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Transition of tensile strength and damaging mechanisms of compacted graphite iron with temperature

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ABSTRACT

Compacted graphite iron (CGI) plays an increasingly important role in the cylinder head of diesel industry because of its good thermal and mechanical properties. In this study, tensile strength, elongation to fracture and the corresponding damaging mechanism observed by in-situ technique at different temperatures have been investigated. The experimental results of CGI show that with increasing the temperature, the tensile strength decreases slightly at first and then dramatically, and the elongation to fracture decreases initially, and then increases. The former trend is mainly controlled by the transitional deformation mechanisms from slip band stage (the dislocation movement inhibition) to boundary sliding stage (vacancy diffusion). Based on these, the corresponding quantitative relationships are firstly proposed: double-exponential and exponential relationships, respectively. In addition, the elongation to fracture is initially divided into uniform and softening elongations. Accordingly, the latter trend is controlled by the similar transitional mechanisms. The newly proposed relationships and corresponding mechanisms can provide new clues for the optimizing design of CGI and the understanding of similar phenomenon for other cast irons and even some metallic materials.

1. Introduction

With increasing power demand in diesel engines, the operating temperature and peak firing pressure in the combustion chamber increase significantly [1], so the working temperature and pressure for the cylinder head correspondingly increases, which makes its thermal conductivity and mechanical properties become very sensitive under these severer conditions. Besides, this situation might become much worse and even lead to the failure of the diesel cylinder head under abnormal working conditions, such as higher pressure induced by engine deflagration [2–4]. Therefore, compacted graphite iron (CGI) has gradually become an important choice [5,6] since discovered in 1948 [7] owing to its good combination of thermal conductivity and mechanical properties, especially at high temperature [8–11]. In recent decades, CGI, as an important unlimited potential material for diesel head, many investigations about its thermal and mechanical properties, especially under extreme working conditions, have been done [12–14].

Among these investigations, the tensile properties of CGIs with different microstructures at different temperatures have been compared in the *Refs*. [15,16]. The similar investigations on the tensile properties for metallic materials such as aluminum single crystal and steels have also been done [16–29]. From their data [16,21–29], two common tendencies about cast irons are concluded: with increasing the temperature, the tensile strength decreases slowly at first, and then dramatically; the elongation to fracture decreases at first and then increases. One quantitative relationship of spherical graphite iron (SGI) between the tensile strength and temperature before tensile strength rapidly decreases has been proposed [26]. For the corresponding tensile damaging mechanisms, some investigations with in-situ technique at room temperature have been carried out [10,30–32]. It is concluded that the incompatible deformation around graphite is the main reason for crack initiation and the work-hardening stage is accompanied with the microcrack initiation and coalescence in the matrix. Besides, the corresponding strengthening mechanisms are also summarized: microstructure evolution, strain aging and precipitation strengthening [15,32–34]. However, at elevated temperatures, except the effect of dynamic strain aging (DSA) on the tensile engineering stress-strain curves [16,24], few investigations on the damaging and strengthening mechanisms have been carried out, especially for CGI. Besides, even though one quantitative relationship between the tensile strength and temperature has been proposed, it is in a monotonously exponential decreasing tendency, and could not illustrate the tendency of CGI which has the lowest tensile strength at about 473 K [16]. Based on the present studies, two open questions for scientists and engineers are raised: 1) Are there common quantitative relationships

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between the tensile strength and temperature? 2) If so, what are the corresponding damaging mechanisms? Therefore, more systematic and deeper investigation should be carried out with the in-situ technique which can offer a chance for the direct observation on the deformation processes.

In this study, the evolution tendencies of tensile strength and elongation to fracture of CGI in the temperature range from 298 K to 873 K were confirmed. The corresponding damaging mechanisms have been investigated with in-situ techniques. Besides, the essence of evolution tendencies and the quantitative relationship between tensile strength and temperature have been discussed.

2. Experimental materials and procedures

Cast RuT300 (Chinese designation of CGI) was chosen in the present study. Its chemical composition and microstructure are shown in Table 1 and Fig. 1, respectively. Conventional and in-situ tensile specimens were cut with electric discharge machine, then the former was produced by finish machining and the latter was treated with abrasive and electrochemical polishing before test. The shapes and sizes of the specimens are shown in Fig. 2. The conventional tensile experiments were conducted under a tensile strain rate of $5 \times 10^{-4}\,s^{-1}$ with an Instron 8862 universal testing machine at 298 K, 473 K, 573 K, 623 K, 673 K, 723 K, 773 K, 823 K and 873 K, and the number of specimens is at least three at each temperature. The in-situ tensile tests were carried out with an in-situ scanning electron microscope (SEM) tensile testing system assembled with Shimadzu Seveo 4830 and JSM 6510 SEM under a constant cross-head speed of 0.033 mm min^{-1} at 298 K, 723 K, 823 K and 873 K. Microstructure evolution is carried out in the same SEM system. An in-situ sample is heated to a certain temperature in the vacuum environment, and then cooled after 10 min thermal insulation. The designed heat temperatures are 298 K, 473 K, 673 K 873 K, respectively. Finally observation on the microstructures at the opted positions is conducted after every cooling. During the observation, energy dispersive spectrometer (EDS) is also used to analyze the corresponding compositions.

