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The role of elevated temperature exposure on structural evolution and fatigue strength of eutectic AlSi12 alloys

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ABSTRACT

Pistons of internal combustion (IC) engines are typically subjected during operation to high cycle fatigue loading at elevated temperatures (up to 350 °C). The materials typically used for piston production are eutectic Al–Si alloys for their excellent fluidity and suitable mechanical properties. Results of a fatigue testing program of eutectic Al–Si alloys at room temperature and at elevated temperatures (250 °C, 300 °C and 350 °C) performed with the aim to support piston design and material optimization are reported in this paper. Specimens were extracted from piston crowns and tested in a rotating bending test machine. The fatigue strength at 10^7 cycles was quantified by a staircase approach.

To investigate the strengthening mechanism based on the formation of precipitates (Guinier–Preston (GP) zones) during decomposition of a metastable supersaturated solid solution, a structural investigation of one of the alloys before and after fatigue testing at elevated temperatures was conducted. Metallography, color etching, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used to elucidate the following aspects: (1) the structural features of the alloy (dendrites of α-phase, primary Si particle size and distribution, morphology and distribution of intermetallic phases); (2) the changes of the strengthening mechanism (GP zones) with elevated temperature exposure.

1. Introduction

Pistons are non-serviceable parts and need to last the lifetime of the engine. Piston operation induce in the material a complex combination of thermal stresses and high cycle, elevated temperature mechanical loading responsible of fatigue cracking in the weakest zone, which is commonly the hottest part, i.e. areas facing the combustion chamber. The elevated temperature exposure in service results in a progressive loss of fatigue strength due to the over-aging phenomenon with crack initiation and propagation [1]. Modern gasoline engine pistons operate at temperatures up to 350 °C. The production may select either the casting or forging routes while the materials of choice are typically eutectic Al–Si alloys. Eutectic alloys are preferred because they have excellent fluidity and feedability due to their near zero solidification range [2].

Pistons of IC engines are typically subjected during operation to high cycle fatigue loading at elevated temperatures (up to 350 °C) in areas facing the combustion chamber. During operation the elevated temperature exposure results in a progressive loss of fatigue strength of the material at the weakest areas of the piston and may eventually results in a premature failure by fatigue crack initiation and propagation.

In order to estimate the design life of IC engine pistons, the temperature and stress distribution within the piston can be obtained by thermo-structural finite element (FE) analysis. Local temperature values can be verified by the hardness vs. temperature correlation approach [3]. The quantification of the temperature effect on material strength in fatigue inevitably requires ad-hoc experimentation since such data are scarce [4].

Numerous works show that the static strength and fatigue behavior of Al–Si alloys strongly depend on casting defects and microstructural characteristics. Especially the presence of casting porosity and oxide films decreases the fatigue life [5–9]. On the other hand, in the absence of casting imperfections, the fatigue fracture of cast Al–Si alloys is mainly characterized by cracking and debonding of silicon and intermetallic particles as well as nucleation of voids in the α matrix [10]. Dendrite arm spacing, grain size, shape and distribution of silicon particles and intermetallic phases can also significantly influence the behavior of cast aluminum–silicon alloys.

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The mechanical properties of eutectic Al–Si alloys typically used in piston production are optimized by an age-hardening or precipitation hardening. Age-hardening treatment consists in three steps: solution treatment, quenching and artificial (at elevated temperature) or natural (at room temperature) aging. The strengthening mechanism is based on the formation of precipitates called Guinier–Preston (GP) zones during decomposition of a metastable supersaturated solid solution α. During this process lattice stresses are generated, thereby increasing the strength and hardness of the material [11]. Al–Si alloys containing Cu and/or Mg are suitably heat treated and artificially strengthened by precipitation of Al_2Cu, Al_2CuMg and Mg_2Si [12–14].

Near eutectic Al–Si alloys containing elements such as Ni, Cu, Mg, Fe and Mn form many different intermetallic phases [2]. Defects and some intermetallic phases, especially iron-based [13], can favor fatigue crack initiation in the material in the case of cyclic loading [14]. Therefore, casting process optimization is aimed at eliminating defects and pores [6].

The piston production route is also expected to affect the elevated temperature fatigue strength. The casting production route is adopted when the geometry of the piston is complex and involves thin wall sections. Hot forging of preliminary cast aluminum bars is an alternative production route often used to obtain a piston with highly compacted material. The geometrical complexity of the part in this case has to be limited.

