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Fatigue strength degradation of AlSi12CuNiMg alloy due to high temperature exposure: a structural investigation

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Abstract

The strengthening mechanism based on the formation of precipitates (Guinier-Preston (GP) zones) during decomposition of a metastable supersaturated solid solution is stable and effective below temperatures, which are typically overcome in the piston region facing the combustion chamber. Therefore, pistons experience a progressive loss of strength due to over-aging during service. This contribution reports of a structural investigation on a eutectic AlSi12CuNiMg alloy before and after fatigue testing at high temperatures (up to 350 °C). Metallography, color etching, SEM and TEM are 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 evolution of the strengthening mechanism (GP zones) with high temperature exposure.

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Keywords: Al-Si alloy; fatigue strength; structural investigation, age hardening, precipitates

1. Introduction

The mechanical properties of eutectic Al-Si alloys typically used in piston production are optimized by an aging treatment (solution treatment and quenching) where the strengthening mechanism is based on the formation of precipitates (GP zones) during decomposition of a metastable supersaturated solid solution. However, such

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strengthening is stable and effective below temperatures, say 170 °C, that is typically overcome in the piston region facing the combustion chamber [1]. Therefore, a progressive loss of strength due to over-aging during service negatively affects the durability of pistons.

The mechanisms behind the high temperature fatigue behavior of the Al-Si materials for piston application needs to be fully understood [1]. Al/Si alloys containing Mg and/or Cu are suitably heat treated and strengthened by precipitation of Mg_2Si, Al_2CuMg and Al_2Cu [2,3,4]. Near eutectic Al-Si alloys containing elements such as Ni, Cu, Mg, Fe and Mn can form many different intermetallic phases [5]. Defects and some intermetallic phases, especially iron-based [6], in the material can favor crack initiation in the case of fatigue loading [7]. Therefore, casting process optimization is aimed at eliminating defects and pores [6].

This contribution reports of a structural investigation on a eutectic AlSi12CuNiMg alloy before and after fatigue testing at high temperatures (up to 350 °C). Metallography, color etching, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are 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 evolution of the strengthening mechanism (GP zones) with high temperature exposure.

Experimental

The material under investigation is a near eutectic AlSi12CuNiMg alloy used for piston production. Chemical composition of this Al/Si alloy was determined by spectral analysis the Spectra Maxx. The chemical composition is given in Tab. 1. Specimens for mechanical and fatigue testing were extracted directly from the piston crowns after heat treatment T6.

Table 1 Chemical composition of AlSi12CuNiMg (in wt. %)

Element	Si	Cu	Ni	Mg	Fe	Ti	Mn	Zn	Cr	Pb	Sn	Al
wt. %	11.30	4.07	1.81	0.95	0.30	0.12	0.10	0.04	0.02	0.02	0.01	Base

The structural analysis was performed on specimens taken from broken bars after fatigue and tensile testing. Metallographic observations were made by optical microscopy (OM) on microscope Neophot 32 using specimens etched with 0.5% HF. Image analysis software NIS Element was used to quantify the microstructure characteristics. Structural details of the specimens were also visualized by color etching with Weck–Aluminum (W-Al) and Ammonium Molybdate (AM). The chemical composition of intermetallic phases was obtained by EDX analysis.

Transmission electron microscopy TEM) studies were carried out on thin foils using a Philips CM12 TEM/STEM microscope working on 120 kV. Thin foils were prepared from 3 x 0.1 mm thick disc by dimpling (spherical grinding), followed by ion milling.

