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Analysis of pre-ignition combustions triggered by heavy knocking events in a turbocharged GDI engine

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Abstract

In this paper, a pre-ignition sequence with detrimental effects on the engine has been analysed and described, with the aim of identifying the main parameters involved in damaging the combustion chamber components. The experiment was carried out in a wider research context, focused on knock damage mechanisms in turbocharged GDI engines. The pre-ignition sequence was a consequence of a high knock condition, induced at high load at 4500 rpm. The abnormal thermal load due to knock caused overheating of the whole combustion chamber, until the spark plug electrodes became a "hot spot", resulting in premature flame initiation in the following cycles, with a self-sustaining mechanism. Slight cylindrical differences, mainly in terms of volumetric efficiency, allowed comparisons and correlations between indicated parameters, pre-ignition sequence and damage. The main responsible in damaging the engine, in this case and for this engine, is the extremely high heat transferred to the walls in the pre-ignited cycles, characterized by higher mean temperatures. Heavy knock triggered the pre-ignited combustions but progressively reduced its intensity as the spontaneous ignition advance increased, thus having a secondary role in damaging directly the combustion chamber.

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Keywords: knock; pre-ignition; damage mechanisms; abnormal combustion; turbocharged engine;

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1. Introduction

Anomalous combustions induced by extreme thermal conditions in the combustion chamber are of high concern in latest generation Spark-Ignition (SI) engines, since higher and higher thermal loads are needed to maximize engine efficiency. The understanding of these phenomena and their consequences is of primary importance during engine development, control and calibration. In this work, a pre-ignition sequence, triggered by heavy knock operation, has been studied and described. After the test, pistons have been analyzed to characterize and quantify the damage, and to correlate it to the in-cylinder pressure history.

2. Experimental setup

The experimental tests were conducted on 3 cylinders of a 4-L SI GDI turbocharged engine, at 4500 rpm and 2200 mbar of intake manifold pressure. The engine has a 1.9 liter displacement and a compression ratio of 9.4.

At steady state operation, extremely heavy knocking combustions have been generated by controlling spark advance. Every cylinder was equipped with a 6045A Kistler pressure transducer, and all the pressure data sequence has been recorded at 200 kHz sampling frequency. The test is part of a wider experimental activity, whose objective is to understand and quantify the knock-induced damage on the combustion chamber components. This test gives the possibility of quantifying the surface ignition resistance of the engine and of the current spark plug heat range at this operating point, it provides some elements on knock damage and it allows the study and the deeper understanding of an undesired run-away operation, not fully detailed in literature.

Following the experimental tests, damage evaluation was carried out on the 3 forged pistons, made of a near eutectic Al-Si-Cu-Ni alloy. Visual analyses have been performed after cleaning with neutral degreaser, through 3D digital microscope (Hirox KH-7700). Investigations have been made both on pistons crown and topland. Further analyses, limited to the most interesting sites, have been carried out through Scanning Electron Microscope equipped with Energy Dispersive X-ray Spectroscopy detector (SEM-EDS); backscattered electrons were used for detection.

3. Pre-ignition sequence

In this specific test, Pre-Ignition (PI) occurs after a relatively short sequence of consecutive heavy knocking cycles, and the operation rapidly migrates toward a self-sustaining condition where all cycles are surface pre-ignited [1]; this phenomenon is also called “run-away pre-ignition” [2]. Surface ignition is the ignition of the air-fuel mixture by a hot spot on the combustion chamber walls (valve, spark-plug, carbon deposits) [1] and the combustion angular position is stochastic and therefore variable. In this experimental test, the main responsible for PI is supposed to be the chamber walls elevated thermal load due to heavy knock, which induces overheating of chamber surfaces. As explained in [3], this condition can occur in case of knocking operation near thermal limit conditions. The “hot-spots” should be high surface-to-volume ratio zones of the chamber, such as the spark-plug electrodes, which showed noticeable evidence of melting at the end of the operation, or the ceramic insulator. Every PI overheats the hot surface due to the early combustion, resulting in a higher PI probability for the next cycle; the result is a self-sustaining operation. With respect to the mentioned works, in this paper the focus is on the effects of this kind of anomalous combustions on the combustion chamber components and some elements to identify them are provided.

