FRACTURE OF FERRITIC DUCTILE IRON AT ELEVATED TEMPERATURES

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Ferritic ductile iron with the mean free path between graphite nodules in the range 200-400 µm was tested. The fracture toughness was tested in the temperature range 20-500°C. The values of J-integral were proportional to the mean free path, while the efeect of temperature was irregular. A local minimum at 400°C was noticed and it was explained by internal micro-cracking of graphite nodules.

INTRODUCTION

Nodular cast iron is a material widely applied in machine-building. It has been reported by Nechtelberger (1) that non-alloyed nodular cast iron can be used up to about 500°C. Simultaneously, no experimental data concerning fracture toughness of ductile iron at elevated temperatures have been published yet. So, the aim of this work has been to establish the relationship between temperature and fracture toughness and to explain how the structure of nodular iron affects this dependence.

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In order to simplify this very complex problem, the two-phase material, i.e. ferritic nodular cast iron has been considered.

The properties of two-phase materials can be predicted knowing the properties of the component phases and their spatial arrangement, i.e. structure of the material (Ondracek (2). The oldest and simplest model of a structure-property relationship is shown in Fig. 1. The properties are related to the concentration of the component phases. At each concentration the properties can vary between two bounds depending on their microstructure. These bounds are the extremes if the component phases are arranged in a serie or parallel to each other.

During a tensile test nodular cast iron can be considered as a parallel-type material. So, its ultimate or yield tensile strength should be proportional to the matrix volume fraction and its strength:

$$\sigma^{N}_{YS} = \sigma^{M}_{YS} (1 - V^{G}_{V}) \qquad (1)$$

Mechanical properties of both ferritic nodular cast iron and Si-ferrite are shown in Fig. 2. Si-ferrite is a model of the cast iron matrix. Taking into account that V^{G}_{V} is about 0.11, it turns out that the relationship (1) describes the strength of nodular cast iron very well.

A similar approach has been proposed by Speidel and Uggowitzer (3) for fracture toughness. They have obtained an equation giving "a means to calculate the fracture toughness of cast irons from the fracture toughness of the matrix and the fracture toughness of the graphite, provided the volume contents, the contiguity and the modulus of elasticity is known for both phases". So, in their equation no effect of the mean free path between graphite nodules on fracture toughness has been predicted. On the contrary, the more systematic research has shown the essential effect of λ on J_{Ic} (Wojnar (4). So, a new model of fracture process for nodular cast iron is proposed (see Fig. 3). Taking into account the absorbed specific energy till fracture (ASPEF) concept, one put after Czoboly and Havas (5):

$$J_{Ic} = W_c \cdot L_0 \tag{2}$$

where

$$W_c = (\sigma_{YT} + \sigma_f) \ \ln\left(\frac{d_0}{d_u}\right) \tag{3}$$

L_0 represents the length of a hypothetical tensile specimen (situated in the vicinity of the crack tip, perpendicularly to the crack edge) in which the energy W_c is absorbed. A very similar model has been proposed by Nishi (6). According to this model the length of the mentioned above hypothetical specimen should be equal to the mean free path between graphite nodules λ. Taking into consideration the fact of the occurrence of the double crack path (see Figs. 3 and 4) this length should be increased up to 2λ. So, the fracture toughness of nodular cast iron can be evaluated as follows:

$$W_c \cdot \lambda < J_{Ic} < 2 \cdot W_c \cdot \lambda \tag{4}$$

The equation (4) is valid for the whole considered temperature range, but the exact value of W_c should be determined for every test temperature separately. The authors, however, have no concept how to predict the effect of temperature on the fracture toughness.

EXPERIMENTAL PROCEDURE AND RESULTS

Material Tested

TABLE 1 - Chemical Composition of the Material Tested (wt %)

C	Si	Mn	P	S	Mg
3.60	2.90	0.09	0.046	0.010	0.09

The melt with the composition shown in Table 1 was cast into Y-shaped moulds. To vary the nodule size and the mean free path, five different moulds were used, with the thickness of 15, 25, 50, 75 and 120 mm, respectively. The blocks cast into moulds were annealed to the ferritic condition, i.e. heating at 950°C for 12 h, followed by furnace cooling to 690°C and holding at this temperature for 24 h with finally cooling to the room temperature.