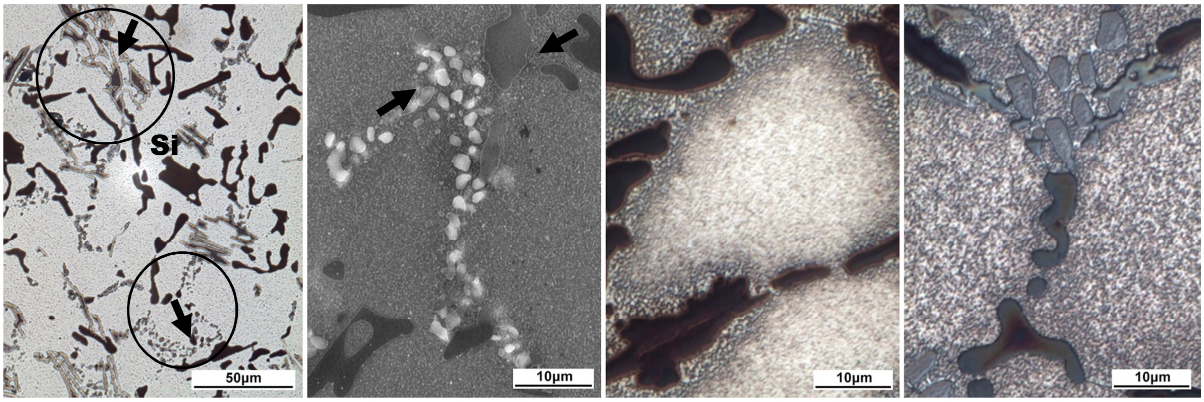
Tensile tests were performed on a MTS 810 servo hydraulic test machine equipped with MTS extensometer at 25 °C and 250 °C. The results presented elsewhere in [8] indicate that tensile strength decreases approximately by 40 % and elongation increases significantly. The decrease of strength was confirmed by Brinell hardness tests. The average HB hardness of the original material after T6 was 128 HBW that was found to decrease to 78 HBW after exposure at 300 °C. This value corresponds to the material hardness without T6 treatment.

Smooth 5-mm-dia fatigue specimens were subjected to rotating bending loading at 50 Hz. The reduced stair-case procedure for determination of the fatigue strength at 10^7 cycles at temperature of 250 °C, 300 °C and 350 °C was applied. If the fatigue strength at 250 °C is taken as a reference, the fatigue strength decrease is considerable (30 %) when the temperature is increased to 300 °C and is very significant (80 %) when the temperature is 350 °C [8].

2. Results and discussion

The structure of the experimental material after T6 heat treatment is characterized by dendrites of α-phase (solid solution Al(Si)), a eutectic compound of (α+eutectic Si) and primary Si particles, Fig. 1a. The average length of dendrites is 720 μm with average spacing of secondary dendrite arms 19 μm. The structure was found very fine, which is very important for improving mechanical properties. Hard and brittle eutectic silicon phases are distributed in interdendritic spaces. In addition, numerous intermetallic phases are present, see Fig. 1a and 1b, because of alloying elements such as Cu, Mg, Mn, Fe and Ni which significantly improve properties of piston alloys [9,10]. Copper and magnesium are added because of strengthening of the material by fine secondary phase precipitates. Nickel is added to enhance strength and hardness at elevated temperature. Addition of copper improves the corrosion resistance [11].

The structural analysis locally detected shrinkage clusters that arise as a result of metal shrinkage during solidification. If present on the surface or in its vicinity, they may act as sites of fatigue crack initiation [7,11,12]. However, their presence was quite limited in the investigated material (i.e. located in middle part of section and only in one specimen). A random distribution of the coarse angular primary Si particles with the mean size of 18 μm was observed, Fig. 1a. The thermal expansion coefficient difference between Si and Al indicates that thermal cycling could lead to cracking/decohesion of larger Si particles due to significant strain mismatch activating a crack initiation mechanism under thermo-mechanical fatigue conditions [1]. Locally, cracked primary silicon particles were identified in the present alloy but the crack did not propagate through the matrix. Since the average size of Si particles was much smaller than ~ 50 μm, the primary Si particles do not favor fatigue crack initiation in accordance to [1].



a) etched AM, OM b) SEM micrograph c) α-phase, etched W-Al, OM d) α-phase, etched W-Al, OM

