Influence of Second-Phase Particles on the Low-Temperature Fracture Behaviour of Iron

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Second-phase particles, like inclusions or cementite particles, play an important role in the low-temperature behaviour of steels(1-3). Cleavage may be initiated by cracked carbides. The resistance to cleavage propagation is improved in the presence of fine oxyde or carbide dispersions(4-6). In order to separate the influence of the particles from other effects, present in commercial steels, we carried out a number of experiments using a model system, consisting of iron-alumina composite materials prepared by powder metallurgy (7). It is thus possible to study the effect of particle size and volume fraction under conditions where all other factors are kept constant. The results apply only to cases where the particles themselves do not fracture.

EXPERIMENTAL PROCEDURE -

The tests were carried out with a sintered iron reference material (theoritical density) and iron-alumina composites containing up to 20% by volume of calibrated particles, the sizes of which ranged from 0.05 to 40 μ approximately. Tensile and subsize impact specimens have been broken at low temperature and the usual parameters measured(ductile to brittle transition curves). The fracture surfaces have been observed by optical and electron microscopy. Tapered sections of broken specimens have also been examined.

EXPERIMENTAL RESULTS -

Ductile to brittle transition

The results are analogous, whether tensile elongation, reduction in area or impact values are used as parameters :

- above the transition range (R.T.), the ductility and the toughness of the materials decrease appreciably as the alumina content increases (initiation on the particles of the cavities leading to ductile fracture(7)).
- for fairly large particles the transition temperature is only slightly lower than in the reference iron and does not depend strongly on particle volume fraction (Fig.1).

- the transition range spreads out over an increasing interval of temperature, as the alumina content rises ;

- for certain distributions of the particles, the composites have higher ductility and toughness than pure iron, in a temperature range where fracture occurs essentially by cleavage (Fig. 2, 3 and 4) ;

- when the size of the particles is less than 1 μ, the transition is far less sharp than in pure iron (Fig. 2 and 5) .

In tensile tests at liquid hydrogen temperature, all materials fracture by cleavage, but the fracture stress and the elongation to fracture depend on particle size and volume fraction (Fig. 4). Large particles embrittle the iron matrix, whereas small ones confer improved properties to the materials (2 to 10 % elongation instead of 0.2 % in pure iron).

Metallographic observations

The examination of the fracture surfaces shows that the alumina particles appear to reduce the tendancy to cleavage fracture and favor the formation of ductile failures : for given test conditions, in the lower part of the transition range, the proportion of ductile zones increases with increasing volume fraction and decreasing size of the particles.

In certain cases, by following the rivers on the cleavaged surface back to their sources, we have found large alumina particles at nucleation or renucleation points of cleavage cracks (Fig. 6). The particles themselves were never observed to be broken. In the case of small particles, no indications of cleavage initiation at the particles have been found. On the contrary, zones of dimple fracture persist at very low temperatures.

From the river patterns it appears further that the particles, especially when they are large, slow down the propagation of cleavage cracks. Additional surface energy is required to pass around the inclusions (Fig. 7). For small particles there are no visible signs of an interaction between cleavage propagation and particles, on the fracture surface (Fig. 8). Fig. 9 shows, however, that in these materials the grain size is rather small and the number of mechanical twins is much smaller than in materials containing no particles or large particles . (Fig.10)

DISCUSSION AND CONCLUSIONS -

The results may be interpreted in terms of simple considerations, analogous to those developped by HAHN and ROSENFIELD (4) and by PLATEAU (8). For large particles, the fracture stress is essentially given by the law of mixtures. The occasional initiation of cleavage by the particles also contributes to decrease the fracture stress of these composites. Small particles, by favoring a more homogeneous deformation of the matrix and decreasing the effective length of dislocation pile-ups, decrease the risk of twinning and of slip blockage : cleavage initiation becomes more difficult. The decohesion at the particle - matrix interface (all particle sizes) helps to relax the stress concentrations and favors the ductile mode of failure. As a result, the transition temperature is lowered.

The stresses corresponding to these different fracture modes can be expressed in terms of particle size and spacing. As shown by PLATEAU (8), one can thus determine the parameters of the dispersion for which each of these mechanisms is most likely to occur : slip blockage in the matrix, propagation of the cracks formed around the particles, ductile fracture. The competition of these processes explains why the ductile to brittle transition is not so sharp in the composites as in the pure matrix.

In conclusion, weakly bonded particles have an effect on cleavage initiation only if they are large enough. Small particles make cleavage initiation more difficult. All particles slow down to some extend the propagation of cleavage. Their major effect is however to favor the ductile mode of failure. Lower transition temperatures and improved fracture properties at low temperature are thus obtained.The effect of the particles on grain size and on twinning can also be a beneficial factor.

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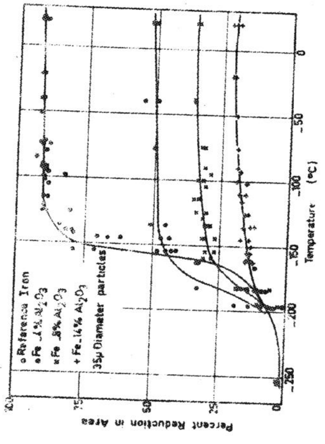

Fig. 1 - Ductile to brittle transition in tension - Fe and Fe-Al_2O_3(35μ particles).

