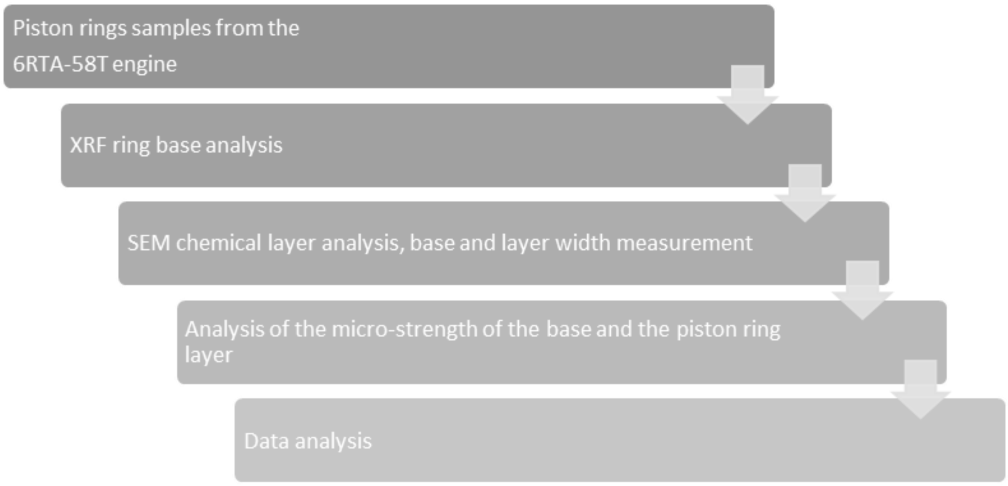


Figure 6. Methodology of analysing the piston ring samples

3.1 Chemical analysis of the base and layer material of the rings GGV and G17 by using XRF and SEM techniques

Modern piston rings commonly consist of the base and the layer of coating that is added to improve the ring's performance. In order to determine their chemical composition, the X-ray fluorescence spectrometry (XRF) analysis was applied. This is a non-destructive technique that has been widely used in scanning electron microscopy instrumentation for elemental analysis of specimens. Obtained results are presented in Table 5.

Table 5. Analysis of the chemical composition of samples by means of XRF technique [21]

Name of specimen	Percentage content of elements								
	% C-carbon	% Si-silicon	% Mn-manganese	% S-sulphur	% Cr-chromium	% Ni-nickel	% Cu-copper	% Mo-molybdenum	% V-vanadium
Top ring GGV	3.29	2.0	0.80	0.005	0.11	<0.1	0.80	0.48	
Top ring G17	2.84	1.3	0.80	0.005	0.14	0.40	1.0	0.69	0.17

Iron (ferrous) makes the base of the analysed samples. The data presented in Table 5 show that the specimen of the GGV piston ring has the higher content of carbon (3.29%) and silicon (2%), while there is much less nickel (<0.1%), copper (0.8%) and molybdenum (0.48%). Hence, according to its chemical composition, the base of the piston ring is grey iron. It is actually cast iron whose structure lies in the metal matrix and consists of graphite lamellae. The improvement of wear-resistant properties of a cast iron piston ring-cylinder liner pair of an internal combustion engine can exert a significant influence on maintaining service properties, extending service life, and reducing the repair costs [22,23,24].

Grey iron has found a wide application primarily owing to the affordable property-value ratio. It has a few particular properties that arise from the presence and form of the graphite lamellae within its structure. It can be easily cast, even into complicated forms, and it has good machinability properties. Grey iron has exceptional features for the application in the conditions requiring the smothering vibrations or heat shocks that are present while the engine is running. As the strength and conductivity of this material are limited, they can be improved by adequate heat treatment. This process reduces the size of the lamellae and defines the metal structure.

Parameters which have to be considered for ranking material of the piston ring and cylinder liner in conditions during combustion are: material microstructure, surface topography, the lubricant and the different operating conditions ranging from boundary to hydrodynamic lubrication [25].

When comparing the measured results with the effects of alloyed elements on the properties of steel [26], it can be noted that the specimen Top ring GGV has increased effects of strength, hardness and elasticity when the high contents of carbon and silicon are present. The analysis of the base material’s chemical composition indicates that both samples have almost identical composition, with a difference in the percentage content of carbon (C) and silicon (Si); however, both samples fall into the category of grey iron, as can be noted in Figure 7, points A and B.

