A study of tensile properties of ferritic compacted graphite cast irons at intermediate temperatures

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Results of an investigation of the influence of carbon and silicon content on tensile properties of ferritic compacted graphite cast irons from room temperature to 500° C are presented. The tensile flow stress plateau of ferritic compacted graphite cast irons occurs owing to dynamic strain ageing from 200 to 400° C with various carbon and silicon contents. Because the ferritic compacted graphite cast irons have irregularly shaped graphite particles, their fracture mechanism is attributed to a mixed fracture mode. With increasing silicon content, the fracture mechanism changes from dimple pattern to transgranular cleavage at room temperature. However, when the test temperature is above the raised transition temperature the specimens fail in ductile manner.

1. Introduction

Compacted graphite cast iron is a relatively new cast iron material, which has only in recent years become the centre of interest for certain applications [1–3], although distinct production methods have been available ever since the sixties [4, 5]. Compacted graphite is one of the morphologies that is between the large flake type A, and the spheroidal graphite of ductile iron. Since its structure is between that of grey and ductile iron, it has properties that are also intermediate.

The general applications of this material are based on its thermal conductivity properties, which approach those of a flake graphite iron with strengths approaching those of ductile irons. Lui and Yanagisaw's investigations [6, 7] demonstrated that the ductility of ferritic spheroidal graphite cast iron tends to decrease extremely at the onset of intergranular fracture in the intermediate temperature range, which is influenced by dynamic strain ageing and triaxial stress fields developed in the ferrite matrix between the graphite particles. However, the deformation and fracture behaviour of ferritic compacted graphite cast iron in intermediate temperature ranges have received very little attention. In this study, several cast iron specimens with various carbon and silicon contents were tensile tested from room temperature to 500°C to investigate the influence of carbon and silcon content on their deformation and fracture behaviour.

2. Experimental procedure

The materials used were melted in a basic high-frequency induction furnace from a charge of raw pig iron spheroidized by Fe (45 wt %) Si (8 wt %) Mg alloy (amount of 0.55 wt %), inoculated with Fe (75 wt %) Si alloy (amount of 0.2 wt %) and cast into a 65 × 90 × 120 mm CO_2 moulds of Y-block shape. The chemical compositions analysed by emission spectroscopy are listed in Table I. These castings were annealed to a ferritic state by keeping them at 900° C for 2 h, 800° C for 1.5 h, 740° C for 5 h and furnace cooled as shown in Fig. 1. The tensile tests using specimens with a dimension of $\phi 6 \times 30$ mm, were carried out in a MTS machine from room temperature to 500° C at a strain rate of $6.6 \times 10^{-4}\,sec^{-1}$. Each specimen was kept at a test temperature with an accuracy of ± 3° C for 10 min before the test, to ensure a uniform temperature of the specimen. The fracture surfaces of the specimen were examined by scanning electron microscopy (SEM).

TABLE I Chemical composition of the compacted graphite cast iron specimens

	C	Si	Mn	P	S	Mg
1A	1.65	2.81	0.117	0.025	0.026	0.011
2A	2.57	2.82	0.153	0.026	0.011	0.012
3A	3.08	2.79	0.111	0.027	0.014	0.014
4A	3.55	2.92	0.079	0.030	0.014	0.013
5A	2.72	3.07	0.123	0.026	0.016	0.013
6A	–	3.58	–	–	–	0.020
7A	–	4.25	–	–	–	0.020
8A*	3.52	2.80	0.012	0.035	0.002	0.050

*Spheroidal graphite cast irons.

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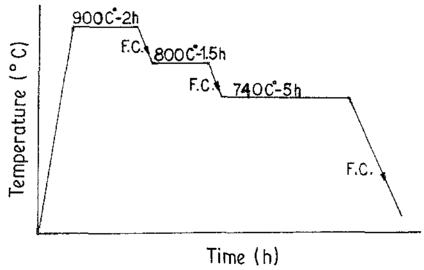

Figure 1 Heat treatment conditions for the specimens.

