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STUDIES ON THE EFFECTS OF COLD STARTS OF THE SHIP MAIN ENGINE

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ABSTRACT

This article presents the influence of various ship's operational conditions occurring during manoeuvres related to entering and leaving the ports and mooring operations. Frequent starts and stops of the ship's propulsion unit are then required, which affect the variability of the energetic loads of the ship's power plant, causing accelerated, non-design wear of the ship's main propulsion engine. The effects of cold start-ups of the main ship engine are the subject of this study. Conditions of the engine inlet valve damage process are discussed. The physics of the degradation process leading to air inlet valve damage was considered. Laboratory tests of structure continuity and their results are discussed, and the valve material defects were excluded as the cause of the damage. The causes of repeated damage to the inlet air valves were identified. The effectiveness of the performed corrective measures was confirmed by a documented control test of the engine start-up. The article is a utilitarian premise for the requirements of the Classification Society.

Keywords: cold start-ups, damage, inlet valves, main engine, ship

INTRODUCTION

Marine engines are complex technical systems undergoing constant modifications in terms of design as well as modes of operation. The said modifications are due to constantly emerging requirements concerning reliability, marine environment protection, and conservation of natural resources related to fuel and raw materials used in the production of marine engines. Consequently, both engine designers and users of the said engines face new challenges.

With the ultimate aim of meeting the requirements, the design process includes various actions that, among others, are taken in order to:

- reduce emission of pollutants from engine exhaust [1, 2, 3, 4, 5];
- use new ecological fuels [6, 7, 8];
- develop new operating principles for ship propulsion [9, 10, 11].

In terms of operation of marine engines, the undertaken actions are aimed, among others, at:

- reduction of fuel and lubricating oil consumption [12, 13, 14];
- operational diagnosis and prevention of component wear [15, 16].

One of the most pressing issues to be addressed in the process of marine engines operation is the reduction of structural component wear due to cold starts of the ship main engine.

In the operation process, there are various technical and energetic conditions of the ship propulsion power. The run and character of these processes significantly depend on the decisions and actions of the crew. Therefore, the process of ship engine maintenance should be considered as being dependent on crew competence and operational proceedings. Real operational conditions of the ship propulsion power system are always different from the designed ones, and the achieved energy condition of the engine is the result of all vectors of control and disturbances in a given technical condition of engine serviceability [17, 18, 19, 20].

Procedurally correct preparation of the ship engine room to work, according to the principles of the accepted operational strategy and the requirements of the engine manufacturer, and, thus, the main propulsion power system is a basic initial condition of ship operation. In particular, ship manoeuvring in a port is a dynamic transient process, significantly deviating from the steady state of sailing at sea, which is a consequence of multiple and rapid changes of the main engine load. Thus, the elements of the engine are subjected to larger and more frequent changes in mechanical loads and thermal stresses, creating more difficult and demanding operating conditions [20, 21, 22].

Operating the main propulsion power system when its energy condition deviates from the design one, contributes to an increase in the probability of accelerated wear, the occurrence of malfunctions, up to eventual failure and breakdown [17, 23, 24].

The ship main engine is responsible for keeping the ship in motion in all operational conditions: during sea passage, in port and in limited water passage, as well as at anchor and in port. Continuity of ship operation in all operational states provides for steady operational conditions and also transient processes, acceleration and load deceleration, as well as engine shutdown. For the purpose of this study, operational documentations of a container ship and a cement carrier were used. Mutual relations of the steady condition operation time to the number of manoeuvres are shown in Fig. 1. During 102 h of sailing of a container ship in a month, 44 start-ups were made during the manoeuvres, while on a cement carrier, 20 start-ups were made during 112 h of manoeuvres.

