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A new fatigue model including thermal ageing for low copper aluminum-silicon alloys

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Abstract

Numerical simulation is more and more used in automotive industry to reduce design time and cost. Moreover, for high performance engines, the development of cylinder heads requires well known and adapted materials to ensure their reliability.
The estimation of adapted fatigue criteria based on few experiments is thus an important challenge: to obtain more predictive model on more complex mechanical phenomena.
This paper describes the methodology adopted by Renault to estimate fatigue life of a new aluminum-silicon alloy.
A low copper aluminum-silicon alloy has been developed for a new generation of cylinder heads. Those kinds of alloys provide a good compromise between the two main failure modes encountered for cylinder heads: high cycle fatigue of water jacket and low cycle fatigue of fire deck.
However, those materials are subjected to thermal ageing that can affect mechanical behavior, such as yield stress and hardening, but also fatigue mechanisms at higher temperatures.
This article presents first the selected constitutive equations that introduce thermal ageing effect in a cyclic elasto-viscoplastic model. The low cycle fatigue criterion is then calibrated on the relevant database, which includes isothermal and non-isothermal tests.
The fatigue criterion is a specific version of a classical model previously developed at Onera. The critical variables for the fatigue part are the stress amplitude and the mean stress, both of them being normalized by an ultimate stress which depends on temperature and ageing state.
Finally, the constitutive and damage models have been applied on 3D cylinder head numerical analysis. The paper proposes a brief comparison of those results with more classical simulations made on cylinder heads and highlights the perspectives offered by this new aluminum-silicon alloy.

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Keywords: Aluminum-Silicon Alloy, Cylinder Head, Thermo-mechanical stresses, Low cycle fatigue, Thermal ageing

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1. Introduction

Nomenclature

N_f	number of cycles at failure
ε_m	mechanical strain (uniaxial formulation)
ε_p	plastic strain (uniaxial formulation)
p	cumulative plastic strain
ε_e	elastic strain (uniaxial formulation)
σ	stress (uniaxial formulation)
E	Elastic Young modulus
LCF	Low Cycle Fatigue
TMF	Thermo-Mechanical Fatigue
FEM	Finite Element Model
UTS	Ultimate Tensile Stress

1.1. Background

Cylinder head is a central and complex part on an internal combustion engine as it has to ensure many important functions: closure of the combustion chamber, admission of fresh gas, exhaust of hot burned gas, cooling of the engine.

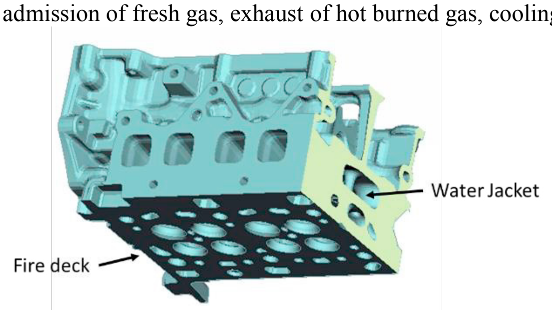

Fig. 1. Half view of cylinder head (Diesel engine)

Consequently to that central position, it supports 3 kinds of loadings:

- Static loading due to tightening on cylinder block and interference fitting of seats
- Thermal loading due to gas combustion flow
  Because of the engine power variation, that loading is cyclic and therefore creates thermo-mechanical stresses located on the fire deck, and then low cycle fatigue cracks.
- Pressure loading at each combustion in the cylinder
  Variation of pressure (with / without), combined with mean stresses coming from static and thermal loadings, induces high cycle fatigue damage, especially on the water jacket.

Those complex loadings generate strong material mechanisms that must be understood to design the cylinder head.

An important challenge of our industry is to define the adapted experiments that allow to estimate an accurate fatigue criteria. Considering in another hand that the number of experiments has to be optimized to reduce the new alloy's cost development.

This is the aim of the collaborative work presented in this paper which was conducted by different specialists from casting industry, material characterization, material behavior and motorist.

1.2. Current work

The material object of the study is a new aluminum-silicon alloy of first melting developed for high performance engines. Renault made the choice of a low copper alloy (Cu 0.5%) described in Table 1.

Table 1. Chemical composition of AlSi7Cu0.5Mg

	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Pb	Sn	Ti
Composition (%)	6.5 – 7.5	0.2	0.4 – 0.6	0.1	0.25 – 0.45	0.15	0.3	0.1	0.05	0.05	0.1

Cylinder head casting is followed by a complete thermal treatment (KT6 Air Quench) to increase mechanical strength by structural hardening and conferring a fine microstructure on the fire deck (fig 2).