3. Results

3.1. Effect of carbon content on tensile properties at elevated temperature

It is shown in Fig. 2 that the number of graphite particles decreased with decreasing carbon content but the size of graphite particles increased. In Fig. 3, the serrated flow stress was observed with low strain rates between 200 to 400° C owing to the dynamic strain ageing. This phenomenon is relevant to the diffusion of interstitial atoms, such as N or C, at higher temperatures [8, 9]. Fig. 4 illustrates the influence of test temperature on the yield stress and flow stress (3% strain) with increasing temperature from room temperature to 200° C in tensile tests. Nevertheless, a flow stress plateau was formed from 200 to 400° C owing to dynamic strain ageing.

The relationship between the elongation and test temperature with various carbon contents is shown in Fig. 5. The results showed that elongation was about 5 to 7% from room temperature to 500° C except for a slightly lower value at 400° C. It is very different with the ferritic spheroidal graphite cast iron whose elongation has a sharp drop at 400° C as shown in Fig. 6. Form the fracture surface of specimen 1A (1.65% C) in Fig. 7a, some transgranular cleavage in the ferritic matrix was observed. Figs 7b–d shows that the fracture was propagated by a dimple mechanism with carbon content from 2.57 to 3.55 wt %. Fig. 8 shows a typical lengthened dimple fractograph at elevated temperature.

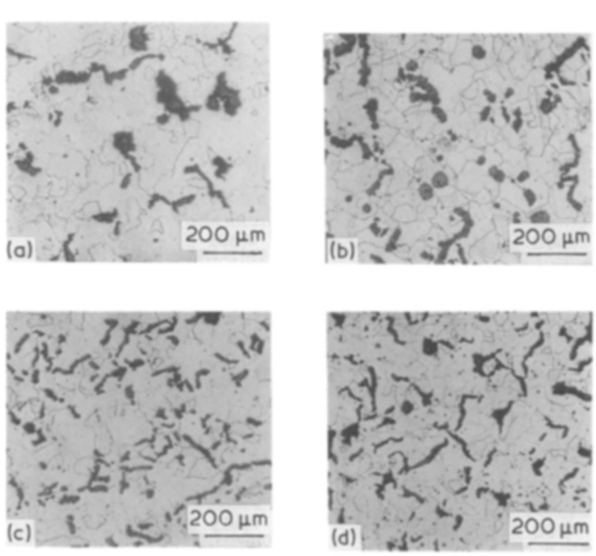

Figure 2 Microstructure of specimens with varying carbon content (1A, 2A, 3A and 4A). (a) 1.65% C; (b) 2.57% C; (c) 3.08% C and (d) 3.55% C.

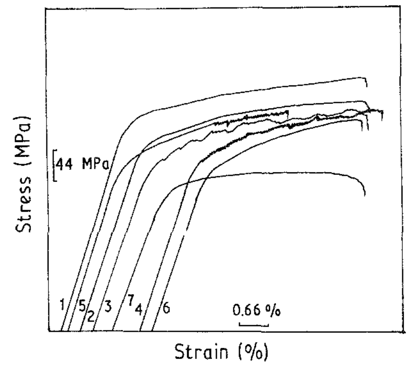

Figure 3 Stress–strain curve of 3.08% C specimens between room temperature and 500° C (1) Room temperature; (2) 100 C; (3) 200 C; (4) 300 C; (5) 350 C; (6) 400 C; (7) 500 C.

