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Selected failures of internal combustion engine pistons

INTRODUCTION

The present development of piston internal combustion engines has contributed to the improvement in the durability and operation reliability of the elements of the piston–cylinder assembly. Many research & development and scientific centres both at home and abroad are conducting studies aimed at increasing the net power and the torque and reducing the fuel consumption, while meeting the applicable EU standards for the emissions of harmful combustion gas components [1, 2]. One of the main objectives of automotive vehicle manufacturers is to ensure the highest possible durability and reliability of the engine [7, 9].

The piston is an element of the crankshaft assembly, which takes part in the conversion of thermal energy into mechanical work [6, 10]. The piston head makes a movable part of the combustion chamber. The piston grooves hold piston rings that seal off the cylinder working space, while each of the piston pin bosses has a piston pin bear-mounted in it, which transfers the gas force to the crankshaft.

The main job of the piston is to take over the piston head-space pressure force by the piston head. This force, increased by inertia forces, is transferred to the piston, the piston pin and, via the connecting-rod, to the crankshaft.

The piston construction must resist large thermal and mechanical loads [8]. It is required to:

– carry away the heat from the hot piston head, heated by high-temperature exhaust gas, to the cooled cylinder walls,
– guide the piston in the cylinder sleeve and to take over the lateral piston pressures on the cylinder bearing surface,
– cause the lowest possible friction losses, and
– ensure a low lubricating oil consumption by the engine.

Materials used for the pistons of automotive internal combustion engines include:

– aluminium alloys,
– alloy steels, and
– cast iron.

Materials that are most commonly used for manufacturing pistons include: cast iron, alloy steel and aluminium alloys, aluminium-silicon (Al-Si) alloys and aluminium-copper (Al-Cu) alloys.

These alloys are characterized by low density, being advantageous due to the small piston mass, and a large thermal conductivity coefficient [5]. Aluminium alloys are distinguished by good formability during casting and good machinability (machine cutting). The major drawbacks of these alloys include: a large thermal expansion coefficient, low hardness and low strength indices at elevated temperatures.

Cast-iron pistons are less and less often used. They can be found in low-speed self-ignition engines. They are characterized by good slide properties, retaining good mechanical properties at elevated temperatures, and a small thermal expansion coefficient. The main disadvantages that limit the use of cast-iron pistons in contemporary high-speed engines are: a low thermal conductivity coefficient and high density that results in a large piston mass and considerable inertia forces.

Due to the high strength indices and low thermal expansion, pistons are increasingly often made of alloy steels. In spite of the high density of steel, to take advantage of the good mechanical properties

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of this material, designers give pistons appropriate shapes with small overall dimensions, which reduces the piston mass and makes it comparable to the mass of aluminium alloy pistons.

The basic piston manufacture technology is by casting in sand or metal (aluminium alloy) moulds. For very heavily loaded engines, aluminium alloy or steel pistons are made by forging. Forging causes very favourable changes in the structure of the material, which improve its mechanical properties.

The aim of this publication is to make a review different, most commonly found types of piston failures, which could be used by specialists working for the automotive industry and being concerned with diagnosing the technical condition of automotive vehicles and examining the causes of their failures. In order to be effectively performed, the diagnosis of an engine and a complete vehicle requires a comprehensive and interdisciplinary approach to the identification of their technical condition.

1. TYPICAL PISTON FAILURES

As the annual vehicle mileages and servicing periods increase, new design solutions are developed. They are intended to ensure the safe and reliable operation of the engine within its servicing period and to protect the catalysts and the particulate matter filters against various pollutants. In the framework of those modifications, engine designs are being developed and modified on an ongoing basis. The construction of contemporary engines is well refined and the manufacturing tolerances and masses of individual elements have been reduced, while improving the quality of materials used for them. In spite of so significant progress in the engine design, the types of engine failures that can be found are still similar. One of the most frequently occurring engine breakdowns is the failure of the engine pistons. Engine piston failures occur at various mileages and are due to different causes. These failures are caused by material defects and engineering and operational errors. Design error can be found rarely, since the engine design has attained a very high level of perfection over the period of more than 100 years. Engineering errors may result from the incorrect choice of clearances between the piston and the cylinder or the use of an inappropriate material. Errors of this type most often occur in repaired engines, in which unoriginal parts or parts not recommended by the manufacturer have been used. The most common causes of piston failures include: their insufficient cooling, insufficient lubrication of the piston guiding part, thermal fatigue of the piston head surface, failures due to an incorrect combustion process, and mechanical damage.