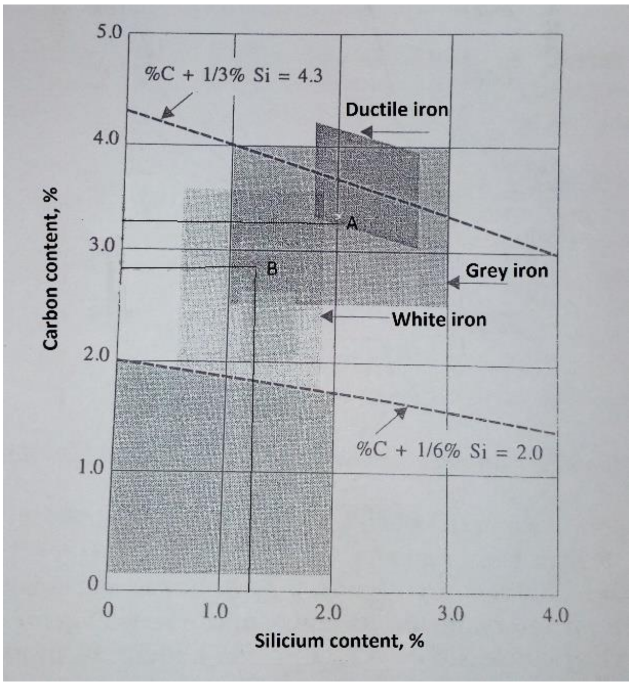


Figure 7. Content of carbon and silicon in specific types of cast iron- Maurer chart [27]

By using high definition SEM (*scanning electron microscope*), type FEI Sirion 400 NC, the image is obtained by regular movement of the beam of electrons across the surface of the sample. This tool is ideal for examining the structure of materials. When complemented by an energetic dispersive spectrometer EDS Oxford INCA 350, it is possible to establish the chemical composition of the sample material on the selected and observed micro surface that is presented as *spectrum* in the obtained images.

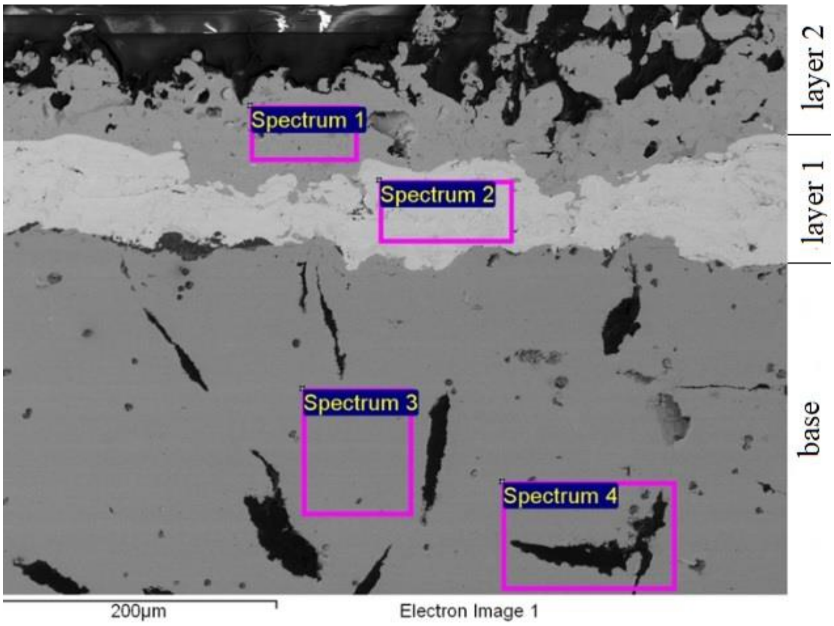


Figure 8. Analysis of elements in the observed areas of the piston ring in layers Spectrum 1 and 2 and base materials Spectrum 3 and 4 [21]

Figure 8 shows the areas selected for chemical analysis, where it is taken into account to select all visible coatings in the piston ring layer. The produced results, presented in Table 6, indicate that the piston ring base is essentially made of iron (96.4% and 68.2%). The neighbouring layer is mostly molybdenum (96%) while the last layer coating the ring is mostly nickel (92.3%). Hence this is the so-called nickel-plated ring.