3.2. Effect of silicon content on the tensile properties at elevated temperature

Fig. 9 shows the microstructure of specimens with various silicon content. The graphite shape becomes shorter and thicker with increasing silicon content. There were many small graphite particles similar to spheroidal graphite as the silicon content was increased to 4.25 wt %. The influence of test temperature on the yield stress with various silicon content is shown in Fig. 10. A stress plateau was shown from 200 to 400° C owing to dynamic strain ageing. At the same time, the results showed that the yield stress increased with increasing silicon content because solid solution hardening increases with increasing silicon content. The relationship between elongation and temperature with various silicon content is illustrated

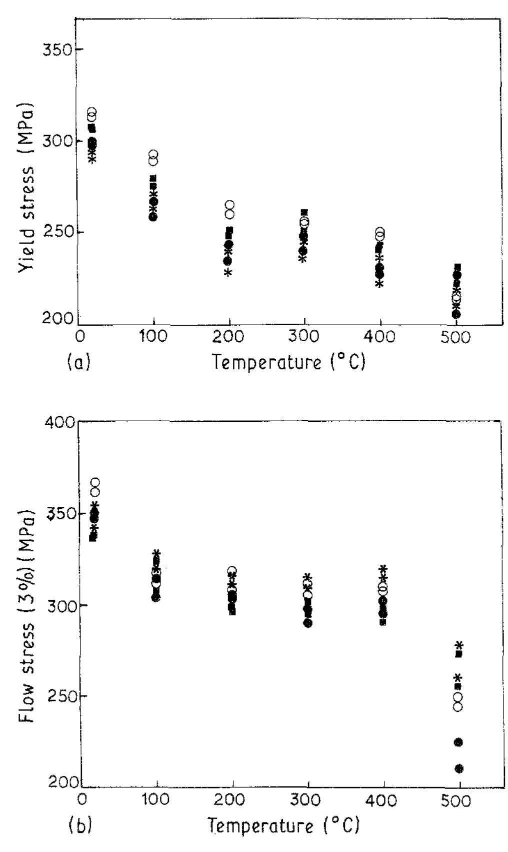

Figure 4 Influence of test temperature on (a) yield stress (b) flow stress with varying carbon content. (O) 1.65% C; (*) 2.57% C; (●) 3.08% C; (■) 3.55% C.

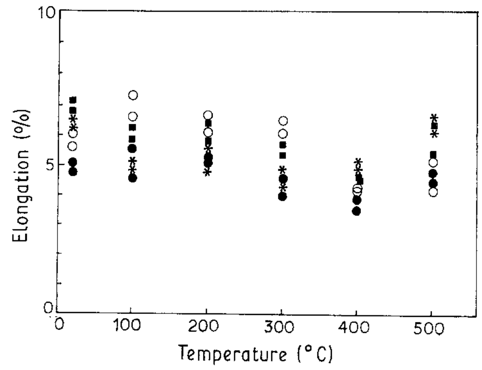

Figure 5 Influence of test temperature on the elongation of specimens with varying carbon content. (○) 1.65% C; (*) 2.57% C; (●) 3.08% C; (■) 3.55% C.

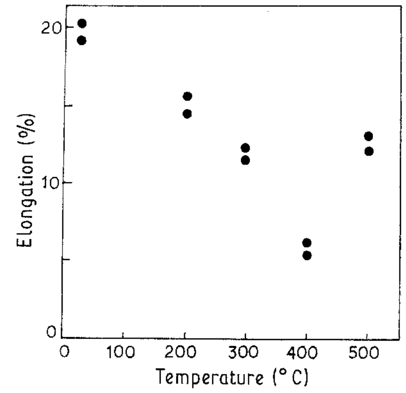

Figure 6 Influence of test temperature on the elongation of spheroidal graphite cast iorn (8A).

in Fig. 11. The elongation sharply decreased with increasing silicon content at room temperature. It decreased as the temperature was raised from 100 to 400° C and then increased as the temperature was raised to 500° C. However, the elongation fluctuated with increasing silicon contents at elevated temperatures (100 to 500° C). The difference in fractography observed with various silicon contents at room temperature is shown in Fig. 12. The fracture mechanism changed from a dimple pattern to a transgranular cleavage with increasing silicon content.

