Knock (and pre-ignition) damage on engine components: case studies

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Due to the stringent regulations in terms of CO_2 emissions, in order to increase engine efficiency, design strategies are oriented towards both increased spark advance and higher compression ratio, determining a higher probability to induce knock and abnormal combustions. Since slight knock does not lead to compromising engine damage, it should be tolerated in order to pursue the maximum efficiency. In the present study, knocking damages on several combustion chamber components after industrial durability tests are shown, aiming to underline the main effects of knock and to guide materials and coatings selection. Some hints are also made to the deleterious effects caused by persistent knocking combustions turning into pre-ignition. Piston Al alloys are usually more sensitive to knock induced thermo-mechanical stresses, but also cylinder heads, liners and spark plugs might be affected.

KEYWORDS: KNOCK - AUTOMOTIVE PISTON - COMBUSTION CHAMBER COMPONENTS - FAILURE ANALYSIS

INTRODUCTION

Knocking combustions are one of the main concern in the latest generation Spark-Ignition (SI) engines, since higher compression ratio and spark advance are desired to maximize engine efficiency, leading to higher pressure and thermal load inside the combustion chamber and thus to a higher probability to induce abnormal combustions [1,2]. This issue is further emphasized by the widely adopted turbochargers, whose aim is to regain a high output power, in spite of engine downsizing [3]. Differently from a normal combustion, which is triggered by the spark plug and it develops through a spherical flame front, knock consists in the spontaneous auto-ignition of the end-gas ahead of the propagating flame. This irregular combustion mode is characterized by a substantial increase of the rate of heat release and pressure oscillations, whose result is an enhanced heat flux coupled with higher mechanical stresses [4,5]. Due to the need to push the limits of engine efficiency, knock should be today partially tolerated, thus it becomes necessary to accurately estimate possible knocking damages [6–8]. In the following paragraphs, knocking damages after typical industrial durability tests are shown, aiming to

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underline both that slight knock is not detrimental to engine life [8,9] and that materials and coating selection plays a key role in limiting the damage, besides a calibration strategy able to promptly switch off abnormal combustion over a certain threshold.

EXPERIMENTAL METHODS

The objects of the experimental activities have been the combustion chamber components which are mainly affected by knocking combustions: pistons, cylinder liners, cylinder heads, spark plugs. All analyzed pistons are forged and made of a nearly eutectic Al-Si alloy, T7 heat treated, whose chemical composition (Table 1 [7,8]) was checked by a Glow Discharge Optical Emission Spectroscope (GD-OES Spectruma GDA 650). Aiming to prevent piston rings sticking, the 1st ring groove is hard anodized. Cylinder heads are made of a gravity die cast A356 Al alloy, whose microstructural characteristics were deeply investigated in [10]. The analyzed cylinder liners are Nikasil coated [11], while spark plugs consist of noble metals electrodes and a brittle, ceramic insulator nose enveloping the ground electrode.

The 1st level analysis of all components was carried out through a high-resolution Nikon D40 digital camera, a stereo-microscope and a 3D digital microscope (Hirox KH-7700 equipment). More in depth analyses have been conducted through the Scanning Electron Microscope Zeiss EVO® MA 50 (SEM), equipped with an energy dispersive X-Ray spectroscope (EDS).

Tab.1 - Results of GD-OES chemical analysis on pistons crown (average of 3 points of measurement)

	Si	Cu	Mg	Ni	Fe	Al.
El. [wt%]	11.87	2.93	0.76	2.25	0.24	Bal.

RESULTS AND DISCUSSION

Pistons damage under low/middle knocking combustions.

As reported in the introduction, pressure oscillations associated to knocking combustions induce increased thermo-mechanical stresses [4,5]. Due to the high sensitivity of Al alloys to thermal loads, pistons are mainly affected by knocking damage and deserve particular attention. Light knocking combustions usually produce almost no damage or typical slight erosion signs on Al pistons head, in particular at valve reliefs or at piston top land. A polished area at valve reliefs edge is frequently observed: due to the high surface/volume ratio of this area, local heating is considerably favored [8]; the consequent local thermal expansion produces a limited contact between cylinder liner and piston valve relief. In this case, none of the other components of the combustion chamber are involved, and typically the cylinder surface treatment is not affected. Many examples of tiny damage under controlled knocking conditions for up to 15h bench tests are reported in [8]: it should be pointed out that, to some extent, this is not a fatal engine damage, since it simply produces debris inside the combustion chamber, without affecting piston structural resistance or engine compression ratio.

