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Thermo-mechanical fatigue property and life prediction of vermicular graphite iron

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ABSTRACT

Thermo-mechanical fatigue (TMF) failure is the major problem of the cylinder head subjected to combined variations in temperature and loading during operation. This study mainly focuses on the TMF property and the life prediction of vermicular graphite iron (VGI). The ferrite clusters can be easily found from the microstructure and fractography images. Compared with the TMF experimental data testing at 125–400 °C and 125–500 °C, significant cyclic hardening occurs in the former and slight hardening does in the latter. Depending on the difference in the damage mechanism between TMF and iso-thermal low-cycle fatigue (LCF), based on the hysteresis energy, a life prediction method has been proposed at first. By the minimum amount of LCF and TMF tests, the present method can predict the TMF life rapidly, accurately and cheaply. And based on the difference in the fatigue crack propagation thresholds between pearlite and ferrite, the fracture mechanism of TMF was also discussed.

1. Introduction

With outstanding casting properties, good thermal conductivity and appropriate mechanical performance, vermicular cast irons (VGI) is widely used [1,2]. Among them, the cylinder head of diesel engine is the most important application field. The engine usually works under non steady states of transient operating conditions, such as starting, suddenly loading and unloading. The processes are usually lead to the large temperature variation and serious fatigue damage. So, the components are exposed for long periods of time and subjected to large number of heating and cooling cycles under cyclic loadings [3–5]. So, the thermo-mechanical fatigue (TMF) failure is one of the most common failure forms. Hence, to make cast iron with higher properties and enhance reliability of components, it is indispensable to study the TMF behaviors of VGI [6–8].

The TMF study is a complex, time-consuming and high-cost process. And it has been drawn public attentions for several decades, as regards the corresponding damage mechanisms of materials, Neu et al. [9,10] pointed out that there are three major aspects, namely, fatigue, environmental oxidation and creep damage. These damage mechanisms may act independently or in combination with the type of materials and the service conditions, such as the maximum and minimum temperatures, the mechanical strain amplitude and strain rate, the phase angle between temperature and mechanical strain, the dwell time service environment, and so on.

But for TMF of cast iron, the studies are not very sufficient. Seifert et al. [11–13] found that graphite particles weaken the material in tension and the interfacial microcracks are closed in compression, which can be attributed to the asymmetrical tension-compression behavior of cast iron. Meanwhile, they also proposed a life prediction model for cast iron materials under TMF loading conditions, which is based on the description of microcrack growth with fracture mechanics and loading parameters. Wu et al. [14] studied the TMF damage of ductile cast iron alloys and Gocmez et al. [15] proposed a life prediction method for isothermal fatigue and out of phase (OP) TMF for three cast iron families. The studies mentioned above can explain some TMF behaviors to some extent. However, it still needs to conduct intensive experiments and explore the damage mechanisms of cast iron especially VGI in the TMF testing [16]. In other words, based on those studies, no time, energy and money can be saved. Furthermore, under TMF loading, the creep and oxidation can hardly be measured rapidly and accurately, so that the life prediction method mentioned above might have some limitations. Alternatively, the energy method to characterize the mechanical and thermal damages is a feasible and high-efficient way, but the relevant studies on cast iron are rare. In fact, numerous fatigue behavior studies based on the energy method have been done [17,18], unfortunately, most of those studies focused on the low-cycle fatigue (LCF) and the applicability to TMF needs to be confirmed.

As mentioned above, a relationship between the LCF and TMF tests should be established. In this study, a damage based method has been

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Table 1
The chemical compositions (*wt*%) of VGI.

C	Si	Mn	S	P
3.5	2.2	0.2	0.04	0.03

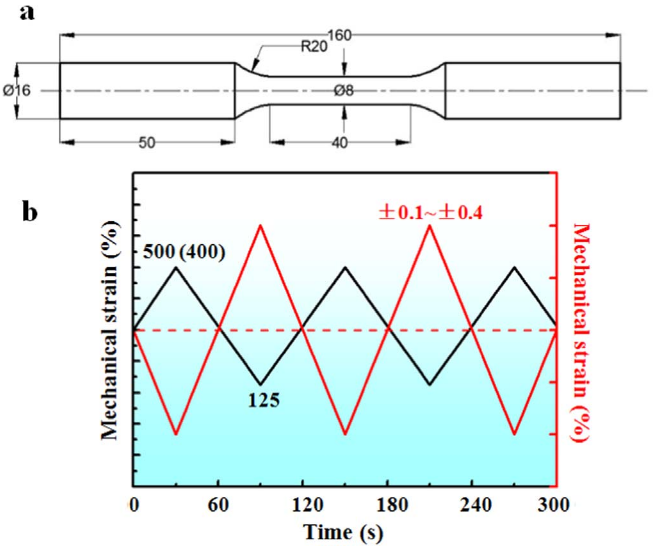

Fig. 1. (a) Specimen schematic diagram and (b) loading spectrum of TMF.

proposed to predict the TMF life reasonably with minimum amount of LCF and TMF tests. Meanwhile, based on the study of mechanical behaviors of VGI, the fracture mechanisms under the TMF were also analyzed.

