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High-temperature low cycle fatigue behavior of a gray cast iron

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ABSTRACT

The strain controlled low cycle fatigue properties of the studied gray cast iron for engine cylinder blocks were investigated. At the same total strain amplitude, the low cycle fatigue life of the studied material at 523 K was higher than that at 423 K. The fatigue behavior of the studied material was characterized as cyclic softening at any given total strain amplitude (0.12%–0.24%), which was attributed to fatigue crack initiation and propagation. Moreover, this material exhibited asymmetric hysteresis loops due to the presence of the graphite lamellas. Transmission electron microscopy analysis suggested that cyclic softening was also caused by the interactions of dislocations at 423 K, such as cell structure in ferrite, whereas cyclic softening was related to subgrain boundaries and dislocation climbing at 523 K. Micro-analysis of specimen fracture appearance was conducted in order to obtain the fracture characteristics and crack paths for different strain amplitudes. It showed that the higher the temperature, the rougher the crack face of the examined gray cast iron at the same total strain amplitude. Additionally, the microcracks were readily blunted during growth inside the pearlite matrix at 423 K, whereas the microcracks could easily pass through pearlite matrix along with deflection at 523 K. The results of fatigue experiments consistently showed that fatigue damage for the studied material at 423 K was lower than that at 523 K under any given total strain amplitude.

1. Introduction

Gray cast iron (GCI) has received extensive attention as a constructional material due to its good castability, corrosion resistance and thermal conductivity, relatively low cost (20–40% less than steel), excellent vibration damping and abrasion resistance [1–3]; this makes GCI more attractive than other types of cast irons and hence widely applied in industry. In particular, it is used in automotive industry like cylinder blocks and heads due to its damping capacity [4] and wear resistance. A key issue regarding automotive applications, such as cylinder blocks, however, is the fatigue performance of the used material. Most previous work on the fatigue of GCI has focused on the application of macroscopic empirical fatigue life correlations [5–7] or on the effects of graphite on fatigue resistance (such as size, morphology and distribution of graphite lamellas) [1,9,10]. It was also reported that the ferritic matrix structure was characterized by cleavage type failure, while a cleavage type failure event happened in the pearlitic matrix structure [11], and other microstructural features, such as the phosphorus content or the size of eutectic cells [1,7], the content of ferrite and pearlite [11], as well as casting defects [12] (i.e. inclusions or porosities), could play a vital role in fatigue behavior of GCI. In addition, studies on the effect of environment [2] and surface treatments [4,13] have provided substantial information on fatigue properties of GCI.

Strain-controlled low cycle fatigue (LCF) can be a primary consideration in the design of products for industrial purposes [14]. Automobile engine cylinders, as is known to all, are frequently subjected to cyclic loading leading to plastic flow, especially under high working temperatures. Thus, strain-controlled LCF is a major cause of damage that, eventually, results in engine material failure at elevated temperatures. However, most previous work [1,6–11,13,15–18] has mainly focused on both stress-controlled high cycle and thermal fatigue behavior in an effort to help design fatigue resistant GCI. Studies on the strain-controlled low cycle fatigue behavior of GCI remain limited to date [19,20]. It was reported by Fash and Socie [19] that cyclic stress–strain response was observed during the tests but the typical stable hysteresis response had not been found. Lee and Lee [20] further observed that tensile–compression asymmetry in the stress–strain response due to the presence of the graphite flakes. However, the influence of the temperature on the strain controlled LCF behavior of GCI is still unknown. For instance, one study has outlined the relationship between temperature and fatigue behavior in stress-controlled high cycle fatigue [21], the fatigue strength remained relatively constant for testing temperatures ranging from 295 K to 523 K, then increased rapidly for temperatures around 623 and 723 K and finally followed by a decrease above 723 K, but such information is not available for strain-controlled LCF condition in GCI. Even worse, this problem has attracted little attentions so far. In this study, by investigating the LCF behavior of HT250 GCI at 423 and

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523 K, the strain controlled LCF mechanism of the HT250 will be studied in depth.

2. Material

The material utilized in this study was a GCI with base composition of C ~ 3.36%, Si ~ 2.06%, Mn ~ 0.71%, Cr ~ 0.23%, S ~ 0.08%, and P ~ 0.02%. Specimens were machined from the boss between commercial automobile engineer cylinder blocks with loading axis along the Z axis direction, as shown in Fig. 1a (marked with red rectangular box). The blocks were made of pearlitic HT250 GCI ("HT" is the abbreviation of "HUI TIE"), which was produced by a gravity casting technology.

3. Experimental procedure

Dog-bone round samples for both tensile and fatigue tests were machined with a parallel gauge section 30 mm long and 6.5 mm in diameter (Fig. 1b). Circumferential machining marks in the gauge length portion of the specimens were mechanically polished by emery papers to minimize machining surface roughness effects on tensile and fatigue. The tensile and LCF tests were performed using an MTS 810 servo-hydraulic test machine (MTS, USA), which was equipped with an induction heating system within the Fangrui Company (China). The temperatures of each sample were monitored by thermocouple and controlled by an induction heating system. The tensile testing was performed at a strain rate of $1 \times 10^{-3}\ s^{-1}$. The LCF tests were carried out at 423 K and 523 K at total strain amplitudes of 0.12%, 0.16%, 0.20% and 0.24%. A symmetrical triangular waveform was used under fully-reversed strain-controlled conditions ($R_\varepsilon = -1$). LCF tests at different strain amplitudes were carried out at a constant strain rate of $0.3 \times 10^{-2}\ s^{-1}$. All tests were started after soaking for 30 min at the test temperatures in order to ensure the uniform temperature throughout the samples. The experiments would be stopped when the stresses dropped about 10%. 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). The gauge sections of the specimens were mechanically thinned for the extraction of transmission electron microscopy (TEM) foils. The longitudinal portion of the gauge section was first reduced to approximately 600 μm. The disks thus obtained were mechanically thinned down to approximately 30 μm using carborundum papers. The disks were electropolished using a twin-jet electropolishing with an electrolyte made of 20% $KClO_4$ and 80% CH_3CH_2OH. Microstructural characterization was conducted using a Hitachi H-800 TEM operating at 200 kV.