3.1. PI identification

The identification of the cycles with pre-ignition has been performed through in-cylinder pressure signal analysis. PI was identified by isolating the Crankshaft Angle (CA) corresponding to a certain percentage of mass of fuel burned (or CAxx%MFB), where xx is a relatively low percentage value (i.e., typically between 1% and 10%) of burned mass, and by evaluating its angular distance to spark ignition angle. Fig. 1 (a) clarifies this approach: until cycle n. 61, the distance between the Spark Advance (SA) angle and CA1MFB (CA1MFB + SA) is stable around 13°CA. The sudden reduction of such value is a clear symptom of a combustion that started much earlier, presumably before the spark discharge. By identifying a reasonable lower threshold (9° CA), it is possible to distinguish between spark-ignited and pre-ignited combustions, and all the PI cycles have been identified by this method. Fig. 1 (b) shows the transition from spark-ignited combustions to completely stable PI mode. The figure shows both the maximum in-cylinder pressure values that have been measured during the tests (after a low-pass filtering stage to eliminate knock effects), and the parallel evolution of one of the most common indexes used for knock intensity evaluation, called MAPO (Maximum Amplitude Pressure Oscillations) [1, 4]. As it can be seen in the Figure, the first 61 cycles are characterized by a very strong knock intensity (average MAPO value equal to 28.1 [bar], with all the 61 cycles presenting close to average MAPO values), which is considered to be the main responsible for the subsequent transition to PI combustion. For cylinder 1, the transition from the 1^{st} PI cycle (n. 62) to the last spark-ignited cycle (n. 81), lasts 19 cycles, of which 12 are with PI. The next section will further investigate the reasons for such transition, by considering also the other cylinders.

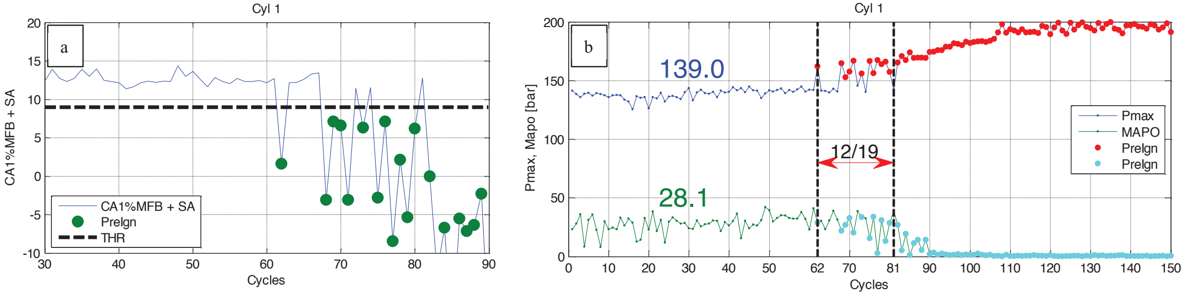


Fig. 1. (a) PI identification through heat release; (b) PI sequence for cyl. 1.

3.2. Knock to pre-ignition transition

As shown in Fig. 1, the earlier the combustion starts, the higher pressure peak is reached within the engine cycle (low-pass filtered, regardless of knock); this is caused by the simultaneous compression work exerted by the piston on the in-cylinder gases, and the exothermal reactions due to combustion. To better clarify this aspect, Fig. 2 (a) shows some in-cylinder pressure signals belonging to engine cycles before (n. 60), during (n. 75) and after (n. 90, 120, 170) the transition from knocking to pre-ignition combustion modes. Once the combustion ends before TDC, peak pressure value is independent of combustion phase: this is why maximum pressure stabilizes at about 200 bar for extremely early combustions, independently on the combustion phase. Correspondingly, as shown in Fig. 2 (b), the maximum mean temperature increases and high temperatures are experienced for a longer time inside the chamber, causing extreme thermal and mechanical stresses to the combustion chamber components.