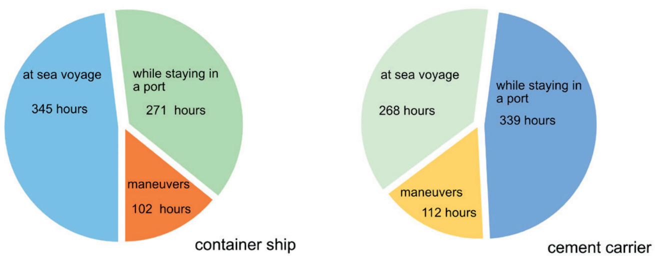

Fig. 1. Total times of operating states of a container ship and a cement carrier realized in one month [own source].

The recorded number of cold start-ups caused degradation of the elements of tribological nodes of the main engine elements, and in particular, it caused damage to the charging air inlet-valve [25, 26, 27, 28, 29]. Their number and recurrence made it necessary to determine the reasons for the valve malfunctions and failures in order to counteract and reduce the number of valve failures associated with the negative effects of cold starts of the engine. Repeated repairs became a burden in the operation and maintenance process, excluded ships from the transport service schedule, and increased costs. Therefore, in order to counteract this phenomenon, the need to analyse the consequences of ship engine cold start-ups arose.

In addition to the above, the effect of cold start-ups on air inlet-valves has a significant influence on the engine performance and emissions from diesel engines. Therefore, the consequences of this effect should also be taken into as they significantly contribute to pollutant emissions in coastal waters [30].

Failure of each engine inlet valve is an individual event, insufficiently recognized in technical literature, both scientific and professional, and limited even in the technical and operation documentation of an engine. This has generated research interests in this area. In the available scientific technical literature, no references to this type of damage to intake valves have been found.

STUDY OBJECT

Repeated difficulties of starting the main engine operation, start-ups, unstable operation in the initial period after the start-up attempt, and recurrent damage to engine elements were observed in the operating practice. Fig. 2 shows the deviations from the mean value of the combustion pressure during the initial phase of the engine start-up.

The runs were recorded using an electronic indicator LEMAG Premet C XL made by LEHMANN & Michels GmbH and equipped with the WPREMET software, enabling the analysis of the measurement results. In Fig. 2, at the time of observation, three units 4, 5, and 8 in operation showed differences of several percent from the average value of the combustion pressure, three other units 1, 2, and 6 initiated operation, while two units did not start the combustion process at all, creating differences in the load of the piston-crank systems.

Fig. 2. Deviations from the mean value of the combustion pressure at the beginning of the first stage of the engine start-up.

Frequent lack of readiness of the main engine to start correct operation and recurrence of this type of damage point to the existence of systemic disturbances in the correctness of the engine start-up process.

This process occurs with irregular frequency and causes different forms of tribological wear of inlet valves. Fig. 3 shows endoscopic images of a damaged inlet valve mounted in the cylinder head of a Deutz 68M628 main power engine of 1715 kW.

Fig. 3. View of a defective inlet valve of the Deutz 68M628 main power engine.

The study of the causes and effects of the main engine damage was carried out on the basis of the operational experience of the ship propulsion plant operation, passive and active operational experiment, ship post-failure and shipowner's documentation, and the results of metallographic and scanning laboratory tests.

DETERMINANTS OF THE DAMAGE PROCESS OF THE SHIP MAIN ENGINE INLET-VALVES

The subject of the research comprised: the thermal condition of the engine and the engine room before starting the ship propulsion plant, including values of the temperature of the main working process media and the processes accompanying the main engine start-up.

On the basis of the analysis of the events in transient processes, it was assumed that the decisive influence on the main engine serviceability, *Z*, is exerted by imposing factors, according to the relation

$$Z(f) = f[t(\tau), \delta(\tau), \iota] \tag{1}$$

where:

- *t(τ)* – thermal factor,
- *δ(τ)* – mechanical factor resulting from the dynamics of engine load changes,
- *τ* – time of intensity of transition processes,
- *l* – factor resulting from human activity including servicing during operation

The consequence of the superposition of such interactions is the mechanical violation of the continuity of the structure, with such consequences of wear processes as loss of materials and changes in the shape geometry of mating elements of the main engine. This kind of damage is a result of various mechanical and thermal loads of varied value and time, occurring at the initial stage of the main engine transient start-up process.