3. Experimental results

3.1. Tensile properties

The tensile engineering stress-strain curves, strength, elongation to fracture and Young's modulus at different temperatures are shown in Fig. 3. There are no obvious yield points in the tensile engineering curves from Fig. 3a, which have been investigated in the previous study [32]. It can be seen that work-hardening abilities are improved at 473 K, 573 K, 623–673 K, comparing with it at room temperature (RT). After the stress reaches the tensile strength, the stress becomes softening with the strain at 823 K and 873 K. This is different from necking [35], because no decrease of local cross-sectional area is observed. In Fig. 3b, both tensile strength and yield strength decrease slowly at first and then dramatically above the temperature range in green color. This is similar to the tendency of cast irons [15,16,22–28]. The transition temperature is defined as the critical temperature T_c. In addition, the tensile strength is gradually close to the yield strength above

Table 1
The chemical composition of CGI (wt%).

Element	C	Si	Mn	P	S	Cu	Fe
Content	3.74	2.03	0.14	0.044	0.006	0.014	Balance

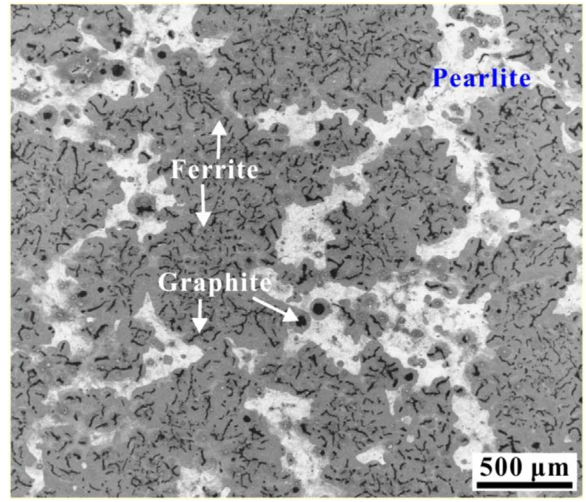

Fig. 1. The SEM microstructure of as-cast RuT300 at 298 K.

723 K. This suggests that the yield ratio (the ratio of yield strength to tensile strength) is stable below 673 K, and then increases. In Fig. 3c, the elongation to fracture decreases initially, and then increases. Even though the transition temperature range in green color is lower than the reported value 673 K [16,23–25], the tendency is similar. Young's modulus is calculated by dividing the tensile stress by the extensional strain in the elastic portion of the engineering stress-strain curve. From Fig. 3d, the Young's modulus appropriately remains stable below 773 K, and then decreases gradually.

3.2. Microstructure evolution

The microstructures at different temperatures are clearly presented in Fig. 4. The white particles pointed by yellow arrows in ferrite begin to appear at 473 K. Two particles in the yellow circles (Fig. 4a and c) have been detected with EDS, and the results are shown in the tables with white borders. They are carbides mainly consisted of $Fe_kC_mSi_nX_l$, where the X is alloying elements and k, m, n, l are the corresponding contents of the elements. The formation of carbide supplies a good support for the diffusion of carbon atom which is considered as a reason for DSA effect [36–38]. At 873 K, carbides start to form along the ferrite grain boundaries (Fig. 4d). Pearlite is mixture of cementite lamella and ferrite lamella in Fig. 4e. Carbide initially forms in the ferrite lamella boundaries as pointed by yellow arrows in Fig. 4h at 873 K. In addition, it is observed that the carbide precipitation initially appears in the ferrite grains at 473 K, and the number increases with increasing the temperature. This implies the similar tendency of carbon diffusion.

3.3. In-situ tensile cracking and fracture behaviors

The surface morphologies of specimens deformed at 298 K, 723 K and 873 K were observed with in-situ technique using SEM, and the engineering stress-displacement curves were obtained (as shown in Figs. 5–7). The observed surface morphology is enclosed by blue dot rectangle (labeled with capital letter A, i.e. see Fig. 5a.), and it is recorded under four selected loading conditions labeled with “b”, “c”, “d” and “e” on the engineering stress-displacement curve. In the figures, graphite debonding, microcrack initiation and propagation were pointed with yellow, black and blue arrows, respectively.

Fig. 5 displays the in-situ tensile cracking behavior of RuT300 at 298 K. At point “b” (Fig. 5a), microcracks exist in the vermicular