During engine operation, the clearance between piston and the cylinder might be reduced beyond the allowable limits or even totally eliminated due to incorrect dimensions of either of the parts or cylinder distortion as a result of excessive thermal loads. Moreover, during engine operation the piston attains higher temperatures than the cylinder does, which results in different thermal expansions of the piston and the cylinder. The thermal expansion of the piston is much larger than that of the cylinder. In addition, the thermal expansion coefficient of aluminium alloys is about two times greater than that of grey cast iron, which should be taken into account in the design.

If the clearance between the piston and the cylinder decreases, mixed friction occurs between the two parts due to the stretching of the oil film existing on the cylinder wall [3, 4]. The consequence of this is that the bearing surfaces on the piston skirt are rubbed into the polished cylinder surfaces. The temperatures of the parts additionally increase due to the existence of mixed friction and the released friction heat. At that time, the piston presses on the cylinder wall and the oil film, thus forcing it out. The piston in the cylinder starts working dry, which leads to the appearance of initial spots showing signs of abrasive wear, with dark discolouration on the surface.

To sum up, it should be noted that seizing due to too small clearances is characterized by these features: very highly polished pressure spots, which gradually change into dark-coloured areas of abrasive wear.

Figure 1 shows a view of a cylinder, on which signs of piston head and ring area fusion in a spark-ignition engine are visible. The fusion of the piston head in spark-ignition engine is caused by a hot-bulb ignition occurring on the pistons, and chiefly on their heads, and in the larger flame extinguishing areas. The hot-bulb ignition occurs due to glowing parts in the combustion chamber, which have a higher temperature than the autoignition temperature of the air-fuel mixture. As a result of that glowing, the temperature of the piston head rapidly increases. In this process, the temperature attains levels that make the piston material soften and melt. The possible causes of this failure may be due to:

- too low sparking plug heat factor,
- too lean air-fuel mixture, and
- valve damage or leak or an insufficient valve clearance. This causes the valves to close incorrectly. The flowing exhaust gas considerably increases the temperature of the valves, which start glowing. This affects primarily the exhaust valves, as the inlet valves are cooled by the inflowing fresh charge,
- glowing piston head, cylinder head, valve and sparking plug burning residues,
- fuel with an inadequate, too low octane number. The fuel quality must correspond to the engine compression ratio, which means that the octane number must meet the octane requirements of the engine for all operation conditions,
- petrol contamination, e.g. with diesel oil,
- a large amount of oil in the combustion chamber, which may result in a fast oil flow onto the piston rings,
- high engine temperature, which can be caused by inadequate engine chamber ventilation, and overheating.

