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ENDOSCOPIC IMAGE PROCESSING AND ANALYSIS OF PISTONS' SERVICE FAILURES OF MARINE DIESEL ENGINES

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Abstract

The paper deals with diagnostic issues concerning endoscopic examinations of working spaces within marine diesel engines. In the beginning, endoscopy apparatus being on laboratory equipment of the Department of Ship Power Plants of Gdansk University of Technology has been characterized. The endoscopy considerations have been focused on theoretical bases of a digital image processing and especially - on the "Shadow" measurement method.

Second part of the paper is devoted to operation damages of medium- and high speed engines that have been physically analyzed in many aspects of origin as well as places and character of their occurrence. There have been also considered possibilities of direct and indirect identification of the well known and recognizable operational unserviceable states of the elements of a piston's constructional system by means of endoscopic methods.

The results of the author's own research as well as the accessible results of diagnostic research of the self ignition engines applied in automotive and railway transport have explained and proved the most probable reasons for the piston failures' occurrence.

Keywords*: technical diagnostics, endoscopic investigation, marine diesel engine, pistons' failures.*

1. INTRODUCTION

A visual examination of surfaces, creating piston engines' working spaces, by means of specialist view-finders called endoscopies represents at present almost the basic diagnostic method for those marine diesel engines which are not equipped with indicator valves in standard [4]. During investigations a surface structure of the constructional material is visible like through magnifying glass, which makes a detection, recognition and also quantitative assessment of the occurring damages and material defects possible. It especially concerns such defects that usually do not generate the observable alterations of diagnostic parameters' values. The endoscopic examination of the engine being stopped (laid off) permits the user to estimate immediately a degree of the constructional elements' waste and fouling. The pistons of cylinder sets represent vulnerable engines elements that, on one hand, are characterized with the significant frequency of damages occurrence and, on the other hand - with high diagnostic susceptibility within the range of the endoscopic method application.

2. ENDOSCOPIC IMAGE PROCESSING

A diagnostic base of the Ship Power Plants' Department of the Gdansk University of Technology is equipped with the EVEREST digital videoendoscope of XLG3 type that has got a special measuring head enabling a qualitative and quantitative identification of the detected surface defects by means of so called the "Shadow" method - Fig. 1.

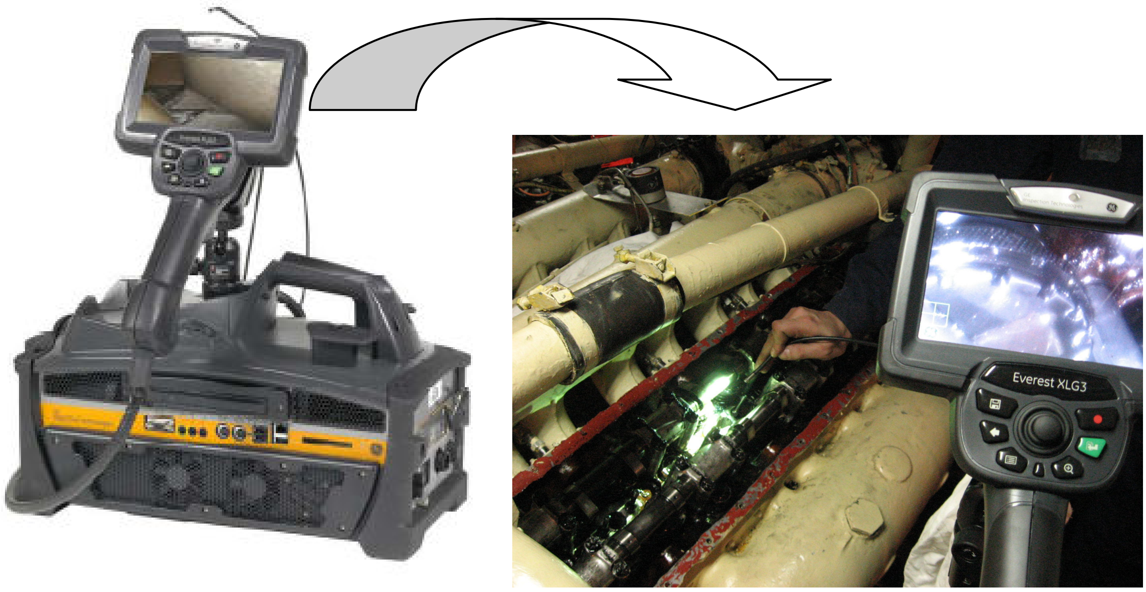


Fig. 1. Engine's examination by means of EVEREST XLG3 digital measuring videoendoscope [12]