Experiments

The fracture toughness tests were carried out on 12 mm thick CT-specimens and the multi-specimen method was applied. The experimental procedure was based on the JSME S-001 1981 Standard (7). The results of these tests are shown in Figs. 5 and 8.

The values of the absorbed energy W_c (shown in Fig. 6) were obtained using the formula (3) from the results of standard static tensile test. The specimens used were cylindrical, 5 mm diameter.

Quantitative fractographic measurements were carried out with the use of R(A) and R(N) coefficients (Wojnar (8). They are defined as follows:

$$R(A) = 2\frac{A'_A}{A_A} \tag{5}$$

$$R(N) = 2\frac{N'_A}{N_A} \tag{6}$$

The more precise description and interpretation of these parameters can be found in the reference (8). The results of quantitative fractography are shown in Fig. 7.

DISCUSSION

As it is shown in Fig. 8, ferritic nodular cast iron shows a linear relationship between the mean free path and the fracture toughness. The constants of proportionality in J_{Ic}-λ lines Fig. 8 are greater than W_c but smaller than $2W_c$ (see Fig. 6 for comparison). It indicates that the relation (4) describes the J_{Ic}-λ dependency in a proper way. Roughly, the range from $W_c\lambda$ to $2W_c\lambda$ covers the scatter of results (see Fig. 8).

The fracture toughness data are arranged in another way in Fig. 5 in order to underline the temperature effect on fracture toughness. A local minimum at 400°C is clearly visible and the point is how to explain this phenomenon. The tensile strength shows no irregular changes with temperature (see Fig. 2). Simultaneously, the fracture toughness of Si-ferrite increases monotonically with the increase in test temperature (Wojnar (9). So, the problem how to clear out the relationship between the fracture toughness of nodular iron and the properties of constituent phases is much more complex than it has seemed when only the properties at room temperature have been considered (3,4). An attempt to solve this problem has been taken by Yamagisawa and Lui (10). They have stated that the embrittlement of ferritic compacted graphite cast iron is attributed to dynamic strain ageing at 200 to 300°C. Unfortunately this explanation is worthless in the case of nodular iron where the embrittlement occours at 400°C.

Piaskowski and Jankowski suggest (11) that the 400°C embrittlement is caused by changes in the distribution of Si in the matrix of cast iron, but they present no supporting results. In order to verify this conclusion a careful X-ray microanalysis has been undertaken by the authors, but the results do not support it.

The use of quantitative fractography has been another attempt to explain the nature of the 400°C embrittlement. The results of fractographic measurements are shown in Fig. 7. A minimum for R(A) and a maximum for R(N) can be observed at 400°C. It supports the conclusion that this particular temperature is a critical one regarding the fracture toughness of ferritic nodular iron. The results of fractographic measurements indicate that no qualitative change in the mechanism of fracture exists. A relatively low value of R(A) and high value of R(N) suggest the embrittlement of the graphite phase. The SEM observations of fractured specimens support this hypothesis. The analysis of Figs. 9 to 12 shows that the size of voids increases together with the increase in test temperature. It agrees with the mentioned above fact that the fracture toughness of Si-ferrite increases with increasing temperature. But the most important thing is that internal cracks in graphite nodules can be observed at 400°C (Figs. 10 and 11). Moreover, 400°C is the only one temperature which gives such a phenomenon. It is suggested that these internal cracks can affect the nucleation of cracks in the matrix. Consequently, it can cause a decrease in fracture toughness at 400°C.

CONCLUSIONS

1. The mean free path between graphite nodules is a factor controlling the fracture toughness of ferritic nodular cast iron at any temperature in the range from 20 to 500°C.

2. The local embrittlement at 400°C is most probably caused by the embrittlement of the graphite phase.

3. A complex model for the evaluation of the temperature effect on fracture toughness of two-phase alloys should be evaluated in the further research.