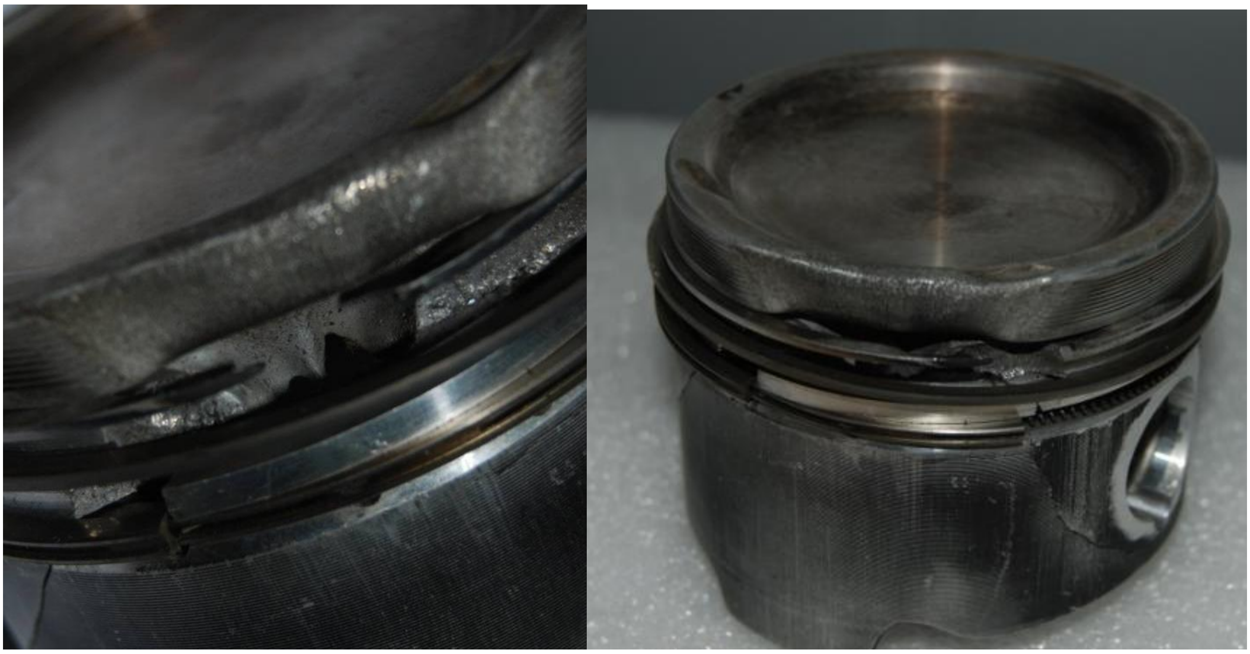

Fig. 1. Fusion of the piston head and the ring area

Figure 2 illustrates the mechanical damage to a piston. During engine operation, a valve or another foreign part fell into the cylinder, causing a piston failure. Mechanical piston damage may occur due to a foreign body entering the cylinder, which has passed through the air filter or got there during repair or maintenance work. Failures due to this cause depend on the size of the part that has entered the cylinder, and its material. It should be noted that, as practice shows, a foreign part that enters one cylinder may, via the inlet or exhaust manifold, get to the other cylinders; so, due to the entrance of one part, failures might occur in many different cylinders. If the size of a foreign body entering the combustion chamber is greater than the minimum distance between the piston head and the valves, then, in addition to the damage of the piston, a valve bending or even valve guide breaking may also occur.