Ship engine start-up is performed with the participation of energy from an external source, which is compressed air from the start-up installation. The energy of compressed air during start-up is converted into kinetic energy of a back and forth movement of a piston-crank system of the engine, causing the heating of the fuel-air mixture in the combustion chamber to temperature T_2 at the stage of compression [17, 19].

$$T_2 = T_1 \varepsilon^{n_1 - 1} > Tsz \tag{2}$$

where:

- T_1 – air temperature at the beginning of the compression stroke,
- T_2 – air temperature at the end of the compression stroke,
- ε – compression ratio,
- n_1 – compression polytrope exponent in a cylinder, higher than the self-ignition temperature T_{sz}

The compression polytrope exponent n_1 is highly dependent on the crankshaft speed n. Increasing the compression time of the air in the combustion chamber favours heat exchange with the walls of the combustion chamber, which results in insufficient heating of the fuel-air mixture, cooled by the start-up air, expanding in the start-up valve. Thus, the process of self-ignition is significantly hindered because the rotational speed of the crankshaft is determined by the pressure of the start-up air and internal resistance of the engine kinematic system. In the case of an unsuccessful start, the main engine requires more starting air to be supplied in order for the fuel-air mixture in the combustion chambers of individual cylinders to self-ignite. In such a situation, the air supply time is extended, which promotes additional cooling of the combustion chamber. After a failed start, the main engine start-up is automatically repeated; thus, further cooling of the combustion chamber takes place. In this way, temperature gradients are created in the valve material, favouring circumferential microcracking of the inlet valves, as shown in Fig. 4 [18, 31, 32].

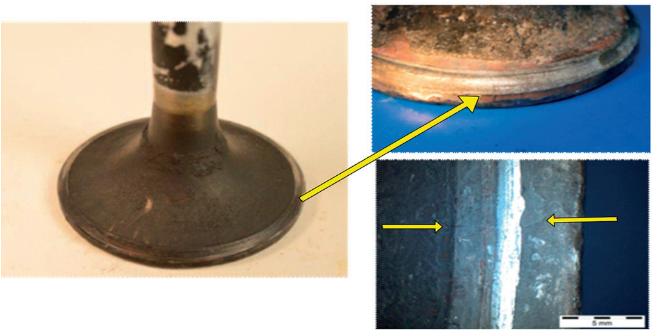

Fig. 4. Location of microcracks on the inlet valve:
a – view of the valve with peripheral microcracks on the inlet valve;
b – enlargement of a valve with visible microcracks;
c – enlargement of circumferential cracking of a disc.

If the equation (2) is not met, starting a diesel engine is difficult and sometimes impossible. Damage to the air inlet-valves generated by cold start-ups is only identified during scheduled engine overhauls if it does not cause extensive damage to the mating parts beforehand.

LABORATORY TESTING OF THE INLET-VALVE STRUCTURE

Two inlet-valves were randomly selected to study the effects of cold starts on the engine. The first valve was removed from the engine after 450 h of operation, while the second one was removed from the engine after it was damaged. Both valves were subjected to non-destructive macroscopic, microscopic, and metallographic examination [31, 32].

MACROSCOPIC TESTING

Organoleptic examination of the first valve revealed a bent stem and scratches in its upper part. These proved the existence of resistance to motion in the valve stem guide and defective operation of the “rotocap”. The second valve also had a bent stem and a partly broken off head. The view of the tested valves is shown in Fig. 5.

Fig. 5. View of studied damaged valves.

On both valves, circumferential cracks were located at the bottom, as shown in Fig. 4a.

The examined separation surfaces (scrap) of the damaged valve show two different breakthroughs in Fig. 6. The first breakthrough (1) shows furrow lines characteristic of fatigue scrap. The second breakthrough (2) is the separation scrap that resulted from the sudden breaking off of the part of the valve that was no longer cohesive. The nature of the scraps indicates that the process of destruction progresses over time.