More interesting from a technical point of view and challenging in terms of both materials research and engine control strategies is a medium knocking level. The result of a persistent condition of medium knocking combustions is shown in Fig.1: the occurrence of a sliding contact between cylinder and piston valve relief is perceivable in the upper polished area, while the jagged edge of the valve relief shows a moderate erosion. An incipient erosion is also perceivable at piston ring groove, highlighted by arrows at higher magnitude: the ring groove is a crevice area, a potential site of knock triggering since it collects the end-gases furthest from the spark-plug [8,9,12], moreover the hard and brittle anodized layer is extremely sensitive to knock pressure waves. It should be also highlighted that the anodized layer grows thanks to Al passivation, therefore it hardly covers eutectic Si or primary Si crystals, which form weak points [8,13]. SEM-EDS investigations have been carried out on the area highlighted in red in Fig.1, in order to depict the first stages of the anodized layer damage. The results are reported in Fig.2: small cracks are observed at ring groove edge, highlighted by the arrows, and EDS analyses in correspondence of cracks show a higher Si content, confirming the presence of primary or eutectic Si crystals beneath.

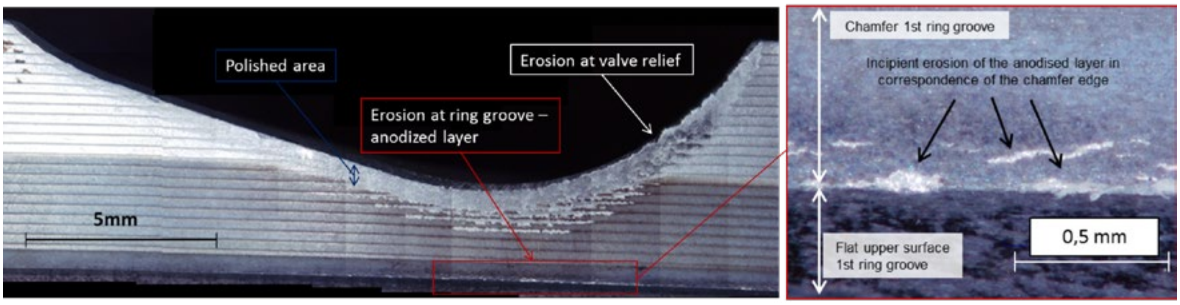

Fig.1 -Hirox image of an automotive piston intake valve relief. Erosion is perceivable both in the upper part of the valve relief (see jagged edge) and in the ring groove (white discoloration). Image from a turbocharged V8 engine.

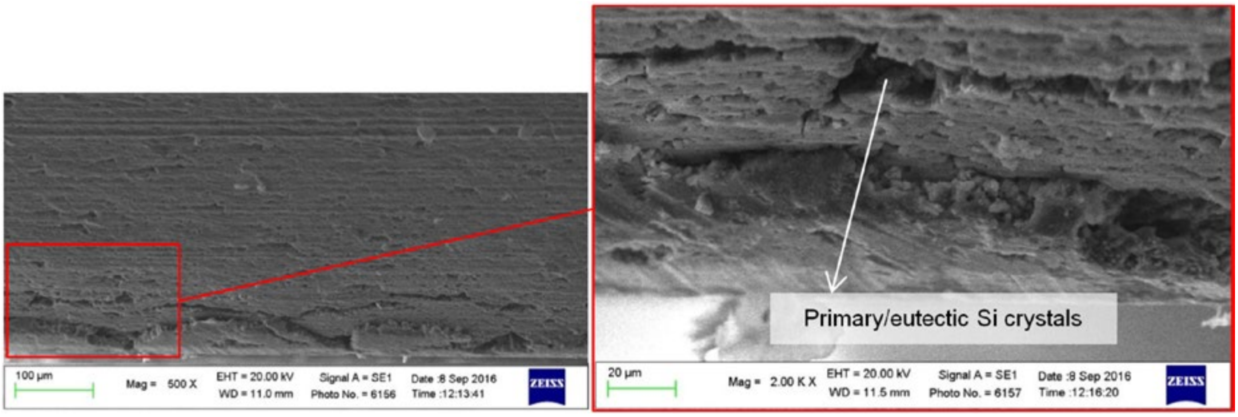

Fig.2 -SEM micrographs of the 1st ring groove anodized layer, characterized by incipient erosion. EDS analyses revealed the presence of a higher amount of Si beneath the cracks. Image from a turbocharged V8 engine.