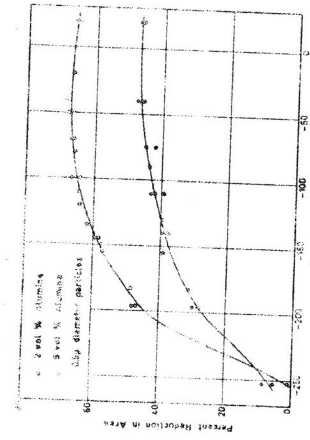

Fig. 2 - Effect of fine alumina particles on the ductile to brittle transition of iron .

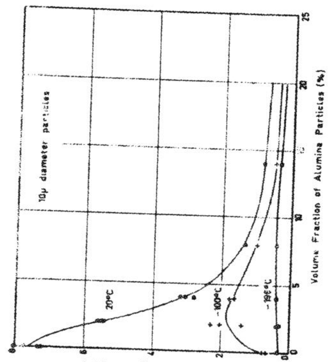

Fig. 3 - Effect of alumina volume fraction on the impact values at different temperatures (10μ particles) - 100°C is below the transition temperature.

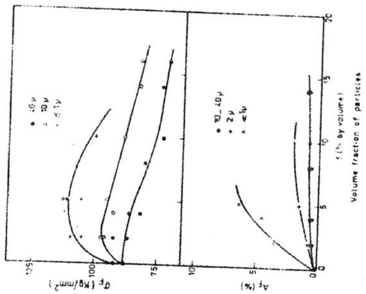

Fig. 4 - Effect of particle size and volume fraction on strength and ductility at 20 K.

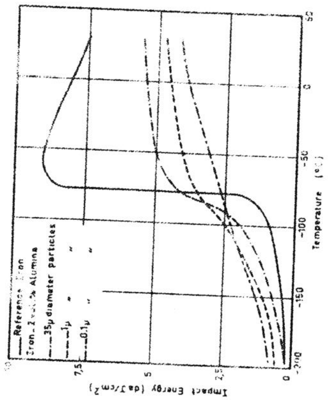

Fig. 5 - Impact tests. Influence of particle size on the transition curves.

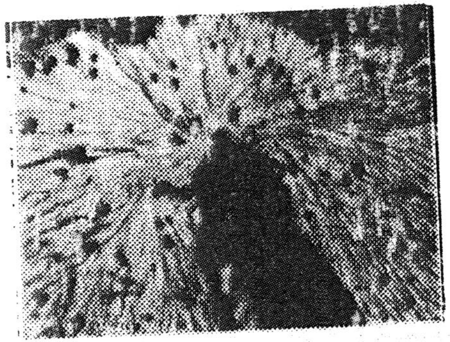

Fig. 6 - Fe - 2 vol% Al_2O_3
Initiation of a cleavage crack at a spherical alumina particle -
(diameter 12 μ)
x 100

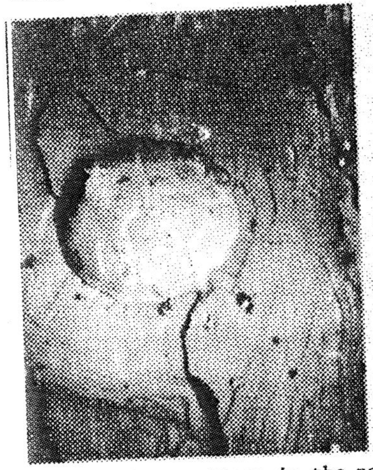

Fig. 7 - River pattern in the neighbourhood of a 12μ alumina particle . x 3500

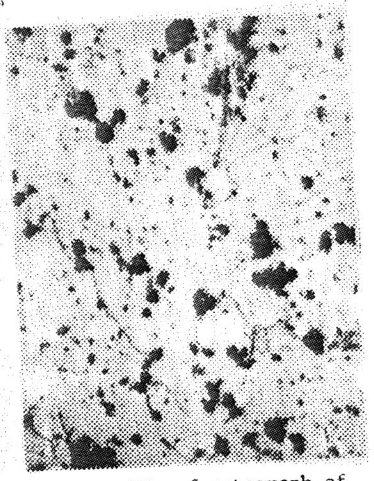

Fig. 8 - Microfractograph of a cleavage crack in a composite containing small alumina particles x 3500

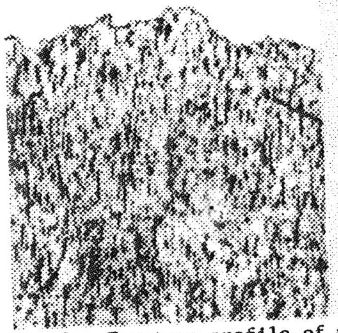

Fig. 9 - Fracture profile of a specimen of Fe-5 vol% Al_2O_3 material broken in tension at 20 K (small particles) x 200

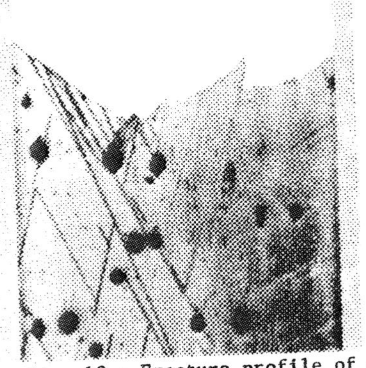

Fig. 10 - Fracture profile of a coarse grained specimen of Fe - 2 vol% Al_2O_3 broken at 77 K (35μ particles) x 200