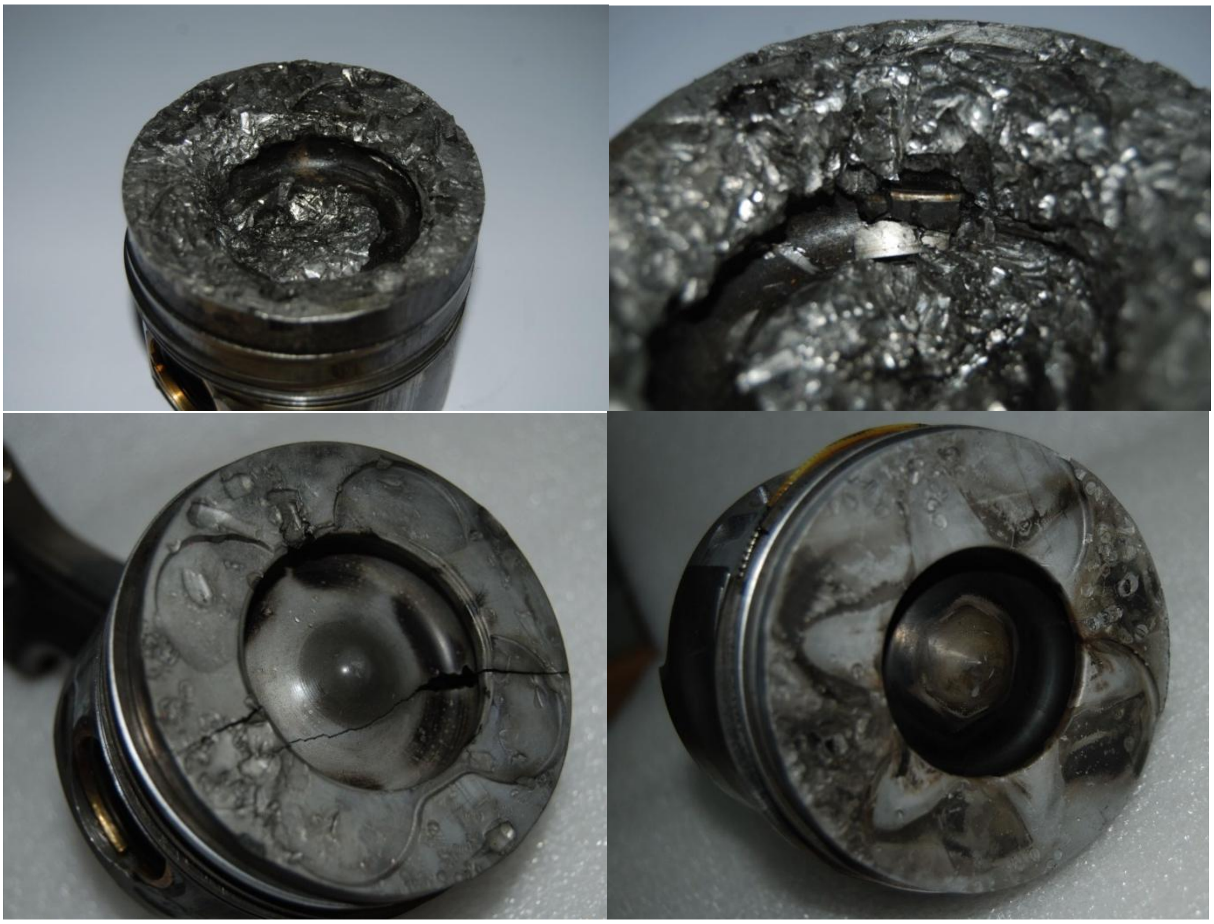

Fig. 2. Mechanical piston damage

Figure 3 illustrates a piston head fusion. The piston head and crown area has been totally damaged. The upper piston part has been melted down as far as to the rings. The melted material on the piston skirt has caused damage and signs of abrasion. An engine overloading occurs as a result of too large an amount of fuel supplied to the cylinder, and consequently the amount of heat exceeding the quantity assumed by the designer, based of which both the strength of the engine's parts and the efficiency of the cooling and lubricating systems have been selected. The increase in the quantity of heat taken by the piston head may be the result of too large a fuel dose injected to the combustion chamber in a self-ignition engine or the occurrence of detonation combustion in a spark-ignition engine. It can also be caused by an excessive supercharging pressure. With an excessive dose of fuel injected to the cylinder or with a faulty atomizer, a fusion of the upper piston part might occur, as shown in Figure 3. So large extent of piston damage has occurred not only as a result of the excessive amount of heat released in the cylinder, but also due to the reduction of the amount of heat transferred to the cylinder wall, caused by immobilizing the piston rings by the material brought in from the piston crown.