Even if no consequences are perceived at the initial stages of the anodized layer erosion, this damage might obstruct the 1st ring functionality. A persistent erosion process might produce a total wear of the anodized layer, leading to a direct contact between the 1st ring and piston Al alloy. Under these conditions, the 1st ring is prone to sticking to the lower flank of the ring groove due to the high pressure and temperature induced by combustion, inevitably resulting in power loss and lower combustion efficiency. Typical images of ring sticking are reported in Fig.3. In case of heavy wear of the anodized layer, several micro-welding spots can be observed (arrows in Fig.3a). At higher pressure/temperature, the damage is rapidly intensified, leading to a complete ring sticking (Fig.3b); an Al transfer layer, typical of adhesive wear, is also perceivable on piston ring (Fig.3c), and confirmed by SEM-EDS analyses (here not reported).

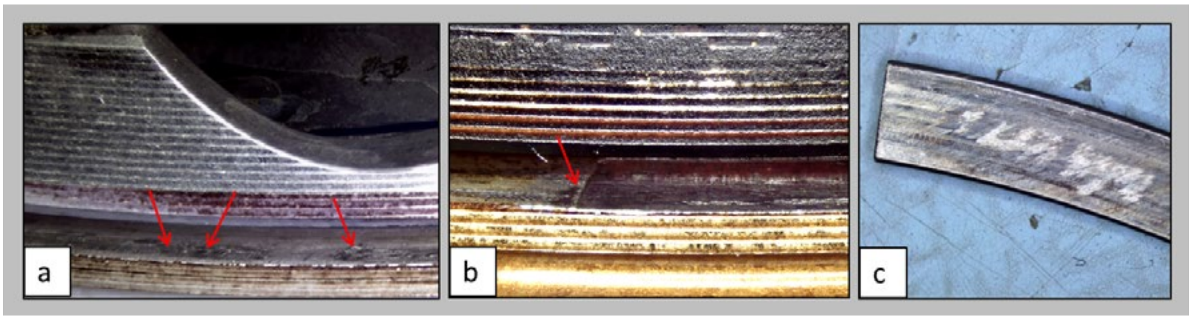

Fig.3 -Stereo-microscopy micrographs depicting 1st ring – piston welding. (a) Micro-welding spots (pointed by arrows) and Al plastic deformation. (b) Noticeable sticking area at the 1st ring groove. (c) Evidences of piston material deposited on piston ring.

Besides 1st ring sticking, one of the most critical knocking damage is piston ring groove deformation, which is usually checked through precision gauge blocks. Under severe knock erosion at piston head, in particular in correspondence of the valve relief (which is characterized by a reduced cross section), the ring groove might undergo significant dimensional changes in the range 10^{-2} – 10^{-1} mm, which in the worst cases culminate in a complete piston groove closure and ring locking. It is usually observed a correlation between plastic deformation and erosion of the valve relief over a certain threshold. An example of that is reported in Fig.4: a tiny ring groove deformation (order of magnitude 10^{-2} mm) corresponds to a middle level erosion of valve relief (Fig.4a), while an increased deformation characterizes the heavily eroded exhaust valve relief reported in (Fig.4b). Ring groove closure should be mainly considered a consequence of knock-increased thermal and mechanical loads, which induce deformation of piston top land towards the con-rod. It should be pointed out that the dimensional changes of the ring groove are frequently observed in combination with valve reliefs erosion, regardless of 1st ring groove erosion: the peaks of eroded material in the ring groove, locally reducing the clearance, provide a very small contribution to ring locking. As well as micro-welding, this is considered a fatal piston damage, since it compromises the combustion gases sealing.

