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A study upon medium displacement Diesel Engine failure

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Abstract. The study aims to determine the failure cause of an internal combustion engine, in a particular case for a medium displacement diesel engine. The general issue of internal combustion engines failure is very complex and comprehensive. The assumed analysis for achieving this objective is complex and involves a multidisciplinary and gradually approach of the problem, as well as the development of an appropriate methodology to ensure the accuracy of the outcome. In principle, the cause of the engine breakdown is related to its mobile equipment. Based on this assumption, the authors identified all the affected moving parts organs and defined the damage they recorded. Neither fixed collaterally affected parts have been neglected, due to the organic interaction between the mobile equipment and the fixed parts of the engine. The present paper is a real "good practice support" in approaching the causes of fatal destruction of engines, the theoretical considerations being accompanied by a case study.

1. Introduction

The objective of the paper was to analyze the complex of circumstances and identify the cause that lead to the destruction of a medium displacement compression ignition engine during operation. The analyzed engine is a 6-cylinder in-line liquid-cooled compression ignition engine. It is medium level supercharged, using a turbo-compressor group, the lubrication of which is provided by the engine lubrication circuit. The engine displacement is 8.7 [litres] and provides a maximum power of 230 [HP]. The engine is of an older generation with a specific output of only 26.43 [HP / l], operating at a compression ratio Σ = 18 [-]. The ignition solution used is that of the Meurer principle, the fuel delivery being provided by direct injection, the nominal engine speed corresponding to an average value of 2300 [RPM].

The engine's constructive solutions are overcomed: it is equipped with two valves per cylinder, driven by rods and shafts from a single camshaft, located in the engine block.

The engine equips a grain-harvesting combine, the J.I.Case-943E brand. The propulsion unit failed while it was operating at full load, with over 1000 operating hours since the last major repair, of which more than 10% since the last oil change. The problem presented to the authors was unprecedented and difficult. The supposed analysis in order to achieve the objective is complex and requires a multidisciplinary approach to the problem without neglecting the overall context.

The authors have developed a logical flow of investigations that ensure a minimum amount of work, but also to ensure that the conclusion has a high probability.

2. Objective solution methodology. Conceptual and experimental aspects

From the conjunctural point of view and its implications, we notice contradictory tendencies. The use of the Meurer principle as an ignition solution and the specific compression ratio results in the capping at an average value of the maximum engine speed and, implicitly, the average mechanical and thermal load of the engine components. The same specificity of the load level is imprinted on the engine by the affiliation to the medium power engine class and the generation of the 1960's and 1970's engines respectively. For such engines, the flexibility of the motor mechanism's organs is collateral, with emphasis being placed on improving reliability.

On the other hand, the engine is overcharged at a medium level, with a medium effective cycle pressure, that will raise the level of the thermo-mechanical loads in the engine components, at least at the high load specific to the predominant operating mode on the agricultural machinery. For the same high level of thermo-mechanical loading plead also the main features of this engine operation; it is frequently used in warm environments, for long periods of time, at loads close to nominal, with low vehicle speeds. These speeds cause insufficient air flow to cool the engine compartment by engine's natural ventilation. The indicator that solves this contradiction is that of reduced specific output and therefore the thermo-mechanical loads of the components can be classified as acceptable.

Due to the engine kinematics and specific thermogazodinamic processes, the forces and moments loading the engine organs are periodically variable and involve the fatigue load of these organs. Moreover, in some moments of the engine's cycle, the load of the mobile organs can be applied with shock.

Considering the physical wear naturally accumulating in the various engine couples, it is expected that the functional clearances of some couples grow dangerously, accentuating the shock loads. Increasing functional clearances can alter the engine's lubrication as a whole. Lubricating conditions are aggravated also by the decrease of viscosity, the reduction of film resistance and the intensification of chemical oxidation following the very severe thermal regime of the engine.

Engine damages are concentrated in the area of the first cylinder, opposite to the clutch position. In this area, the motor block is broken bilaterally, with important material releases (Figure 1).

