WORKING LIFE OF DIESEL ENGINES: A RETROSPECTIVE ANALYSIS

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ABSTRACT

This published review article shows that diesel engines of the first post World II generation were characterized by inherent structural deficiencies of new developments, unfinished ideas. The results of studies carried out in that period are considered, technical solutions taken at that time are critically analyzed, including those that aimed at addressing identified problems. The analysis allowed the authors, in particular, to draw conclusions that there were brands of used metals, wear resistance and fatigue strength of cast iron, features of bearing fillets, cylinder block group, the quality of welded joints that had fundamental importance for that generation of diesel engines. As follows from the obtained data, engine components are not equivalent in their impact on its reliability and working life, form a certain hierachy as for their importance for design of the engine structure as a system.

ENGLISH SUMMARY

Background. *Four decades – from the late 1940s to the early 1990s – were a period of development and testing of domestic diesel locomotives and diesel engines. In the course of this work the problem of reliability and working life remained one of the main ones, causing hard-calculable economic losses (sudden failures, unplanned repairs, etc.). Commissioning of a new diesel engine was accompanied, as a rule, by massive failures of important components and consequently by setting of multiple tasks for urgent solutions.*

Objective. *The objectives of the authors is to investigate diesel engines of the first post World war II generation, find out their advantages and disadvantages and to draw a conclusion on their working capacity.*

Methods. *The authors use historical retrospective method and engineering analysis.*

Results.

1.

The main purpose of the first generation of diesel engines was to ensure transition from steam locomotive manufacture to a significantly more efficient type of traction – diesel locomotives. During the Second World War, engine building made a significant step forward; the new diesel engines used turbocharging, were faster, and had greater dimensions and weights.

Domestic engine-manufacturing problem was the lack of own prototypes, since engines produced at that time were obsolete and their modernization was essentially impossible. The role of prototypes was taken by the American samples, which were mounted on the equipment supplied under the military assistance [land-lease] – on locomotives (ALCO-539, Russian version was called D50), ships-icebreakers (Fairbanks Morse10-38D8⅛-2D100). Locomotive diesel engines of the first generation had a common drawback of all copied models of equipment, which was lack of information on issues related to production and ensuring reliable operation of engine components. For example, it related to information on what design elements were key to risk situations, whether hardening technologies had been used in the manufacture of certain nodes and what this technology was.

The problems first appeared in diesel engines such as D50 (denoted by [national standards' system] 10150–88–6CHN31, 8/33, 1,000 hp at 740 rpm), produced since 1946. The engine was a four-cycle, six-cylinder with in-line cylinders, pulse turbocharging and intercooling, which was very progressive for engines of the postwar period. The engin based on molded cast-iron frame-crankcase, in transverse bulkheads of which seats of crankshaft bearings were located. A massive crankshaft of 2100 kg was located on them. Molded cast iron cylinder block was mounted on the top surface of the crankcase and was fastened thereto with tie rods. This design was characterized by a combination of nodes, excessive by weight, with reserves of a working life (cylinder block, crankshaft, cylinder head) and nodes with limited working life, requiring regular monitoring (pistons, crankshaft bearings).

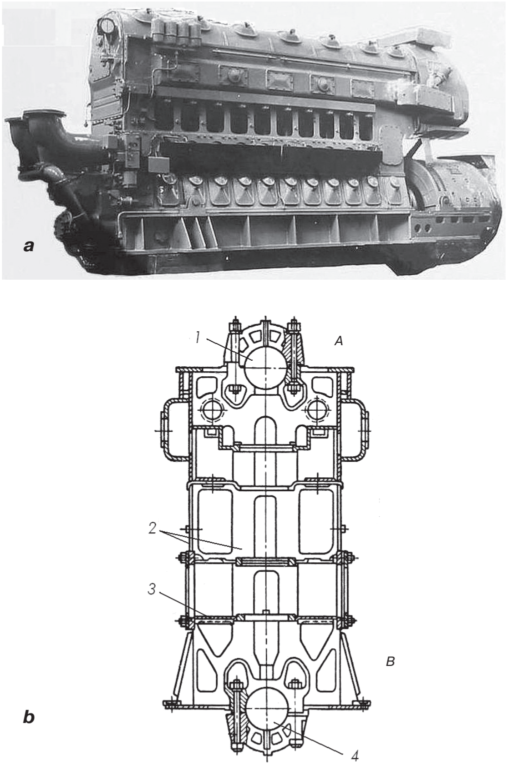
The most vulnerable in D50 were nodes of piston block – piston heads and compression rings. Piston design had no internal cooling; the greatest portion of heat within such a scheme was given to the cylinder liner, which served as the coolant through the piston rings. Gumming-up of upper O-rings occured on pistons, they lost mobility, there were breakthroughs of gases in the crankcase, partial melting of heads and burnout [1].

