DIN - DEPARTMENT OF INDUSTRIAL ENGINEERING

PhD Course in Mechanics and Advanced Engineering Sciences (DIMSAI)

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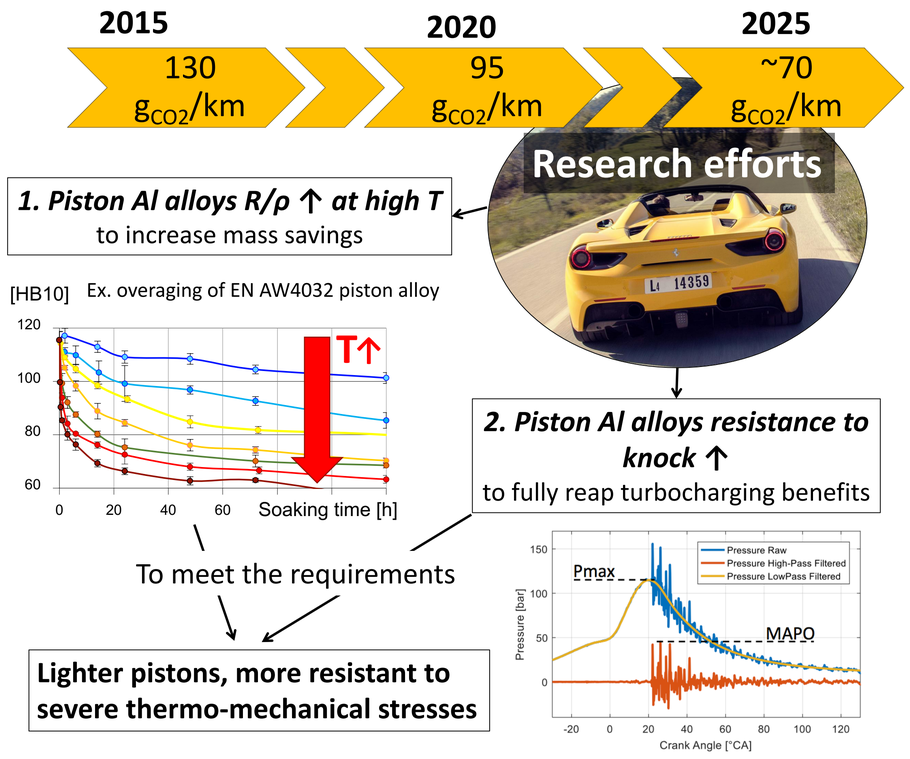
Innovative Al alloys for high performance automotive pistons: characterisation and resistance to knock damage

Introduction and aim

The stringent EU regulations on the reduction of CO_2 emissions for new cars lead the automotive manufacturers to boost fuel economy through few main strategies:

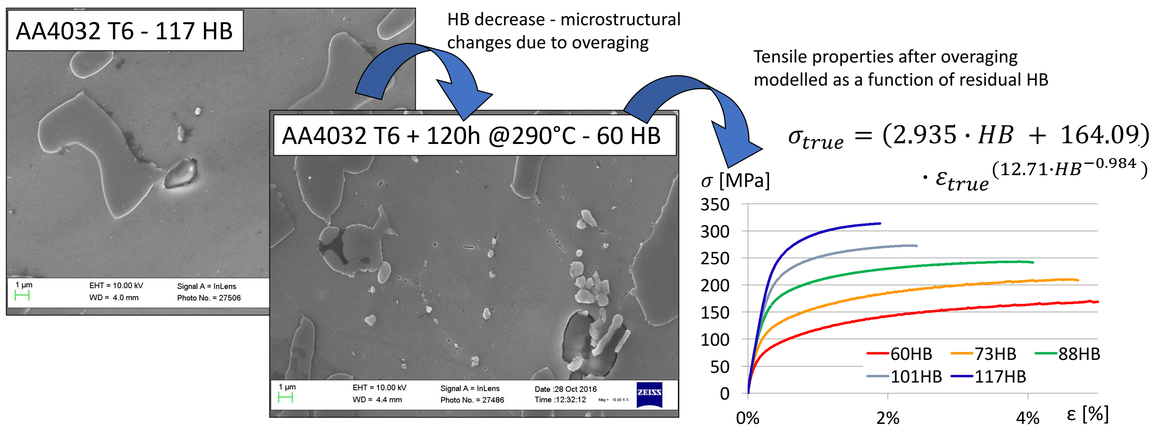
- **Vehicle lightweighting**. Due to their high specific strength, Al alloys play a key role in mass savings, and are therefore used for both structural (i.e. body in white elements) and critical engine components operating at high temperature (such as cylinder heads and pistons). Focusing on pistons, the major limit of the heat treated Al alloys is overaging, which consists in a rapid coarsening of strengthening precipitates and occurs at T > 200°C. To further promote mass savings, it is fundamental to increase Al alloys resistance at high T.
- **Engine downsizing.** Beside hybridisation, the current tendency is to raise engine specific power through turbochargers, which produces more severe (p, T) conditions inside the combustion chamber, negatively affecting the thermo-mechanical stresses on pistons under normal combustions. Moreover, the higher (p, T), the higher combustion efficiency, the more likely is the occurrence of knocking combustions. It is therefore necessary to accept light knocking combustions in order to reap the full benefits of turbocharging. Due to its p oscillation and local heating, knock further increases the thermo-mechanical stresses of pistons. Once again, it is fundamental to increase R/ρ of Al alloys in order to meet the current requirements for piston alloys, studying besides their resistance to knock.