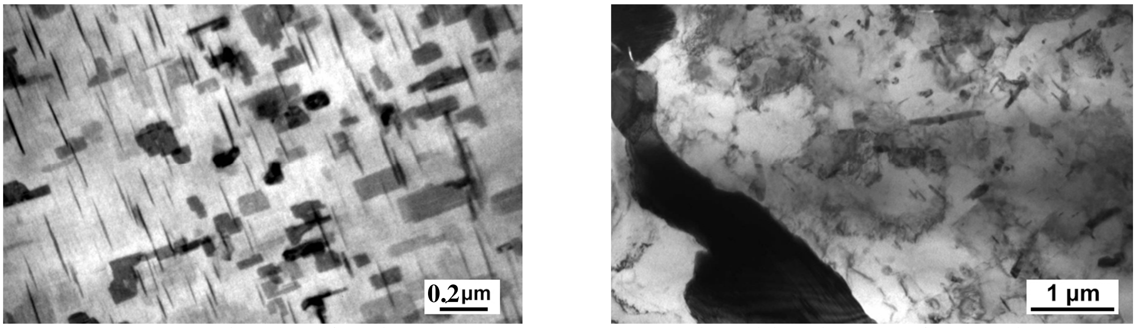
Fig. 1 Microstructure and intermetallic phases in cast AlSi12

Beyond optical microscopy, Fig. 1a, identification of intermetallic phases was performed by EDX analysis using SEM TESCAN VEGA II LMV. The intermetallic phases are indicated with arrows in Fig. 1a and b. Skeleton formations of Al(NiCuFe)Si, Fig. 1a, were the most frequently found structural details, followed by fine globular particle aggregates of Al(CuNi)Si, Fig. 1a, b. Very small disc particles of Al(MgCu)Si were identified only by high magnification with SEM, Fig. 1b.

The color etching technique is based on the thin film formation whose thickness corresponds to the local chemical composition [13]. Color etching (with W-Al) of the studied alloy showed chemical inhomogeneity in α-phase areas with light central areas associated to high Cu concentration, Fig 1c, where the GPI zones form. The high concentration of Cu in α-phase is typical of age hardening by precipitation of Al_2Cu/Al_2Mg or Al_2CuMg precipitates in dependence on content of these elements in the alloys [14]. A structure detail of the α-phase after exposure to 300 °C during testing, Fig. 1d, shows a different etched effect when compared to the Fig. 1c. In this case the Cu concentration is uniform over the whole area as revealed by the uniform gray color. Therefore, the high temperature exposure influenced the initial strength of the original material similarly to an over-aging treatment.

TEM micrographs of microstructural changes between the T6 state and the over-aged state (exposure at 300 °C) after fatigue testing are shown in Fig. 2. A high density of very fine homogeneously distributed precipitates (Al_2Cu/Mg_2Si/Al_2CuMg) in the α-phase coherent with matrix [14] is observed. GPI zones in the form of thin lamellas appear as thin dark segments or as rectangles according to their position in the foil, Fig. 2a. GPI zone sizes in three dimensions can be determined. The structure and high hardness of the material correspond to the T6 aging treatment [15].

The microstructure after high temperature exposure is shown in Fig. 2b. The GPI zones are evidently degraded according to a coalescence mechanism with the formation of large precipitates. The big dark particle is a part of an intermetallic phase $Al_2(CuNi)Si$. The low hardness (78 HBW) of the present material after high temperature fatigue tests is similar to the as-cast hardness of a similar alloy and after its heat treatment at high temperatures (310 °C) as reported in [5,15].



a) GPI zones in α-phase after aging b) precipitates in α-phase after over-aging

Fig. 2 Micrographs of cast AlSi12 after aging T6 and over-aged like (exposure at 300 °C during testing), TEM

3. Conclusions

The structural investigation of a eutectic AlSi12CuNiMg alloy before and after fatigue testing at high temperatures (up to 350°C) have reached the following conclusions:

- The fatigue strength is dramatically reduced at high temperature (i.e. above 200 °C) because the strengthening mechanisms disappear with time and temperature level.
- Intermetallic phases are observed to form complex structures, which may support the soft phase at high temperature.
- The formation of GPI zones is responsible for the strengthening of the eutectic alloy after T6 treatment.
- GPI zones are found to coalesce into large precipitates following high temperature exposure with a reduction in hardness.

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