Materials and Design 45 (2013) 279–285

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Heat treatment effect on thermo-mechanical fatigue and low cycle fatigue behaviors of A356.0 aluminum alloy

Mohammad Azadi [a,b,*], Mehdi Mokhtari Shirazabad [c]

[a] School of Mechanical Engineering, Sharif University of Technology, Tehran, Iran
[b] Fatigue Workgroup, Vehicle/Engine Laboratory and Validation Department, Irankhodro Powertrain Company (IPCo.), Tehran, Iran
[c] School of Metallurgy and Materials Engineering, Iran University of Science and Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 13 June 2012
Accepted 25 August 2012
Available online 19 September 2012

Keywords:
Heat treatment
Aluminum alloy
Thermo-mechanical fatigue
Low cycle fatigue

ABSTRACT

In the present paper, the heat treatment effect on A356.0, a cast aluminum alloy which has been widely used in diesel engine cylinder heads, is investigated under out-of-phase thermo-mechanical fatigue and low cycle fatigue (at different temperatures) loadings. A typical heat treatment is applied to the material including 8 h solution at 535 °C, water quench and 3 h ageing at 180 °C. The experimental fatigue results show that the heat treatment process has considerable influence on mechanical and low cycle fatigue behaviors, especially at room temperature, but its effect on thermo-mechanical fatigue lifetime is not significant. The improvement in the strength can be explained by the dislocation theory. Under thermo-mechanical fatigue loadings, the difference between the fatigue lifetime of A356.0 alloy and A356.0-T6 alloy decreases when the temperature range increases. In this condition, plastic strain increases severely during the fatigue cycles in A356.0-T6 alloy due to over-ageing phenomenon and therefore, the amount of cyclic softening in heat treated alloy is more.

1. Introduction

Aluminum alloy cylinder heads, as a part of combustion chamber, are required to meet two essential material properties. One of them is the resistance to deformations under combustion pressure and assembly loads. The second one is the toughness at high temperatures of the combustion flame to prevent cracking. These thermo-mechanical loading conditions can be handled by a combination of modern cooling methods or protective coatings. As an example, thermal barrier coatings lead to lower thermal stresses due to lower temperature gradient. Another example is to strengthen the material with a typical heat treatment process [1–3].

Several studies have been established for the fatigue behavior of aluminum–silicon alloys but less number of scientists investigated the effect of heat treatment. As an example, Takahashi and Sasaki [2] tried to show that an additional ageing process after T6 heat treatment was much more effective on low cycle thermal fatigue life of A356.0 aluminum alloy. As the alloys were aged longer and tempering enhanced, the fatigue lifetime lengthened.

A number of researchers proposed fracture mechanics of aluminum alloys, such as Caton et al. [4] who monitored the small-crack growth in Al–Si–Cu alloy for three different solidification times. Two conditions including peak-aged (T6) treatment and over-aged (T7) process were considered in this article. The fatigue behavior of aluminum foams was investigated at the macro- and micro-scales by Zhou and Soboyejo [5]. They compared the foams in various states including as-fabricated, annealed and T6-strengthened conditions. The effect of ageing treatments on the fatigue crack growth of 7010 aluminum alloy was studied by Desmukh et al. [6].

Some other researchers worked on the fatigue lifetime. Sadeler et al. [7] improved high cycle fatigue behavior of 2014 aluminum alloy by the heat treatment. Firouzdor et al. [8] investigated the effect of micro-structural constituents on the thermal fatigue life of A319 aluminum alloy. They showed that although T6 and T7 heat treatments appeared to be highly beneficial for the thermal fatigue performance, but T7 treatment could not improve the material performance more than T6 treatment. The effect of ageing time and temperature on fatigue and fracture behaviors of 6063 aluminum alloy was studied by Siddiqui et al. [9] under seawater conditions. They demonstrated that the increase in the fatigue resistance property with ageing time was linked with the vacancies assisted diffusion mechanism and also by the hindering of dislocation movement by impure atoms. AA7030 aluminum alloy was tested under low cycle fatigue loadings by Hoernqvist and Karlsson [10]. Their objectives were to determine the cyclic deformation

---

* Corresponding author at: Fatigue Workgroup, Vehicle/Engine Laboratory and Validation Department, Irankhodro Powertrain Company (IPCo.), Tehran, Iran. Tel.: +98 910 210 7280; fax: +98 21 22243621.

E-mail addresses: m_azadi@ip-co.com, azadi@mech.sharif.ir, m.azadi.1983@gmail.com (M. Azadi).

0261-3069/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2012.08.066

properties and to investigate the influence of heat treatment. Their results showed that although the fatigue life is longer in the natural ageing temper at a given plastic strain amplitude, but also the fatigue life can be described by a total strain amplitude approach, where both natural ageing and peak ageing fall on the same straight line. Toda et al. [11] improved thermo-mechanical fatigue resistance of aluminum alloys with the age-hardening. They illustrated that applying out-of-phase thermo-mechanical treatment within small temperature and strain ranges prolonged in-phase thermo-mechanical fatigue life by 34%. The influence of heat treatment was evaluated by May et al. [12] for the fatigue lifetime of aluminum alloys. They demonstrated that the fatigue performance increased in 2024 alloy of about 34% just by using different age hardening, however, the diffusion phenomenon has made their surface very fragile, what led to the reduction in their lifespan.

According to the literatures review, studying the heat treatment effect on high temperature fatigue behavior of aluminum alloys is so rare, especially under thermo-mechanical fatigue loadings. Therefore, the objective of this work is to investigate out-of-phase thermo-mechanical fatigue (OP-TMF), room temperature (RT-) and high temperature (HT-) low cycle fatigue (LCF) behaviors of A356.0 aluminum alloy with and without the heat treatment. Therefore, experimental fatigue results are illustrated in graphical figures including the lifetime and stress–strain hysteresis loops.

