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Tensile and fatigue properties of gravity casting aluminum alloys for engine cylinder heads

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ABSTRACT

The mechanical properties were evaluated on specimens of $AlSi_9Cu_3$–T6 (333-T6) gravity casting (GC) alloy at room temperature. The GC 333-T6 alloy showed higher yield strength (YS), ultimate tensile strength (UTS) and quality Index but lower hardening capacity than GC 333 aluminum alloy without heat treatment. In addition, the GC 333-T6 aluminum alloy offered a five-fold higher hardening capacity in the cyclic deformation than in the monotonic deformation. Cyclic deformation characteristics of GC 333-T6 aluminum alloy were obtained from the LCF test. The alloy exhibited cyclic stabilization at low strain amplitudes (0.2%) and cyclic hardening at higher strain amplitudes (0.25–0.35%). The extent of cyclic hardening increased with increasing strain amplitude. The Basquin' s equation and Coffin–Manson relationships could be used to describe the fatigue lifetime of this alloy. Additionally, micro-cracks initiated at pores would preferentially pass through the elongated Si particles at lower strain amplitudes. The fatigue crack propagation was mainly characterized by the formation of dimples or fatigue striations at different strain amplitudes. Meanwhile, the larger fatigue crack propagation zone and smaller spacing of fatigue striations at the lower total strain amplitude (0.2%) gave rise to a longer fatigue life. Furthermore, final fast fracture tended to preferentially occur from the larger defects in the fast-fracture region, such as large voids, small pits and inclusions.

1. Introduction

In recent years, Al–Si–Cu alloys are extensively applied in the automotive industry owing to their high cast-ability, high specific strength and low shrink rate [1]. Conventional casting technologies proposed up to date for Al alloy include die casting (DC) and gravity casting (GC). Compared with the high pressure die casting (HPDC) method, which is the most commonly employed casting method in Al–Si–Cu alloy [2], the GC method, for high-volume production, has the advantage of a low production cost. Moreover, GC alloy can satisfy the demands of critical automobile components with complex geometries especially for thick wall parts, such as cylinder heads. GC alloy can also provide excellent mechanical properties through heat treatment after casting. In order to employ Al–Si–Cu alloys for automobile applications, information about their mechanical properties would be required, such as their tensile and fatigue properties.

The tensile properties of Al–Si–Cu alloys have been investigated in previous research. Ceschinia et al. found that the tensile strength (yield strength YS and ultimate tensile stress UTS) of $AlSi_{10}Cu_2$ alloy increased with the decreasing of the average secondary dendrite arm spacing (SDAS) [3]. In addition, Elhadari et al. [4] indicated that both monotonic and cyclic yield strengths increased with the addition of alloying elements Ti/Zr/V. It was also reported that the tiny eutectic structures and fine round α-Al phases are favorable for better tensile strength [1,5], and other microstructural features, such as morphology and composition of the Copper-rich phases, as well as Fe-rich intermetallic compounds, can play an important role in tensile behavior [6–8]. These fundamental studies have proven that the tensile properties of Al–Si–Cu alloys depend very strongly on the microstructure feature. However, a link to strain hardening is often not made, particularly under both monotonic and cyclic loading conditions. For example, one study has outlined the relationship between tensile behavior and strain hardening under monotonic loading [4], but such information is not available for fatigue loading conditions in cast $AlSi_9Cu_3$ (333) alloy. On the other hand, for applications as load-bearing automobile components, it is essential to evaluate the fatigue properties of the material to be utilized.

Strain-controlled low-cycle fatigue (LCF) can be a primary consideration in the design of products for industrial purposes [9]. However, ongoing work [3,5,10,11–15] has mainly focused on high-cycle fatigue (HCF) behavior in Al–Si–Cu alloys. Only limited studies on low-cycle fatigue behavior have been reported [4,16–18]. Elhadari et al. [4] and Chen et al. [16] reported the degree of cyclic hardening increased with increasing total strain amplitudes,

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and the fatigue lives determined under strain control could be nicely described by well-known Basquin's equation and Coffin–Manson relationship. Ovono et al. [17] observed that fatigue cracks always nucleated from larger pores and intermetallic compounds of cast 333 aluminum alloys. They also found that the fatigue life of Al–Si–Cu alloys was essentially controlled by the volume fraction of pores and the density of intermetallic compounds. Despite several researchers have examined the LCF properties of Al–Si–Cu alloys, there is very little consistency in the available data for the design of automobile applications. To the authors' knowledge, no study has been performed investigating in the literature for the LCF behavior of GC 333 aluminum alloy.

The aim of this study is, therefore, to investigate experimentally the room temperature mechanical properties of GC 333-T6 aluminum alloy under monotonic and cyclic loading conditions. A thorough investigation on the fatigue mechanism related to various strain amplitudes under LCF condition was also analyzed.

2. Material and experimental procedure

Specimens used for the microstructure analysis, as well as for the tensile and LCF tests, were made of Al–Si–Cu alloy. The nominal composition of this material is 9.15% Si, 3.23% Cu, 0.37% Fe, 0.36% Zn, 0.30% Mg, 0.26% Ni, 0.16% Mn, 0.038% Sr, and the balance Al.

Specimens were machined from the bolt boss of commercial automobile engineer cylinder heads with loading axis along the ZC direction, as shown in Fig. 1 (marked with red rectangular box). The heads were made of the GC 333 aluminum alloy, and then were heat-treated to the T6 condition, solution treated at 500 ± 3 °C for 8 h in an air circulated furnace, followed by artificial aging at 150 °C for 4 h.