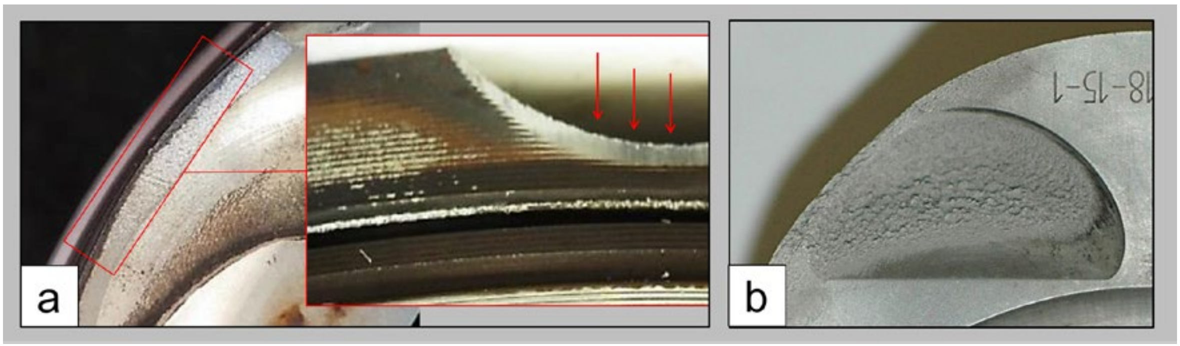

Fig.4 -Images of two pistons valve reliefs characterized by ring groove plastic deformation, V8 turbocharged engines. (a) Stereo-microscopy images at the intake valve relief, medium knocking erosion and tiny ring groove closure. (b) Macrograph at the exhaust valve relief, heavier knocking conditions: erosion is more pronounced, as well as ring groove closure.

A separate discussion should be made for naturally aspirated engines. In this case, a considerably lower pressure inside the combustion chamber is reached, leading to both:

- Lower probability to induce knock at the ring groove; anodized layer erosion is thus rarely observed.
- Slower wear rate of anodized layer due to lower contact pressure between piston ring and groove.
- Lower temperature inside the combustion chamber (since it is directly related to the combustion pressure [6,8]); this leads to higher structural resistance (in particular of heat-sensitive Al components such as pistons) and lower probability to incur in plastic deformation of the ring groove.

However, as well as pistons equipping turbocharged engines, knock-induced erosion is typically observed at piston valve reliefs. An example of middle-high level erosion is reported in Fig. 5: it should be pointed out that no deformation of the ring groove is detected and no damage is observed at the anodized layer, even if both polishing and erosion are clearly perceivable, indicating the occurrence of knocking combustions.

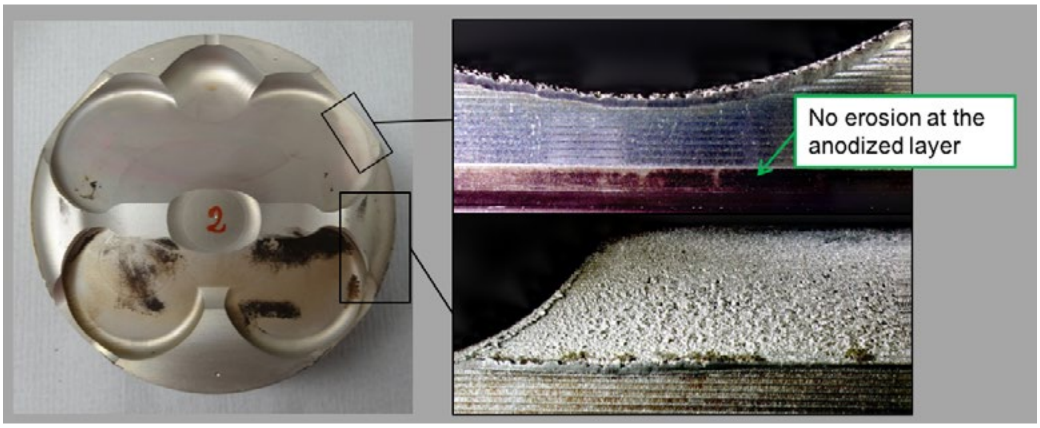

Fig.5 - Knock induced erosion (middle level) in an automotive piston belonging to a naturally aspirated engine. Stereo-microscopy micrographs focus on intake valve relief and piston pin axis side; no damage of the anodized layer at the 1st ring groove is observed.

