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Microstructure evolution of Al–12Si–CuNiMg alloy under high temperature low cycle fatigue

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ABSTRACT

Microstructure evolution of the Al–12Si–CuNiMg alloy under high temperature low cycle fatigue was investigated with scanning and transmission electron microscopy. The alloy exhibits cyclic softening at diverse total strain amplitudes and loading temperatures. The material fatigue life obviously decreases with the increase of the strain amplitude at the same temperature. However, fatigue life increases and microstructure improves with temperature increase at the same strain amplitude. At certain loading temperatures and strain amplitudes, the microstructure can be refined. The fracture morphology changes gradually from brittle quasi-cleavage fracture, with numerous small cracks, to quasi-cleavage fracture with numerous small dimple gliding fractures.

1. Introduction

Al–Si alloys have been widely used as piston components due to the good wear resistance, low thermal expansion coefficient, volume stability and good thermal conductivity. However, because pistons actually work under the cyclic loading, fatigue is the main form of failure. The intrinsic defects characteristics, such as the size, quantity and location of the casting defect, secondary dendrite arm spacing (SDAS), the size, quantity and shape of the eutectic Si phase, may act as crack initiation sites. These cracks expand, finally leading to the failure of the piston [1–4]. Therefore, it is important to study the fatigue behavior of cast Al–Si alloys. Numerous studies show a decrease in fatigue life with increase in the size of casting defects [5]. The larger the defect size, and the shorter the distance to the surface, the lower the fatigue life is, otherwise fatigue life is extended [6]. The SDAS is mainly determined by the cooling rate. With the decrease of the SDAS, the fracture strength and elongation of the alloy are obviously increased, and the fatigue crack initiation can be also delayed significantly [7–9]. The fatigue microcrack is easily produced near eutectic Si, so the fatigue strength is obviously increased with the size of eutectic Si phase decreasing [10,11]. However, the above reports were limited to cyclic loading at room temperature, and there is little information available on the microstructure response and fatigue behavior of cast Al–Si alloys in cyclic loading at high temperature. Due to the disadvantages of high thermal expansion coefficient, poor thermal stability and low strength at high temperature, the application of aluminum alloys as piston materials is severely limited in harsh environments. It is well known that high Si content can significantly improve the alloy flowability, decrease casting defects and increase the high temperature strength of the alloy. Meanwhile, the high temperature strength of the alloy can be improved by Cu, Ni, and Mg alloying elements, which can produce precipitate strengthening phases, such as $CuAl_2$, Mg_2Si, Al_2CuMg [12]. Therefore, the Al–12Si–CuNiMg alloy proves to be one of preferred materials for pistons in harsh environments, including high temperature, high speed, heavy loads, etc. At present, the Al–12Si–CuNiMg alloy has been comprehensively studied with regard to the high temperature tensile, thermal, creep, thermal cycling, fatigue and creep-fatigue interaction behavior [13–15]. However, the microstructure evolution of the alloy under alternate loading at high temperature is lacking of systematic and in-depth research, which seriously restricts further applications of the Al–12Si–CuNiMg alloy in automotive and aerospace industries. Therefore, the microstructure evolution of Al–12Si–CuNiMg alloy after high temperature, low cycle fatigue tests was investigated to provide experimental basis for the aluminum alloy usage in the harsh environments.

2. Materials and experimental procedures

The nominal composition of the alloy is Al–(11–13)Si–(5.0–5.5) Cu–(0.7–1.0)Mg–(2.5–3.0)Ni, in wt.%. The alloy was produced by a high pressure, squeeze casting process by BoHai Piston, Binzhou,

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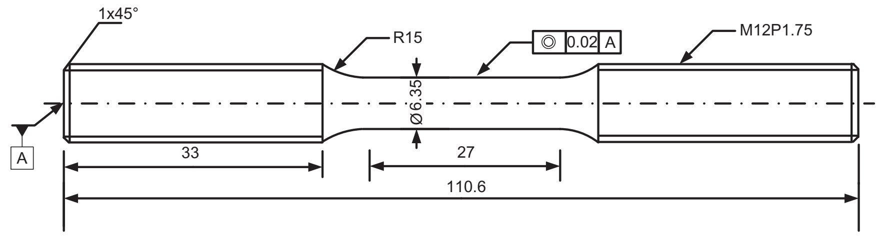

Fig. 1. Geometry of the low cycle fatigue test specimen (dimension in mm).

China. The cast material was homogenized at 750 K for 1 h, oil quenched to room temperature, retained at room temperature for 24 h. In order to obtain material properties same with the actual situation as far as possible, the analyzed alloy in the study was artificially aged at 513 K for 7.5 h. The heat treatment condition of the studied alloy are in accordance with the actual situation. The specimens used in low cycle fatigue tests have a gauge length of 27 mm and a diameter of 6.35 mm, as shown in Fig. 1.