4. Discussion

4.1. Effect of graphite morphology on fracture behaviour

Fig. 13 shows that the intergranular fracture of spheroidal graphite cast iron occurs at 400° C and is similar to Yanagisawa and Lui's reports [6, 7]. They suggested that the elevated temperature brittleness of ferritic spheroidal graphite cast iron was induced by dynamic strain ageing and the triaxial stress field developed in the ferritic matrix between the graphite nodules. At the same time, they demonstrated that a larger triaxiality built into the matrix with a lower carbon content of the ferritic spheroidal graphite cast iron leads to more embrittlement.

The ferritic compacted graphite cast irons with various carbon content are also affected by dynamic strain ageing at elevated temperature. However, the morphology of compacted graphite is an irregular shape which has different triaxial stress field compared to that of spheroidal graphite. It is deduced that in the ferritic compacted cast iron the fracture mechanism is probably attributed to a mixed mode. A good identification is the lengthened dimple pattern as shown in Fig. 8. Because the shearing yield stress is equal to one half of the tensile yield stress, the onset of plastic deformation becomes easier. Therefore, the intergranular fracture was not found in ferritic compacted graphite cast irons in all tensile tests from room temperature to 500° C.

4.2. Effect of silicon contents on fracture behaviour

A number of theories [10, 11] have been proposed to account for the effect or segregation on grain boundary cohesion. Seah [10] showed that silicon reduced the grain boundary cohesion in the iron matrix. Mclean and Hondros [11] showed that the grain boundary would always fail in preference to cleavage, since the orientation of slip planes and the surface energy of the low-index cleavage make cleavage

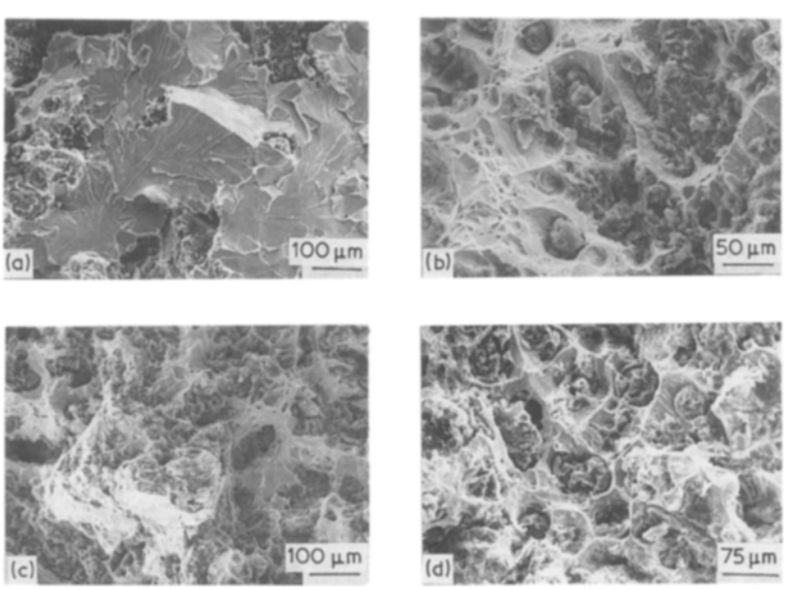

Figure 7 Scanning electron microscopy (SEM) of the fracture surface of specimens with varying carbon content deformed at room temperature (a) 1.65% C; (b) 2.57% C; (c) 3.08% C; (d) 3.55% C.

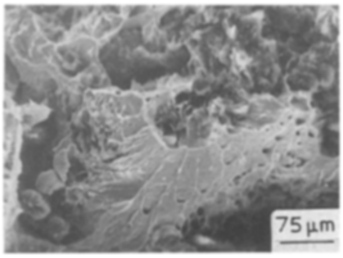

Figure 8 Scanning electron microscopy of the fracture surface of specimen 3A (3.08% C) deformed at 200° C.