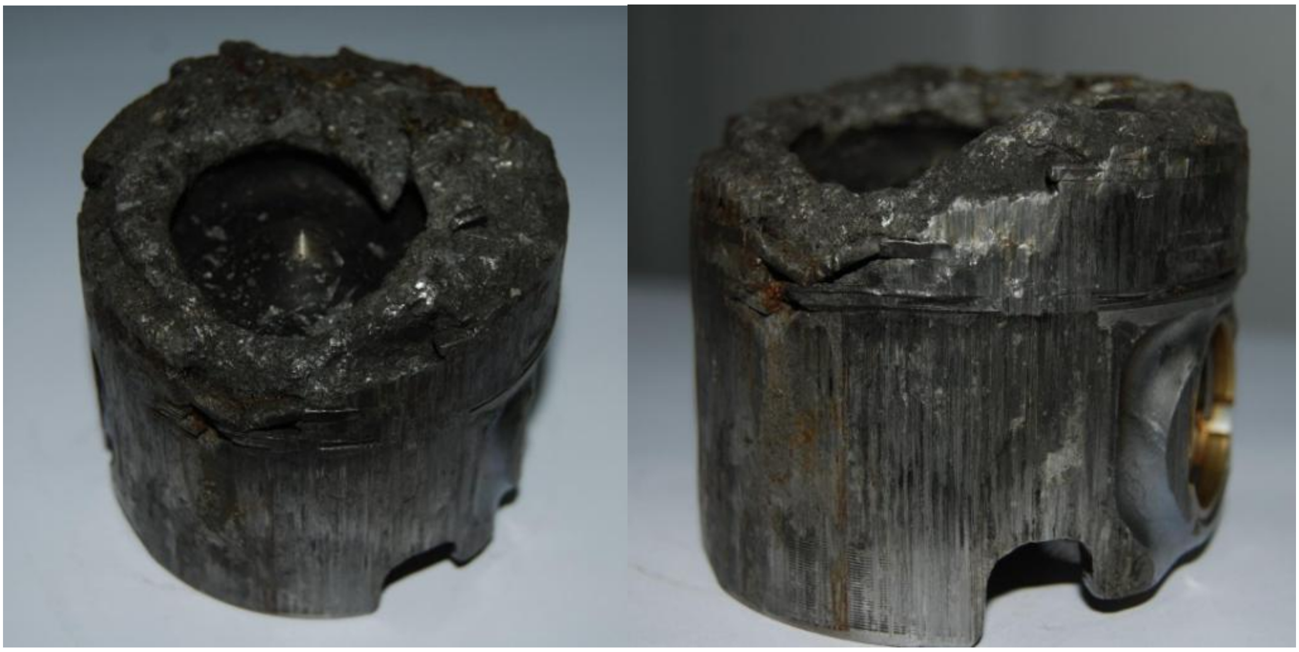

Fig. 3. Fusion of the piston head and the ring area

Figure 4 illustrates a piston skirt seizure. The piston skirt has been almost completely seized. The surface of the abrasion spots has a dark colouring, is rough and heavily over-ground. The ring area is slightly damaged due to the worn piston material that has been rubbed out upwards. The heavy overheating of the whole engine is caused by the deterioration of the cylinder lubrication process. This has resulted in characteristic abrasion signs, caused by the insufficient lubrication with surface over-grinding. The absence of abrasions on the piston crown and the damage located on the piston skirt preclude overloads caused by an incorrect combustion process. Likely causes of this failure include:

– engine overheating due to a malfunction of the cooling system (cooling medium shortage, fouling, a faulty water pump, a broken thermostat, a broken V-belt, an inadequate or incorrect system responsible for the cooling system),
– in air-cooled engines: overheating due to deposits and fouling inside the cylinder, a broken cooler or a malfunction of the air cooling ventilation system.