It stands for a milestone of the endoscopy evaluation because eliminates the largest weakness of the traditionally applied optical boroscopes and fiberoscopes, namely, a dependence of the observed object's dimension on a distance between the speculum probe's lens and studied surface. In such a situation there is a lack of appropriate reference patterns that could be used in order to qualify real dimensions of the detected surface defects. In traditional, optical approach to such an issue the comparative method is applied by the calibrated measuring profiles being put on speculum probe's ending [2,4]. However, this is the very inconvenient method that requires a large experience and manual skills of the operator. Moreover, it creates essential threats for the studied engine's reliability, because measuring profiles might be accidentally broken off during manipulating the endoscope optics. Even the smallest part the profile left in an engine's working space excludes its further usage until the left element is removed (but this is not an easy operation and always possible to work out in operation conditions).

The "Shadow" digital image processing method, basing on theory of triangulation[1], enables measuring the seen paintings in such way, to give the quasi three-dimensionality impression, with its depth, the massiveness and the mutual distribution. The ending of videoendoscope's speculum head is equipped with the special optics generating the shadow of a characteristic shape (the most often the shape of a straight line).inside the light stream (like

[1] W. Snellius was the creator of triangulation theory (1615). The measurement method consists in division of the measuring area into adjacent rectangular triangles and marks on the plane the co-ordinates of points by means of application of the trigonometrical functions.

the projector) on surface of the studied element. The projection of the shadow holds at a known angle of the speculum head position, in relation to the observed surface and a known angle of the observation sector. The shadow generated in the vicinity of a detected defect is then located and recorded by a CCD camera which is placed inside an assembly head. The nearer to the observed surface is the speculum head the nearer from the left side of monitor screen is the shadow line. Because, a position of the shadow generating the painting on the matrix of LCD monitor screen is well-known, a magnification of the painting can be simply calculated. Moreover, the linear dimension of distance among individual pixels, and then the real dimensions of detected surface defects can be consequently evaluated.

Advertisement brochures and guides published by the EVEREST Company, as the patent's owner, as well as publications of the present article's Author contain a detailed characterization of the "Shadow" method measurement technology [4,5,12].

Within the "Shadow" method the following measurement options are accessible.

- length,
- multi-segment length, length broken (circuit),
- distance from point to base straight line
- depth (salience),
- area of surface (the area).

In every metrological option the measurement exactness is defined. When the operator possesses high skillfulness it reaches even 95-98% [12,14]. The maximum approach to studied surface of the speculum head represents the most essential factor of a high measurement exactness (the line of shadow moves towards the left side as the speculum head gets closer to the surface) as well as maintaining perpendicular to this surface the position of speculum head (the line of shadow runs perpendicularly to the basis of a monitor screen).

The possibility of taking the immediate decision in case of doubts regarding proper interpretation (unambiguous distinction) of detected surface defects being effective with decrease or accumulation of material is the very essential advantage of the "Shadow" method. Such diagnostic problems step out during the evaluation process of the working spaces' technical shape of combustion engines: piston or turbine.

Often, because of optical and light impressions the usual dirt on internal surfaces of the air and exhaust passages, in figure of mineral settlings or the products of burning the fuel (the carbon deposit), is interpreted as the corrosive or erosive decrements of the constructional material. The depression of surface (its larger distance from the speculum head) is associated with the shadow line's break and shift towards the right side of the screen, and its salience (its larger approaching to speculum head) - the shadow line's refraction and shift towards the left side of the screen.

3. PHYSICS OF THE OPERATION FAILURES

The piston, as a movable bottom of an engine combustion chamber, represents the constructional element that is liable to suffer the largest mechanical and thermal loads. A working medium pressure, achieving 20 MPa and temperature, up to 800 K make a great impact on the piston head's constructional material [10]. It might lead to significant deformations of the piston's shape as well as changes of mechanical properties of its. In the result of their further development serious primary failures of the piston usually occur. They inevitably drive to extensive secondary damages of the piston-crankshaft assembly and the engine as a whole.