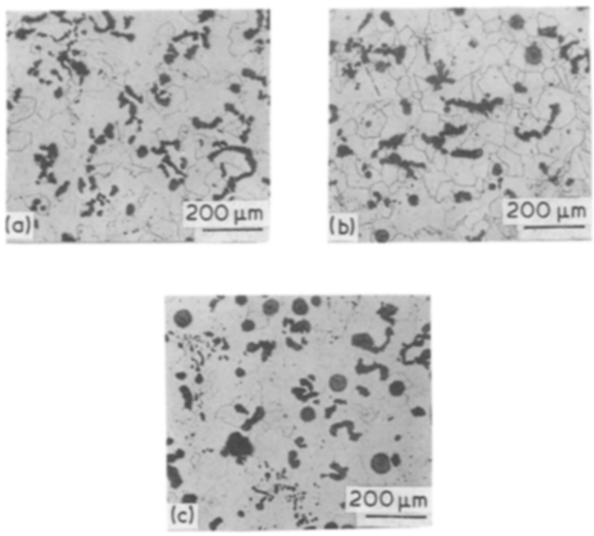

Figure 9 Microstructure of specimens with varying silicon content (5A, 6A and 7A) (a) 3.07% Si; (b) 3.58 Si; (c) 4.25% Si.

generally more likely than intergranular failure in bcc metals. The fracture behaviour of a ferritic compacted graphite cast iron, as a function of the test temperature, is shown schematically in Fig. 14. If the grain boundary contains the segregation (Si), the boundary cohesion may be sufficiently lowered so that the

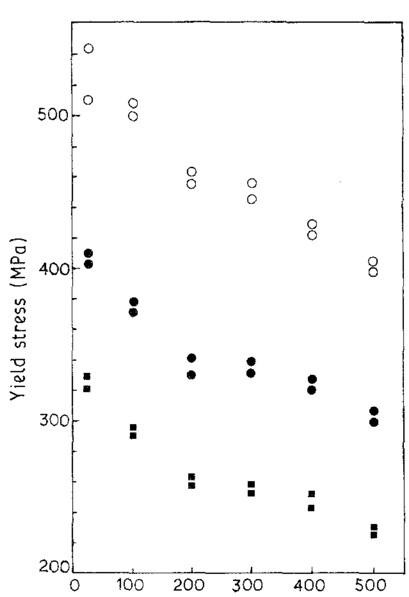

Figure 10 Influence of test temperature on the yield stress with varying silicon content. (■) 3.07% Si; (●) 3.58% Si; (○) 4.34% Si.

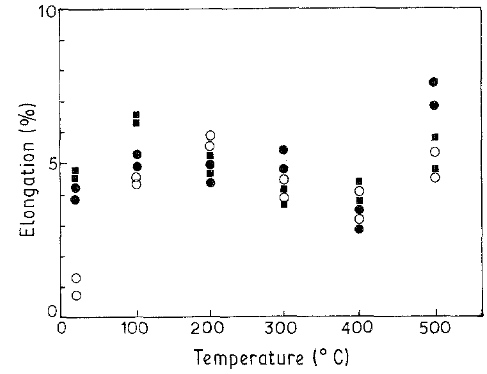

Figure 11 Influence of test temperature on the elongation with varying silicon content. (■) 3.07% Si; (●) 3.58% Si; (○) 4.34% Si.

transition temperature is raised and ductile material becomes brittle. This is the reason why the fracture mechanism changes from dimple pattern to transgranular cleavage with increasing silicon content at room temperature, see Fig. 14. When the test temperature is above the raised transition temperature, the yield stress is lowered and the specimen fails in a ductile manner.

5. Conclusion

1. The tensile flow stress plateau of ferritic compacted graphite cast irons occurs owing to dynamic strain ageing from 200 to 400° C with various carbon and silicon contents.