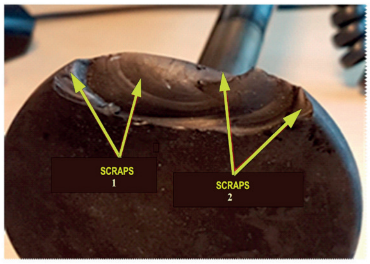

Fig. 6. View of the place of separation of the missing part of the inlet valve with visible separation lines:1- fatigue scrap; 2 - separation scrap.

MICROSCOPIC TESTING

During the visual inspection of the examined valves, a micro-crack was found, which was the beginning of the propagation of further destruction proceedings. The microcrack was a result of thermal stresses that occurred in the second phase of the cold engine start-up [28, 31, 32]. The crack expansion was probably caused by a cyclic action of varying mechanical loads resulting from the repetition of transient engine operating states. The location of the micro-crack is shown in Fig. 7 [32].

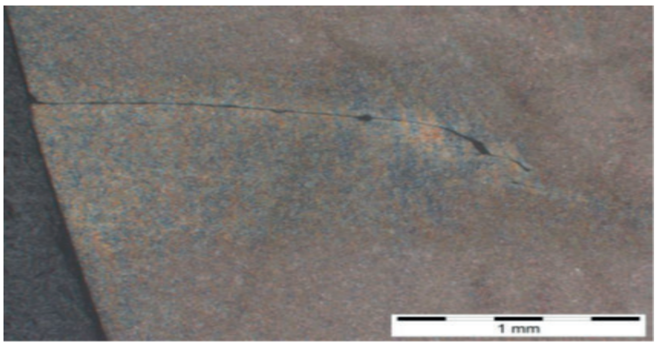

Fig. 7. View of a microcrack on the working surface of the damaged valve 2.

Circumferential cracks in the valve head found during examination using scanning electron microscopy revealed the formation of areas of local corrosion at the microcrack site, as shown in Fig. 8 [32].

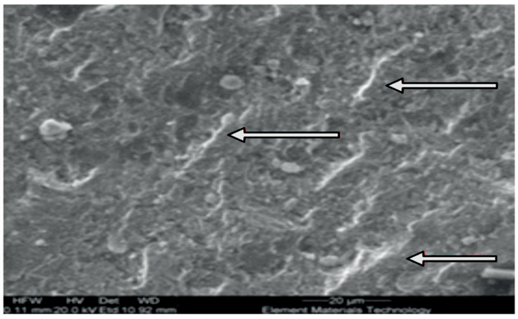

Fig. 8. Microscopic image of the surface of the tested valve.

At the same time, the structure of the valve material at the place of the fracture showed lines formed by fatigue crack growth. This phenomenon is documented by the electron microscope image shown in Fig. 9 [32].

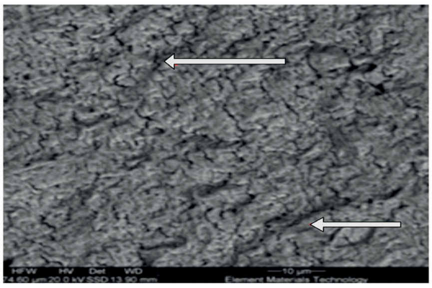

Fig. 9. Scanning electron microscope image of the surface of a cracked valve.

The revealed microcracks are the result of thermal stresses occurring during the process of exchange of the working medium [17].

METALLOGRAPHIC TESTING

For metallographic testing, a section of the head material, shown in Fig. 10 [31], was taken.

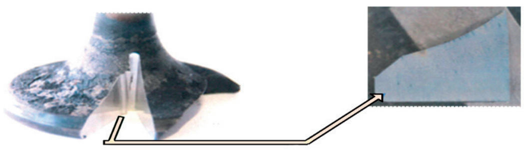

Fig. 10. View of valve 1 and a section of a valve for metallographic examination.