In dependence on a place and character of the damages occurrence the piston's constructional form can be divided into elements as follows:

- piston head - cracks, plastic deformations, overheating and overburning,
- annular part - cracks, seizing, ring shelves' breaking off,
- leading part (bearing[2]) - corrosion, cracks, sizing,
- hub of the piston gudgeon pin - hub's cracks and seizing, cracks and chipping of the rings' grooves establishing the gudgeon pin.

However, taking into consideration the possibilities of the failures' direct endoscopic detection they are exclusively limited to the piston's head. Therefore, in order to explain possible reasons of the failures situated in the piston's other elements the piston has to be firstly dismantled from the engine because of the failures being identified (accessible by means of endoscopy) on the cylinder bearing surface (alternatively after disassembling a cylinder block).

Functioning disturbances of the engine's fuel and air fed system represent the most frequent reason of piston damages, particularly during the engine's start-up process. That kind of disturbances usually leads to the engine's knocking (detonating the fuel combustion process), which is characterized by the very large speed of flame spreading within the combustion chamber (even a dozen or so times greater than at the normal burning). The intensive growth of pressure and temperature pulsation of the working medium follows. Consequently, the growth of thermal and mechanical loads of the combustion chamber's elements, in peculiarity the piston, occurs [6]. In the result of increasing temperature gradients within the piston's constructional structure its cyclic deformations and growth of thermal tensions appear. They exceed considerably the value limits that correspond to the engine's steady states running (even twice) [3]. Moreover, the piston's internal surface, where the largest material accumulation takes place (a region of the hub of the piston gudgeon pin), represents the particularly vulnerable piston's region, from a thermal tension point of view sight [3,10]. The thermal tension of this piston head's region, in case of high-charged marine diesel engines (a mean effective pressure above 2 MPa), is able to achieve comparable values in relation to internal tensions from gas forces [10].

A considerable, local piston head's overheating, up to exceeding a plasticity border of the constructional material, causes its local upset. If a temperature growth of the piston's head is only temporary there could be also affected a temporary wearing down and even seizing the piston's crown in the cylinder bearing surface - Fig. 2a [4].

A low-cycle fatigue of the piston's head up to cracks' occurrence, connected with cyclic squeezing and spreading tensions of the constructional material represents a different consequence of this phenomenon - Fig. 2b. They result from cyclic, respectively: the material overheating and widening as well as its cooling down and shrinking, during the engine's work cycle realization.

If a temperature growth of the piston's head is so large that the engine's cooling system is not able to take over a warmth stream from the combustion chamber's constructional elements a stable growth of external dimensions of the piston's crown occurs. Consequently, lubricating conditions of the friction pair: piston-cylinder are altered. In such a situation, with regard on "favorable" conditions of appearing the second kind adhesive waste, a decay of the surface layer of the piston's constructional material (made of an aluminum alloy) takes place. Such a phenomenon consists in a local joining the frictional surface's tops of the piston and cylinder liner together as well as a tearing off the aluminum particles and in consequence - their smearing over the cylinder bearing surface - Fig. 2c. Often, a surface of the rolling areas does not encircle the whole circuit of the cylinder liner. It proves, at small rolling thickness, that only a short-lived excess of the flow temperature of the piston's crown happened. The rings, that work properly, take off the piston's material rolled on the cylinder surface after lowering

[2] It transfers a normal force on the cylinder bearing surface.

the piston head's temperature when the lubricating conditions get better. Unfortunately, it usually produces undesirable results - an intensive growth of the aluminum particles quantity in the engine's lube oil system - Fig. 2d.

The introduced course of the failure appearing is the most probable in a situation when the engine runs on idle or on partial loads. In that kind of conditions the engine's fuel fed system works in the especially adverse mode having a direct impact on a course of the combustion process in the engine's cylinders. According to obligatory principles of the marine engines operation exploitation as well as the producers' technological requirements the injection system's regulating parameters i.e.: a fuel dose of fuel and geometrical beginning of the pressing are adjusted to conditions of the nominal load [11].

However, an inequality of the injection pumps' dosage enlarges considerably on partial loads. It means that the fuel dosage delivered to some cylinders is much larger than the required, optimum one foreseen on the assigned, settled engine's load. In case of multi-cylinder engines such a situation even gets worsened because in some cylinders, despite having delivered the fuel, self-ignitions do not come into existence. Hence, a delivering the larger than required fuel dose, either in the result of the dosage inequality or in the result of a fuel gathering during fallen out self-ignitions, leads also to detonating fuel combustion along the above mentioned consequences[3].