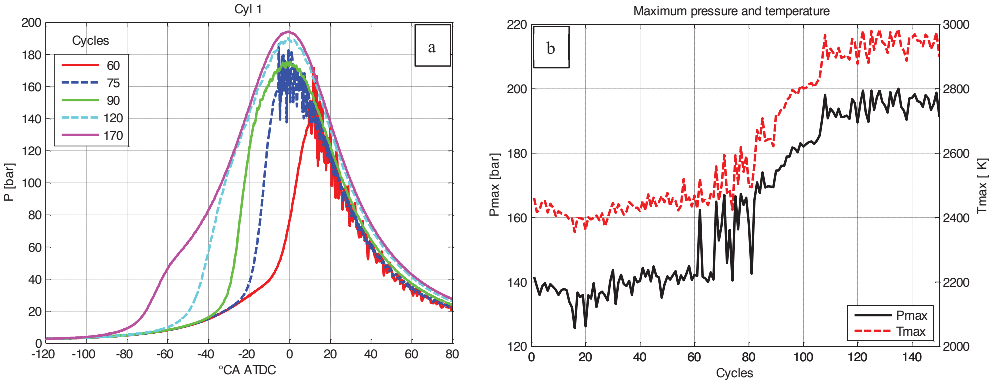


Fig. 2. (a) Pressure curves for some cycles; (b) maximum pressure and temperature.

The wall thermal load (i.e. the heat transferred to the walls) is directly dependent on pressure level and knock intensity, which respectively influence mean gas temperatures and heat convection coefficient [4]. For each cylinder, and considering only combustion cycles preceding the start of the transition phase, Table 1 reports the average maximum pressure value, the average MAPO value, the 95th MAPO percentile, and the number of cycles before the first PI occurs (i.e., all the cycles over which $\overline{Pmax}$, $\overline{MAPO}$, and MAPO95% values have been calculated).

Table 1. Wall thermal load

Cylinder	$\overline{Pmax}$ [bar]	$\overline{MAPO}$ [bar]	MAPO 95% [bar]	# cycles to PI
1	139	28.1	36.6	62
2	141.5	29.1	39.6	50
3	134.7	27.8	36.5	80

As it can be clearly seen, the number of cycles before the first PI event is inversely dependent on the thermal load conditions, defined by gas temperature (related to $\overline{Pmax}$) and knock intensity ($\overline{MAPO}$ and MAPO95%).

As combustion gradually starts earlier, due to rapid increase in PI combustions occurrence during the transition phase, and due to increasingly premature flame initiation during the subsequent PI stable combustion mode, knock intensity reduces until such combustion mode disappears below a certain CA50%MFB (see Fig. 1 (b)), as also observed in [5]. The relation between knock intensity and combustion phase is reported in Fig. 3 (a), showing that MAPO values tend to zero once the combustion is initiated particularly early during the compression phase. This behaviour can be explained by considering that the unburned end gases do not reach auto-ignition conditions if the combustion fully takes place at relatively low pressure and temperature conditions (such as the ones encountered during the initial part of the compression stroke). For this specific operating condition, all pre-ignition combustions are non-knocking when CA50%MFB occurs before -20°CA After Top Dead Center (CA ATDC).

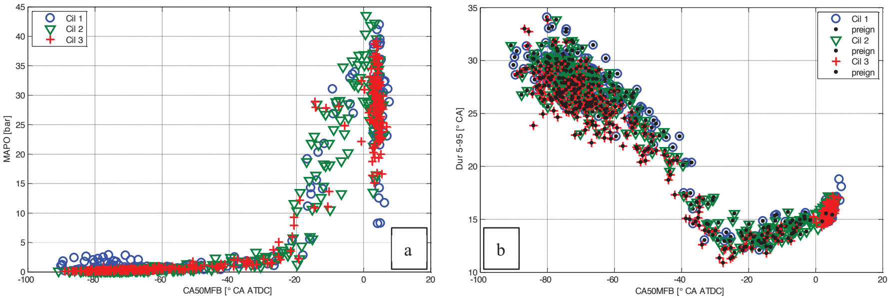


Fig. 3. (a) Knock intensity vs. combustion phase; (b) Combustion duration vs. combustion phase.