Table 6. Percentage chemical content of the layer of the top ring G17 [21]

Spectrum	In stats.	C	O	Si	Fe	Ni	Mo	Total
Spectrum 1	Yes	5.73	1.93			92.33		100.00
Spectrum 2	Yes		3.94				96.06	100.00
Spectrum 3	Yes	2.04		1.51	96.45			100.00
Spectrum 4	Yes	30.86		0.93	68.21			100.00

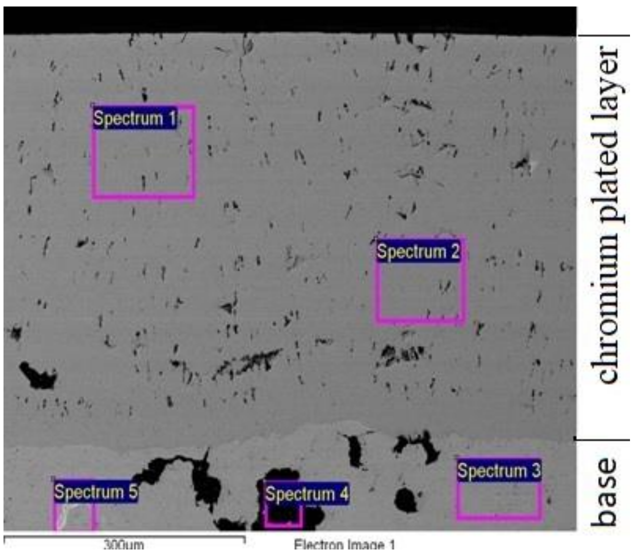


Figure 9. Polished section of composite coating Cr-Al2O3 by piston ring producer Goetz [21]

Figure 9 shows the enlarged areas selected for the analysis of the GGV ring. The data presented in Table 7 indicate that there is only one chromium layer as the ring's plating (96.4% and 98.9%), whereas the base of this ring is also essentially made of iron (96.4% and 81.2%). Therefore, this ring can be called chromium-plated. The small particles are aluminia particles (O_2=1,95 Table 7). Between the galvanic deposited Cr-layer and the cast iron surface is a Cu interlayer.

Table 7. Percentage chemical content of the layer of the Top ring GGV [21]

Spectrum	In stats.	C	O	Si	P	Cr	Fe	Mo	Total
Spectrum 1	Yes	1.67	1.95			96.38			100.00
Spectrum 2	Yes	1.12				98.88			100.00
Spectrum 3	Yes	1.87		1.71			96.42		100.00
Spectrum 4	Yes	82.24	8.74				9.02		100.00
Spectrum 5	Yes	3.72		1.49	1.12		81.22	12.46	100.00

3.2 Analysis of the thickness of the piston ring layer

This segment of the research focuses on the layers of the GGV and G17 piston rings. When observing the plating of the top ring GGV, it can be noticed that this ring has a thick layer of chromium amounting to 400 μm, while the micro-structure of the base material features simple graphites (Figure 10).

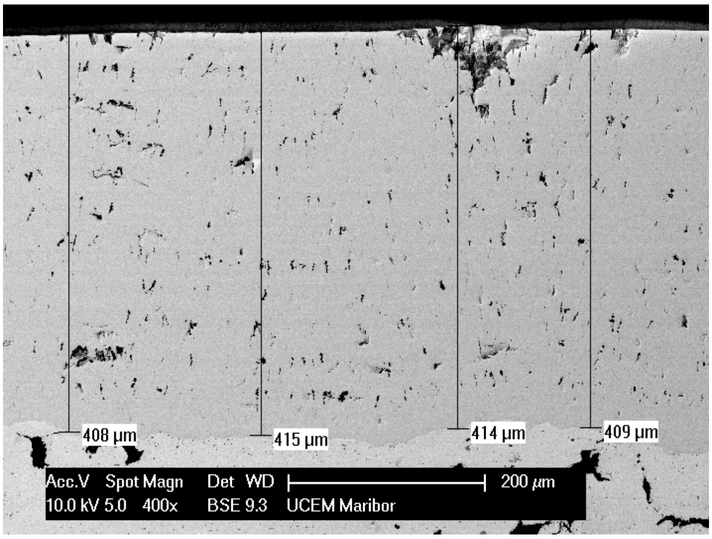


Figure 10. Thickness of the Cr-Al2O3 coating on the Top ring GGV examined by electronic microscope (SEM) [21]

In contrast to the GGV ring, the G17 Top ring has a completely different structure of the surface layer. In Figures 11 and 12, two different platings can be noticed, having the maximum thickness of 95.6 μm and 110 μm respectively. The prominent feature of this ring is the overall thickness of its layer (205 μm, both platings). It can be noted that this value is double in the chromium-plated ring.