Very often, a self-ignition's time decay takes place along with detonating fuel combustion. In case of shifting the fuel burning beyond TDC an intensive temperature's growth of all the combustion chamber elements occurs (particularly the piston). A transfer of the combustion process on the expansion stroke (work), at an incomplete and imperfect character of this process, produces undesirable results with a quantity enlargement of carbon deposits settled on the surfaces that restrict the combustion chamber. A thick layer of the carbon deposit on the piston's head (Fig. 2e), coming into existence particularly intensely during the engine work on partial loads while it is maladjustment, worsens significantly the warmth flow conditions and consequently drives to the piston head's overheating - Fig. 2f.

An insufficient cooling in the vicinity of the first packing ring represents another one reason of the piston's overheating. If the time among starting, coupling and full loading a marine engine is compliant the producer's requirements and the engine cooling system is patent and correctly functioning, the engine should be in a settled thermal state. It means that the cooling system should "keep up" with a warmth stream from the unit: piston-rings-cylinder liner (so called PRC unit).

However, in result of, for example, the excessive deposits of calcium carbonates ($CaCO_3$) and magnesium ($MgCO_3$), creating so called the boiler scale, which is formed in the engine's cooling spaces after a thermal splitting the hydrogen carbonate contained in the water, a total or local patency loss of the cooling system may occur. Additionally, an impact of excessive vibrations transferred on the engine's constructional elements from the vessels properell does not stay without meaning. The vibrations could intensify a process of tearing the boiler scale layers off from internal surfaces of the cooling channels, which choke the cooling medium's flow. An extensive character of piston damages, especially considerable decrements of the piston crown's material (through the high-temperature diffusion) testify about the long-lasting high temperatures' impact. It is also very essential a location of the largest piston damages that, in such cases, occur in direction of the normal force effect i.e. in natural direction of the carrying away heat stream. Extensive damages in this piston's region testify about losses of the possibility of the effective carrying away heat to the cylinder liner through the first sealing ring. In case of temporary engine's torque overload, a different waste image occurs - the

[3] A rings shelves' fracture often stands for an additional consequence of the detonating fuel combustion in engine's cylinders (between the first and the second packing ring) as well as mechanical damages witin the crank arrangement.

piston crown, at the correctly functioning injector, widens uniformly and the waste area on piston's surface is also proportionate on its whole circuit. Moreover, a whole phenomenon of the adhesive waste proceeds at the considerably lower temperature. In such a situation grooves and rollings both on the piston and cylinder bearing surface are clearly visible. However, because of injectors' disfunctioning e.g. in result of losses of the sprayer's tightness or its spraying holes patency, a chronic fuel burning along with piston's overheating is possible. Traces of the fuel after-burning occur on the piston head's surface (fig. 3a), and in the extreme case - even the constructional material's burn out until a total piston melting.

An incomplete fuel burning in engine's cylinders causes the intensity enlargement of the forming carbon deposits which are washed-off from the cylinder bearing surface with lube oil. However, a part of the carbon deposit, gathering in rings' grooves, creates a tight and hard deposable layer in which piston rings are successively bring to a standstill. They lose an ability to adhere springy to the cylinder bearing surface. Consequently, a combustion chamber loses its tightness what follows a blow-by of the hot exhaust into the crankcase along the cylinder bearing surface. Finally, an oil film burns that drives to the total piston rings' immobilization - fig. 3b. In such a situation the extensive seizures within a piston' leading part occur very quickly. There is also another reason of the piston rings' immobilization associated with the metallic particles' penetration into rings' grooves. They represent a product of the adhesive waste of a piston and cylinder bearing surface. Prime reasons of this phenomenon have been precisely described in an initial part of this paragraph.