As shown in Fig. 3 (b), also the combustion duration is strongly affected by its phase. Initially, when PIs are alternated with spark-ignited combustions (during the so-called transition phase), the duration is reduced, as a result of slightly higher temperatures during flame initiation, and probably because of the quasi-simultaneous ignition of the air-fuel mixture by the spark and the “hot-spots” (resulting in a bigger equivalent flame kernel). In the following phase, when PI is fully stable, the duration increases because of the lower temperatures at the combustion start due to early ignition (see Fig. 3 (b)).

As it is well known, the Indicated Mean Effective Pressure (IMEP) is strictly related to CA%50MFB and it progressively reduces as the combustion is more and more anticipated, thus implying that the overall engine efficiency critically drops (more and more fuel energy is converted during the compression stroke, and then exchanged with the chamber walls, or transferred to the exhaust gases). This aspect is further analyzed in the following section.

4. Heat-transfer evaluation

4.1. Knocking cycles

To further analyze the influence of knock intensity on heat transfer, and specifically on heat transfer coefficients, correlations can be evaluated between an estimation of the heat transferred to the walls and MAPO, if the analysis is limited to non PI cycles.

$Qwall$ is defined as the integral of the negative portion of net ROHR (Rate Of Heat Release) between the end of combustion and EVO (Exhaust Valve Opening), since a negative value of ROHR corresponds to a loss of energy of the considered closed system. In-cylinder pressure based ROHR determination is very complex, and it is particularly sensitive to the assumptions made on the specific heat ratio γ. For ROHR calculation, model D_1 proposed in [6] has been applied. $Qwall$ thus represents only a fraction of the total energy transferred to the walls, since the heat exchange during the combustion is ignored. Since knock takes place towards the end of combustion, the consequent increase of heat transfer should be clearly evident after the knock occurrence, and therefore $Qwall$ should be strongly correlated to knock intensity, as shown in Fig. 4 (a). As previously stated, the effect of knock is evident also on IMEP, which reduces as knock intensity increases (see Fig. 4 (b)). The cycles considered in Fig. 4 are characterized by approximately the same CA50%MFB, so any change on IMEP is due to different heat quantities transferred to the walls.

4.2. Pre-ignited cycles

Conversely, if only cycles with PI are considered, $Qwall$ is strongly dependent on in-cylinder maximum temperature, which is the main cause for increased heat fluxes (see Fig. 4 (c)), while knock is marginal or absent for most of the cycles. The outlier cycles of cylinder 1 are due to excessive blow-by, caused by exhaust valve failure at the end of the test.

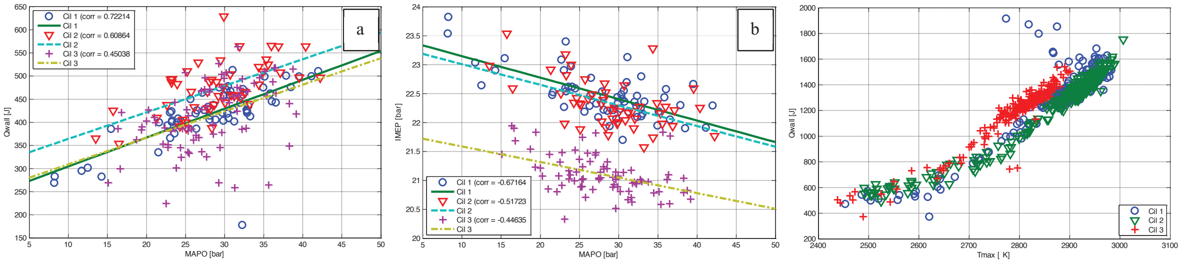


Fig. 4. (a) Knock effect on heat transfer (Qwall vs MAPO) and (b) on IMEP; (c) heat transfer dependence on Tmax for pre-ignited cycles.

