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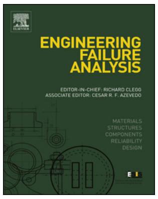

Knock induced erosion on Al pistons: Examination of damage morphology and its causes

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ABSTRACT

In the present study, a systematic and deep examination of knocking damage on Al pistons is carried out, highlighting that only when exceeding a certain threshold knock compromises engine functionality. Controlled knocking combustions were induced during bench tests, by varying the spark advance for each cylinder. Several knock intensities and frequencies were investigated, with the aim to evaluate the possible knocking damages and to understand their influence on piston functionality. All the observed damages have been separately described and studied through failure analysis techniques, in particular optical and scanning electron microscopy and 3D digital microscopy, providing explanations of their occurrence. Among them, the erosion damage was predominantly observed and therefore fully evaluated. Preliminary attempts to relate engine parameters to knock damage were also made.

This study is part of a wider project, whose aim is to increase knocking limits from the “safe calibration area” up to the limits which produce acceptable damages on pistons, in order to enhance engine efficiency.

1. Introduction

Knock is a well-known phenomenon which might affect spark-ignition engines and consists of the spontaneous ignition of a portion of the end-gas ahead of the propagating flame. When this abnormal combustion process occurs, the extremely rapid release of the chemical energy in the end gas causes very high local pressure and the propagation of pressure waves of substantial amplitude across the combustion chamber [1]. Its typical acoustic emissions provided the name of “knock”.

Knocking combustions were one of the main concerns during the ‘80s and ‘90s, when turbocharging technology started to be applied in production automotive engines. It is in fact widely accepted that the turbocharger produces higher pressure and temperature in the combustion chamber, and both these factors make the engine more prone to abnormal combustions, like knock and pre-ignition [2–8].

After many years of naturally aspirated engines, knock is again a topical issue. In fact, in view of the growing concerns on global environmental protection, the improvements of engine performance and fuel economy has become the most pressing factor for automotive manufacturers. Due to the lack of today infrastructures to meet the global requirements, hybrid or electric vehicles are considered long-term alternatives [2,3], which further encourages the research to increase the efficiency of internal combustion engines. The nowadays most promising strategies to increase the fuel economy are: (i) engine downsizing, which necessarily passes

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through an increase of the boost pressure [2,3,5,6]; (ii) increased compression ratio [7,9]; (iii) advanced spark timing [8]. As a drawback, all of these strategies make the engine more susceptible to knock, and detonation thus turns out to be the major limit on the efficiency of spark-ignition engines.

It is reported in literature that severe knock can significantly damage the engine components which form the combustion chamber, such as cylinder heads, cylinder liners, and above all pistons [10–14]. Possible damages on pistons include erosion at piston top land and crown, lands fracture, blow-by channel with subsequent power loss, piston seizure and jammed or broken rings in the most severe cases [11]. In the authors experience, however, most of the catastrophic failure that are traditionally attributed to knock (such as piston seizure, formation of blow-by channels, ring gap closure, lands fracture…) are not merely caused by knock itself, but are rather the result of repeated, persistent knocking combustions, which grow in intensity, finally turning into mega-knock or pre-ignition [15].

Since the term “knock” is still deeply related to unfavourable consequences, the current guideline in engine calibration is that knock must be totally and carefully avoided [16], even if the strategies to prevent knock (namely to decrease the compression ratio, to retard the spark timing, to use cooled Exhaust Gas Recirculation [16]) strongly penalise engine efficiency.

However, as already reported by Nates et al. in the '90s [10,11,13], it is worth pointing out that *only when exceeding a certain threshold* knock compromises engine functionality. Light knock is not harmful and might be even beneficial in terms of both engine efficiency and low emissions: if light knock is accepted, in fact, the engine operating point can be shifted towards the maximum efficiency conditions. The rising questions are therefore: “Which is the knocking threshold not to be exceeded to avoid damage?” And above all: “Are there engine parameters/indexes which can be related to knock damage?” [8,10,11,13,17].

In order to provide thorough answers, a careful experimental campaign is necessary, focusing both on the variation of single knocking parameters during bench tests and on the analysis of corresponding pistons damage. Extreme knocking conditions in the experimental campaign are not of scientific interest, since the aim is not to study the deleterious effects of knock, but to slightly increase knocking intensity from the “safe calibration area”, to determine the acceptable damage on pistons.

In the “Experimental methods” section, the technical information for the different steps of the activities are reported: an overview of the as received pistons and the methods for alloy characterisation, the characteristics of the engine used for knock bench tests and the control strategies adopted to induce knock, points of interests and equipment for pistons visual analysis at different levels and the methodologies for the final alloy characterisation after bench tests. Most of the suitable methodologies to evaluate knocking damage have been defined in a previous study by the authors [17].

In the “Results and discussion section”, the results of different bench tests have been schematically reported, following the abovementioned organisation. The most consistent part, piston visual analysis, was however divided into different paragraphs: the first one aims to lay the basis of a first level visual inspection, while each of the subsequent paragraphs focuses on different piston areas which might be affected by knocking damage: valve reliefs, 1st ring groove, piston top land and crown.

2. Experimental methods

2.1. Starting material and alloy characterisation

The experimental activity of knock damage evaluation was carried out on 12 forged pistons, made of a near eutectic Al-Si-Cu-Ni-Mg alloy, heat-treated to the T7 condition. The heat treatment consists of solution treatment, quench and artificial aging (prolonged over the peak aging condition, in order to provide the alloy stability). The starting material was characterised by an average hardness equal to 120 HB. As can be observed from the illustrative macrograph of piston intake side before engine bench test (Fig. 1a), all pistons exhibit:

- An anodised layer, starting from the lowest part of the top land up to the relief groove below the 1st ring groove, as clearly

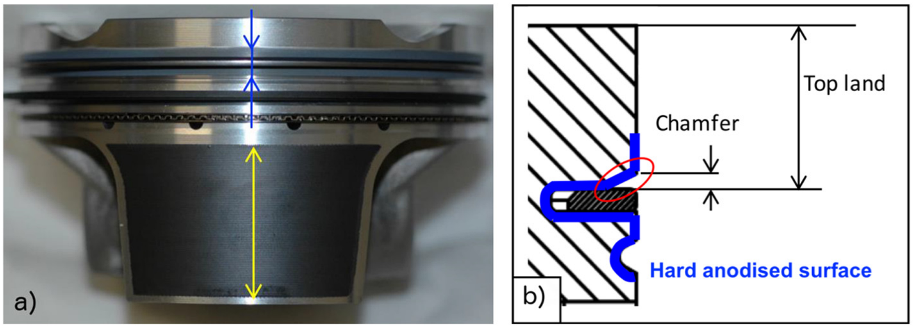

Fig. 1. (a) Macrograph of an as-received new piston, lateral view from the intake side; blue arrows highlight the piston anodised layer, yellow arrow indicates the graphitic layer on piston skirt. (b) Schematic of piston section with focus on the 1st ring groove: the extension of the anodised layer is highlighted in blue; the chamfer area (most sensitive to knocking damage, as reported in the next paragraphs) is encircled in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)