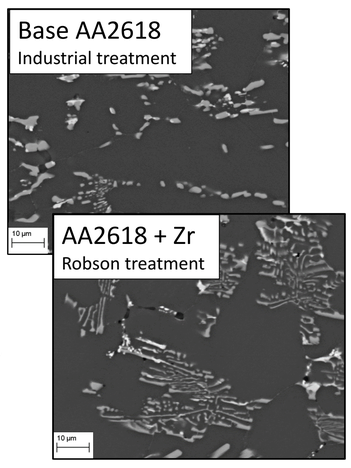
Experimental activities

Piston Al alloys R/ρ ↑ at high T

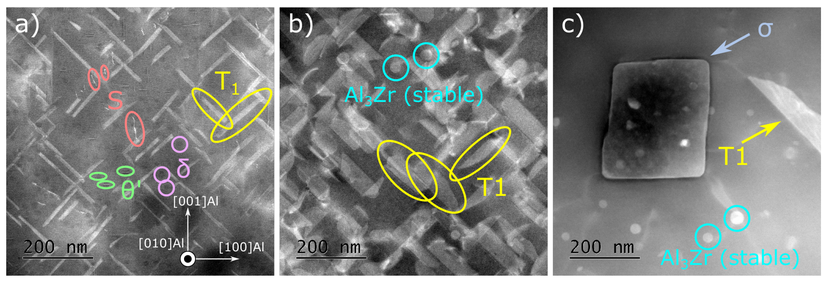
1. Two conventional Al alloys currently adopted for pistons (Al-Si AA4032 and Al-Cu AA2618) were characterised after overaging, in terms of both residual hardness, tensile properties and microstructural features. For each alloy, a relationship between microstructure and material performance was established. [1] (by Ceschini et al.) was considered as the main reference for the high performance AA2618 piston alloy, whereas most of the data on Al-Si alloy and a comparison of Al-Si / Al-Cu have been collected in [2],[3] by the candidate.



2. Chemical and heat treatments modifications have been performed on both Al-Si and Al-Cu conventional piston alloys, aiming to enhance the formation of heat resistant precipitates/ dispersoids. In agreement with literature data [4-7], transition elements additions have been investigated.
   - A variant of AA4032 (commercial "M142P", characterised by higher amount of Cu and Ni, therefore most promising at high T) was modified by adding Mo and Zr.
   - The high performance AA2618 was modified by adding Zr, and a different heat treatment was evaluated to promote Al_3Zr formation.



3. Two innovative lightweight Al-Cu-Li alloys (AA2099 and AA2055, the latter containing a significant amount of Ag) were characterised before and after overaging, through both SEM/ STEM microstructural investigations and tensile tests (at RT, at 200°C, at 250°C). Due to the significantly lower density, their R/ρ ratio was proven to be higher than the high performance AA2618 piston alloy. The main results were collected in [8,9] by the candidate. The activities have been carried out in cooperation with **Ducati Motor Holding S.p.A.**