SYMBOLS USED

A_A = area fraction on polished surface

A_A' = area fraction in the projected image of the crack surface

d_O = initial diameter of the specimen (mm)

d_u = diameter of the specimen at fracture (mm)

J_{Ic} = critical value of J-integral (N/mm)

L_O = length of hypothetical tensile specimen (μm)

N_A = number of particle sections per unit area (mm^{-2})

N_A' = as above, per unit area of projected image (mm^{-2})

R(A) = coefficient describing the fracture surface

R(N) = as above

t = temperature (^{o}C)

V_V = volume fraction

V_V^G = volume fraction of graphite

W_c = absorbed specific energy till fracture (MPa)

λ = mean free path (μm)

σ_f = true stress at fracture (MPa)

σ_{YS} = tensile yield strength (MPa)

σ_{TS} = ultimate tensile strength (MPa)

σ_{YS}^{M} = tensile yield strength of matrix (MPa)

σ_{YS}^{N} = tensile yield strength of nodular iron (MPa)

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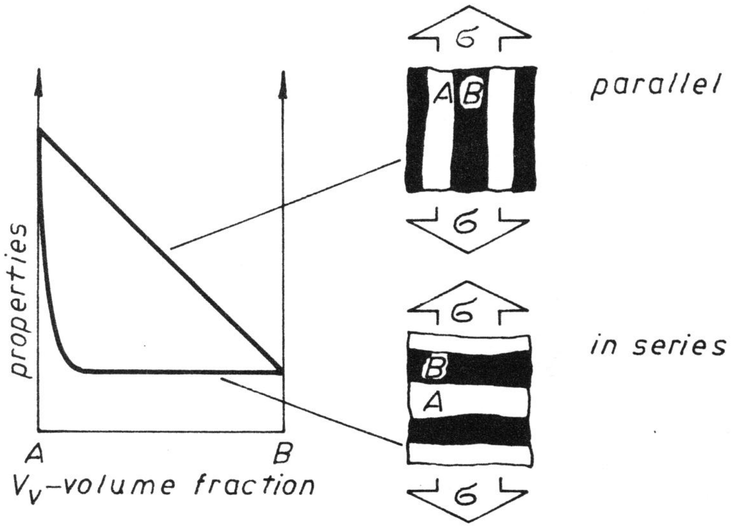