There were various opinions about causes of failures. They presumably refered to a large proportion of idle operation, high content of sulfur in the fuel, etc. However, the paper [2] showed for the first time that the heat loads on the surface of the piston D50 were very close to the critical value at which the non-cooled unit was losing its efficiency, i. e. partial melting and burnout became natural. The problem was solved by replacing the piston head alloy with low thermal expansion LowEx with the alloy PS12 with high heat conductivity, increasing the thickness of the bottom to facilitate heat transfer to the rings, transfer of the first ring to a less heated zone and the change in its cross-section and material [3]. Due to this it became possible to reduce failures; but the problem was finally eliminated only after the transfer of diesel locomotives with diesel D50 from mainline operations to shunting work where the pistons suffered from a lower heat load.

Thus, the most critical elements in the design of the piston D50, as it was found, were heads of the piston and upper (compression) piston rings. Efficiency of heat removal, which was provided by these structural elements, determined performance of cylinder-piston block of diesel engine.

More serious problems arose during the commissioning of diesel engines such as 2D100 (10DN20,7/ 2 × 25,4 of 2000 hp at 850 rpm). Locomotives with this diesel engine had to replace steam locomotives in freight and passenger traffic. Engine, simple in design and easy to manufacture (Pic. 1a), appeared for a long period since the mid-1950s to the early 1970s, to be the main one for domestic freight locomotive fleet, despite accompanying difficulties.

It was a two-cycle engin that had ten cylinders with two crankshafts – upper and lower, with opposed pistons and direct-flow slot drain of cylinders. In such a scheme technologically complex and unreliable

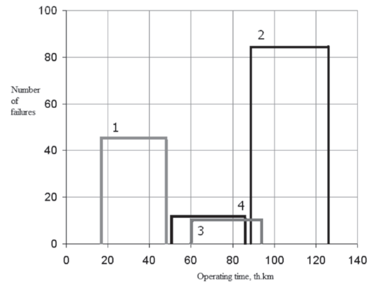


Pic. 1. Diesel 2D100.
a – general view: 1 – upper shaft crankcase; 2 – lower shaft crankcase; 3 – vertical transmission compartment; 4 – solid displacement blower pump of ROOT type.
b – block of diesel engine, a cross-section: 1 – suspension node of the upper crankshaft; 2 – vertical sheets; 3 – horizontal sheets; 4 – suspension node of the lower crankshaft; A-B – places of cracks formation.

nodes were excluded. These features gave, as it seemed, advantages in terms of reliability. However, there were a also shortcomings. The presence of the second crankshaft assembly of vertical transmission of power from the top to the bottom of the shaft complicated and charged diesel (it had 20 pistons, 44 crankshaft bearings). Respectively, engine failure due to accidental failure of any of its multiple nodes was more probable. The vertical arrangement of the nodes, including the presence of the crankshaft on the top, made it difficult to perform repair and maintenance of quite extensive cylinder-piston group, so maintainability of diesel was low.

By 1960, the fleet of these diesels exceeded a thousand units; period (mileage) between overhauls was set at just 600 th. km, and not less than one third of its locomotives had to be repaired ahead of schedule due to the failures of critical components. The greatest number of failures amounted to pistons, cylinder block, crankshaft [1, 4].

Piston of so-called original version was structurally different from the prototype, it was amended to adapt to the technology adopted at the producer factory. Piston had a composite structure, in the center of the head engine oil went through the hole in the rod. Under the influence of inertial forces oil was stirred up in the cavities between the housing and insert, extracted heat from hot surfaces and was



Pic. 2. Failures of pistons of 14A variant of diesels 2D100 (data [5]):
1 – cracks on streams; 2 – network of cracks of the bottom; 3 – through crack at the bottom; 4 – destruction of piston.

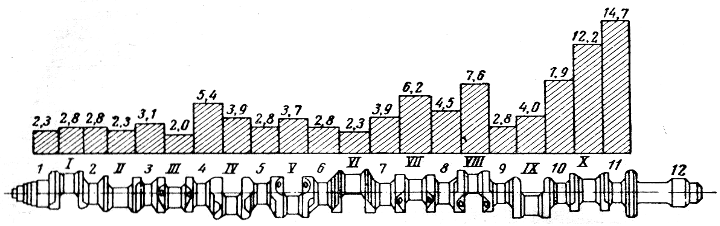
discharged through the tube section into the crankcase. After less than a year of work on the outside (fire) surface of the pistons small cracks appeared in the form of a net, through cracks in the center of the bottom and breaking of mounting studs were observed [5].