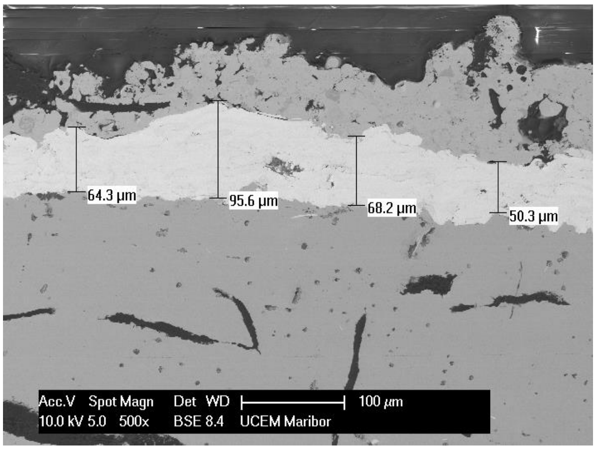


Figure 11. Thickness of the plating in the lower layer of the G17 ring

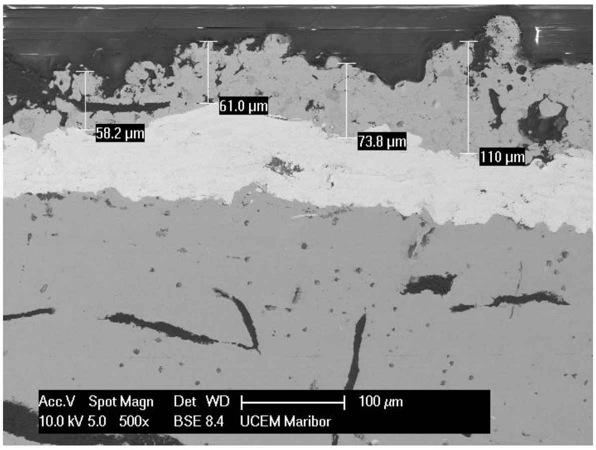


Figure 12. Thickness of the plating in the upper layer of the G17 ring

3.3 Analysis of the micro-hardness of the piston ring base and layers

Measurements of the hardness of both specimens were performed with the aid of Zwick 3212 tester for Vickers hardness (HV0.2). As the sample of the Top ring G17 has rough surface, micro-hardness of the transversal section of coating (Figure 13) could not be measured. Attempts were made by applying a lower load of a HV 0.2, i.e. 1.961 N and a higher load of HV 5, i.e. 49.03 N in order to obtain the pyramid indentation, but the indentation was not visible through the electronic microscope due to the specimen's rough surface. Glazing the surface would wear out the coating, so that the measurement would not be satisfactory.

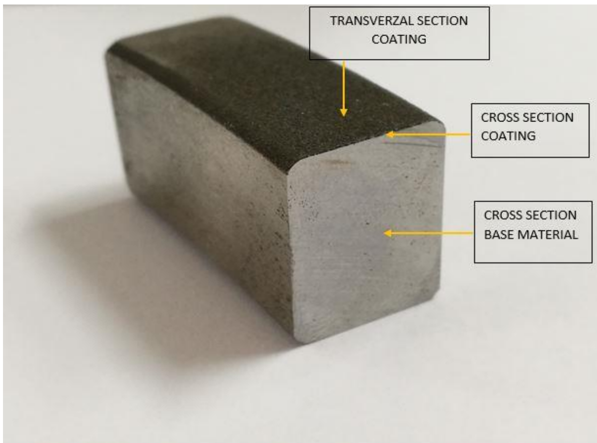


Figure 13. Points of measurement for Vickers micro-hardness [21]

The points of the micro-hardness measurement are shown in Figure 13. The procedure established that the Top ring G17 had a greater average hardness of the base material, amounting to 306.5 (HV 0.2). However, its hardness at the cross section coating is only 385.5 (HV 0.2), which indicates that the surface layer of the ring is just a bit harder than its base material.