Figure 1 A model of the dependency between alloy structure and its properties

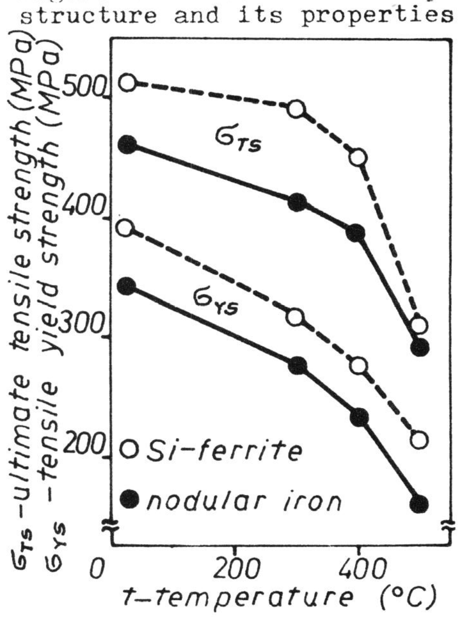

Figure 2 Tensile strength of cast iron and Si-ferrite

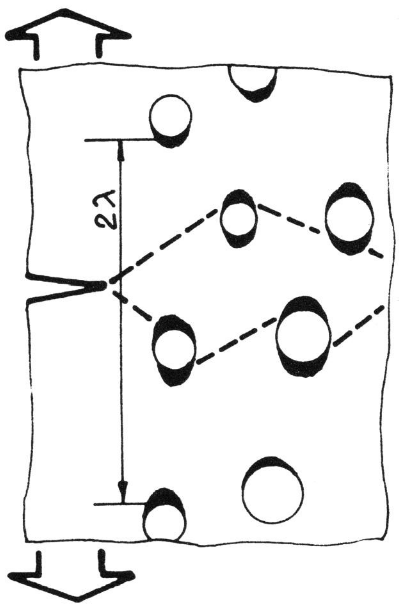

Figure 3 Model of fracture of cast iron

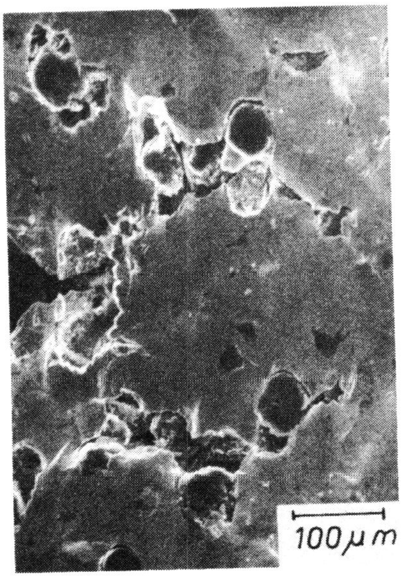

Figure 4 Vicinity of crack tip, test temperature 20°C

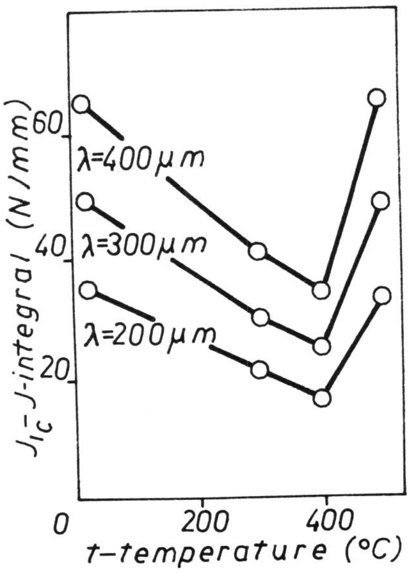

Figure 5 Fracture toughness versus temperature

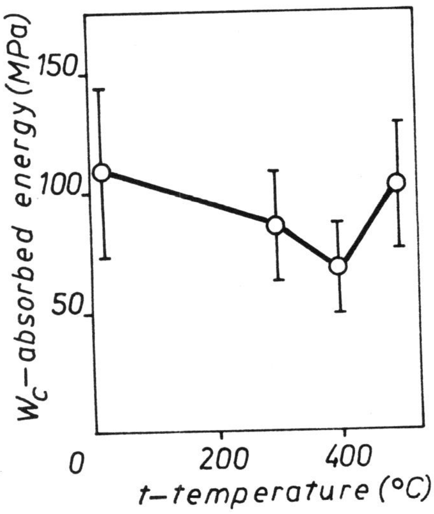

Figure 6 Absorbed energy W_c versus temperature

