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On the fracture characteristics of heated iron

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The fracture of polycrystalline iron wires was studied in the temperature range (R.T. 500°C). It was found that heating decreased the fracture surface energy. This was attributed to increase in cleavage crack distances caused by excess formation of minute cavities at the grain boundaries.

1. Introduction

The fracture surface energy (γ) is one of very important material characteristics that appear in the models of brittle fracture initiation (Dobbs *et al* 1973). In this work (γ) was evaluated from the results of stress-strain experiments done for wires having different grain diameters. The principle of this evaluation consists of the comparison of the Petch (1953, 1958) and Cottrell (1959) relations

$$\sigma_y = \sigma_0 + K_y l^{-\frac{1}{2}}, \qquad \ldots (1)$$

$$\sigma_F = \left(\frac{B.G.\gamma}{K_y} \right) l^{-\frac{1}{2}}, \qquad \ldots (2)$$

where
- σ_y : yield stress.
- σ_0 : frictional stress.
- K_y : Petch slope.
- l : average grain diameter.
- σ_F : fracture stress.
- B : a constant which is unity for tensile stress experiments.
- G : rigidity modulus.

From the evaluated fracture surface energy, the cleavage fracture distance (d) taking place in the fracture process could be calculated using Gilman's (1960) relation.

$$\gamma = \frac{2d^2}{l} (\sigma_y \epsilon_p), \qquad \ldots (3)$$

where ($\sigma_y \epsilon_p$) is the energy absorbed during plastic flow. The object of this paper is to show the effect of heating up to 500°C on the fracture of polycrystalline iron wires.

2. Experimental Procedure

The meterial used was supplied by the British Steel Corporation in the form of wires 0.25 mm diameter. Precise chemical analysis is as follows (in wt. %) C-0.012, Si, 0.018, Mn, 0.92, Po, 0.014, S, 0.016, and Cu, 0.02. Wires of different grain diameters were prepared by annealing in vacuum (10^{-5} mm Hg) for 4 hours at different temperatures. The attained average grain diameter as measured by the line intercept method for each of the annealing temperatures is given in table 1.

Table 1

Annealing temperature (°C)	605	660	725	780
Average grain diameter (mm)	.065	.076	0.11	0.14

X-ray photographs using CoK_α radiation for these annealed wires showed that all these grains have fully recrystallized structure. The stress-strain experiments for these annealed wires were done using conventional type tensile testing machine at a constant rate of extension of 0.5 mm/min. The wires were heated to the working temperature while they were clamped in the tensile testing machine.

3. Experimental Results

Typical stress-strain curves for the annealed wires at the different temperatures R.T. (25°C), 100°C, 205°C, 310°C, 400°C, and 500°C are given in figure 1. It is clear that there are no sharp yield points in agreement with similar previous

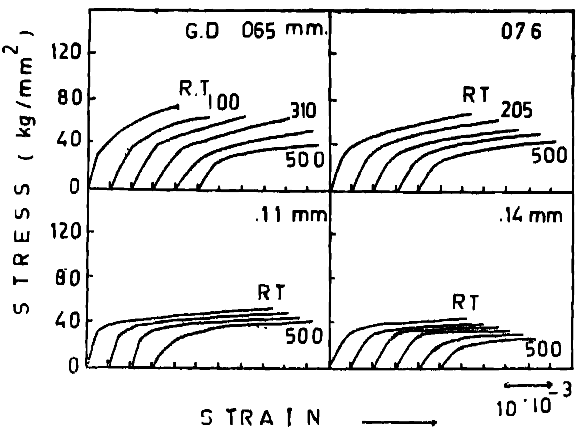

Fig. 1. Stress-strain curves for tested iron wires. Numbers on curves refer to working temperature.

observations on iron (Keh 1962, Youssef *et al* 1974). The Petch-Cottrell relations (2) and (3) proved to be valid for the studied wires. This was judged from the linear dependence of yield and fracture stresses on $l^{-\frac{1}{2}}$ shown in figures (2*a*), (2*b*), from which it can be deduced that (a) the friction stress (σ_0) is constant for all relations independent on the wroking temperature and (b) the Petch slope (K_y) decreased by increasing working temperature. It was found that at all temperatures the wires fracture in a brittle manner as shown in figure 3, which shows intergranular fracture with little or no localized necking. A metallographic study was done for fractured wires, and revealed the existence of many grain boundary cracks as shown in figure 4 in which a triple point crack occurs behind a fracture area.