Figure 1. The engine block. Bilateral breakup

The piston of this cylinder shows breakups with material releases, bilaterally in the plane of the connecting rod oscillation, in the lower half of its skirt. The segments, the piston pin and the shoulder of the piston are integral without significant traces of impact (Figure 2).

The positioning of the damages on the engine block and the piston, corresponding to the oscillation plane of the first cylinder connecting rod, clearly demonstrates that the two components were destroyed by impact with a part of the connecting rod.

Figure 2. First cylinder piston – breakup with releases from the piston skirt

Figure 3. The connecting rod body, broke in two parts

For this reason, the authors' investigations focused on the connecting rod, which broke into several pieces. The rod cap has detached from the body due to rupture of the bolts (Figure 3). The investigations focused on both the overall connecting rod and its weak points (bolts, crankshaft bearing journals) and the connecting section of the rod's small end eye with the body, and took into account the particular functional constructive solutions of this connecting rod.

The piston pin type is full floating, the solution being common in the case of medium power engines with aluminum alloy pistons. Starting the engine is ensured by providing a functional clearance between the piston pin and the rod bushing; to ensure sufficient lubrication in the piston pin bearings, oil access holes are provided both in the piston bosses and the connecting rod small end eye, corresponding to the oil hole in rod bushing.

The rod bushing does not show pitting marks, scratches, surface dislocations, or adhesion on its interior surface, even though its whole body is deformed and broken on generators. In conclusion, the bush has fulfilled its functional role and has not initiated the destruction of the engine.

The rod cap as a whole does not show any significant traces of impact or significant changes in the geometric-dimensional configuration. The holes for fixing the cap to the body have been found free from the bolt remains. The bearing journals as well as the bolts do not show any traces and / or deformations relevant to elucidating the causes.

The rod body is broken by tearing into two parts, the rupture being produced approximately halfway of the beam. The lower part (towards the rod cap) is strongly bent in the rupture area, in the plane of the rod oscillation, demonstrating that it has undergone a bending effort in this plane beyond the permissible limit.

Most likely, this rupture was caused by the impact of very rigid parts of the engine (such as the cylinder and the engine block) in the joint motion of the rod with the connecting rod journal. The upper part of the body (from the small end) is strongly deformed, the rupture being produced by a mechanism similar to the lower part.

The rod's small end is strongly deformed and shows a tear-off of material in the area of the eye, bounded by the generators in the incision area with the body and through the center of the lubrication hole, respectively. The piece detached from the rod eye and also the rod bushing were found in the engine crank.

The above aspects outline a small scenario-mechanism after which the engine was destroyed: first was broke the wall of the connecting rod small end eye's, thus the movement of the rod was not anymore guided by the evolution of the piston in the cylinder. The rest of the rod was detached from the piston and uncontrollably rotated a few cycles with the crankshaft, hitting and piercing the piston, the cylinders and the block.

The energy required to destroy these organs was ensured by the operation of the other engine cylinders. Finally, the rest of the rod broke in 2 pieces after being hit by the cylinder walls of the engine, causing the bolts to break. This failure mechanism will be further proven with rigorous scientific arguments, but also with the counter-argumentation of the other possible causes. The period in which the engines was designed was an enthusiastic one, with extensive development of engines that tested new materials and solutions in engine construction. For this reason, the validity of some solutions has been investigated conceptually.

Initially, the conceptual aspects of connecting rod have been approached. Typically, the engine rods are made of high quality carbon steel or alloyed steels by one-piece deformation (monoblock). In this case, an OLC45 steel with 0.5 - 0.8 [%] Manganese was identified by macroscopic methods and subsequently confirmed as the basic structure, by EDAX analysis.

The cross section of the connecting rod has the "I" shape, with the center of the heart in the motion plane, which ensures effective bending behavior. For the rod, it was verified that its cross-section would ensure the geometric-dimensional configuration respecting the optimum ratio of 4: 1 between the inertia moment of the section in the oscillation plane and the moment of inertia in the incision plane.