The often happened damage of the piston's head is the result of direct strikes over its surface the valve heads, injector as well as broken out constructional elements which are placed in a bottom plate of the cylinder head. Usually, such damages do not eliminate the pistons from further operation, but under condition, that their character and dimensions are contained in borders of operation tolerances that are determined by the engine's constructors [11]. A presence of shallow dents on the surface of a piston's crown of which correspond to the valve heads' sizes and shape (fig. 3c), confirms piston strokes over the valves caused by a canceling clearance between the valves being open and piston head, while the piston is in TDC position after the scavenging stroke. Timing angle maladjustment or valve stem's hang-up in the valve guide might represent a prime reason of such strokes. Moreover the strokes often result from the excessive clearances in the assembly of crank-shaft, that occur e.g. in the result of an excessive waste of the piston pin's hub, bearing shells etc. There is also possible a further transfer of impact (shock) loads on other elements of the valve timing assembly: cams, lifter, valve rockers etc. which might also undergo extensive damages, representing a secondary consequence of the piston's strokes.

In selected pistons' solutions the special necks in the shape of valve heads are milled on the pistons' crowns, but they are considerably deeper. The necks aim to eliminate a possibility of mechanical damages of the valve stems (and their secondary consequences in the aspect of extensive cylinder assembly damages) in case of the valve timing maladjustment. However, it makes sense only if a neck's depth is larger than the valve lift.

Piston mechanical deformations represent its relatively often occurred damages. They are usually caused by the valve's part (the exhaust valve generally) e.g. a broken off valve's head, which has fallen into the combustion chamber - fig. 3d. During its operation the cylinder valve is forced to move along its spindle in the guide which undergoes irreversible friction wear. The process goes at high temperature of the spindle whose additional task is to absorb heat from the valve head. As a result an excessive increase of radial clearance is produced between the guide and spindle, which, in all the cases, leads to an undesirable skew of the valve especially, that it is loaded with transverse component from the pressure of the timing lever or cam. Consequently, a loss of cylinder tightness (compression pressure drop), gas eruption, returnable flows, lubricant leakage from the spindle – guide precision pair until an intensive wear of the entire valve unit is reached. The phenomenon may especially intensive develop in the case of supplying the engine with fuel oil of high sulphur content. The cases are known of completely burned-out valves as a subsequent result of extensive wear of the valve guide [8,10,11]. In the extreme case, cracking the valve spindle, its falling down into cylinder space and subsequent failures of the "piston-piston rings-cylinder" system, including piston cracking, can happen. An observable symptom of worn valve guides are smoked valve springs, that indicates a lack of tightness of the combustion chamber.

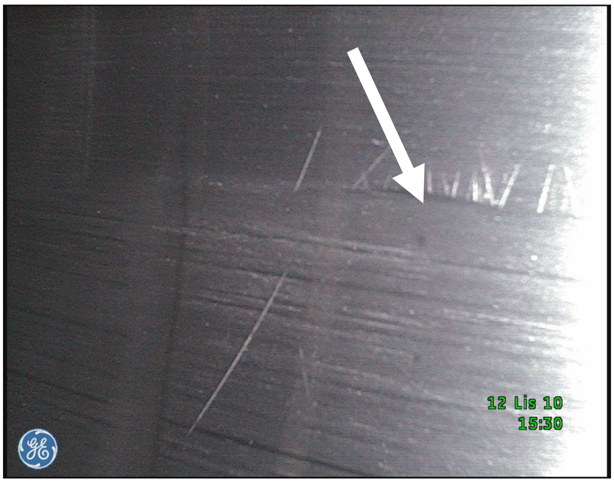
A presence of the punctual dent on the piston head, that is placed in an injector's axis (fig. 3e,f) testifies about the piston's mechanical strokes over the injector resulting from e.g. the elongated piston stroke (for some high- speed engines, a distance between the piston head and injector's ending at TDC is not more than 3-4 mm [11]). Such a situation might represent a consequence of excessive clearances in an assembly of crank-shaft or intensive wear and tear of bearing pans.