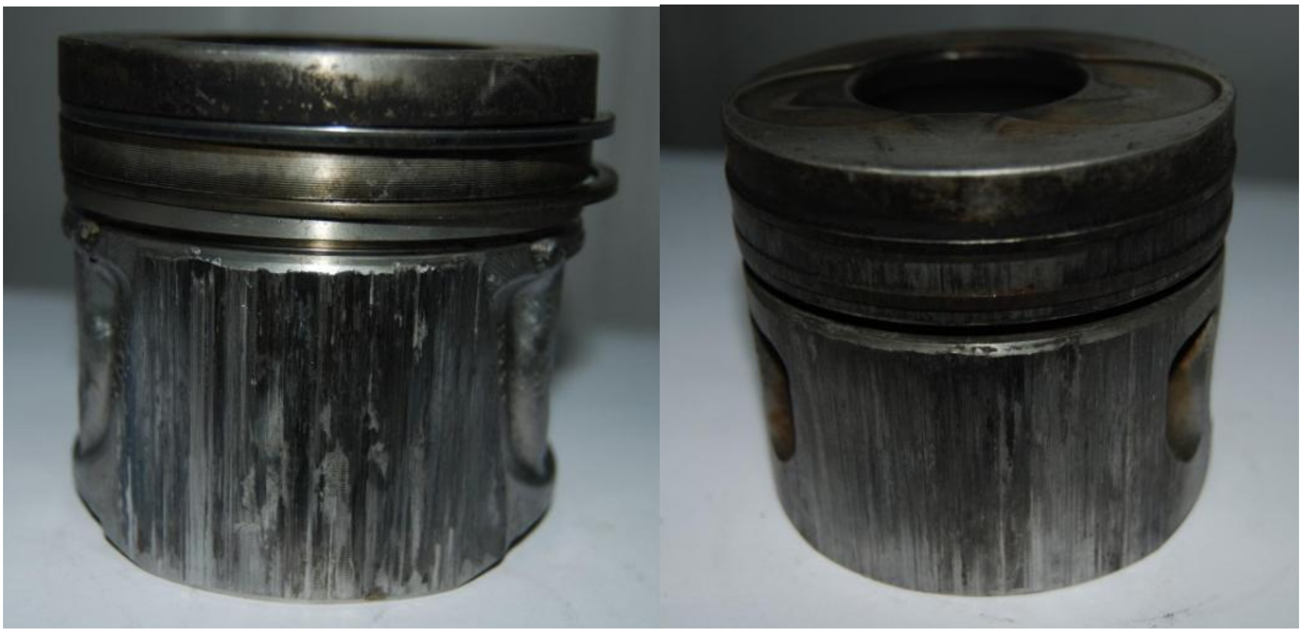

Fig. 4. A piston skirt seizure

A fatigue crack of the piston pin propagates along the semicircle around the initial point. The so called fracture form from the initial crack, which divides the piston head into two parts – as can be seen in Fig. 5a. These are cracks that result from excessive loads. This process can be accelerated, if there is no sufficient amount of lubricating oil. The initial crack on the piston pin forms as a result of excessive overloads. It will then propagate even at nominal loads and will ultimately result in a break of the piston. Likely causes of the failure include:

– an incorrect course of the combustion process, and in particular a self-ignition caused by the delayed ignition,
– excessive or incorrect starting of the cold engine,
– a liquid (water, fuel or oil) present in the cylinder causes a hydraulic lock,
– improving the effective engine power by using, e.g., the chip tuning with no piston replacement, and
– using incorrect or reduced-mass piston pins. The piston pin might be distorted to form an oval shape by applying excessive loads on the bearing in the boss.

a) b)