In addition to the initial version performance tests were conducted for pistons of four more experimental options – 14A, 14B, 14V, 22. At the designing stage an explicit decision was made to waive the cooling with churning as inefficient and to move to cooling of circulation type in which the oil flowed into the piston under pressure and moved to the inner cavity for a specific circuit, thereby effecting cooling, and then discharged to the crankcase (option 14A).

Mounting studs were upgraded. The piston of 14B type differed from the 14A type in location and configuration of cavities, versions 22 and 14V combined the structural elements of 14A, 14B and the initial piston version, the piston of 22 version had removable bottom to facilitate its restoration in case of damage (tests, however, were soon discontinued due to low reliability of removable connection). For all pistons the strength properties of the material of the head (gray iron) were increased by 40%, however thermal conductivity decreased slightly. The design of the diesel engine used a more advanced fuel injection equipment to prevent accidental approximation of the injector component flame to the bottom of the piston; there were oil pumps with capacity up to 100 m^3/h instead of the earlier versions of 68–72 m^3/h.

The test results were discouraging: netting of cracks similar to the one that was in the initial version, was observed at the pistons of all options. Moreover the engineers observed cracks on the streams to accommodate the piston rings (14A, 14B), internal cracks – on the edges of the head (14B), through cracks – at the bottom (14A, 14B), and other types of damages [5, 6]. For pistons of 14A type, for example, a net of cracks (82 damaged pistons, or 54%, Pic. 2) became apparent at a sufficiently high operating time – more than 90 th. km, which indicated a periodic overheating and accumulation on the surface of thermal fatigue damaged. Cracks on streams (46 cases, or 30%) were observed as a result of carbon deposits in the inner side cavities of the piston also due to overheating. At the same time, through cracks, damages of pistons had likely a random character.

Tests of pilot pistons continued, and by the beginning of the production of second-generation diesel engines (1960s) the causes of high failure rate were not identified.



Pic. 3. Distribution of damages of the upper crankshaft of diesel 2D100 on its elements in% of total damage [13]. I–X – crank journals; 1–12 – main journals.

Damages of pistons 2D100 were mostly of thermal nature: design changes were aimed at increasing the strength of the studs and their mounting, heat stability of the head, rational layout of the internal cavities for oil circulation.

The second place by frequency of failures was occupied by cylinder block with unusual, for that labour time, construction of vertical and horizontal rolling steel sheets (Pic. 1b), interconnected by electric welding using mainly fillet welds. Such a design is more time consuming and more expensive in comparison with molded and welded-molded blocks [7], but at the same time allowed to quickly master the production of the unit, for example, in wartime. In terms of specific weight (2,5 kg / hp) cylinder block was very light. Horizontal sheets formed together with vertical sheets a sort of cross-links or «floors» that increased the overall flexural rigidity. However, despite this, the whole structure had a large static deflection under its own weight, as well as deflections in vertical and horizontal planes [8, 9].

In the initial period of operation cracks were observed in welded seams, running into studs of the block, the most common damages were observed in connection node of indigenous supports (straps) of crankshafts with upper and lower horizontal plates of the block (Pic. 1b – A), in the anterior vertical sheet of control unit and in the place of coupling of the inclined and vertical plates with the bottom band (Pic. 1b – B). A residual deformation of the crankshaft bearing points was observed, wherein misalignment of the upper line of the crankshaft reached 0,18 mm [9, 10].

Subsequent overhauls revealed that at least 30% of diesels, arrived for repair, had inherent deformations of strain bearing of crankshafts (curvature of the shaft line, misalignment and crack). Damages were located closer to the support units of the crankshaft, horizontal sheets adjacent thereto (30% of cracks), and primarily – to the structural elements that received the load of the vertical transmission (50%). Attempts to strengthen the structural elements of the block, to improve the quality of boiling of seams did not bring the desired result, they only reduced the severity of the problem.

Thus, it had been found that the most loaded and damageable elements in cylinder blocks of diesel 2D100 were nodes of hanging upper and lower crankshafts with adjacent horizontal plates and vertical transmission compartment.

The crankshaft was the third in failure rate and the first in the consequences of those failures.

For the production of crankshafts 2D100 the technology of iron castings was applied, which was new for its time. Casting made it possible (as compared to conventional forging) to produce the elements of a more complex shape and with less consumption of the metal. The fact that the irons were inferior to alloy-treated steels in their strength properties, resistance to fatigue failure, was not considered fundamental. In a constructive scheme crankshafts had the greatest (of the then known diesel engines) index of overlapping of center shafts (122 mm), a rational form of the cheeks and internal cavities [8, 7].