Dog-bone round samples for both tensile and fatigue tests were machined according to ASTM-E8 standard with a gauge length of 26 mm. The tensile and LCF tests were performed using an MTS 809 servo-hydraulic test machine (MTS, USA) at the ambient temperature. The tensile testing was performed at a strain rate of 1×10^{-3} s^{-1}. The LCF tests were performed at a constant strain rate ($d\varepsilon/dt = 1.5 \times 10^{-3}$ s^{-1}). A triangular waveform, under fully-reversed strain-controlled conditions ($R\varepsilon = -1$) was used. The tests were conducted with total strain amplitudes lying between $\pm 0.2\%$ and $\pm 0.35\%$.

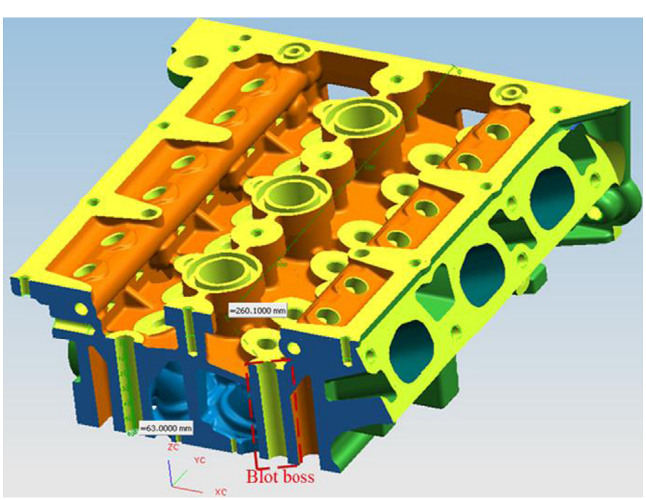

Fig. 1. Location of specimens taken from the automobile engine cylinder head (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

The metallographic microstructures of the tested alloys were examined using an optical microscope equipped with an image acquisition and analysis system. Fractography and surface relief observations were performed by scanning electron microscopy (SEM) coupled with energy dispersive X-ray (EDX) facility. Phase identification was analyzed via X-ray diffraction (XRD) and with an operating voltage of 40 kV and a current of 40 mA, using CuKα radiation and scanning in a 2θ range from 20° to 90°.

3. Results and discussion

3.1. Microstructural evaluation

The following constituent phases of GC 333-T6 alloy were identified in the XRD spectra (Fig. 2). It is mainly composed of Al, Si, θ-Al_2Cu and α-$Al_{15}(FeMn)_3Si_2$ (α-Fe) phases. The presence of β-Al_5FeSi (β-Fe) or β-Mg_2Si could not be detected in the present XRD patterns. This indicates that either this phase does not form or the precipitates are of nanometric size and therefore cannot be detected by XRD.

In Fig. 3, representative SEM micrographs (BSE mode) obtained in the GC 333-T6 are presented. The light gray phases are the intermetallic θ-Al_2Cu and α-Fe phases, and the α-Fe phase exhibits Chinese script morphology. The dark gray areas correspond to the α-Al matrix and eutectic Si particles, and these Si particles are seen to lie around the α-Fe phase, suggesting that α-Fe phase favor the formation of Si particles. In addition, shrinkage pores were also observed in this material because of inefficient feeding during casting.

3.2. Tensile properties and strain hardening behavior

The tensile properties of the GC 333-T6 alloy obtained at a strain rate of 1×10^{-2} s^{-1} are listed in Table 1, in comparison to the typical tensile properties of GC 333 alloy without heat treatment. It is notable that the YS and UTS for the GC 333-T6 samples were higher than that for the GC 333 samples, but slightly lower ductility. Obviously, the GC 333 material exhibits excellent mechanical properties under T6 treatment. This may be attributed to the following microstructural feature. (i) For the GC 333-T6 alloys with smaller SDAS, the numerous and highly branched interdendritic channels would disperse micro-cracks and delay the final fracture [19]. (ii) Due to the T6 treatment, the blocky

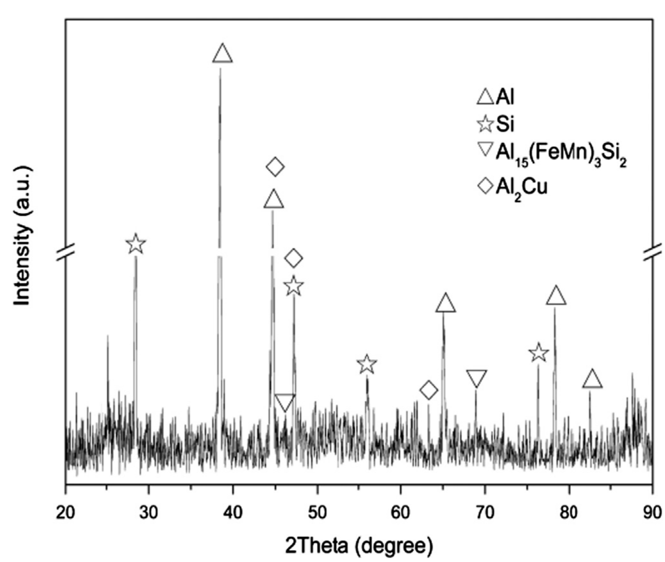

Fig. 2. XRD pattern obtained in the GC 333-T6 aluminum alloy.