Materials Science & Engineering A 715 (2018) 62–72

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Thermo-mechanical fatigue behavior and life prediction of the Al-Si piston alloy

M. Wang[a,b], J.C. Pang[a,⁎], M.X. Zhang[a], H.Q. Liu[a,b], S.X. Li[a], Z.F. Zhang[a,b,⁎⁎]

[a] Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, PR China
[b] School of Materials Science and Engineering, University of Science and Technology of China, Hefei 230026, PR China

ARTICLE INFO

Keywords:
Al-Si piston alloy
Thermo-mechanical fatigue
Life prediction
Damage mechanism

ABSTRACT

The thermo-mechanical fatigue (TMF) behaviors and corresponding damage mechanisms of Al-Si piston alloy were investigated in the temperature ranges of 120–350 °C and 120–425 °C in this study. For TMF cyclic stress response behavior, the rapid cyclic softening occurs in the initial stage and then the cyclic stress maintains stable at lower strain amplitudes; but the cyclic stress displays gradual decrease up to the final failure at higher strain amplitudes. For TMF damage behavior, the cracks mainly initiate from the broken primary silicon in the temperature of 120–350 °C range, and commonly nucleate from the boundary between primary Si and matrix in the temperature of 120–425 °C range. For both cases, creep may have obvious influence and result in the formation of many micro-voids, but the oxidation may only have a little effect. A new energy-based model for low-cycle fatigue (LCF) and TMF life prediction was proposed based on the hysteresis energy with strain rate modification, considering both fatigue and creep damages. The predicted results agree well with the experimental ones for the Al-Si piston alloy.

1. Introduction

To develop more efficient diesel engines, lightweight high performance pistons are essential. The Al-Si alloys have been focused as the perfect material for pistons because of its high strength to weight ratio, excellent wear resistance, outstanding formability and low coefficient of thermal expansion [1–3]. Similar to other engineering applications at high temperature, the piston always undergoes cyclic thermal and mechanical stresses/strains at the service process [4]. To increase engine efficiency and fulfill emission standard requirements, the maximum operation temperature and pressure of the engine must be raised, in particular in diesel engines. This has increased the maximum operating temperature of cylinder heads from below 170 °C in earlier engines to temperatures above 250 °C in recent engines [3]. In order to withstand the increasingly crucial service condition, the Al-Si alloys are added with elements such as Cu, Ni, Mg, Mn etc. to enhance their elevated temperature strength [5–8]. The combined damage effect of cyclic thermal and mechanical loading on a component is referred to as thermo-mechanical fatigue (TMF). The TMF damage usually can be divided into three types: creep, fatigue and oxidation. It is introduced to account for damage associated with a certain type of strain-temperature phasing; for example, sometimes the fatigue and creep damages dominate in-phase (IP)-TMF whereas fatigue and oxidation damages occur in out-of-phase (OP)-TMF. Some studies on TMF of Al-Si alloys have been conducted, for example the hypoeutectic Al-Si cast systems (Al-Si-Mg and Al-Si-Cu) [9,10]. It is noticed that no oxidation layer was observed on all specimens in microstructural investigations after TMF tests for the Al alloy [11] and the prediction of oxidation damage is not precise [12]. Whereas the high temperature corrosion in oxidative condition of Al-Si alloys cannot be found without enough electrolytes during TMF [10]. Based on the damage behaviors of Al-Si alloys, the corrosion of pistons under TMF loading should be not essential.

Because of the complexity of damage behavior, the TMF life is hard to predict. Treatment of this problem has been a challenge for over half a century. In the early 1950s, Manson made a study of thermal stress and pointed out the complexity of TMF [13]. Later, a large number of life prediction methods were proposed or optimized to evaluate the TMF life, such as strain-range partitioning (SRP) [14] and Coffin's frequency modified model based on the Manson-Coffin equation [15], Neu-Sehitoglu model based on creep, fatigue and oxidation damages [16,17], Miller model based on the accumulation of damage rates (pure creep, fatigue, oxidation) [18], J-integral model based on fracture

⁎ Corresponding author.
⁎⁎ Corresponding author at: Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, PR China.
E-mail addresses: jcpang@imr.ac.cn (J.C. Pang), zhfzhang@imr.ac.cn (Z.F. Zhang).

https://doi.org/10.1016/j.msea.2017.12.099
Received 1 December 2017; Accepted 27 December 2017
Available online 28 December 2017
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mechanics (the crack initiation and propagation for brittle materials) [19], energy-based models based on the dissipated energy per cycle [20,21] and so on. Among these TMF lifetime approaches, the energy-based models have been considered as a better possibility to combine prediction accuracy with clear physical mechanism involving various influencing factors such as the dwell time, the maximum temperature and the strain amplitude [21,22]. In addition, the energy-based models have an obvious reduction of parameters, usually one or two parameters are sufficient [23]. With regard to Al alloys, the ageing and cyclic softening behaviors are the cyclic deformation characteristics at elevated temperatures [24–26], so the time-dependent strain rate is important for the strain-controlled TMF testing. A considerable amount of efforts have been devoted to investigate the effect of strain rate [27–31]. Minichmayr et al. [31] carried out TMF/LCF lifetime assessment of Al alloys using the damage rate model of Sehitoglu under various strain rates. Azadi [28] and Farrahi et al. [30] applied material constants obtained by LCF data at various temperatures to predict the TMF behavior of light alloys by considering strain rate.