On the other hand, the chromium-plated Top ring GGV has 217% greater hardness of the coating, amounting to 838.17 (HV 0.2), as presented in Table 8. This is essential in terms of abrasive wearing because the surface layer (coating) makes a physical contact with the cylinder liner, lube oil film and catalyst fines.

Table 8. Micro-hardness HV 0.2 of both piston top rings, G17 and GGV [21]

MICRO-HARDNESS HV 0.2					
Top ring G17			Top ring GGV		
	cross section			cross section	
	coating	base material	coating	coating	base material
	337	353	909	802	418
	409	306	672	857	285
	401	325	557	825	274
	494	265	505	753	209
	278	289	937	909	274
	394	301	753	883	206
Average	**385.5**	**306.5**	**722.17**	**838.17**	**277.67**
Min.	278	265	505	753	206
Max.	494	353	937	909	418
STDEV	72.86	30.21	178.31	56.77	76.97

Traditionally, it is considered that wear resistance of the coatings just depends on the hardness but nevertheless, elastic modulus also plays a vital contribution in the wear characteristics. [28]. The modulus of elasticity of the G17 piston ring is 110-140 GPa [29], whereas the modulus of elasticity at the complex chromium alloyed grey iron is 154-196 GPa according to DIN 1695 [27].

4. Suggested procedures for further research and improvement of quality of the piston rings on the market

For the purpose of further analysis, it would be beneficial to compare the measured values of the worn-out piston rings with the equivalent data obtained from the rings that are not worn-out, prior to examining the cylinder liner. When taking samples from the cylinder liner, the latter becomes damaged and therefore useless. As there is typically only one spare liner on board, sampling becomes difficult. Furthermore, performing a complex simulation of exposing both types of piston rings to abrasion would be helpful in future analyses, providing that the prevailing operating conditions in the main engine can be simulated. One of the specific features of such a simulation would be the use of both types of fuel, i.e. marine diesel oil (MDO) and heavy fuel oil (HFO), as the durability of the piston rings is considerably affected by the quality of used fuel. The expected durability of the piston ring corresponds to the time between overhaul and is much longer when the engine runs on cleaner MDO, as shown in Table 9.

Table 9. Durability of the diesel engine parts with regard to the quality of used fuel [30]

Engine parts	Time between overhaul (h)		Expected durability (h)	
Quality of fuel	HFO	MDO	HFO	MDO
- piston rings	12-20,000	20-24,000	12-20,000	20-24,000
- cylinder liner	12-20,000	20-24,000	60-100,000	60-100,000

Apart from the different quality of fuel used by the engine in operation, the simulation of abrasion effects will also depend on the use of adequate lubricating oils having different recommended base number (TBN). Simulation and accurate recommendations referring to the above parameters are essential as today's diagnostic parameters indicate problems only when the piston ring wear is greater than 75%.

Companies should introduce the "cat fine risk surveys", i.e. reports including the state of the engine fuel system components, analysis of the specific features of the marine power system, classification of risks based on the long-term experience of the crew members and superintendents, and recommendations on optimal protection of the engine against damage caused by catalyst fines. This sort of report would be also suitable for education and training of the engineer and their crew who would be able to take better care of the engine. Besides, if damages caused by catalyst fines do occur, the well-trained engineer will be of vital importance for gathering evidence and producing damage reports that can be subsequently used in the process of damage compensation or possible international arbitration. A continued understanding of the piston-cylinder-contact assembly only helps engineers, scientists and any other stakeholder to improve on the piston ring and cylinder liner interaction [31].

One of the critical measures for improving the piston ring quality on the market should be the marking of rings in line with the Technical Code requirements, in order to enable the control quality and reduce the possibility of using poor quality or poorly reconditioned rings [30]. It is necessary to enforce standardisation that would bind all ring manufacturers in terms of the quality of material and production, but also in terms of providing the specification of materials the rings are made of.

5. Conclusion

Catalyst fines are always found in heavy fuel oil. Their presence has to be carefully monitored (used Veritas Petroleum Services BV - VPS laboratory for fuel testing) and their amount should be reduced to a minimum. After settling in fuel tanks, separation and filtering, catalytic fines enter the combustion chamber through the fuel injector. Being highly abrasive, they can create huge problems, damage to the main engine and, consequently, high direct and indirect costs.