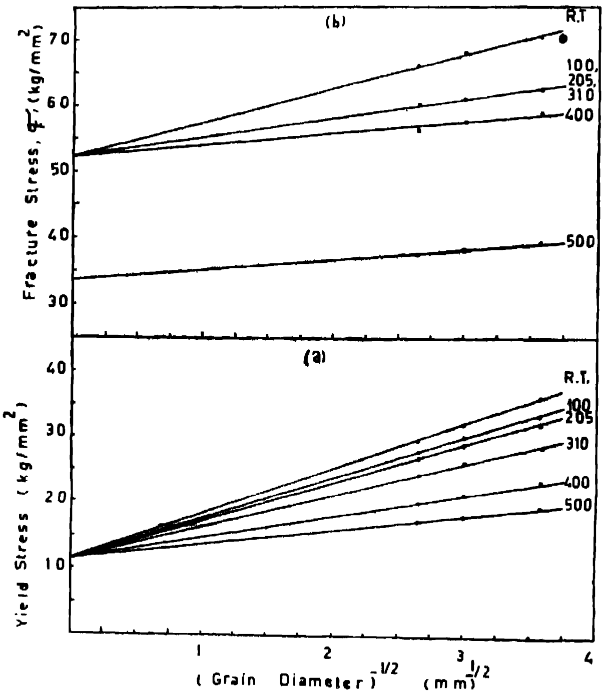

Fig. 2. Temperature and grain diameter dependence of the yield and fracture stresses of iron.

By taking rigidity modulus (G) for iron as 7.9×10^{11} dyne/cm^2 (Keh 1962), and substituting in Cottrell's relation (2), the fracture surface energy for tested wires at the different temperatures was calculated. The dependence of fracture surface energy on working temperature is given in figure 5, which indicates that (a) the fracture surface energy at room temperature (25°C) equals 3.5×10^4 erg/cm^2 in reasonable agreement with that previously calculated (Vreeland *et al* 1953) and (b) the temperature dependence of fracture surface energy yielded negative temperature rate of 46 erg/cm^2/°C.

Fig. 3. Cross-section on tensile tested wire showing intergranular fracture. Magnification × 100.

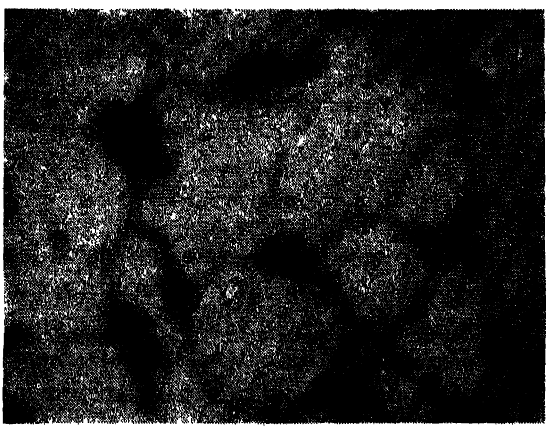

Fig. 4. Triplet point crack in fractured wire. Magnification × 600.