Pistons damage under heavy knocking combustions (eventually turning into pre-ignition).

As highlighted in the previous paragraphs, the major damages connected to knocking combustions are, in order of importance: ring groove plastic deformation, complete wear of anodized layer leading to micro-welding, erosion of the anodized layer, erosion at piston head (in particular at valve reliefs). It should be however pointed out that knock is an autocatalytic phenomenon: due to the induced temperature increase, a persistent knocking condition might rapidly degenerate into more severe knocking cycles and finally into pre-ignition sequence (as confirmed by [14]). In-cylinder pressure signals reporting a similar event are displayed in Fig.6a: pressure oscillations due to knock are rapidly intensified, then suddenly switched off due to pre-ignition occurrence. A V8 turbocharged engine, without a calibrated knock control strategy, was involved. The effects of this sequence on the 8 pistons are shown in Fig.6b and here schematically described:

- At all Al pistons heads, melting signs are observed, often resulting in the formation of blow-by channels; under these conditions, also other combustion chamber components are covered by molten Al spots, such as injectors, spark-plugs, cylinder liners and heads.
- The significant temperature increase and induced thermal expansion produce seizure marks, perceivable at all pistons lands, in particular at pin axis side for the absence of piston skirt constraint.
- In the severest cases, 1st ring is completely jammed or subjected to a substantial plastic deformation.

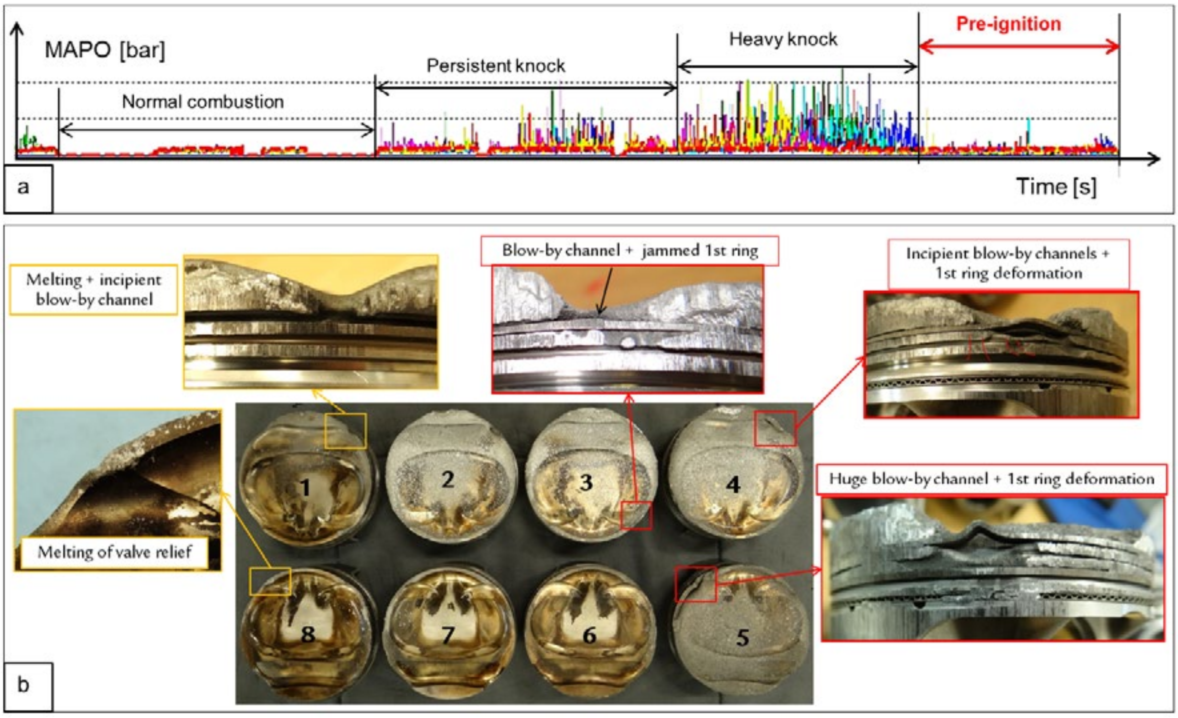

Fig.6 - Degeneration of severe knocking combustions into pre-ignition sequence. (a) In-cylinder pressure signal, filtered in order to show MAPO parameter (MAPO explanation in [6]). (b) Effects on pistons of severe knocking combustions + pre-ignition.