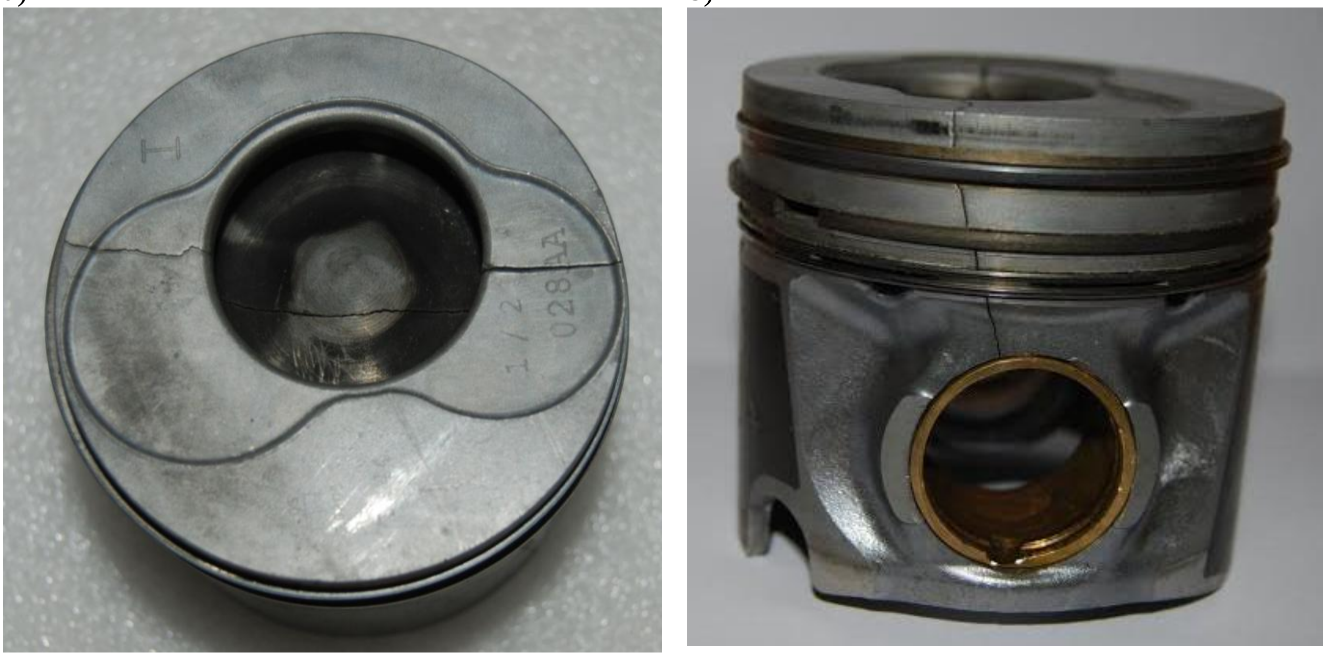

Fig. 5. A crack on the piston pin: a) cracked piston head; b) cracked piston skirt

The engine working process must proceed in a defined manner in order to get the maximum efficiency at maximum pressures and pressure increase rates, not exceeding the levels assumed in the design of the engine. To ensure the correct combustion process, the control parameters, and especially the ignition advance angle or the injection advance angle, must be contained within the limits recommended by the manufacturer. An earlier start of the combustion process due to the premature generation of the ignition spark or the premature start of feeding fuel to the cylinder of a self-ignition engine will result in an increase in the maximum pressure and maximum temperature of the combustion process.

The ignition advance in a spark-ignition engine may be caused by the improper adjustment of the advance angle or be due to a failure of the timer-distributor or a failure of the electronic ignition spark timing system. A delay in ignition relative to the moment specified as optimal by the manufacturer is not dangerous to the engine. What is very dangerous, however, is an excessive ignition advance, which will result in an increase in the maximum combustion pressure, an increase in the pressure increase rate during the combustion process, and a rapid temperature increase in the cylinder. This will generate a considerable amount of heat which will be taken by the piston head. Apart from the above-mentioned causes of the incorrect ignition advance angle, a premature ignition can be caused by glowing particles of carbon deposit built up on the combustion chamber walls or a sparking plug with an inadequate heat factor. The hot-bulb ignition may also be induced by a damaged insulator of the central sparking plug electrode. As the combustion of the air-fuel mixture takes place simultaneously within the entire combustion chamber volume, therefore temperature differences occur. The highest temperatures occur in those combustion chamber locations, where the combustion process starts, that is in the vicinity of the sparking plug or the hot-bulb ignition occurrence place. This also causes differences in piston head temperature, with the highest temperatures occurring in those locations that are situated closest to the ignition initiation location. In the piston head spots that are in contact with the air-fuel mixture at the highest temperature, the greatest increase in piston head material temperature will occur. The strength of the piston material decreases with increasing temperature. At the moment, when the strength of the piston material becomes lower than the medium pressure prevailing in the combustion chamber, its failure will occur in the form of a fairly regular hole blown out in the piston head.