Low wear resistance of shaft journals surfaces was recorded at the very beginning of operation. Depreciation was on average three times higher than the predicted values and limited a working life of the crankshaft to 600 th. km run period [11]. There were also cases of fractures. With the increase in diesel locomotives and their service hours the problem of cracks and fractures came to the fore. On diesels, produced in 1956–1961 for this reason 33 to 40% of the crankshafts were changed [12], approximately in half of the cases it happened due to cracks that were detected during routine repairs after the engine had been lifted.

Damages of crankshaft were of fatigue nature, and their length distribution was fairly uniform (Pic. 3). «This uniformity indicates that the crankshaft of diesel engine 2D100 is quite equal in strength in neither by sections», as it was optimistically pointed out in [13]. Rather, it indicates that the loading conditions of the shaft all along were equally bad. The predominance of failures in the tenth crank and eleventh main journals was explained by ineffectual location of the bevel pinion of the vertical transmission causing additional shaft deflection, not compensated by its rigidity or structure of supporting nodes. A major influence on the stress-strain state of the shaft was provided, as it turned out, by the deformation of the shaft support units in the cylinder block and the presence of misalignment.

The first notable step to solving the problem was to strengthen the crankshaft due to replacement of the material – (alloyed iron Cr-Ni-Mo), from which it was originally casted on, with high-strength cast iron with globular graphite. Due to this change wear decreased by several times, but it did not influence the process of cracks and breaks appearance [14]. The assumption that new crankshafts had deviations in chemical composition, mechanical characteristics and structure had not been confirmed, studies showed that the quality of broken metal of shafts of high-strength cast iron was more than good [15], and therefore, structural elements were the most dangerous.

Transition fillets between the journal and cheek of the crankshaft, where the majority of cracks was formed [11], were recognized as most dangerous, as the radius of that unit was of only 8 mm. After rounding the fillet, increasing its radius from 8 to 12 mm, introduction of rolling technology, i. e. creation of compressive stress zones, which prevented the formation of sites of residual tensile stresses on the surface, the number of cracks and fractures decreased by 4,5–6 times.

So the transition fillets of main and crank journals on the cheeks of the shaft became in fact the most critical elements in the design of the crankshaft 2D100 determining the reliability of its work.

Conclusions. *Drawing some conclusions about what has been written, it is necessary to note the following. The first generation of diesels shortly after the* start of their production got a series of apparent failures of the pistons (D50, 2D100), cylinder blocks, crankshafts (2D100). The prototype engines did not have so many damages of that kind. It is obvious that when copying technical solutions, important circumstances, known only to developers, were not taken into account. This refers to the material properties (important chemical components, required physical characteristics), to the role of certain constructive proposals that might have been simplified for greater workability, to hardening technology. It was found that for this generation of diesel engines the following characteristics were of a fundamental importance:

– Thermal conductivity of alloy for the piston head, durability of cast iron piston rings (D50);

– The stiffness and strength of the elements of the cylinder block, quality of welded joints (2D100);

– The material of the crankshaft (high-strength cast iron) with higher mechanical properties (wear resistance, fatigue limit), the rational design of fillets (corner radius) and their hardening (2D100).

The complexity of the situation was that the identified weaknesses were at the nodes of particular importance for the operation of the engine, and might lead to sudden failures. The importance in this case refers, primarily, to the place of this node among other nodes in the design of a diesel engine as of a system defined by statistical frequency of failure of the diesel engine caused by a certain node's failure. We should note that the nodes or groups of nodes form conventional levels of significance, and thus constitute a kind of hierarchy, namely:

(1) The crankshaft. The engine is very sensitive to its failures. In 45–50% of the failures of crankshafts 2D100 («pure» breaks) the entire plant broke down. At the same time, the loading conditions of the crankshaft directly depend on the hardness and the state of the cylinder block bearing points, so the reference node of the crankshaft in the cylinder block must be included in this group.

(2) The cylinder-piston group. From 15 to 20% failures of pistons (destruction, through cracks) were fatal to the entire diesel, its working capacity.

This distribution is fixed according to data on the operational work of the first generation diesels. The analysis of characteristics of the engines of the second and third generations will expand and clarify the hierarchy of componentwise importance. The second part of the article will be devoted to it.

(To be continued)

Keywords: railway, history, diesel locomotive manufacturing, diesel locomotive, working life, failures, retrospective analysis, regularities of the postwar generation.

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