5. Pistons damage evaluation

Focusing on pistons crown, the exhaust side was the most damaged area of all pistons. A representative 3D micrograph of the exhaust side of piston 2, reported in Fig. 5, provides a clear evidence of erosion spots, most of them reaching 1mm average diameter, a few of them exhibiting elongated features in the radial direction. These morphologies, highlighted in Fig. 5 (a), are related with spark-plug failure and subsequent debris formation. Since spark-plug metal body is composed of a Ni-based alloy (characterized by a considerable higher hardness with respect to the Al piston), debris acted like hard particles against Al piston crown, causing damage due to impact and wear erosion (Fig. 5 (b)); moreover, it has to be taken into account the possibility that large size debris remained trapped between piston crown and engine head, during compression or exhaust stroke, causing plastic deformation of the piston crown.

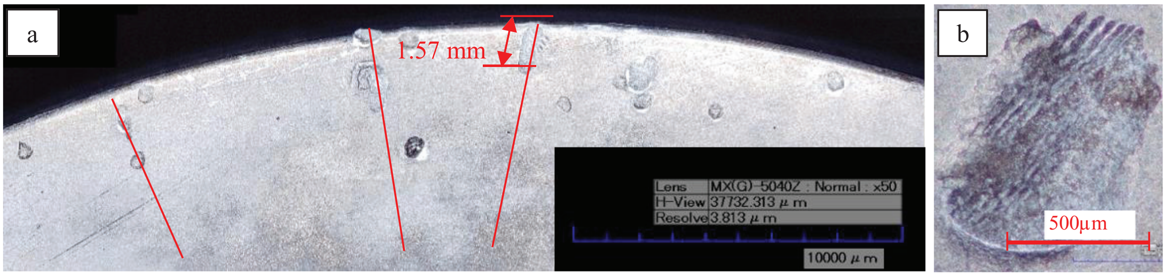
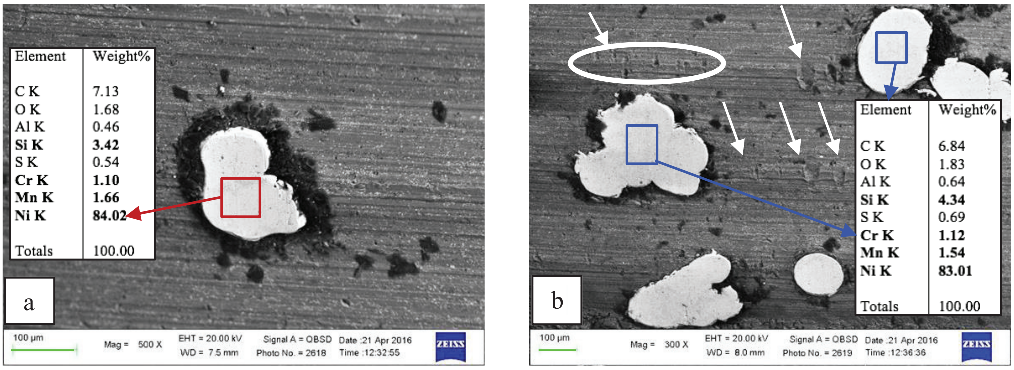


Fig. 5. (a) 3D micrograph of exhaust side of piston 2 crown, after cleaning with neutral degreaser; (b) higher magnification 3D micrograph focusing on impact erosion spot on piston 2.

Several Ni-rich particles (therefore belonging to spark-plug electrodes) have been found embedded into the exhaust side of pistons topland, mainly in the not-anodized area; Fig. 6 shows a focus on the topland of piston 1. Clear plastic deformation marks, highlighted by arrows in Fig. 6 (b), further confirm the vertical path of these particles, coming down from piston crown. Spark-plug debris caused, at first, the damage of pistons crown; due to piston motion, part of the debris squeezed into the small clearance between cylinder and piston topland, finally sticking into piston topland; the remainder particles probably found their way out through the exhaust valves.

Evidences of knock occurrence have been found in the 1st ring groove of all pistons; an example referring to piston 3 is reported in Fig. 7. This is in agreement with literature data, which suggest that knocking phenomena are more likely to initiate from crevices (i.e. the 1st ring groove) [7, 8, 9].