Examination of the valve revealed a tempered martensitic microstructure typical of the material of this type of valve [31]. The test results ruled out a material defect in the tested valve and, thus, excluded it as the cause of the failure. No deviations were found in the place of the fracture (scrap) and in the fragment away from it.

The Vickers hardness measurement of the tested valve head confirmed the required hardness of the valve material, while the measurement of the valve thickness and angles showed that the permissible thickness loss exceeded the design value by 1 mm. This indicates repeated regeneration of the valve by grinding-in. The measurement of the valve thickness is shown in Fig. 11 [31], and the angle measurement location is shown in Fig. 12 [31].

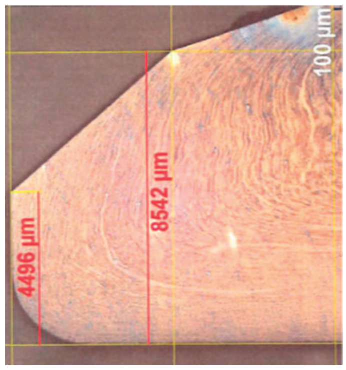

Fig. 11. Valve thickness measurement in the faying section.

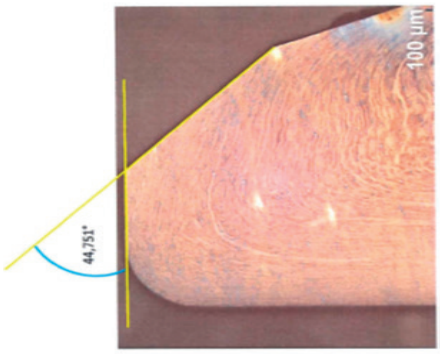

Fig. 12. Angle of faying face inclination measurement.

IDENTIFYING CAUSES OF DAMAGE

The causes generating damage to inlet-valves, bearing pans, and fuel apparatus are a consequence of various conditions resulting from the operational realities of the main propulsion power plant including cold starts of the engine [18, 22]. These causes are grouped according to the similarity of their destructive impact.

MALFUNCTION OF THE MAIN ENGINE HEATING SYSTEM

When the ship is stationary in port, the main engine should be heated by heating water in a circuit bypassing the heat exchanger. The temperature of the heating water and, thus, of the engine when it is not working should be in the range of 50–55 °C to ensure correct ignition during the engine start-up and its further operation. At the beginning of the research, as a result of the initial recognition of the heating water temperature and the quality of the circulating oil purifying system and, consequently, the engine energy state, it was found that the temperature of the heating water and, therefore, the temperature of the engine before the start-up was only 20–25 °C. Starting of the engine in such a defined energy condition is known as the so-called "cold start". The correct temperature of the low-temperature cooling circuit (LT – Low Temperature) of 60 °C, compliant with the operational documentation, was established only after 20 min of engine work at its load corresponding to about 50% of its nominal power. Looking for the correctness of the process course, Fig. 13 shows comparative diagrams of the engine cooling water temperature variation as a function of load. Diagrams were made during shop tests, by the crew of the ship, and for the purpose of verifying the engine cooling circuit functionality during the manoeuvres and sea passage (after the transient start-up process).

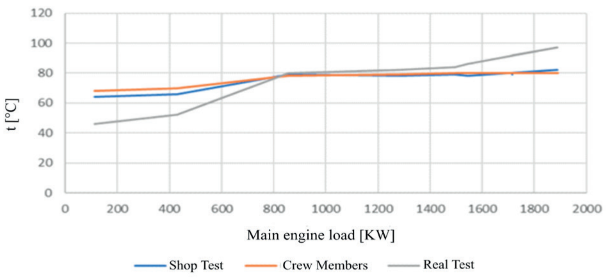

Fig. 13. Dependence of cooling water temperature on the main engine load: blue line - measurement from engine shop tests; red line - measurement taken by the crew; grey line - measurement taken for the sake of the case study.