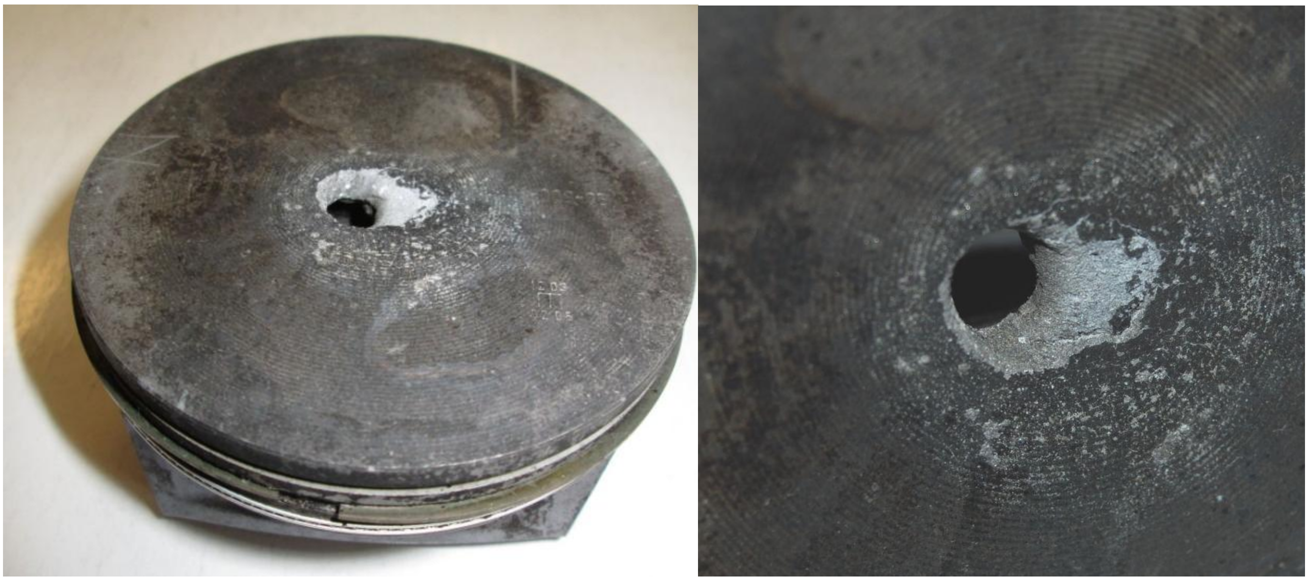

Fig. 6. A hole in the piston head in a spark-ignition engine is caused by a premature ignition or a hot-bulb ignition

CONCLUSIONS

The piston failure cases discussed in the paper are the most common ones. Often, in a specific case, failures can be found, which have the features of not only one of the above-mentioned cases, and are therefore complex failures, caused sometimes by several factors. Due to the improper use of the engine or its incorrect repair, a failure of the piston may occur. Therefore, unless the error that has contributed to the piston failure is clearly identified during the repair, it will be assumed that the failure has been caused by the improper operation of the engine. The primary cause of the failure is not responsible for the whole range of failures occurred in the engine as a result of its operation in a faulty condition. If it is possible, efforts should be made to identify the primary cause of the failure and the extent of damage that would occur in the engine, should its operation be stopped immediately after receiving the signal of engine malfunction.

Abstract

The paper presents typical, most frequently found failures of pistons used in four-stroke internal combustion engines. Typical piston failures caused by the poor quality of fuel, the maladjustment of the engine feed system or wrong engine operation have been discussed. The most common cause of piston failures is an incorrectly performed repair of the engine or its improper operation.

Keywords: combustion engine, piston construction, pistons failures

Wybrane uszkodzenia tłoków silników spalinowych

Streszczenie

W artykule przedstawiono typowe, najczęściej spotykane uszkodzenia tłoków stosowanych w czterosuwowych silnikach spalinowych. Scharakteryzowano typowe uszkodzenia tłoków spowodowane złą jakością paliwa, nieprawidłową regulacją układu zasilania silnika lub złą eksploatacją. Najczęstszą przyczyną uszkodzeń tłoków jest nieprawidłowo przeprowadzona naprawa lub błędna eksploatacja silnika.

Słowa kluczowe: silnik spalinowy, konstrukcja tłoka, uszkodzenia tłoków

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