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Full Length Article

Fatigue characteristics of sand-cast AZ91D magnesium alloy

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Abstract

The fatigue characteristics of the AZ91D-T6 alloy samples taken from engine blocks have been investigated at 20 °C and elevated temperature (150 °C). The fatigue strength and cyclic stress amplitude of the alloy significantly decrease with the increase of the test temperature, although cyclic hardening occurs continuously until failure for both temperatures. With the increase of the temperature, the decreased fatigue life of the alloy tested at the same stress amplitude is mainly attributed to the decreased matrix strength and the increased hysteresis energies. Fatigue failure of the engine blocks made of AZ91D-T6 alloy is mainly controlled by casting defects. For the defect-free specimens, the crack initiation behavior is determined by the single-slip (20 °C) and by environment-assisted cyclic slip (150 °C) during fatigue, respectively. The low-cycle fatigue lives of the alloy can be predicted using the Coffin-Manson relation and Basquin laws, the three-parameter equation and the energy-based concepts, while the high-cycle fatigue lives of the alloy fitted well with the developed long crack life model and MSF life models.

Keywords: Magnesium alloy; Engine blocks; Fatigue properties; Cyclic deformation behavior; Temperature; Fatigue life prediction

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1. Introduction

Use of light weight magnesium alloys in automobiles can achieve the most weight reduction decreasing fuel consumption and reduce emissions [1]. Reduction of engine block's weight is an important goal for powertrain system and the whole vehicle. Because many of magnesium alloy component applications involve cyclic loading, the fatigue performance has been considered as one of the most important technical indicators of magnesium alloys [2–4]. It has been reported that the high-cycle fatigue (HCF) properties of casting components are determined strongly by the maximum defects located at the sample surface or subsurface [5–7]. In contrast, the HCF behavior of the Mg alloys without casting defects is correlated with the microstructural characteristics (i.e., grain size, eutectic particles, solid solution matrix and precipitates) [8–10]. In this case, the fatigue performance of the magnesium alloys depends significantly on the alloy compositions, heat treatment conditions and test temperatures [11]. Li et al. [12] reported that for the defect-free Mg castings the fatigue cracks initiate and then propagate mainly from the cracked twin grain boundaries (T4: solution-treated condition) or persistent slip bands (PSBs) (T6: peak-aged condition).

Mg–RE alloys have excellent comprehensive mechanical properties [13,14] and corrosion resistance [15], which is becoming increasingly attractive for producing automotive components such as engine blocks. For instance, Li et al. [16] found that the T6-treated NZ30K (Mg–3Nd–0.2Zn–0.5Zr) alloy engine block exhibited high tensile strengths (YS ~ 140 MPa, UTS ~ 245 MPa at 150 °C) and fatigue strength (~70 MPa at 150 °C). However, higher production cost of Mg–RE alloys would limit their actual applications. In contrast, the AZ91 (Mg–9Al–1Zn–0.2Mn) alloy with moderate strength, corrosion resistance and cost is generally used to produce the non-structural parts (i.e., brackets, covers, cases and housings) [17–19].

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However, whether the AZ91 alloy can be used for structural parts such as engine blocks is still to be clarified.

The aim of this paper is to investigate the stress-controlled HCF properties of the peak-aged AZ91D alloy engine blocks at elevated temperature (ET) of 150 °C so as to expand the practical application of this alloy. In this work, the room temperature (RT) fatigue properties of the AZ91D-T6 alloy engine blocks were also included as a baseline. The plastic deformation behavior of the alloy was evaluated to discern the effect of test temperature on the fatigue properties of the AZ91D-T6 alloy. Because fatigue testing is costly and time-consuming, to seek some methods in the past to predict the fatigue lives of the castings has drawn considerable interest [12,20–23]. Li et al. [12,16] suggested that the fatigue lives of the NZ30K alloys can be predicted using the MSF (multi-scale fatigue) life models (for defect-free samples) [20] or the long crack model (for samples containing some defects) [21]. For a rolled AZ31 magnesium alloy, as suggested by Park et al. [22], the strain-life curve can be nicely described using the energy-based criterions based on plastic strain and total strain energies. Furthermore, Yu et al. [23] also pointed out that a three-parameter equation can be used to predict the LCF lives of an extruded ZK60 magnesium alloy. In this work, the energy-based concepts [22], the three-parameter equation [23], the revised long crack model [16] and MSF (multi-scale fatigue) models [12] were successfully used to predict the LCF or HCF lives of the AZ91D-T6 alloy engine blocks tested at RT and 150 °C, respectively.