To ensure the design operating conditions of the studied engine, the inlet cooling water temperature must not be lower than 60 °C. The inlet water temperature measurements made for the research in Fig. 13 show a lower temperature, while the outlet water temperature took correct values in the range of 78–82 °C.

Fig. 14 shows the variation of the engine cooling water temperature measured for the present study, from the value of the heating starting level during engine idling and port exit manoeuvres to the design value of the continuous operating temperature with the engine loaded at its nominal power. The relationship indicates that the water temperature at the beginning of the start-up is too low, reaching the correct value only after 20 min of operation with the engine load of 80% of its nominal power. The dotted line in the figure, reflecting the trend of the temperature change, confirms the correct operation of the automatic engine cooling system.

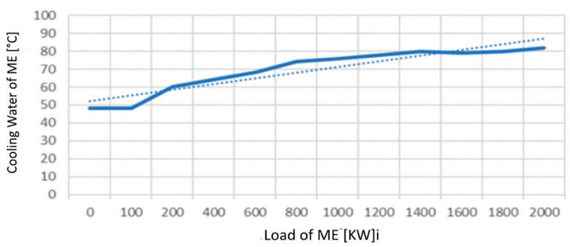

Fig. 14. Changes in the cooling water temperature as a function of engine power.

UNBALANCED ENGINE UNIT LOADS

In the case of an underheated main engine, underheated fuel injection pumps are the natural

consequence. This caused deterioration of the operating conditions of the barrel/plunger of the injection pumps and, consequently, the organization of the combustible mixture. The underheated engine operated unstably with a temporary reduction in speed and fuel delivery rate. Fig. 15 shows a run of the rotational speed and a representative of the fuel dose recorded during the engine start-up with the help of the Norris type control system.

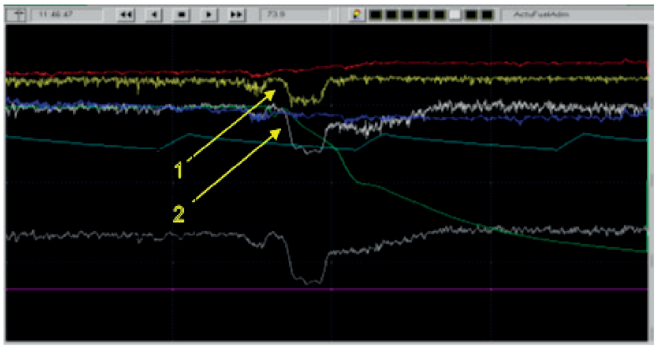

Fig. 15. Runs of the monitored parameters of the main engine operation during start-up:
1 - engine speed, 2 - fuel dose equivalent (Actual Fuel Admin).

An examination of the run of the start-up and the initial phase of engine operation showed an uneven distribution of loads on individual units. Lack of balancing of unit loads significantly hinders the start-up and the start of stable engine work and, thus, its ability to accept the load. The cylinder imbalance that is occurring, represented by the compression pressure, is shown in Fig. 16, with the distribution of the combustion pressure difference between the units.

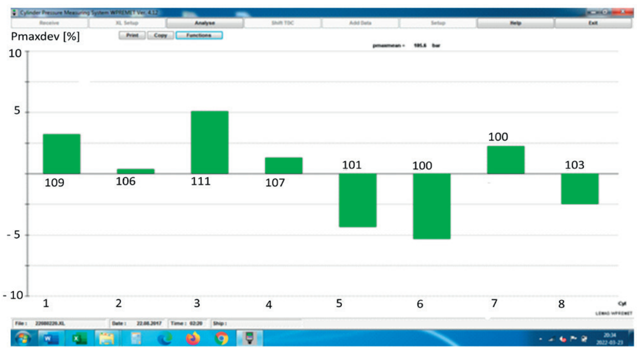

Fig. 16. Deviations from the mean value of the combustion pressure at the beginning of the second stage of engine start-up.