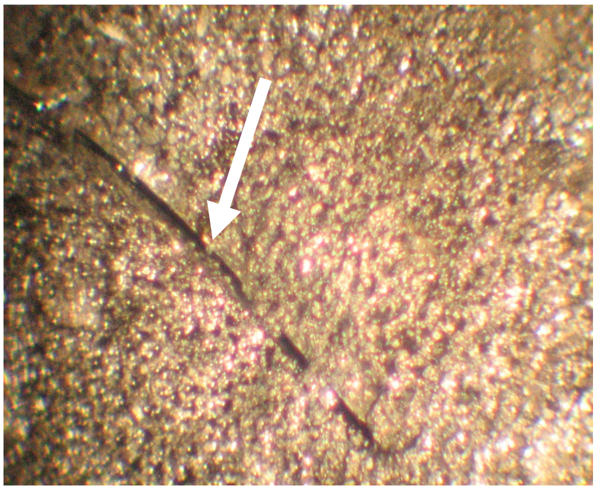
An excessive injector's lowering which is mounted in the head stands for different probable reason of this type dents' formation, caused by the inappropriate-chosen washer under the injector. It in such a situation was one should explain the prime causes of the dent's presence, and independently - the injector has to be definitely exchanged. Further operation in such state usually drives to cracks and even breaking-off the injector's ending. Moreover, an intensive fuel leakage to cylindrical spaces and thinning the lubricative oil with fuel might occur until to development of the extensive secondary damages in cylindrical sets, threatening with the engine's breakdown.

4. FINAL REMARKS AND CONCLUSIONS

Many material defects detection on the surfaces, which limit working spaces of an IC piston engine, by means of endoscopies represents one of the youngest methods in technical diagnostics. On the basis of a character and dimensions of identified damages it is possible to evaluate a technical state of not only directly accessible constructional elements of the engine's working spaces, but also, in indirect way, it is possible to create an opinion about a technical state of these engine's constructional elements, which are not directly accessible and which co-operate with working spaces [10,11,12]. For example, the diagnosis about technical state of piston's annular or leading part could be formulated in indirect way on the basis of endoscopic investigations of the cylinder bearing surface and a character of detected-on surface defects, even though there is no possibility of carrying out an direct endoscopic evaluation of these piston's regions [4,5,9].

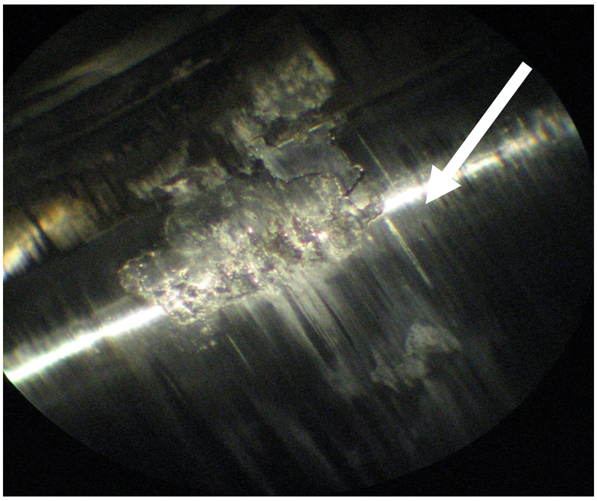
Within a characteristic of endoscope identified pistons' damages of marine diesel engines a lot of attention was devoted to medium- and high-speed engines that characterize a larger intensity of damages' occurrence of this constructional element in relation to slow-speed engines. In order to explain the most probable reasons of a piston damages' formation, the Author's own investigations were used as well as accessible results of diagnostic investigations of the SI engines applied in the road and rail transportation.

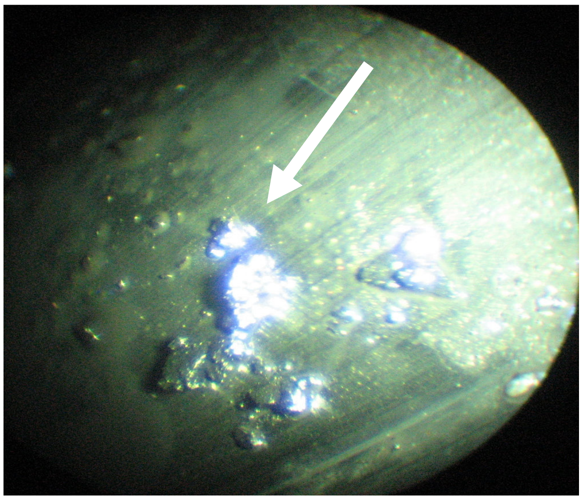




a) cylinder bearing surface - friction traces originated from the piston leading part