Damage of combustion chamber components under heavy knock: cylinder heads, liners, spark plugs

In case of heavy pressure oscillations, besides pistons, other components of the combustion chamber are usually affected by knocking damage. Among them, as can be expected, Al cylinder heads are sensitive to knock-induced mechanical stresses, further emphasized by temperature increase. The typical knock damage of Al cylinder heads is limited to surface erosion, as reported in Fig.7: in this case, the intake side is involved. Erosion at cylinder head does not usually compromise engine functionality, until the integrity of its cooling channels is preserved. This damage is however rarely observed and it is a marker of persistent high-level knocking combustions, which should be avoided.

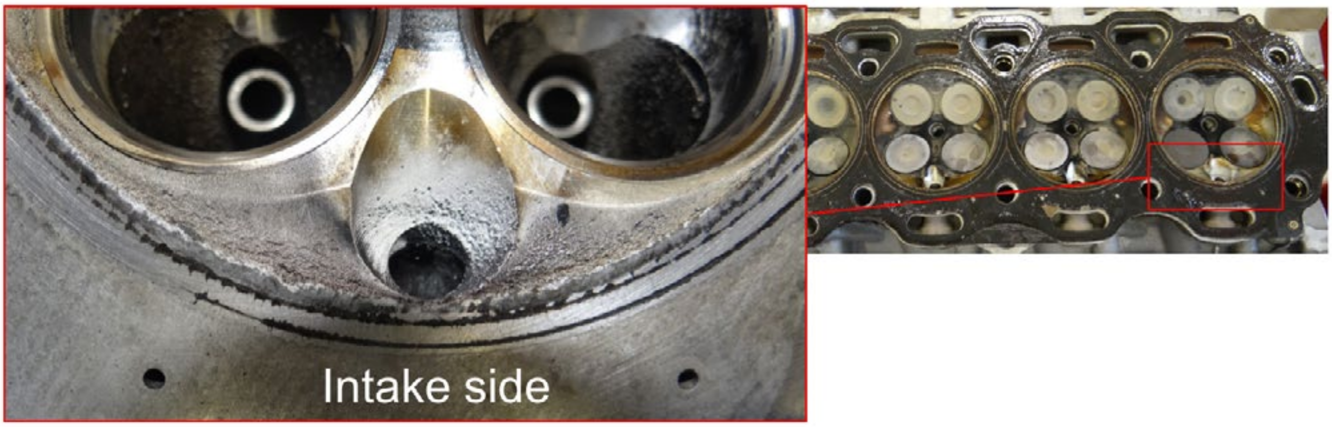

Fig.7 -Macrographs reporting erosion at cylinder heads, V8 turbocharged engines.

Even if made by steel and Nikasil coated, cylinder liners as well might also be affected by knock. The damage is mainly related to the knock-induced overheating, which leads to a reduced functionality of lubricants, possible breakdown of the lubrication film and significant piston thermal expansion, though localized and limited to piston top land in case of efficient knock control strategy (see tiny seizure marks in the thrust and anti-thrust side in Fig.8a). In case of repeated knock and pre-ignition, the insufficient clearance between the matching surfaces and the resulting friction further intensify the heat-induced expansion, finally resulting in complete piston seizure. Such destructive effects are reported in Fig.8b: several seizure marks are visible on cylinder liner, together with transferred Al material. It is interesting to point out that also melting of the liner is visible at the TDC, beneath the location of piston valve relief, which is supposed to be the hot spot triggering knocking and pre-ignition combustions.

Also spark-plugs might be affected by severe knock or pre-ignition and their damage inevitably compromises the combustion process. In particular, partial rupture of the ceramic insulator due to thermal shock might be produced by increased thermo-mechanical stresses (Fig.9a); in this case, usually spark leaks can be observed, indicating reduced spark plug functionality. Al deposits coming from pistons are usually observed, while melting of the electrodes and ceramic insulator is perceivable in the severest abnormal combustions, due to higher thermal loads.