Temporary disengage/operation off of individual injection pumps from work was also observed. It disappeared after the energy condition of the main propulsion power plant had stabilized. Indicator tests of the combustion process and engine load condition were carried out using the LEMAG Premet C XL electronic indicator equipped with the WPREMET software, enabling the real-time measurement of combustion pressures. Disturbances in the operation of the fuel system of individual injection pumps in the form of combustion pressure runs of the fuel-air mixture are shown in Fig. 17.

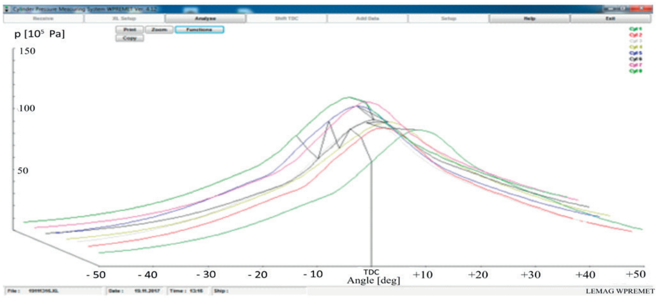

Fig. 17. Runs of combustion pressure in the first stage of the main engine operation as a function of the crankshaft rotation angle.

The combustion pressure runs for each cylinder showed significant differences. Identified by means of a diagram (Fig. 17), the hanging-up selected injection pump, disassembled for verification of its technical condition, revealed local traces of scuffing (B) and overheating in the form of a dark purple discoloration of the surface layer, as shown in Fig. 18.

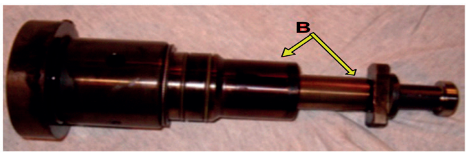

Fig. 18. Local traces of scuffing on the barrel/plunger injection pump.

The revealed precision pair scuffing, manifested by pump hang-ups, is the result of the engine starting when the engine elements are at too low of a temperature during a cold start-up.

LUBRICATING OIL AT TOO LOW OF A TEMPERATURE

Starting the main engine when oil temperatures in the lubrication system are too low is difficult and sometimes even impossible. Frequently, if the main engine circulating oil is not purified long enough at standstill, it cannot be heated up to the required temperature by running the circulating pumps, removing sludge and possible water, and thus, heating up the engine crankshaft to the required temperature is not possible [18].

When the oil temperature is lowered, its rheological properties change. The viscosity of the engine lubricating oil increases and the resistance of the crankshaft movement increases. Oil with a higher viscosity does not reach all the motion pairs to the required extent. These conditions make it difficult to create an oil wedge in the hydrodynamic lubrication of the crankshaft bearings at the beginning of a start-up, which in turn leads to bearing pan damage. An example of such damage to the crankshaft bearing pan of the engine under study is shown in Fig. 19.

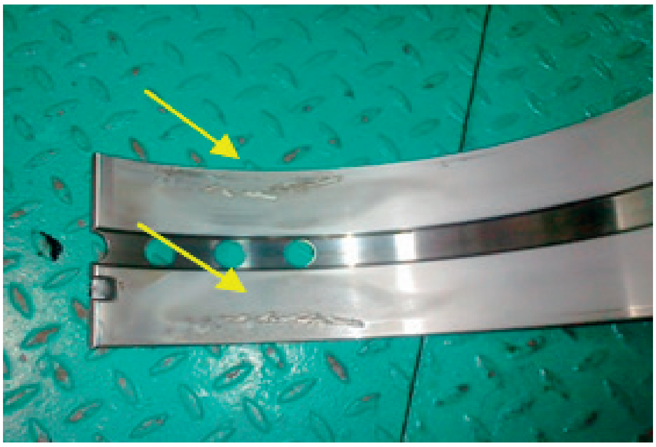

Fig. 19. View of the damaged surface layer of the crankshaft bearing pan.