In the study, for obtaining $\Delta\varepsilon_t$–N and $\Delta\varepsilon_p$–N curves, the cyclic stress response and microstructure evolution in the loading process, low cycle fatigue test under total strain control, which is effective and economical of cost, especially for high temperature test, was conducted. A servo-hydraulic machine (MTS-810) equipped with a heated furnace was used to perform the low cycle fatigue test at high temperatures. Before loading, the specimens were heated and kept at the test temperature for 30 min to ensure a uniform temperature throughout the specimen. The total strain, $\Delta\varepsilon$, ranging from $\pm 0.15\%$ to $\pm 0.40\%$ was applied with a constant strain rate of 3×10^{-3} s^{-1}. A symmetrical triangular waveform was used with a load ratio of $R=-1$. The real-time stress and strain data were recorded and saved to evaluate the cyclic deformation behavior of the alloy.

A JSM-5610LV (JOEL, Japan) scanning electron microscope (SEM), coupled with the compositional analysis, using an energy dispersive spectroscopy (EDS), was used to characterize both the microstructure and fracture surface. Microstructure evolution of the Al–12Si–CuNiMg alloy at different strain amplitudes and different loading temperatures was investigated by using an H-800 (Hitachi, Japan) transmission electron microscope (TEM), operated at 200 kV. TEM samples were taken from the distance of 1 mm from the fatigue fracture. Mechanically polished 40 μm thin foil was utilized for TEM sample preparation, using double jet electrolytic thinning technique (20–25 V, 50 mA) in a solution, consisting of 70 vol.% methanol + 30 vol.% HNO_3. Liquid nitrogen was used for cooling during the thinning process with the temperature not higher than −25 °C.

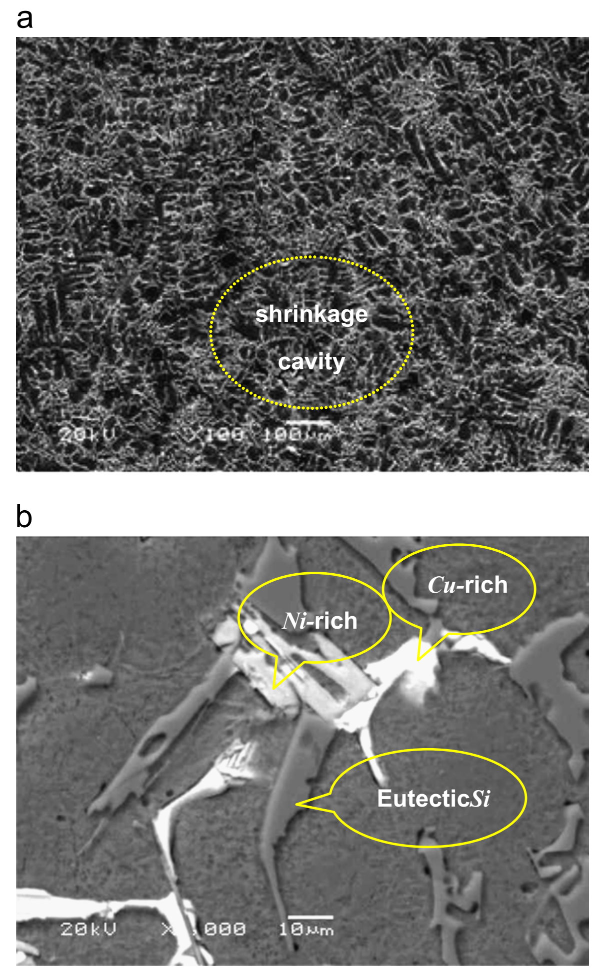

Fig. 2. (a) Original microstructure of the Al–12Si–CuNiMg alloy, (b) phases identified based on the SEM/EDS analysis.

3. Results and discussion

The original organization morphology of the Al–12Si–CuNiMg alloy is shown in Fig. 2. It clearly shows that the microstructure of the alloy primarily consists of dendritic grains, uniformly distributed large, angular silicon platelets, and fine intermetallic particles embedded in aluminum solid solution phase. Meanwhile, the shrinkage cavity defects are also present, mainly due to the lack of the feeding in the pouring process. Examination of the microstructure at higher magnifications reveals that the alloy is strengthened by large volume fractions of Cu-rich (bright white), Ni-rich (light gray) and intermetallic compounds, as seen in Fig. 2b. Evidently, Si platelets are widely distributed in the alloy. The Si platelets are intended to be disintegrated and spheroidized at high temperature during the low cycle fatigue [16]. Compared with large and elongated Si platelets, the spherical Si particles fracture less frequently [17].

Fig. 3 shows the $\Delta\varepsilon_p$–N curves of the Al–12Si–CuNiMg alloy at different loading temperatures. It can be seen that the strain amplitude has a significant effect on the fatigue life. The fatigue life of the studied material decreases with the increase of the strain amplitude at the same temperature. With the increase of the loading temperature, at any particular strain amplitude, the fatigue life of the material obviously increases.

The cyclic stress response (CSR) of the alloy was analyzed in terms of the variation of the stress amplitudes with elapsed fatigue cycles. For diverse total strain amplitudes, the alloy shows the cyclic softening effect at 200, 350 and 400 °C, as shown in Fig. 4. The studied aluminum alloy exhibits moderate cyclic softening behavior at 200 °C, as shown in Fig. 4a. At 350 and 400 °C, continuous softening can be seen and becomes stronger with increasing total strain amplitudes, as indicated in Fig. 4b and c. The cyclic softening behavior of the alloy presents a strong dependence on the total strain amplitude and temperature.