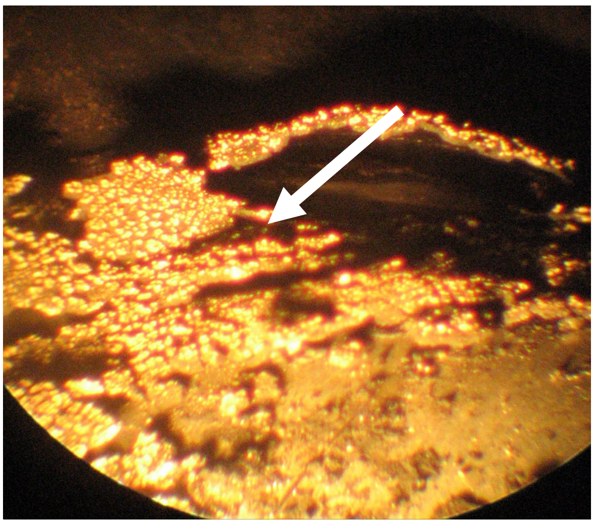
b) piston head – a crack fatigue

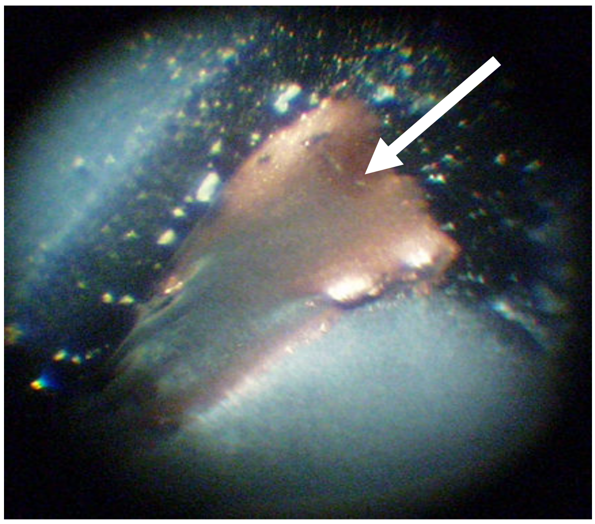




c) cylinder bearing surface – smearing traces of the piston material's layer (aluminum alloy)

d) cylinder bearing surface – metal fillings (aluminum alloy)

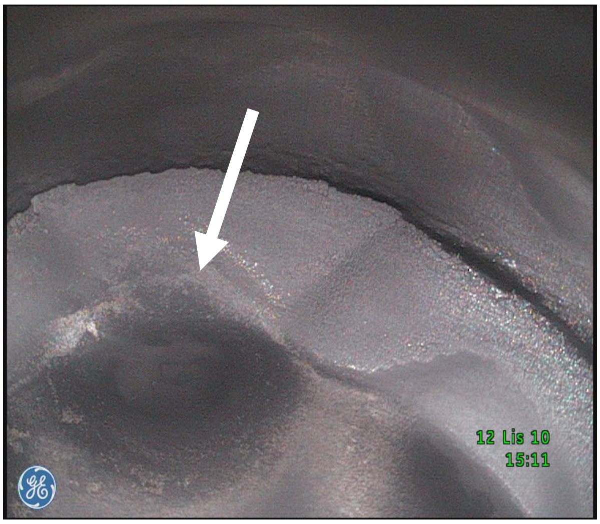




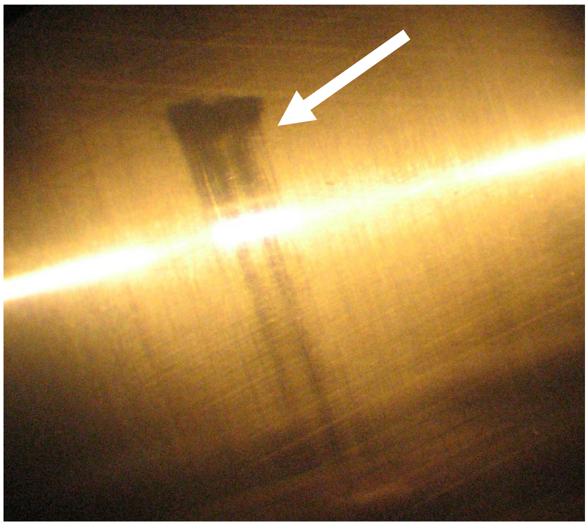
e) piston head – a thick layer of the carbon deposit