Last but not least, the overall dimensions of the connecting rod as well as the center angles of the big and small end sections in the body of the rod meet the precepts of dimensioning on a statistical basis for the medium power Diesel engine category.

The rod was also analyzed from the point of view of the reglementations of a relatively new scientific field, namely the mechanical and the fatigue of the rupture. In principle, the rules for designing structures with fatigue stress have been respected. However, the piston pin lubrication hole (which is practiced at the upper part of the eye of the rod's small end in its symmetry plane) has been identified as not being optimized in terms of stress concentration. For the geometric-dimensional data configuration (tronconic section connected to the cylindrical section) of this hole, a theoretical coefficient of stress concentration in the elastic range k_t = 7 [-] was evaluated. By reducing the minimum cross-section of the hole by 20% and using an elliptical profile for the walls of the punched hole, the k_t coefficient could have been reduced approximately 3 times.

The suspicion of a malfunction of the thermogazodinamic process in the first cylinder was easily removed; the piston head and the conjugated combustion chamber in the cylinder head are integrated and look normal at the visual inspection.

The possible influences of fuel under the qualitative and quantitative aspects were also dropped; besides the functional insensitivity of the engine, the fuel quality given by M principle of the combustion, the injector has been checked from the point of view of opening pressure and geometry, jet quality, being diagnosed as normal.

Regarding the quality of the lubricating medium, an acceptable degree of impurity was found based on the SKF technique of assessing the degradation of the oil by measuring its dielectric constant.

An oil degradation of 41.7 - 42.3 [%] was measured with the TMEH-1 (Figure 4) tester, which summarize up the cumulative effects of altering the oil quality by increasing the water and metal content and by oxidation of constituent molecules and fuel contamination with various other products. For the calibration of the tester, the oil from the engine lubrication was used, namely URSA TD10W40, ACEA E7, A3 / B4, AP CI-4, with a mineral base and a high quality additive.

To assess the lubricating qualities, engine oil was subjected to the extreme pressure oil resistance test on the Timken machine, according to the ASTM D 2783 test standard. TIMKEN OK LOAD value was determined for the trial oil (maximum load without film break) of 250 N, acceptable for use of the oil in the engine.

Figure 4. Sample for lubricant contamination determination

Finally, ultra-modern scanning techniques, using scanning electron microscopy (SEM) and EDAX/EDS spectroscopy, were used. For this, it was used a microscope TESCAN equipped with 4th generation BRUKER QUANTAX shotgun. For the analysis we chose the upper tear-off section of the detachable piece from the rod’s small end which contains the bushing hole (Figure 5). The general aspect of this section, which lacks the direct strikes, suggests that this section has initiated the fissure that triggered the mechanism that destroyed the engine. These investigations allow qualitative -morphological and quantitative-compositional analysis at defined points of the section.

Element analysis was done based on the specific energy spectra of the chemical elements in the predefined points of the section. Two areas of interest (photo 6) were defined, zone 1 (closer to the inner fiber of the connecting rod’s small end and in the vicinity of the lubrication hole) and zone 2 (closer to the outer fiber and to the exit section in the small end).