This paper provides new information on the role of elevated temperature during cycling on fatigue strength of eutectic Al–Si alloys used for piston production and on the structural changes associated to the observed loss of strength [11]. An extensive fatigue testing program on two eutectic Al–Si alloys with different content of alloying elements specifically developed for piston production was performed. Specimens were extracted from actual pistons and the high cycle fatigue strength at room temperature and at three elevated temperatures (250, 300 and 350 °C) was determined. The influence of alloy composition and piston production route on material behavior was investigated before and after fatigue testing at elevated temperatures. Metallographic analysis of etched specimens on light microscope (LM), special color etching, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used to elucidate the structural features of the alloys (dendrites of α-phase; shape, size and distribution of primary Si particles; morphology, distribution and chemical composition of intermetallic phases) and the changes of the strengthening mechanism (GP zones) due to cycling at elevated temperatures.

2. Experimental procedures

2.1. Material characterization

The materials under investigation are two near eutectic Al–Si alloys, namely a eutectic AlSi12 denominated as A and AlSi12CuNiMg denominated as B. Both the alloys are used for piston production. The materials differ in content of alloying elements, i.e. Cu, Ni and Mg, which are added to improve the resistance to corrosion and to the influence of elevated temperature exposure which is typical in engine applications. The chemical composition of both alloys is given in Table 1. The chemical composition of the alloy A corresponds to the standard composition of AlSi12. The chemical composition of the newly developed alloy B was checked using spectral analysis by the SPECTRO MAXx metal analyzer.

Table 1
Chemical composition of eutectic Al–Si alloys (in wt.%).

	Si	Cu	Ni	Mg	Fe	Ti	Mn	Zn	Al
A	10.5–13.5	0.9	0.3	0.35	0.50	0.10	0.15	0.15	Balance
B	11.3	4.07	1.81	0.95	0.3	0.12	0.10	0.04	Balance

The production of Al–Si pistons can follow two different routes: (i) gravity casting and (ii) hot forging. In the first case, when the geometry of the piston is complex involving thin wall sections, the gravity casting production route is adopted. In the second case, blanks of extracted from cast aluminum bars are hot forged to obtain a piston with highly compacted material although of limited geometrical complexity.

Specimens for the microstructural characterization were extracted from the pistons crowns. The aging treatment was optimized by the company in dependence of the forming process. In both cases of Alloy A and B, the aging treatment of the forged pistons was an exposure to 200 °C for 9 h while the treatment of the cast pistons consisted in an exposure to 215 °C for 9 h. The structural changes were investigated on metallographic specimens extracted from broken fatigue specimens tested at room and elevated temperature. Metallographic analysis of basic microstructural characteristics (dendrites, eutectic, primary silicon particles and intermetallic phases) on polished and etched specimens with 0.5% HF was performed by light microscopy observation on Neophot 32 equipment. Detailed investigation of microstructure was performed on metallographic specimens after new polishing and etching with special color etching agent named Weck–Aluminum (W–Al) with the aim to reach higher and color contrast at high magnification on LM.

Image analysis software NIS Element was used to quantify the microstructure features, such as content and size of the primary Si particles, dendrite characteristics and the shape and content of intermetallic phases. The chemical composition of intermetallic phases according to their shapes were analyzed by EDX analysis using SEM TESCAN VEGA II LMV.

TEM was used to study the influence of elevated temperature exposure on the microstructure and on the strengthening mechanism. TEM studies were carried out on thin foils using a Philips CM12 TEM/STEM microscope operating at 120 kV. Thin foils were prepared from 3×0.1-mm-thick discs by dimpling (spherical grinding), followed by ion milling.

Brinell hardness measurements were performed on specimens prepared from the gauge length of the fatigue specimens before and after fatigue testing.

2.2. Tensile and fatigue tests

Specimens for mechanical and fatigue testing were extracted directly from age-treated piston crowns. Tensile tests were performed on a MTS 810 servo hydraulic test machine equipped with a 10 kN load cell and a MTS extensometer at room temperature (i.e. 25 °C) and at temperature of 250 °C on conditioned specimens (i.e. preliminary exposure to 300 °C for 20 h) to investigate the loss of the effect of the strengthening mechanism expressed by the stress–strain curve. The specimens were heated with an induction coil. The temperature was monitored by a thermocouple touching the specimen gauge length. The specimen geometry is shown in Fig. 1.

Smooth fatigue specimens with 5 mm in diameter (Fig. 2) were subjected to rotating bending loading at 50 Hz. A split furnace surrounds and heats the rotating specimen while the temperature of the specimen is continuously monitored during the test with a thermocouple inserted into the axial hole shown in Fig. 2.

A reduced stair-case procedure was applied to determine the fatigue strength at 10^7 cycles at room temperature and at elevated temperatures (250, 300 and 350 °C). The stair-case procedure (or up and down method) involves a testing of a sequence of identical