Diagnosing bearing shell wear is only possible during periodic inspections of piston-crank systems. Determination of the causes of wear depends on the correct assessment of the type of damage to the working surface of the slide bearings and their surface layer and the assessment of the quality of operation of the oil system.

Routinely during operation, causes of this type of wear are not associated with cold engine start-ups or underheated lubricating oil.

CORRECTIVE ACTIONS RESULTING FROM RESEARCH CONCLUSIONS

On the basis of the partial conclusions from the research, corrective actions were carried out during stay in port and verified during start-ups and registration of initial periods of engine work. Cooperation of the engine start-up time controller with the crankshaft speed meter was verified. Temperature controllers of the engine heating water and the state of the non-return valve at the connection of the engine heating and cooling circuits were corrected. Operation of the thermoregulatory valve adjuster in the engine circulating oil purifier system was adjusted.

The automatic setting of the starting fuel dose was adjusted. Settings of the injection pumps (fuel doses) and the moment of starting the fuel injection were corrected. The correction was made on three injection pumps with the use of a fuel dose corrector, included in the equipment of the injection pumps. The correctness of the timing phases of the mutual angle of rotation of the crankshaft and the camshaft was checked using an electronic meter.

Ship installations were tested during the engine preparation for operation. Temperature values of the heating water and lubricating oil were in accordance with the operation manual of the tested engine, i.e., temperatures of the heating water and lubricating oil were 50 °C and 45 °C, respectively.

After taking the corrective measures, control tests of the main engine preparation for starting and its start-ups were carried out in accordance with the technical and operational manual [19]. The engine start-ups proceeded and continued correctly. The start-up took place after a single feeding of the starting air with a small decrease in the air pressure in the starting air system.

The performed corrective actions balanced the load distribution across the engine units to some extent, as shown by the engine indicator graph in Fig. 20.

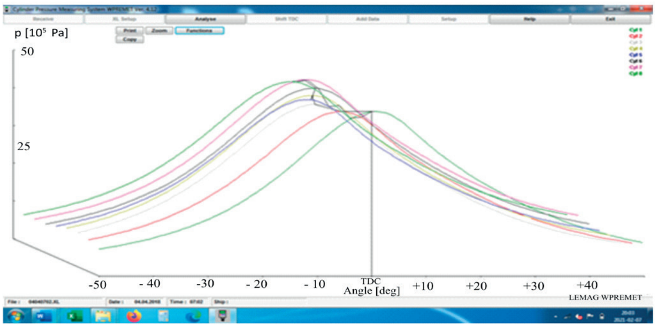

Fig. 20. Combustion pressure runs in the ship main power engine as a function of the crankshaft rotation angle, after correction actions, taken at the load of 50% of the nominal engine power.

The recorded runs of the pressure show more balanced loading of individual piston-crank systems. The effectiveness of the performed corrective actions, taking into account the conclusions of the conducted tests as fully as possible, was confirmed by the successful control tests of the engine start-up and its further operation without unscheduled repairs and valve damage.

FINAL REMARKS

Damage to each engine inlet-valve is an individual "random" event, not repeatable in nature, with different physics of the phenomenon course, although it most frequently occurs as a result of the so-called "cold starts" of the engine. The causes generating damage to the inlet valves and fuel system are the consequences of various conditions often resulting from random operational realities of the ship main propulsion system, e.g., cold starts of the engine and a periodically occurring phenomenon of pumping-up in its turbocharging system [33]. Superimposition of variable loads during manoeuvres on such a condition poses a threat to the stable operation of the power system and, thus, to the safety of navigation during the ship manoeuvres and subsequent sea passage.

The results of the conducted start-up tests and the procedure for assessing the effectiveness of engine work during normal operation confirmed the correctness of the applied methods for evaluating the causes of accelerated tribological wear and damage to engine elements as well as the validity of the undertaken predictive corrective actions in the applied operational strategy.

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