2. Experimental materials and procedures

In present work, the VGI specimens were cut from the bottom deck of cylinder head. The chemical compositions are shown in Table 1. The TMF specimens with gauge dimension ofφ8 mm × 40 mm and total length of 160 mm (Fig. 1(a)) were machined using finish turning and followed by grinding. In the axial direction, all specimens were polished using emery paper having a mesh of #400, #800, #1200 and 2000# in order.

The cast iron specimens were cyclically deformed in air under axial strain amplitude control which was measured by a 25 mm gauge length extensometer, on a hydraulic servo testing machine MTS 810. The specimens were inductively heated using a 5 kW generator and cooled by compressed air from three directions. The mechanical chucks were cooled by circulating water. The spiral induction coil was used for minimizing temperature gradient of the gauge length of specimens. The temperature was measured and controlled by a ribbon Ni-CrNi thermocouple element, positioned at the middle of the gauge length with spot welding. Based on the actual service conditions of engine cylinder head, all the TMF specimens were tested under opposite phase (OP) conditions, both temperature rising and cooling periods are 60 s. Different temperature ranges and different strain amplitudes, from 0.1% to 0.3% for 125–400 °C (Condition A), and 0.15–0.4% for 125–500 °C (Condition B), were used. The TMF loading spectrums were exhibited in Fig. 1(b). The defined TMF cycles were repeated until fracture of the specimen or until the maximum stress in a cycle falls below 60% of the stable cycles. Before TMF test, two or three cycles of thermal fatigue (without mechanical strain loading) were needed. This was used to measure the relationship between temperature and thermal strain of the materials.

The lateral sections of fractured specimens were prepared by wire-electrode cutting near the fatigue initiation site. The original microstructures, TMF fractographies of specimens and lateral sections were examined by Quanta 600 scanning electron microscope (SEM). The vermicularity was measured by the method of Chinese testing standard GB/T 26656-2011 [19].

3. Experimental results

3.1. Microstructure

The VGI consists of ferrite, pearlite and vermicular graphite. And the area fractions are 69.6%, 19.6% and 10.7%, respectively. And the vermicularity is about 87.4% and the microstructures of VGI are demonstrated in Fig. 2. The gray zone is equiaxed ferrite, and the mean grain size of ferrite measured by intercept method is about 9.6 µm (shown in Fig. 2(c)). The white zone is laminar pearlite and the black zone is graphite (shown in Fig. 2(b)). The ferrite zone can be divided

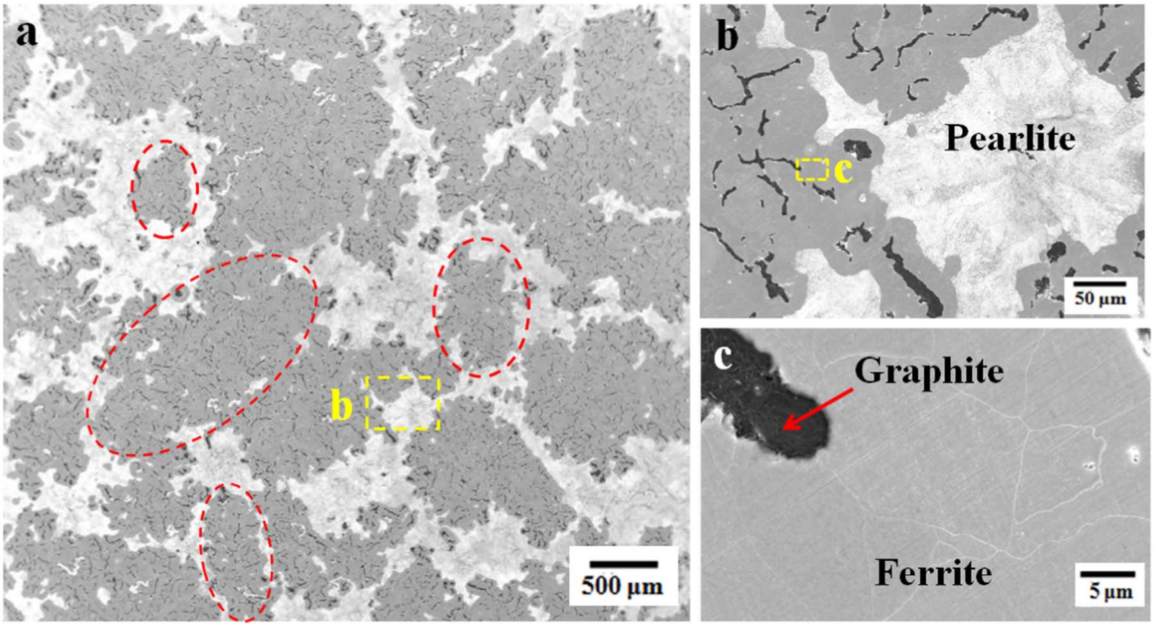

Fig. 2. (a) The microstructures of VGI, partial enlargement of (b) pearlite zone and (c) ferrite zone.