2. Experimental procedure

2.1. Materials and sample preparation

The AZ91D alloy (the actual chemical compositions of Mg–9.03Al–0.87Zn–0.19Mn) was prepared from high-purity Mg and Zn, Al–10Mn master alloy in an electrical resistance furnace under protective gas consisting of SF_6 and CO_2, and then cast to produce the engine block by low pressure sand mold casting. Fig. 1 shows the parameters of low pressure sand casting for the AZ91D alloy engine blocks. The engine blocks were made at a pouring temperature of 740 ± 5 °C, a filling pressure of 0.025 MPa (filling time of 30 s), and a holding pressure of 0.08 MPa (holding time of 190 s). The blocks were first solution treated at 415 °C for 8 h, quenched into hot water of ~70 °C, and then aged at 180 °C for 14 h (T6).

Blanks with dimensions of $15 \times 15 \times 130\ mm^3$ were sectioned from the bulkhead areas of the block castings for making mechanical test specimens. Cylindrical tensile samples (ASTM B557: gauge diameter of 6 mm and gauge length of 30 mm) and fatigue samples (ASTM E466: gauge diameter of 6 mm and gauge length of 12 mm) were machined from these blanks [10]. To eliminate the influence of machining on the experimental data, electrolytic polishing was applied to the fatigue samples.

2.2. Tensile and fatigue testing

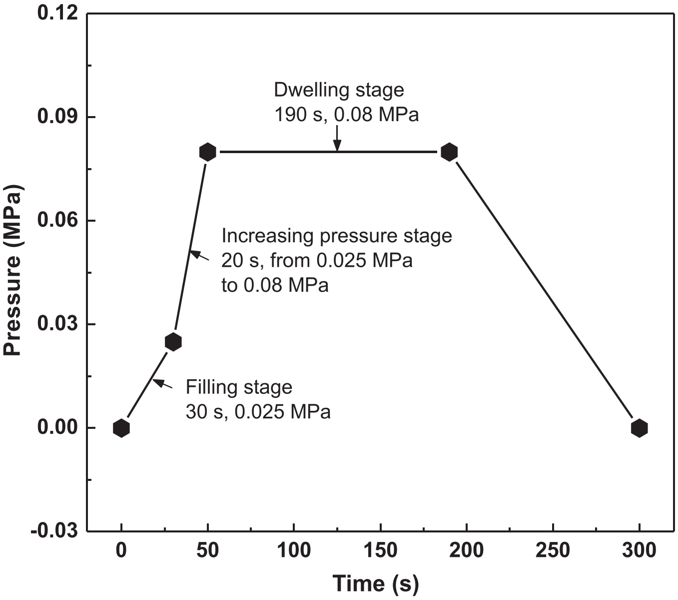

Fig. 1. The pressure profile used for low pressure sand casting of AZ91D alloy V6 engine blocks.

Both 20 °C and 150 °C tensile and fatigue tests were performed on a Zwick/Roell-20kN tensile testing machine and a servohydraulic Instron (8805) fatigue machine attached with split resistance furnaces, respectively. For elevated temperature testing, the samples were first heated to 150 °C and held at test temperature for 15 min. The temperature of tensile and fatigue tests was controlled within ±3 °C. The tensile stress–strain curves were determined using the knife-edge extensometer (strain rate of $1 \times 10^{-2}\ s^{-1}$). The yield strength (YS, $\sigma_{0.2}$), ultimate tensile strength (UTS, σ_b), and elongation were obtained from these curves. Four tensile specimens were tested and the average value of the four tests was adopted as the final results.

Stress-controlled fatigue (push–pull sinusoidal loading $R = -1$) tests were carried out in laboratory air (RT ~ 20 °C, relative humidity 40%) and at 150 °C at a frequency of 30 Hz, respectively. A load-controlled staircase testing (SC) reported by Li et al. [14] was used to calculate the limit fatigue strength (at a given cycles of 10^7) and standard deviation of fatigue strength.

Fully-reversed strain-controlled tests (push–pull triangular loading, strain ratio $R_s = -1$) were performed under the total strain-control mode (in the range from 0.2 to 0.6%, at a frequency of 1 Hz). The cyclic stress and strain were obtained using a knife-edge extensometer. The majority of tests were carried out at a zero mean strain at room temperature (RT ~ 20 °C, relative humidity level of ~40%) and 150 °C, respectively. When the number of cycles reaches 10,000, the fatigue tests were changed from strain-controlled loading to stress-controlled loading (push–pull sinusoidal loading, $R = -1$, at a frequency of 30 Hz) until fatigue failure occurred or the cycles above 10^7.

2.3. Fractographic and microstructural examination

The fracture surfaces of the fatigue samples tested at 20 °C and 150 °C were observed in a ZEISS EVO scanning electron microscope (SEM) attached with an energy dispersive spectroscope (EDS) to characterize the fatigue crack initiation site,