Fig.8 - Macrographs reporting cylinder liners damage. (a) Tiny seizure marks (severe knock but efficient knock control). (b) Heavy seizure marks due to knock + pre-ignition; in addition, transfer of Al and partial melting under valve relief location are observed.

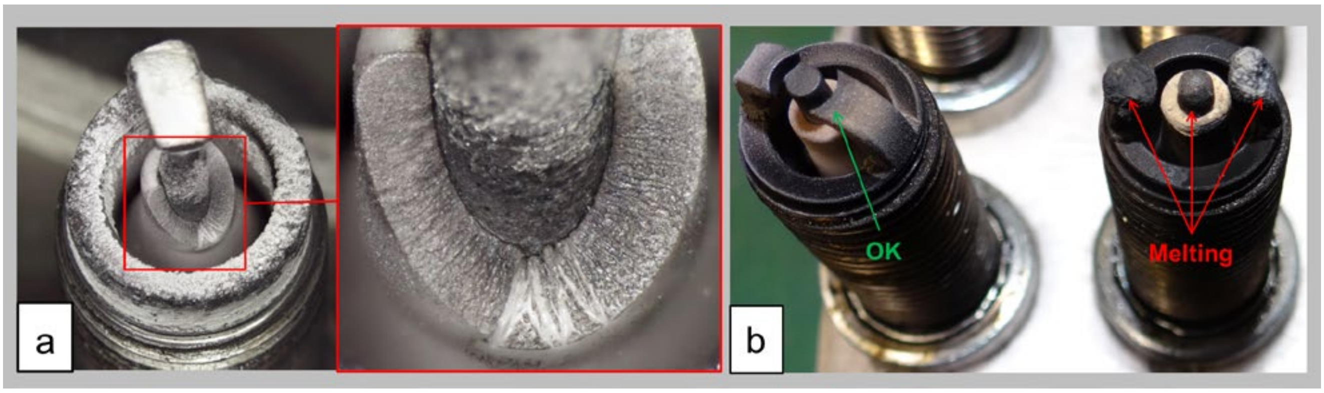

Fig.9 - Spark plugs damage due to knock or pre-ignition. (a) Breakage of ceramic insulator and spark leaks. (b) Electrodes melting.

Conclusions

In the present paper, different case studies collecting knock and pre-ignition damage on several engine components after industrial durability tests are reviewed, aiming to underline the critical issues to be taken into account for materials selection in case of high output power engines, which are more likely to encounter abnormal combustions during their life.

The following damages are frequently observed at mid/high knocking level on automotive pistons equipping turbocharged engines, and should be avoided in order not to compromise pistons functionality: (i) significant wear of the anodized layer at the piston ring groove (potentially turning into micro-welding), (ii) ring groove closure due to plastic deformation. Piston head and valve reliefs erosion is not compromising to some extent. Piston material selection plays a decisive role in partially limiting these unfavorable effects, thus making it possible to accept light/mid knocking combustions, which allow a higher efficiency engine operating point. The understanding of the damage mechanisms offered in the present paper suggests various insights for materials selection.

For example, it has been observed that the wear of the ring groove anodized area is directly related to the intrinsic brittleness of the anodized layer, which is substantially sensitive to knock pressure waves. It follows that, due to its increased brittleness and defects density, a thicker anodized layer cannot improve the ring groove response to knocking combustions. It should be also stressed that the anodized layer hardly covers the primary Si particles of the Al-Si base alloy (here taken into account), and a more dense and uniform PEO layer (plasma electrolytic oxidation) might help. Another solution could be a co-forged steel ring carrier, but its higher cost makes it a preferential candidate for racing applications rather than for mass production pistons.

As regards ring groove closure, it is evident that the solution is continuing to work towards an increased alloy resistance to knock induced thermo-mechanical stresses, thus shifting the plastic deformation limit of the alloy.

Under heavier and persistent knocking combustions, often degenerating into pre-ignition, deleterious damages are witnessed, such as piston seizure and ring locking, coupled by cylinder heads, cylinder liners and spark plugs damage. These high-intensity abnormal combustions should be completely avoided through effective engine calibration strategies, since materials selection is no more able to limit the effects on engine functionality.

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