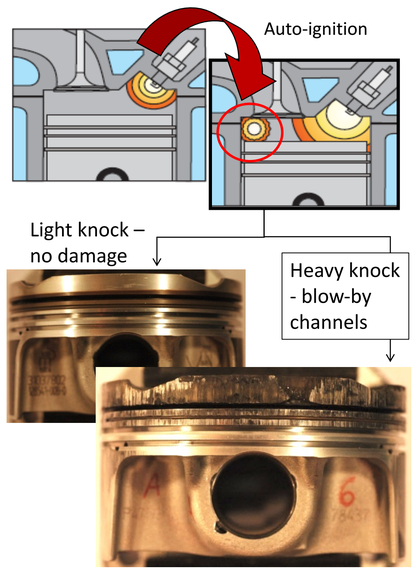


STEM analyses on AA2099: a) T83 and b)-c) overaged at 245°C – 305°C

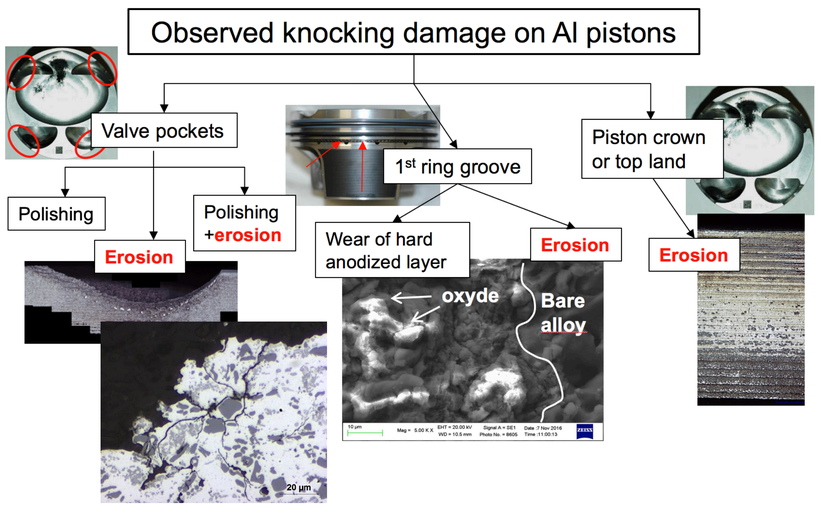
Piston Al alloys resistance to knock ↑

Starting point of the experimental activities is the idea that *knock compromises engine efficiency only when exceeding a certain threshold,* consistently with what reported by Nates et al. [10]. Since pistons are the engine components mainly damaged by knocking combustions, attention was focused on pistons damage to define the acceptable knocking threshold. Several bench tests (11 until now) have been carried out on a V8 GDI turbocharged engine, in cooperation with **Ferrari Auto S.p.A.** and **Fluid Machinery Research Group – Unibo**. The spark advance of each single cylinder was separately controlled by imposing a targeted MAPO 99.5% or 98%; the max test duration was set to 20 h. Pistons consist of the commercial Al-Si alloy M142P.

The following results have been achieved:



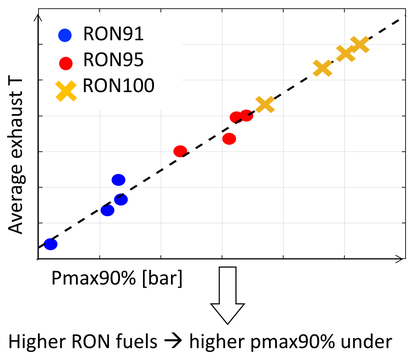
1. The most frequent damages due to light - medium knock levels (MAPO 99.5% up to 20 bar max) were determined, as well as the most suitable techniques able to evaluate the damage intensity. Few preliminary results are reported in [11, 12]



Several failure analysis techniques were employed:

- Visual analysis (macrographs, stereo-microscope / Hirox)
- Determination of thermal fields (hardness tests)
- Determination of plastic deformation in the 1st ring groove (dimensional analyses)
- Determination of eroded material (roughness/profile measurements)
- Determination of erosion mechanisms (OM, SEM-EDS)

2. A preliminary relationship between in-chamber pressure parameters and piston damage was determined. Damage intensity was found to be strongly dependent not only on MAPO level, but also on the in-chamber pressure at which knock occurs (which basically determines piston thermal field). This aspect was underlined in [13], by inducing knocking combustions with RON91 and RON95 fuels. To now, additional tests with RON100 fuel were performed, confirming the trend.



Higher RON fuels → higher pmax90% under normal combustions → when knock is induced, material is more sensitive to knock pressure oscillations

Main references

[1] "Effect of thermal exposure on mechanical properties of EN AW-2618 and EN AW-4032 piston alloys", E.Balducci*, L.Ceschini, Al.Morri, An.Morri; *La Metallurgia Italiana*, vol. 6, 2016
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[3] "Effect of thermal exposure on the residual hardness and tensile properties of the EN AW-2618A piston alloy",L.Ceschini, Al.Morri, An.Morri; M. Di Sabatino, *Materials Science & Engineering A*, vol. 639, 2015
[4] "Criteria for developing castable, creep-resistant aluminum-based alloys – A review", K.E. Knipling, D. C. Dunand, D. N. Seidman, *Int. J. Mater. Res.*, vol.97, 2006
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[6] "Dispersoid strengthening of a high temperature Al–Si–Cu–Mg alloy via Mo addition", A. R. Farkoosh, X. Grant Chen, M. Pekguleryuz, *Materials Science & Engineering A*, vol. 620, 2015
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[10] "Knock Damage Mechanisms in Spark-Ignition Engines", R.J. Nates, A.D.B. Yates, *SAE International*, 1994
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[12] "Analysis of Pre-ignition Combustions Triggered by Heavy Knocking Events in a Turbocharged GDI Engine", N.Cavina, N.Rojo, A.Businaro, L.Ceschini, E.Balducci*, A.Cerofolini; *Energy Procedia*, 2016
[13] "Investigation of Knock Damage Mechanisms on a GDI TC Engine", N.Cavina, N.Rojo, L.Ceschini, E.Balducci*, L. Poggio, L. Calogero, R. Cevolani, SAE 13th International Conference on Engine & Vehicles, 2017

*** My publications are reported in bold**

What's next?

- AA2618 + Zr additions: microstructural characterisation work in progress
- Additional bench tests will be carried out on AA2618 pistons, whose microstructure is thought to be more resistant to knock due to the lack of coarse and polygonal primary Si crystals
- In addition to the aforementioned failure analyses methods to evaluate piston perceivable damage, piston residual functionality should be determined during bench tests: evaluation of engine blow-by or oil consumption is needed to validate the knocking threshold which is thought to be tolerated.