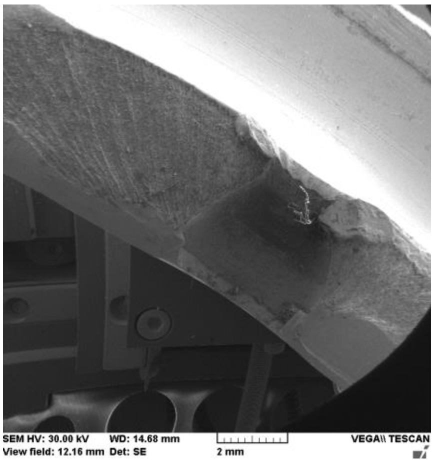

Figure 5. The rupture section of the connecting rod small end

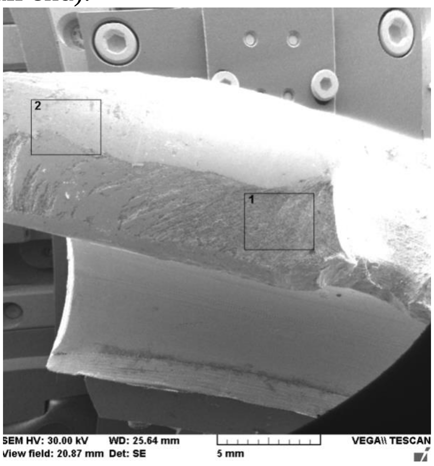

Figure 6. Positioning of analysis areas in the section

Figure 7 shows the dispersion diagram of the specific energy for the chemical elements identified in zone 2. First of all, we note the morphology of the rupture section through fatigue from the outer fiber to the inner one. The rupture surface is relatively smooth and has distinct areas. To the outer fiber (to zone 2) the fissure primer appeared, favored by the brutal concentration of stresses at the lubrication hole. The initiation could be favored by possible non-metallic inclusions, superficial structural irregularities or even micro fissures caused by heat treatment applied to the connecting rod.

Descending from the outer to the inner area, there is the fracture section during the operation, in a median position, with a smooth aspect, but with lines / micro edges waiting, with the appearance of "sand dunes" and indicating the progressive but intermittent propagation of the crack. The walls of these "dunes" are larger to the inner fiber of the rod’s small end, indicating the direction of evolution. The final break area, placed on the inside of the small end's eye, has a matte and quasi-planed appearance, with rare specks of material, not profound.

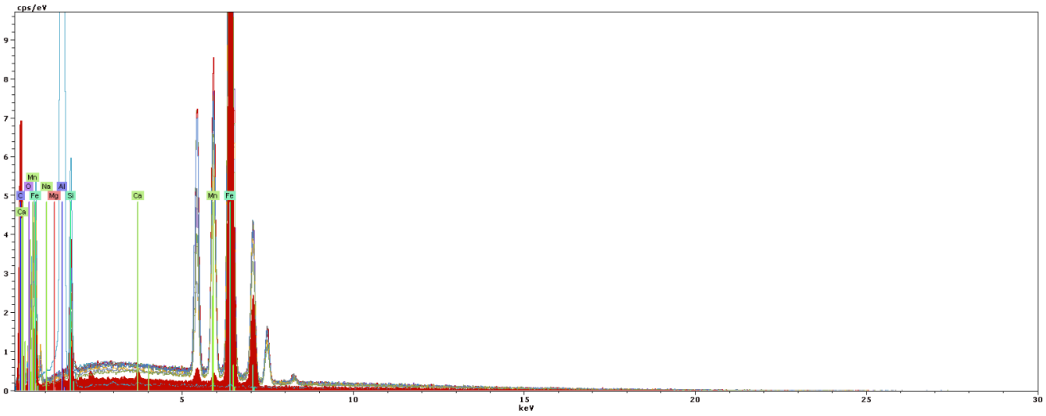

Figure 7. Elementary energy dispersion diagram (ie on chemical elements).

Tables 1 and 2 present the results of the chemical analyzes in zones 1 and 2.

Table 1. Chemical composition in zone 1

Element	AN	series	Net	[wt.%]	[norm. wt.%]	[norm. at.%]	Error [%]
Oxygen	8	K-series	428	59.45464641	59.45583553	53.18331822	47.0219716
Carbon	6	K-series	21822	38.9427753	38.94355417	46.40246564	12.30282775
Iron	26	K-series	4757	1.238992294	1.239017074	0.317513418	0.062371771
Manganese	25	K-series	755	0.191515924	0.191519755	0.049891363	0.039765012
Chromium	24	K-series	681	0.170070071	0.170073473	0.046811363	0.040621767
			Sum:	99.998	100	100	