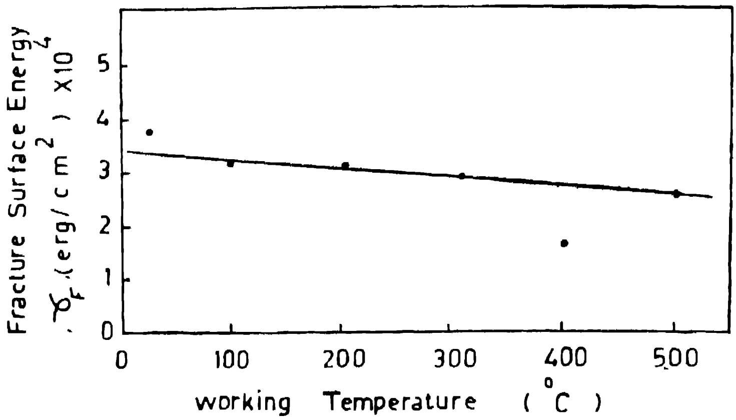

Fig. 5. Dependence of fracture surface energy on working temperature.

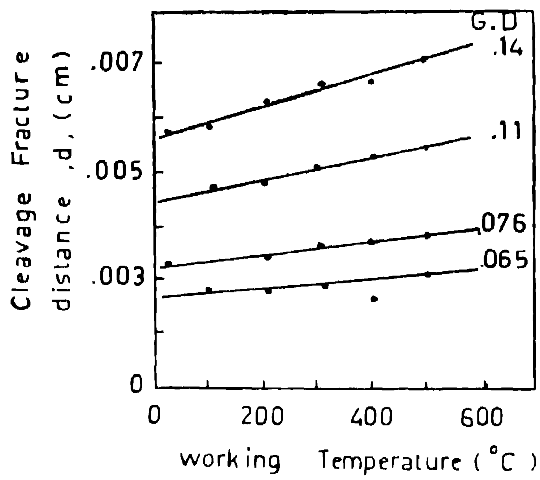

Fig. 6. Dependence of the cleavage fracture distance on working temperature for iron wires of different grain diameters.

4. Discussion

It was argued that three mechanisms were considered for fracture in polycrystalline metals, these were (a) boundary strength, (b) unpinning of Frank-Read sources, (c) generation of dislocations from within grain boundaries. Since neither Frank-Read sources nor dislocation pile-ups were observed in iron (Roberts *et al* 1970), the only possible mechanism for fracture in iron is the generation of dislocations from within grain boundaries. However, the fact that all data shown in figure (2*a*) extrapolate back to the yield stress of a single crytstal at $l^{-\frac{1}{2}} = 0$ would indicate that matrix dislocations are playing a minor role in the fracture process, and that dislocations in grain boundaries offer a much stronger barrier to slip dislocations than the dislocations in the matrix, and it is the grain boundary dislocations that control the yield stress. This might explain the intergranular fracture seen in photomicrograph 3, and the triple point crack shown in photomicrograph 4 which is often caused by grain-boundary sliding (Garafalo 1967).

The different Petch slope (K_y) values observed in figure (2*a*) are no doubt due to the varying character of the grain boundaries in the different working temperatures. It is generally believed that (K_y) value is related to difficulty of propagating slip across grain boundaries. Such propagation is assisted by the stress concentration ahead of a slip band in the yielded grain initiating slip in a neighbouring grain, and consequently cleavage cracks would be nucleated at the point of sliding grain boundaries as had been previously observed (Golland *et al* 1967). Calculating the cleavage fracture distance (d) for tested wires by substituting in Gilman's relation (3), and putting (γ) as taken from results of figure 4. The dependence of cleavage fracture distance on working temperature is given in figure 6, which indicates that raising temperature increased cleavage fracture distance, and the rate of such increase rises with grain diameter. On the basis of these data the negative dependence of fracture surface energy observed in figure 5 might be attributed to the thermal activation of the fracture mechanism, because while straining at elevated temperatures minute cavities were nucleated in the grain boundaries, and weaken the boundary more than in the bulk of the grain, and decrease the stress concentration in the boundaries, consequently less energy would be supplied for the creation of cleavage cracks in the grain boundaries, and as a result decrease the corresponding fracture surface energy.

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