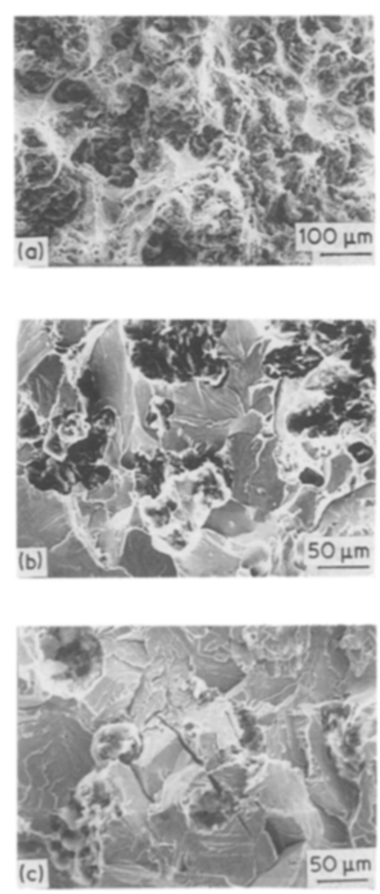

Figure 12 Scanning electron microscopy (SEM) of the fracture surface of specimens with varying silicon contents deformed at room temperature (a) 3.07% Si; (b) 3.58% Si; (c) 4/25% Si.

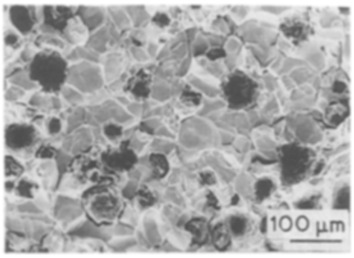

Figure 13 Scanning electron microscopy (SEM) of the fracture surface of spheroidal graphite cast iron deformed at 400° C.

2. The intergranular fracture has not been found in ferritic compacted graphite cast irons in all tensile tests from room temperature to 500° C in this study, because the ferritic compacted graphite cast irons have a mixed fracture mode due to the irregular graphite morphology.

3. The fracture mechanism changes from the dimple pattern to a transgranular cleavage with increasing silicon content at room temperature. On the other hand, when the test temperature is above the raised transition temperature the specimen fails in a ductile manner.

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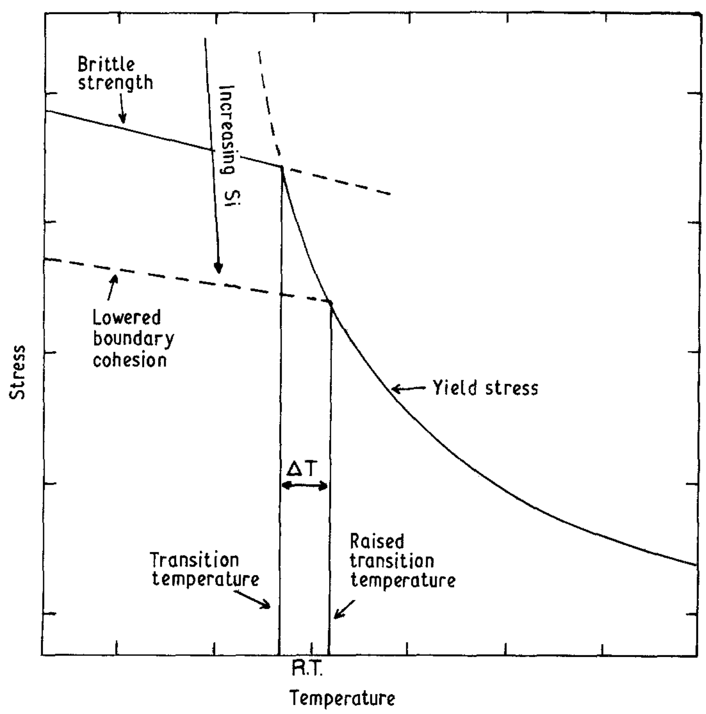

Figure 14 The effect of temperature on the tensile properties of ferritic compacted graphite cast irons showing, schematically, the lowering of grain boundary cohesion and the resultant increase in the ductile–brittle transition temperature [11].