Table 2. Chemical composition in zone 2

Element	AN	series	Net	[wt.%]	[norm. wt.%]	[norm. at.%]	Error in %
Iron	26	K-series	114087	63.75961067	61.64309264	32.46399593	1.645378716
Oxygen	8	K-series	5061	16.27746504	15.73713006	28.92938774	2.620329605
Carbon	6	K-series	11277	11.09624656	10.72790357	26.26957815	1.622734991
Silicon	14	K-series	9161	5.286780817	5.111284656	5.352606448	0.273369365
Aluminium	13	K-series	2697	2.122444165	2.05198904	2.23679255	0.14766055
Sodium	11	K-series	870	2.05170441	1.983597511	2.537676938	0.204493437
Manganese	25	K-series	2344	1.088769765	1.052627749	0.563533028	0.099593251
Magnesium	12	K-series	708	0.878447353	0.849287049	1.027723484	0.095441182
Calcium	20	K-series	2546	0.872035188	0.843087737	0.618705727	0.057657712
			Sum:	103.433504	100	100	

The list of identified chemical elements is more comprehensive for zone 2. In both areas are found the inherent elements (Fe, C, Mn) of the basic structure and atmospheric oxygen. In Zone 2, we find, in addition to zone 1, chemical "traces" of Silicon, Aluminum, Sodium, Magnesium and Calcium. In zone 1 we find isolated and accidental Chromium. In principle, all of these elements contaminated the section by washing it during operation, with hot lubricant.

The superior wealth in the elements of the zone 2 compared to 1 indicates the direction of propagation of the initial crack, respectively from the outer fiber to the inner one of the small end's eye.

We take into account that the penetration and fixation of some elements (especially of aluminum and silicone) consumes time and proves once again the temporal development of the phenomenon that initiated the destruction of the engine.
As a rule, the presence in oil of aluminum and silicone suggests an old, dirty engine. The source can be made up of certain oil additives and more modern additives for consistent greases. In most cases, aluminum and silicone are not split, the usual ratio aluminum: silicon is between 1: 2 and 1: 5. On the other hand, the singular aluminum can come from mechanical wear of pistons and other aluminum based organs. Single silicon comes from the self-foaming additive of modern oils.
Sodium may come from oil contamination with engine coolant, specific to old engine. On the other hand, Na and Ca may have as their source various oil additives. Magnesium may come from various coatings or from various engine equipments in which it enters as an alloying element.
Chromium has the widest range of sources, which can come from shafts, segments, hard coats, internal coolant losses, coatings, contamination with grease deposits.

2. Conclusions

A notable first result is the destruction analysis methodology, as it ensures a high degree of certainty of the conclusions. It was identified as the cause of the engine's destruction, the central cross section of the connecting rod small end eye (which contains the oil hole) and which has a typical appearance of fatigue break. Obviously, the oil hole is an important stress concentrator under the bending load. The rupture occurred in time, probably initiated by an initial microfissure.
Running such an analysis is initially conditioned by the state of conservation of the destroyed engine. Any engine contamination can compromise the results of the study. Secondly, a serious limitation is imposed by the level of endowment with specific equipment of the investigator's laboratory.
The complex methodology of solving such a difficult problem is original as well as the "step by step" manner in which the authors approached the cause. Last but not least, the authors used the technique of punctual chemical analysis of fracture sections based on energy potentials to validate the already obtained result.
Any problem regarding the identification of the cause that led to the failure of an engine is solvable with enough accuracy if none of the possible causes are neglected, and if a comprehensive experimental basis is available. The present paper is a real "good practice support" in approaching the causes of fatal destruction of engines.
Finally, the source that initiated the destruction of the engine was a microfissure placed on the outer fiber of the stick of the bead in its plane of symmetry. The area in question was potentially dangerous due to the important stress concentrator represented by the piston pin lubrication hole. This microfissure propagated over time by running untill it penetrated the entire section after a fatigue rupture mechanism.

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