National legislations place increasing efficiency requirements for passenger cars in terms of reducing fuel consumption and emissions. The continuous search for solutions that reduce the overall weight is therefore focused on the optimal design of critical engine components such as pistons with full exploitation of the material performance, [1]. Since cast eutectic Al-Si alloys [2] are used for the production of engine piston, there is a need for a design framework and material data that clarify aspects, such as alloying elements, modifier elements, heat treatment, process dependence of casting defects, etc. in the context of high temperature fatigue. Pistons made of Al-Si alloys are typically subjected during engine operation to fatigue loading cycles at temperatures from 100°C up to 300°C - 350°C in areas facing the combustion chamber.

This paper first discusses a thermo-mechanical design framework for pistons of high performance internal combustion engines highlighting the importance of an experimental material data base. High cycle fatigue test results of a cast eutectic alloy (AlSi12) used for piston production are also presented and discussed.

Thermomechanical piston design
Fatigue design of engine components is based on the thermo-mechanical stress state and history to be correlated to the admissible stress for the material under relevant operating conditions.

Thermo-mechanical stresses are currently calculated with the finite element method (FEM). Load cycles taken into account depend on the component and the type of service, such as the engine power on-off cycle or durability test at the engine test bench. The FEM analysis begins with the generation of the geometric model of the piston and the elements connected to it, the definition of the boundary conditions and a calculation that provides the temperature field. Heat transfer coefficients and heat flows are typically defined on the basis of industrial experience and optimized by experimental validation. Figure 1 shows the temperature map superimposed on a piston model. In this case the maximum temperature is approx. 300 °C reached on the surface facing the combustion chamber.

All the loads that the part exchanges with the neighboring components are then entered in the mechanical FEM model in addition to the temperature field. When operating at full power, the mechanical stresses due to explosions in the combustion chamber and the inertial effects of the reciprocating motion result in high frequency stress cycles. Such dynamic loads can be analytically calculated for different conditions of rotation and applied to the FE model of the piston through the connecting rod and pin. The lateral support provided by the cylinder liner is also modeled. Figure 2 shows a map of the principal stress showing that the central part of the piston behaves like a circular plate in bending. The peak stress values are found in the piston crown. For a fatigue assessment of this kind of loading, the high temperature fatigue behavior at high number of cycles of the material is critical.

Material testing
The eutectic Al-Si alloy is characterized by multi-phase microstructure, [2]. Allooying elements (e.g. Cu, Ni, V) are added to optimize the response to fatigue at high temperature without compromising the strength at room temperature. Figure 3 shows the microstructure of an gravity cast AlSi12 alloy after etching with 0.5% HF. Primary silicon particles and eutectic silicon in the matrix and intermetallic compounds are also visible.

A fatigue test machine subjecting the material to rotating bending at a frequency adjustable up to 80 Hz and applied temperatures up to 400°C was developed, [3]. The specimen is induction heated with closed-loop temperature control using a thermocouple inserted into the specimen. The set temperature is reached with a transient of a few tens
of seconds and is kept for the entire duration of the test with an error less than 1 °C.

A stair-case procedure and a test frequency of 50Hz was used to determine the fatigue strength at a set number of cycles (i.e. $10^7$ cycles). The stress amplitude and temperature were kept constant throughout the test. Samples were extracted from gravity cast AlSi12 pistons and fatigue tested at three temperatures: 250°C, 300°C and 350°C.

The plot in Figure 4 shows the dependence of high cycle fatigue strength with the test temperature for this material. Taking the fatigue strength at 250°C as reference, a considerable (30%) decrease is observed at a temperature of 300°C and a substantial fall (80%) in resistance at 350°C.

Conclusions

- High temperature fatigue design of engine pistons is based on the thermomechanical stress fluctuation computed by FEM and relevant fatigue data for the piston material.
- The key role in fatigue design of the maximum temperature reached by the piston during service of cast AlSi12 is experimentally demonstrated by high temperature high cycle fatigue tests.
- Microstructure rather than defects controls the high temperature fatigue strength of cast AlSi12 alloy.

References