Element	Weight%
C K	7.13
O K	1.68
Al K	0.46
Si K	**3.42**
S K	0.54
Cr K	**1.10**
Mn K	**1.66**
Ni K	**84.02**
Totals	100.00

Element	Weight%
C K	6.84
O K	1.83
Al K	0.64
Si K	**4.34**
S K	0.69
Cr K	**1.12**
Mn K	**1.54**
Ni K	**83.01**
Totals	100.00

Fig. 6. SEM-EDS investigations on debris embedded in the exhaust side of piston 1 topland; both images (a) and (b) reveal the presence of similar Ni rich debris; arrows in (b) highlight plastic deformation marks.

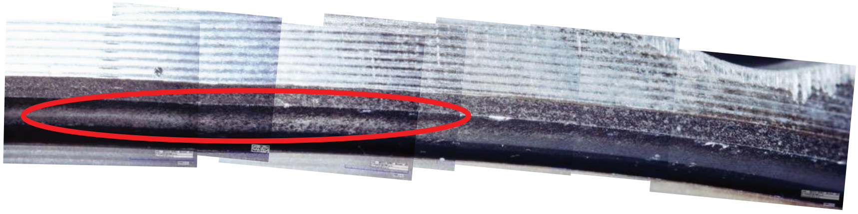


Fig. 7. 3D micrograph of the 1st ring groove of piston 3; the encircled lighter areas are due to oxide layer erosion.

The high thermal and mechanical stresses gave also origin to an extended area of seizure, focused on the pin-axis side of the topland (images not reported). Exhaust valve relieves exhibit the more extended damage in all cylinders, the size of the damaged area increasing from piston 1 to piston 3, as shown Fig. 8.

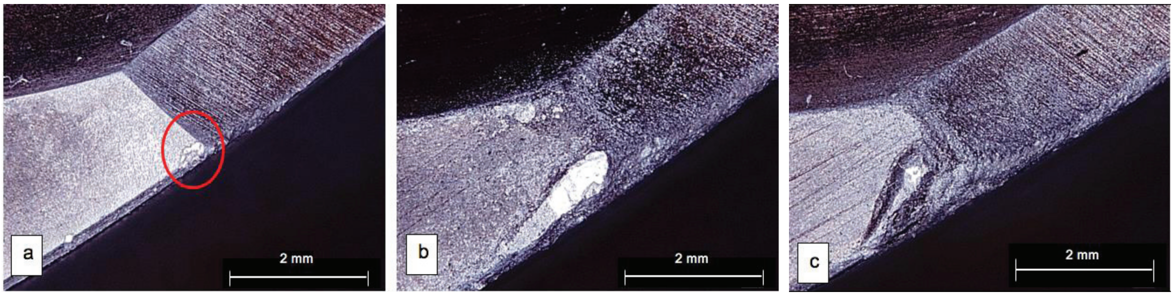


Fig. 8. Detail of exhaust valve relief for pistons 1 (a), 2 (b) and 3 (c).

Piston 1 gives evidence that the damage starts from the external sharp corner, encircled in red in Fig. 8 (a): this is the most sensitive area when it comes to the increase of temperature in the combustion chamber, given its high surface/volume ratio; moreover, it is exposed to end-gases which are involved in knocking phenomena. Micrographs also allow stating that piston 1 suffered less from pre-ignition damage (and therefore from temperature increase) with respect to pistons 2 and 3, which exhibit a localized melted area.
Evidences of melting have been found in the exhaust side of piston 3, both on piston crown (see Fig 9 (a)) and piston exhaust valve relief (see Fig. 9 (b)).