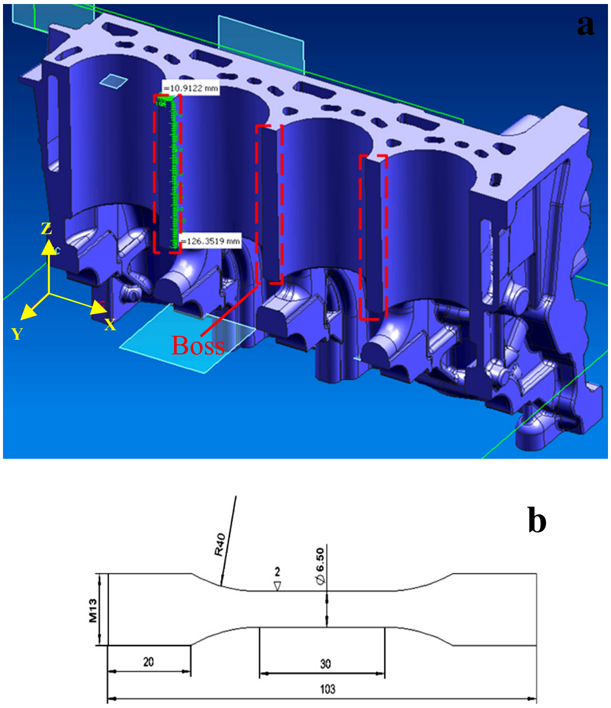

Fig. 1. (a) Location of specimens taken from the automobile engine cylinder block. (b) Sketch of specimen (dimensions in mm). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

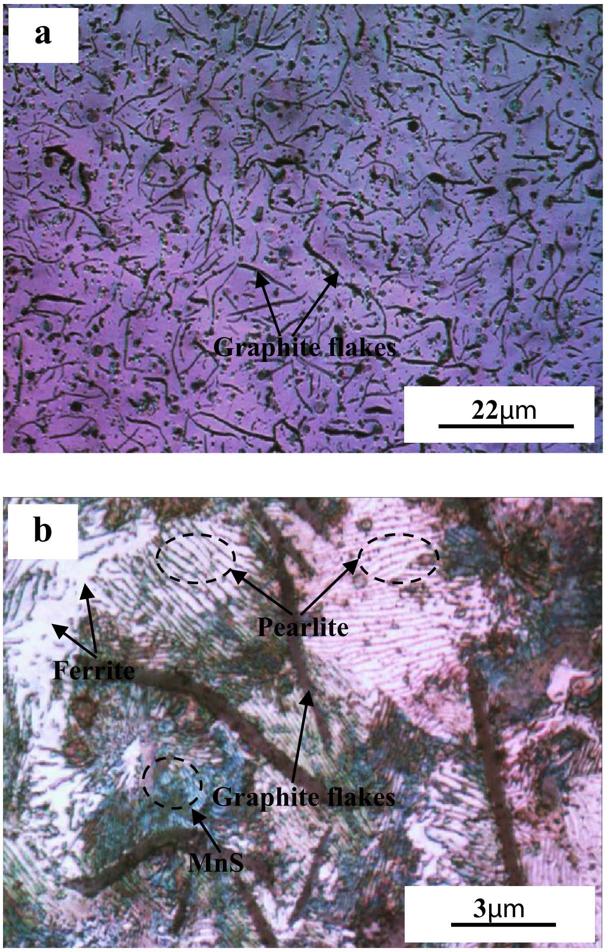

Fig. 2. Typical microstructures of the HT250 sample. (a) Unetched and (b) etched.

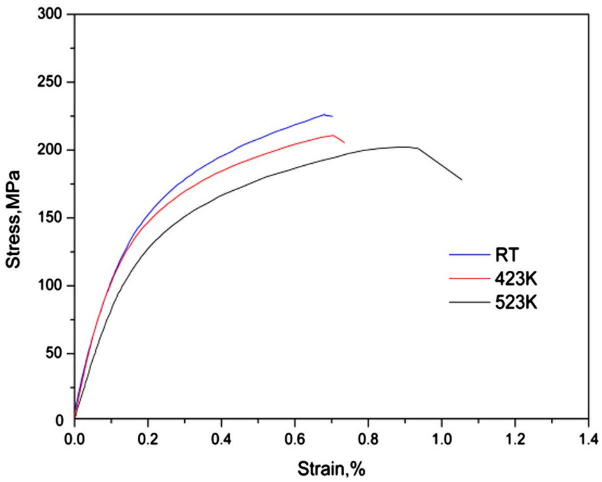

Fig. 3. Tensile stress–strain curves of HT250 GCI at RT, 423 and 523 K.