This research focused on the analysis of the running in coated (RC) and chromium coated (CC) top compression rings in Wärtsilä RTA two-stroke slow-speed diesel engine on an Aframax tanker. Examination and measurement carried out on board enabled the insights into the state of the piston rings, while the fuel analysis revealed the amount of impurities. During the tests the RC piston rings were damaged or broken, while the wear of the cylinder liner was faster. The analyses of chemical composition established that the grey iron CC ring had a coating of chromium whose thickness amounted to around 400μm, whereas its base material contained more carbon and silicon than the RC piston ring. The latter had a coating consisting of two layers containing nickel and molybdenum, having the overall thickness of 200μm. In addition, the modulus of elasticity of the chromium-plated grey iron ring was higher than in the RC ring. Micro-hardness measurement revealed that the CC ring had a surface layer that was 217% harder than the surface layer of the RC ring.

The results obtained by the analyses and measurements indicated that the chromium-plated piston ring had higher hardness and was more efficient in withstanding abrasive effects of catalytic fines, while the higher modulus of elasticity of its base material enabled a better resistance to breaking.

Acknowledgement

All laboratory measurements in this research were performed at the Faculty of Mechanical Engineering of the University of Maribor (Fakulteta za strojništvo Univerze v Mariboru) through the bilateral project **BI-ME/18-20-024 (2019-2020)**. Practical testing of the samples required for the analysis was performed on board an Aframax tanker. We would like to thank our Slovenian colleagues for the use of laboratory facilities and consultations.

REFERENCES

[1] Wright, A.: *Marine Fuel Quality 2015 An Objective Review (FOBAS).* Lloyd's Register EMEA, February 2017 Southampton.

[2] Ford, M.C.: *A master's guide to: Using fuel oil onboard ships*.pdf file, Standard P&I Club, February 2012 London. https://www.standard-club.com/media/24163/AMastersGuidetoUsingFuelOilOnboardships.pdf (accessed: 22.11.2018)

[3] Breamar, J. H.: *JHC Report - Marine Engine Damage due to Catalytic Fines in Fuel* (Part I-Technical Analysis), Joint Hull committee, September 2013. https://iumi.com/images/documents/JHC_Catfines_Pack.pdf (accessed: 08.9.2018)

[4] https://marine.man-es.com/ (accesed:15/10/2018)

[5] DNV: *Engine worn out in less than 100 hours by catalytic fines*. Det Norske Veritas, Classification Support. December 2010.

[6] https://www.alfalaval.com (accessed: 15/01/2019)

[7] Zamiatina, N.*: Comparative overview of marine fuel quality on diesel engine operation*, 9th International Scientific Conference Transbaltica 2015. https://doi.org/10.1016/j.proeng.2016.01.055

[8] International Council on Combustion Engines, CIMAC Guideline ISO 8217:2017 - FAQ 03-2017.

[9] http://www.dan-bunkering.com (accessed: 12.10.2018)

[10] International Council on Combustion Engines: *Onboard Fuel Oil Cleaning, the ever-neglected process – How to restrain increasing cat-fine damages in two-stroke marine engines*, Paper No. 51 CIMAC Congress, 2013 Shanghai. http://www.nanonord.dk/media/1134/onboard-fuel-oil-journal.pdf (accessed: 05.11.2018)

[11] Trivedi, H.K. and Bhatt, D.B.: *Effect of lubricants on the friction of cylinder liner and piston ring materials in a reciprocating bench test*, Faculty of Mechanical Engineering, Belgrade. FME Transactions (2019) 47, 23-28, https://doi.org/10.5937/fmet1901023T

[12] Bukovac, O., Medica, V. and Mrzljak, V.: *Steady state performances analysis of modern marine two-stroke low speed diesel engine using mlp neural network model*, Internatinal journal Brodogradnja (Shipbuilding) Vol. 67, No. 4, pp. 81-90, 2015

[13] Nikolic, D., Marstijepovic, N., Cvrk., S. Gagic, R. and Filipovic, I.: *Evaluation of pollutant emissions from two-stroke marine diesel engine fueled with biodiesel produced from various waste oils and diesel blends*, Internatinal journal Brodogradnja (Shipbuilding) 2017, https://doi.org/10.21278/brod67406

[14] Lalic, B., Radica, G. and Racic, N.: *Analysis of exhaust gas emission in the marine two-stroke slow-speed diesel engine*, Internatinal journal Brodogradnja (Shipbuilding) 2016, https://doi.org/10.21278/brod67302