Some researchers have made attempts to investigate the TMF of hypoeutectic Al-Si alloys as mentioned above. But for TMF of eutectic Al-Si piston alloys, the studies are not very sufficient for both damage behavior and life prediction method. The present study mainly focuses on the frequency factor effect on the fatigue life prediction of LCF and TMF based on an energy method for Al-Si piston alloy. Meanwhile, the microstructure, damage processes and fracture mechanisms under the TMF are also analyzed.

2. Experimental materials and procedures

The samples used in this study were taken from the crown of cast pistons after T6 (solution treated at 500 °C for 8 h, quenched in hot water and artificially aged at 215 °C for 6 h) heat treatment and the reference chemical composition is given in Table 1, hereafter the material is named as Al-Si piston alloy. The tension-compression loading tests with strain controlled symmetric triangular waveform were carried out on an Instron 8862 testing machine at total strain amplitudes ($\Delta\varepsilon_t/2$) of 0.15%, 0.20%, 0.30%, 0.40%, with a strain rate of 5×10^{-4} s^{-1} at 350 °C and 425 °C in air [25].

The TMF test specimens were machined to a parallel gauge section with the length of 30 mm and the diameter of 8 mm (Fig. 1a). All of samples were ground using SiC papers up to grit number of 2000. The thermo-mechanical loading was performed with a servo-hydraulic testing machine MTS 810 in air. The specimens were heated with an induction heating coil and cooled with compressed air from three directions. The temperature was measured and controlled by K-type thermocouple, attached to the center of the gauge length. Based on the actual service conditions of engine piston, all the TMF specimens were tested under IP-TMF conditions (Fig. 1b), both heating and cooling rate are 5 °C/s. The TMF life, N_f, was defined as the cyclic number when the stress amplitude drops to approximately 60% of the maximum value. Axial total strain was measured with 25 mm high temperature extensometer, under temperatures and mechanical strain amplitudes varying from 0.2% to 0.6% for ΔT_1 = 120–350 °C (hereafter, TMF-350 °C), and 0.3–0.8% for ΔT_2 = 120–425 °C (hereafter, TMF-425 °C). The relationship between the test temperature (T), the reference temperature (T_0 = 25 °C), total strain (ε_t), mechanical strain (ε_m), thermal strain (ε_{th}) and the thermal expansion coefficient (α) of the alloy can be written as [3,32]:

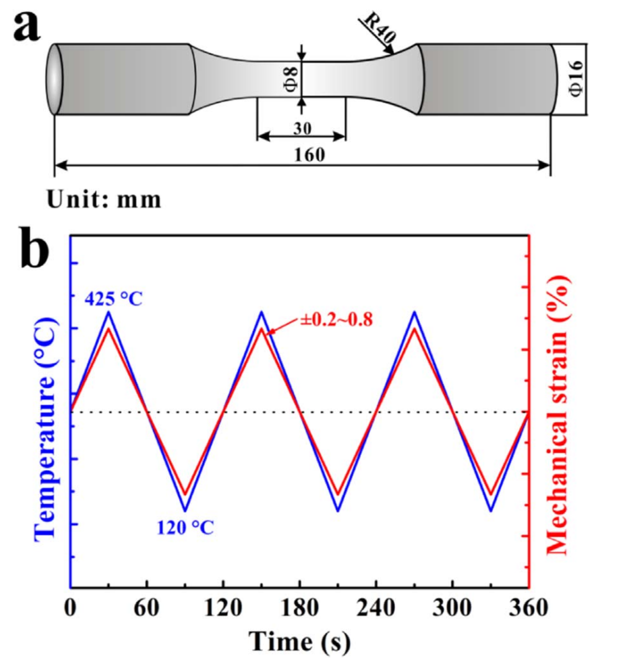

Fig. 1. (a) The dimension of TMF specimen (b) IP loading condition of TMF-425 °C.

$$\varepsilon_t = \varepsilon_{th} + \varepsilon_m = \alpha(T - T_0) + \varepsilon_m. \quad (1)$$

Before TMF test, α was measured by temperature cycling for about 5 cycles under zero-load condition and the value is about 20.8×10^{-6} °C.

After TMF tests, the fractography and damage features around main crack were observed by scanning electron microscopy (SEM) JSM 6510. The samples were sectioned longitudinally near fracture surfaces, ground using SiC papers up to a number of 5000, polished using 1 µm diamond paste.

3. Experimental results

3.1. Microstructure

Some typical phases of the Al-Si piston alloy are identified and labeled briefly in SEM image (Fig. 2). The material contains α-Al, Si phases (primary Si, eutectic Si) and several intermetallics including AlCuNi, β-Al_5FeSi, Al_3(Ti, Ce) and AlFeMnNi phases. The atomic percent ages of intermetallics were measured by EDS, similar types of intermetallics, phase morphology, and the formation mechanism were reported in detail in the previous studies [25,33,34]. The ultimate tensile strength (UTS), yield strength (YS) and elongation to fracture are 290 MPa, 286 MPa and 0.4% at room temperature; 79 MPa, 56 MPa and 5.1% at 350 °C; 51 MPa, 45 MPa and 7.3% at 425 °C, respectively. With temperature increases from room temperature to 425 °C, the UTS of Al-Si piston alloy decreases by 82%.

3.2. Cyclic stress-strain responses under LCF and TMF

The information about the thermal and mechanical cyclic stress-strain responses are important for understanding the damage mechanisms associated with deformation evolution. Typical half-life hysteresis

Table 1
Chemical compositions (wt%) of the Al-Si piston alloy.

Element	Si	Cu	Ni	Mg	Mn	Ti	Zn	Ce	Fe	V	Al
Content	14.30	3.22	2.06	0.824	0.536	0.214	0.188	0.166	0.141	0.016	Bal.

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