f) piston head – a local overheating of the constructional material

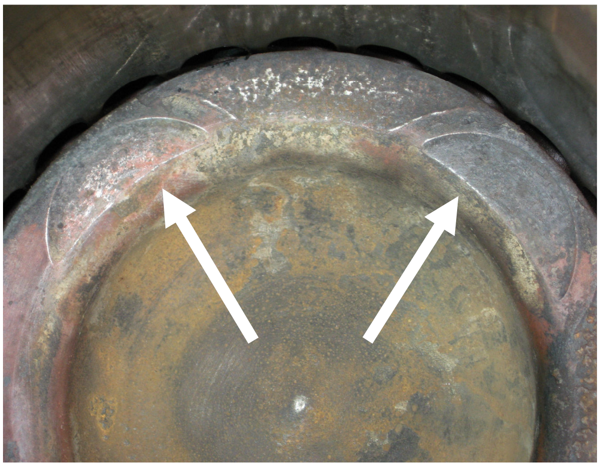
Fig. 2. Endoscopic image of marine engine pistons' damages and their consequences



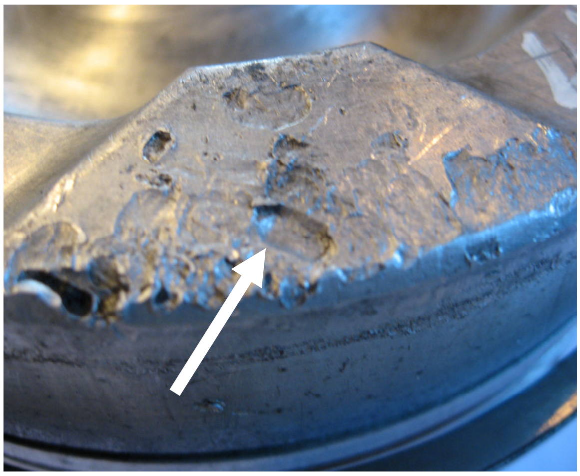
a) piston head – traces of the fuel after-burning



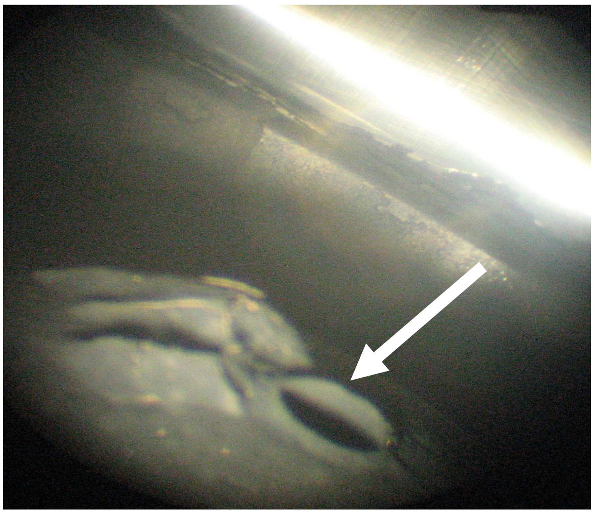
b) cylinder bearing surface – traces of the piston ring's seizing



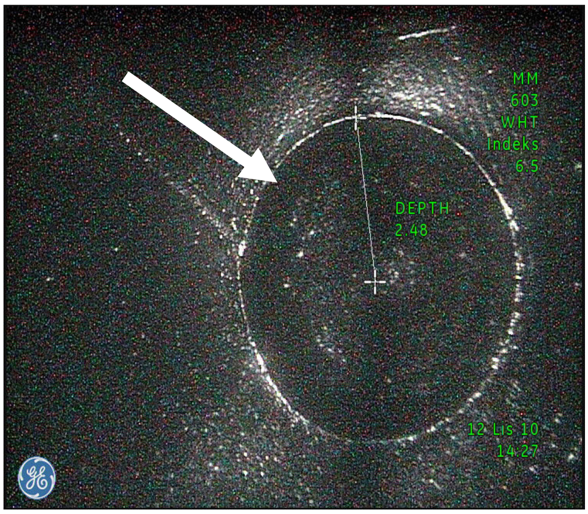
c) piston head – traces of the piston strokes over the valves (a state after the "water hammer")



d) piston head's crown – traces of the strokes made by the broken-off part of the valve head



e) piston head – a dent after the piston stroke over the injection sprayer



f) piston head – a measurement of the dent's depth by means of the „Shadow" method (2,48 mm)

Fig. 3. Endoscopic image of marine engine pistons' damages and their consequences

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