[15] Singh, S.K., Chattopadhyaya, S., Pramanik, A., Kumar, S. and Basak, A.K.: *Effect of lubrication on the wear behaviour of CrN coating deposited by PVD process*, Int. J. Surface Science and Engineering (2019), Vol. 13, No. 1, pp.60–78, doi: 10.1504/IJSURFSE.2019.10019189

[16] Lalić, B. Komar, I. Dobrota, Đ.: *Structural modifications for improving the tribological properties of the cylinder unit in two-stroke slow speed marine diesel engines*, Transactions on Maritime Science (ToMS), Vol. 01, No. 02, 2012. https://doi.org/10.7225/toms.v01.n02.004

[17] Sulzer Wärtsilä, Spare parts notice Piston ring standard, SPN/RTA 001 03/12/2002. pdf. file.

[18] Fuel analysis by Veritas Petroleum Services BV, 2015. pdf. file.

[19] Wärtsilä Service report done at vessel, 28/03/2015. pdf. file.

[20] Winterthur Gas & Diesel Ltd. *Guide for judging condition of relevant piston-running components: liners, pistons and piston rings.* Version 3.0 , WinGD,June 2018 pdf. file.

https://www.wingd.com/en/documents/engine-operation/wingd-guide-for-judging-condition-of-relevant-piston-running-components-v3-june-2018.pdf/ (accessed: 15.10.2018)

[21] Results of the measurements performed at the University of Maribor, the Faculty of Mechanical Engineering (Fakulteta za strojništvo Univerze v Mariboru), through the bilateral project BI-ME/18-20-024 (2019-2020).

[22] Singh, S.K., Chattopadhyaya, S., Pramanik, A. and Kumar, S.: *Wear behavior of chromium nitride coating in dry condition at lower sliding velocity and load*, International journal of advanced manufacturing techology (2017), https://doi.org/10.1007/s00170-017-0796-x

[23] Bakowski, H.: *Wear mechanism of spheroidal cast iron piston ring-aluminium matrix composite cylinder liner contact*, Archives of metallufrgy and materials, vol 63. (2018) https://doi: 10.24425/118965

[24] Shen, Y., Yu, B., Lv, Y. and Li, B.: *Comparison of Heavy-Duty Scuffing Behavior between Chromium-Based Ceramic Composite and Nickel-Chromium-Molybdenum-Coated Ring Sliding against Cast Iron Liner under Starvation*, Materials 2017, 10, 1176; https://doi:10.3390/ma10101176

[25] Wopelka, T., Cihak-Bayr, U., Lenauer, C., Ditrói, F., Takács, S., Sequard-Base, J. and Jech, M.: *Wear of different material pairings for the cylinder liner – piston ring contact*, Industrial Lubrication and Tribolog (2018) y, Vol.70 Issue: 4, pp.687-699, https://doi.org/10.1108/ILT-07-2017-0218

[26] Kraut, B.: *Strojarski priručnik*, deveto izdanje, Tehnička knjiga 1988. Zagreb.

[27] Radulović, B., Perović, B., Mišović M.: *Metalni materijali I*, Metalurško tehnološki-fakultet, Univerzitet Crne Gore, 2001 Podgorica.

[28] Uddin, G.M., Kamran, M.S., Ahmad, J, Ghufran, M., Asim,M., Zafar,M.Q., Irfan,M., Waseem,B., Khan,A.A. Jawad,M.,Zeid,I and Kamarthi,S.:*Comparative Experimental Study of Tribo-Mechanical Performance of Low-Temperature PVD Based TiN Coated PRCL Systems for Diesel Engine*, Hindawi Advances in Tribology,Volume 2018, Article ID 9437815, 12 pages https://doi.org/10.1155/2018/9437815

[29] http://www.federalmogul.com (accessed: 05.10.2018)

[30] Kuiken, K.: *Diesel II engines for ship propulsion and power plants*, Target Global Energy Training ,2008 The Netherlands.

[31] Rozario, A., Baumann, C. and Shah, R.: *The Influence of a Piston Ring Coating on the Wear and Friction Generated during Linear Oscillation*, Lubricants 2019, 7, 8; https://doi.org/10.3390/lubricants7010008

Submitted: 21.03.2019.
Accepted: 13.05.2019.

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