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Experimental observations of engine piston damage induced by knocking combustion

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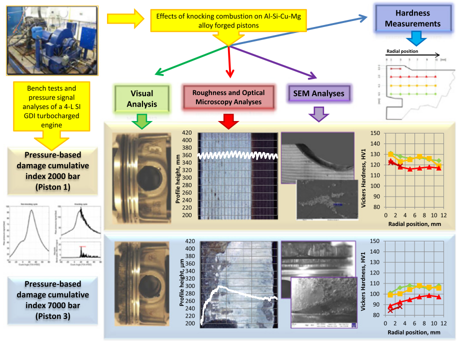
HIGHLIGHTS

- Dedicated facilities and processing algorithms were adopted to study the in-cylinder pressure signal, allowing a classification of the knocking level experienced by the Al alloy pistons.
- Visual and optical microscopy analyses are useful techniques to qualitatively determine the level of knocking combustions undergone by the pistons.
- Wear traces, carbon deposits, erosion, melting and seizure were detected on the top lands by means of SEM-EDS analyses.

GRAPHICAL ABSTRACT



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ABSTRACT

Abnormal combustion leads to a significant increase in combustion speed, pressure and temperature at the surfaces enclosing the combustion chamber. Severe and lasting knock or pre-ignition can permanently damage and, in many cases, destroy engine pistons, due to very high and localised thermomechanical stresses. The deleterious effects of abnormal combustions have led car manufacturers to set extremely precautionary thresholds in spark advance calibration (in terms of temperatures and pressures) of turbocharged spark ignition direct injection engines, often limiting engine performance and efficiency. Since the mechanisms of piston damage due to abnormal combustion are not currently fully understood, the aim of this study was to characterise its effects on Al forged pistons. The more suitable characterisation techniques were evaluated. The results highlighted that roughness measurements, as well as visual, optical and scanning microscopy analyses on specific zones of the top land and piston crown are useful techniques to qualitatively relate piston damage to combustion regime. Moreover, a significant quantitative relationship was observed between the MAPO (Maximum Amplitude Pressure Oscillations) index and residual piston hardness.

1. Introduction

The normal combustion of the air-fuel mixture in the cylinder of a Spark Ignition (SI) engine takes place with a well-defined process. The flame front starts from the spark plug and then spreads from there with a quasi-spherical front and increasing combustion speed, resulting in a gradual pressure increase in the combustion chamber. Various factors can interfere with this regular combustion mode, resulting in knocking combustion or pre-ignition. In the first case, the temperature and pressure increase, associated with flame front expansion, may trigger self-ignition in one or more points of the unburned end-gas. In the

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second case, combustion starts before the spark and the consequent higher gas temperature and pressure usually induce knock. Abnormal combustion modes lead to a substantial increase in the combustion speed, and induce a significant increase in pressure and temperature at the surfaces enclosing the combustion chamber [1]. While light knock has no detrimental effects on the piston and other combustion chamber components, and in certain cases it could also be beneficial, severe and lasting knock or pre-ignition are able to permanently damage and, in many cases, to destroy the very same components [2–4].

It is well known that pistons, also in their normal use, simultaneously undergo different and complex damage mechanisms such as fatigue, wear, oxidation, etc. Pistons need to withstand significant mechanical loads, due to combustion pressure, and additional thermal stresses, due to the local heat flux which causes surface temperature oscillations and non-uniform temperature distribution [5,6]. Moreover, pistons themselves are part of the combustion chamber, which means their service temperature might exceeds 300 °C on the crown [7]. Since pistons are highly thermomechanical loaded components, many researches are focused on the thermomechanical fatigue damage of pistons [8–10], and on its modelling [11] while other studies deal with wear damage and scuffing of both piston skirt and piston rings [12–15]. Very few studies, instead, are available about the specific damage mechanisms induced by knocking combustion and the relationship between different knocking levels and corresponding piston damage.

It is generally reported [2,3] that the causes of this damage are probably the increased heat flux and the high and localised thermomechanical stresses occurring during the process. The limited literature data available on knocking combustion [1–4,16,17] show that erosion, pound-out (significant local wear of the 1st piston ring groove) and piston rings and lands fracture are the main mechanisms of piston damage induced by knock. Otherwise, piston melting and seizure are mainly induced by pre-ignition and its extreme heat flux [4,18]. Due to its deleterious effects, pre-ignition phenomena have to be avoided, while light knocking combustions might be beneficial in terms of engine efficiency. However, as reported by Nates [19], research activities about knock are often focused on the avoidance of knock, rather than on the right identification of the damage mechanisms and on the evaluation of the acceptable knock threshold. Supporting the theory based on the observation of erosion sites, according to which failure is due to a fatigue process, the author [20] describes a fatigue cycle due to alternation in the shock waves and thermal expansion effects. Some authors [3] instead highlight that microscopic investigations of knock damage reveal erosive surface destruction, which very much resembles the damage caused by cavitation on the blades of water pumps and turbines. The cause of erosion seems mainly related to the direct shock pressure waves, while minor attention is focused on the effect of thermal stresses. However, the destruction of the thermal boundary layer [3] leads to a sharp increase in the convective heat transfer coefficient, thus causing high heat flux to the walls. This influences the temperature profiles and, therefore, the size and tribology of the components; moreover, it can lead to a significant loss in material strength (mainly in the case of aluminium pistons) favouring a consequent mechanical damage.