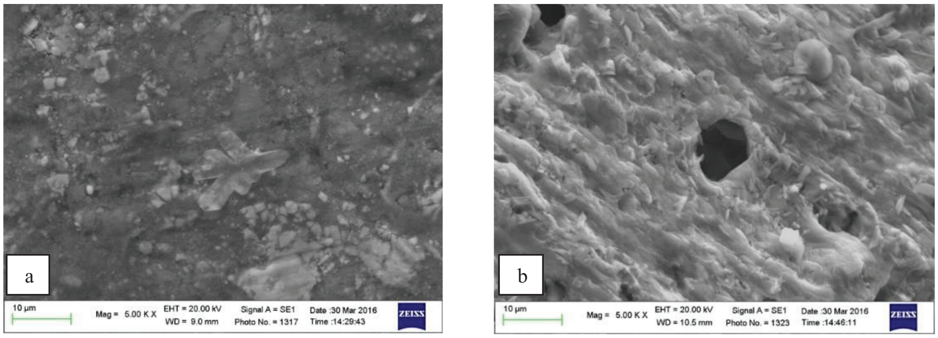


Fig. 9. Melting evidences for Al piston: (a) dendrite and (b) porosity.

6. Diagnosis

This kind of anomalous combustions is not tolerable because of the catastrophic effects on the engine. The extreme pressure and temperature levels cause the combustion chamber components to operate under off-design conditions in terms of thermal and mechanical stresses, and even few events can irremediably damage the engine [1, 2]. The ability of diagnosing these events is crucial, due to the increasingly specific torque demand, which can be achieved through operation ever closer to anomalous combustions, permitting to act quickly on effective control parameters (injection, instead of ignition timing, for example) to preserve engine integrity and functionality.

Well-known reliable in-vehicle solutions for knock detection use ionization current, accelerometer or microphone signals [10, 11, 12, 13]. Ion current can diagnose PI [14], if the signal before the spark is monitored, providing information about early flame initiation. Accelerometer or acoustic signal can be used to determine knock intensity, but do not give any information about the flame initiation mode. Knock intensity associated to PI is usually very high and it could be used as PI indicator by itself. This test showed that the angle of knock onset (AKO, defined as the angle corresponding to the maximum amplitude of the high-pass filtered pressure signal, i.e. MAPO) calculated on the pressure signal can be a good indicator of PI. Indeed, as cycles with PI are defined by earlier combustion angles, they also are characterized by an earlier knock onset (see Fig. 10).

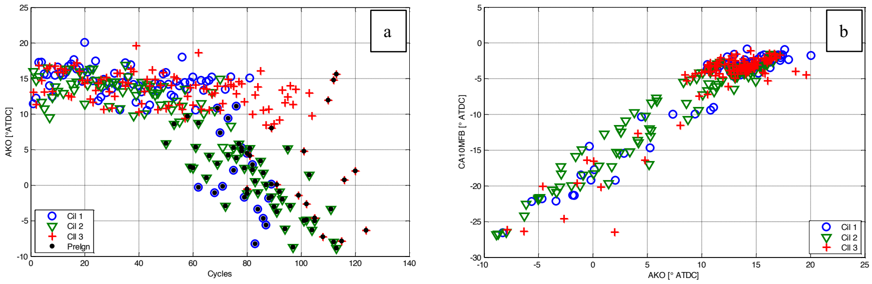


Fig. 10. (a) Angle of knock onset and PI; (b) Angle of knock onset vs CA10%MFB.

Supposing a good correlation between in-cylinder pressure knock-related features and accelerometer or acoustic signals, which is a fundamental requirement to use these signals for combustion monitoring, the information related to the angle of knock onset could be used in on-board diagnosis algorithm.

7. Conclusions

Abnormal combustions, like knock and pre-ignition, are of high interest in spark-ignited engines, since they represent the main limiting factor for higher engine efficiency. On the one hand, control strategies and precautionary engine calibration can reduce the occurrence of such kind of combustion; on the other hand, the engine should withstand a certain number of unavoidable anomalous events. This paper describes a sequence involving both knock, controlled by spark advance, and consequent pre-ignition and it illustrates their harmful effects on the engine. The failure analysis gives information about components to be considered critical. Some elements of the in-cylinder pressure signal analysis can be used in a pre-ignition on-board diagnosis algorithm that uses the available knock-related signal (block vibration or acoustic emission).

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