2. Material

Mechanical and fatigue properties of a cast aluminum–silicon-magnesium alloy, A356.0 (Al–Si7–Mg0.3) is studied in the present paper. This aluminum alloy has been widely used in diesel engine cylinder heads. The chemical composition of the material includes 7.06% Si, 0.37% Mg, 0.15% Fe, 0.01% Cu, 0.02% Mn, 0.13% Ti and the remainder is aluminum. The production method is a gravity casting process in permanent molds. The initial microstructure of A356.0 alloy before fatigue tests is shown in Fig. 1 including as-cast state and with a typical T6 heat treatment. This picture consists of eutectic Al and Si particle phases. The dendrites (α-Al phase) can be observed with about 31.9 μm (as an average value) for the second dendrite arm spacing (SDAS). It should be noted that the heat treatment has no effect on SDAS [13].

A heat treatment process, entitled T6 is applied to the material including 8 h solution at 535 °C, water quench and 3 h ageing at 180 °C [14]. As mentioned in the literature, the ageing parameters (the temperature and the time) were optimized by Siddiqui et al. [9] for 6063 aluminum alloy under fatigue loadings. They concluded that the best precipitation hardening temperature is 180 °C when 6063 alloy is aged for 9 h and has achieved a maximum fatigue resistance property. But 3 h ageing has the highest lifetime for 6063 alloy when the ageing temperature increased. As another literature, Rometsch and Schaffer [15] presented an age hardening model for Al–Si7–Mg alloys. They showed that after about 5 h ageing (at 180 °C of ageing temperature), the hardness of A356.0 alloy will be maximized. Also, the cylinder heads manufacturers tend to reduce the ageing time to decreases the costs [16]. In such this case, the changes rechecked by the designer to have no major loss in the performance of cylinder heads under real TMF loading conditions. This typical heat treatment is considered for a passenger car with a diesel engine cylinder head made of A356.0 alloy [16].

The morphology of the microstructure changed obviously after the T6 heat treatment. As illustrated in Fig. 1, the solution treatment leads to the spheroidization of the eutectic silicon [17]. The irregular eutectic phase after the solution treatment is converted into fine spheroidized silicon particles uniformly distributed in the aluminum matrix [18]. Indeed, the T6 heat treatment provides two beneficial effects in Al–Si alloys. One is improvements in the ductility and the fracture toughness through the spheroidization of the eutectic silicon particles in the microstructure. The other is higher yield strength through the formation of a large number of fine β'' precipitates which strengthen the soft aluminum matrix. The first benefit is realized through the solution treatment while the second benefit is achieved through the combination of solution treatment, quenching and artificial ageing [19,20].

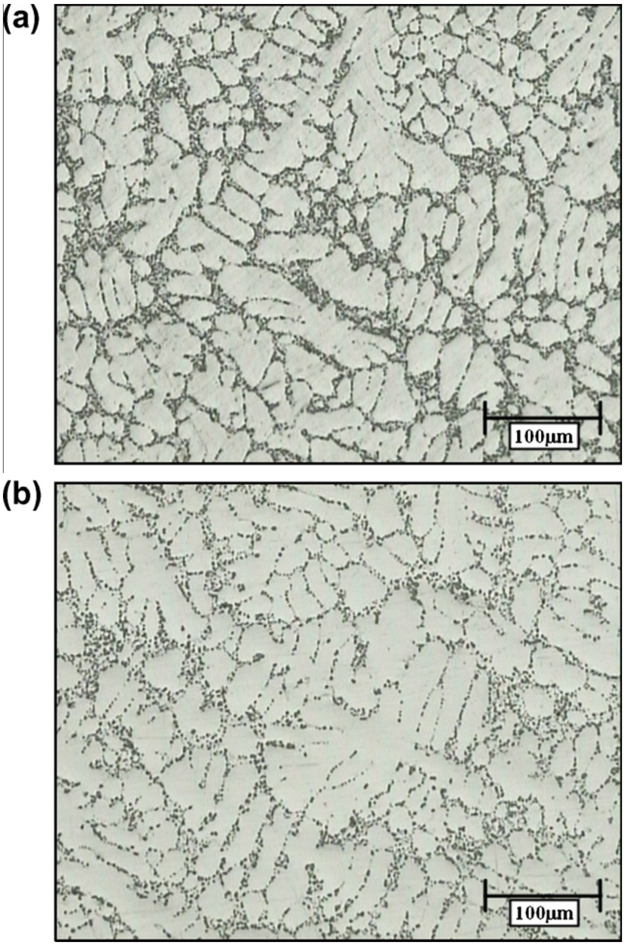

Fig. 1. The microstructure of A356.0 alloy before fatigue tests including (a) as-cast state and (b) with a typical T6 heat treatment.

The hardness of A356.0 alloy is measured as 65 HB and 102 HB, before and after the heat treatment, respectively. Therefore, as expected, the heat treatment process increases the hardness and consequently, should increase mechanical properties, especially at room temperature [14]. The improvement of the tensile properties in the T6 heat treatment is directly related to the spheroidization of eutectic silicon particles and the precipitation of Mg_2Si particles during the ageing process [17].

3. Test conditions

In LCF tests, the temperature is constant during the lifetime and mechanical strain amplitude varies with triangular wave form between maximum and minimum values. This amplitude is set to 0.2, 0.3, 0.4 and 0.5% under the strain rate of 1%/s considering ASTM: E606 standard. TMF tests are carried out based on COP-EUR22281-EN procedure [21]. In OP-TMF tests, the temperature reaches to its maximum value, when the strain has a maximum compressive value and vice versa. This condition is comparable to start-stop cycles