In conclusion, the mechanisms of damage induced by knock on the combustion chamber components are not currently fully understood. Moreover, the development of a knock index directly related to the damage induced on engine components, and the corresponding methodology to identify proper diagnostic threshold values, is still an open and crucial challenge. For these reasons, the main aim of this work was firstly to gain a preliminary understanding of the damage mechanisms induced by knocking combustion on Al pistons, also evaluating the most suitable experimental techniques for qualitative and quantitative damage evaluation. In this study, the damage induced on Al pistons was related to a standard knocking index.

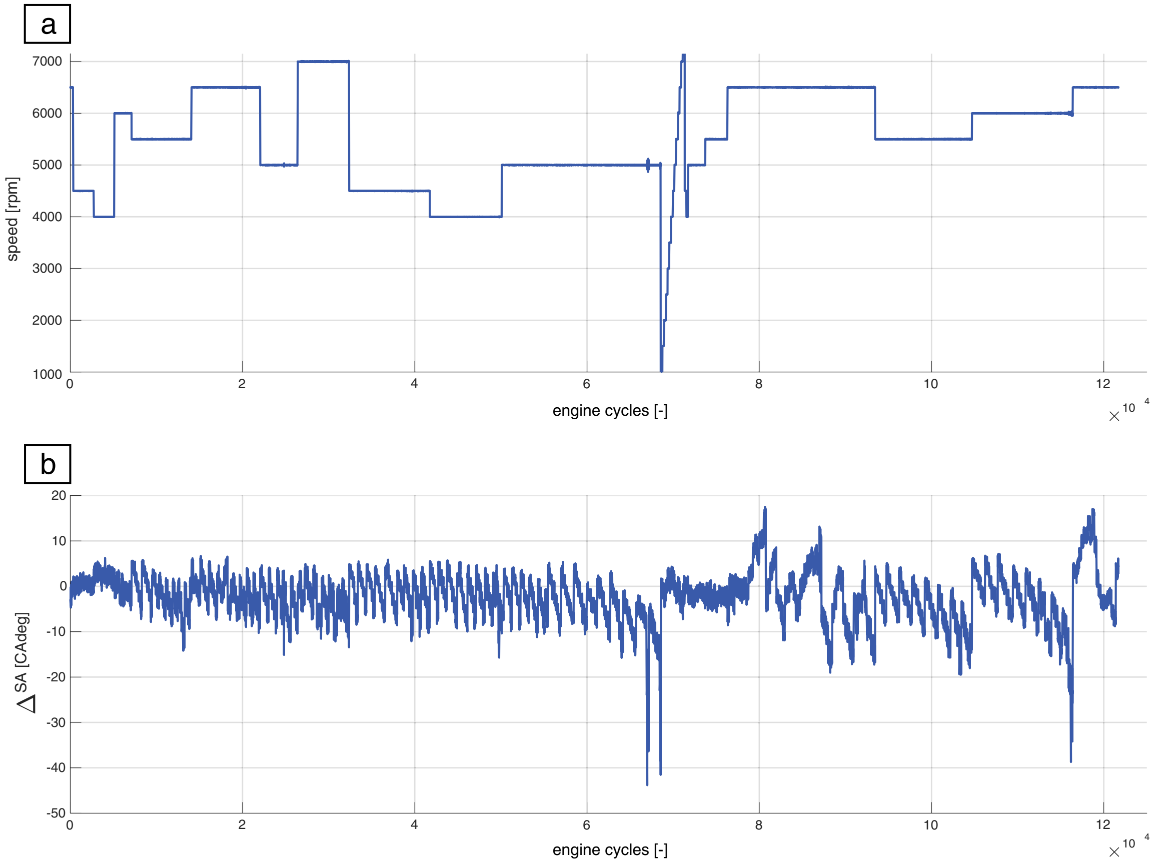

Fig. 1. Time history of the test performed while controlling different knocking levels: engine speed (a) and Spark Advance variations (b).

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