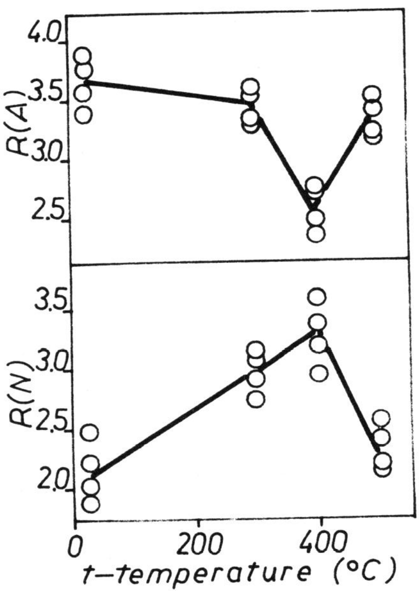

Figure 7 Fractographic measurements vs. temperature

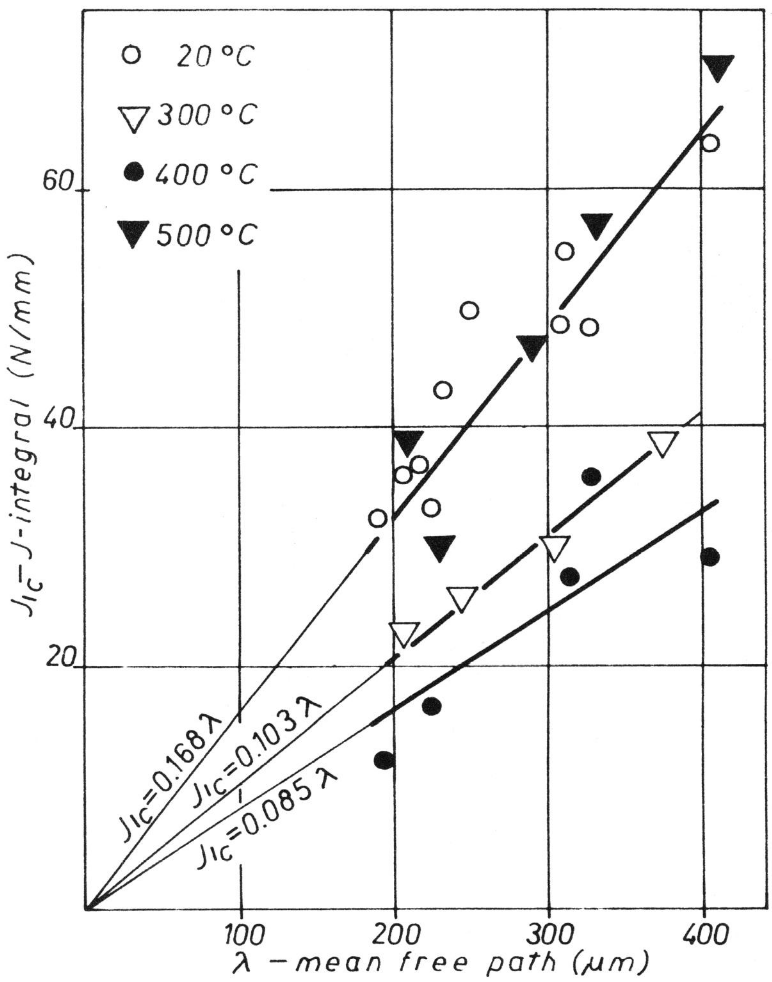

Figure 8 Fracture toughness of ferritic nodular iron vs. mean free path between graphite nodules

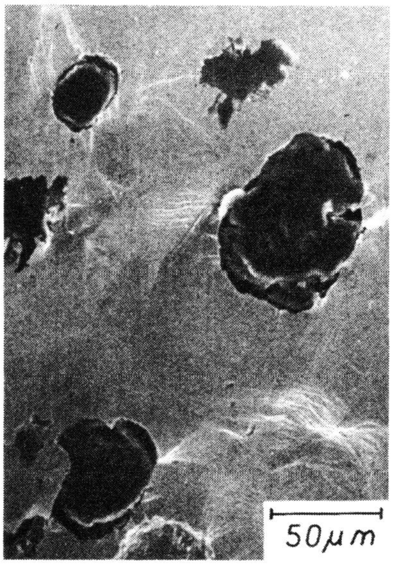

Figure 9 Small dimples observed at 300°C

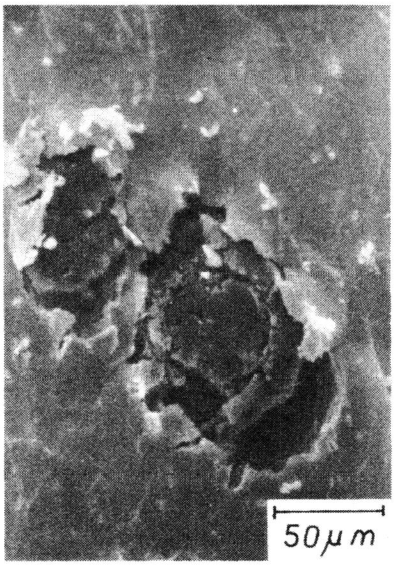

Figure 10 Cracks in graphite nodules at 400°C

Figure 11 Cracks in graphite nodules at 400°C

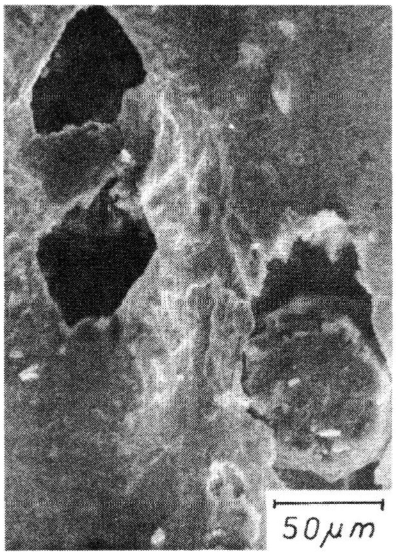

Figure 12 Large dimples observed at 500°C