THE INFLUENCE OF GRAIN BOUNDARY CARBIDE DENSITY ON THE BRITTLE FRACTURE OF FERRITE PEARLITE STEELS

B. Mintz

The City University, Northampton Square, London EC1, England .

ABSTRACT

The influence of carbide density on the charpy impact transition temperature of pearlite free and pearlite containing steels has been examined. Carbide density was measured optically using a linear intercept method. Because of the strong inter-relationships between grain size, carbide thickness and density, the carbide density could not be examined independently, and a linear regression approach had to be used. Using this approach increasing the number of carbides intersected per m.m. by 20 raised the ITT by ∿20-30°C. Generally the influence of carbide density on ITT is small compared with carbide thickness and grain size. Nevertheless, it is significant and probably accounts for the rather poorer than expected impact performance exhibited by some Nb and Ti containing steels. Nb and Ti seem to actively encourage carbide precipitation at the boundaries giving a tendency for both coarser carbides and a greater carbide density. Grain boundary carbides may also assist propagation of cracks but this influence on fracture cannot at present be separated from the influence of carbide density.

KEYWORDS

Grain boundary carbides, brittle fracture, steel.

INTRODUCTION

Recent work (1) on ferrite/pearlite and pearlite free steels has indicated that the criterion for brittle fracture in a charpy test can be both grain size and grain boundary carbide thickness controlled. Of the two, grain size seems to have a dominant effect but at a constant grain size, changes in carbide thickness can result in a 60°C rise in the impact transition temperature (ITT). The results from this work are summarised in Fig.1, where they have been compared with the predictions given by the Almond, Timbres and Embury model (2), for various average carbide thickness, t - curves AB, AC, AD, AE and AF for 0, .15, .5, 1 and 1.5μm respectively. A further fracture criterion based on the stress needed to propagate a penny

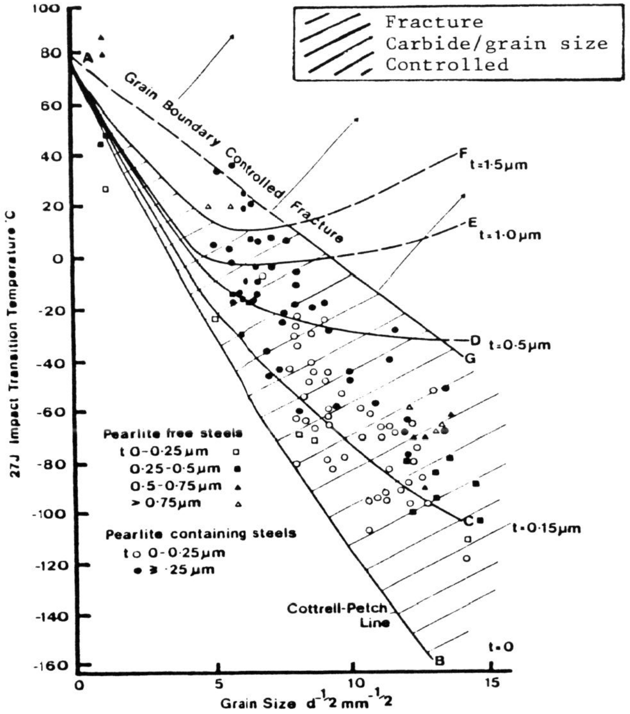

Fig.1 Calculated curves of 27J ITT vs $d^{-\frac{1}{2}}$ together with experimental data points, after (1).

shaped crack equal in size to the grain diameter was also included in the analysis and generally defines the upper limit for ITT (curve AG). This second criteria arose because it was observed that at constant grain size size increasing the carbide thickness beyond a certain value produced no further increase in ITT. It was inferred from this behaviour that the fracture process must be changing from mixed carbide/grain size controlled to grain boundary controlled, the energy to crack a carbide and propagate it into the surrounding ferrite matrix being insufficient to propagate the crack across the boundary.

Although agreement between theory and practical results was reasonable for grain sizes ⩽ 40 µm, this was not so at very coarse grain sizes (see Fig. 1). At a grain size of $d^{-\frac{1}{2}}$ of 1 $mm^{-\frac{1}{2}}$ where d is the mean linear intercept grain diameter, the Almond et al model predicted that changes in carbide thickness would have little influence on ITT, whereas experimentally a change of 60°C was observed. This would suggest that the dislocation pile up contribution to fracture was not as great as given by the Almond et al model.

The experimental work also suggested that at these coarse grain sizes when the carbides are coarse, the critical event in the fracture process may be the ability to propagate a crack across the boundary. (See Fig. 1)

As the grain boundary carbides (gbc) have been shown to be important in dictating the ITT, it is felt that at a given thickness the more carbides present the greater would be the statistical probability of propagating a crack from a carbide. It would therefore be expected that the greater the density of the carbides the higher should be the ITT. In order to investigate this possibility the density of carbides has been obtained for most of the steels previously examined Ref. (3, 4), and compared to their respective ITT's.

EXPERIMENTAL

The steels examined consisted of a variety of structural steels having ferrite/pearlite structures to which a selection of micro-alloying additions viz. Al, Nb, V and Ti had been added singly or in combination. In addition the following series of very low C steels (<.06%C) were examined.

1. a commercial 13% Cr ferritic stainless steel having a very coarse grain size of 1-1.2 $mm^{-\frac{1}{2}}$,
2. laboratory cast and hot rolled C-Mn steels having a grain size range of 5-6 $mm^{-\frac{1}{2}}$,
3. fine grained Ti-treated commercial steels having a grain size range of 12-15 $mm^{-\frac{1}{2}}$.

A range of average grain boundary carbide thickness was achieved for these steels by different heat treatments. Full details of the composition and impact and tensile properties of the steels, their grain size and carbide thickness measurement can be found in the references 3 & 4. Samples for microstructure examination were etched in picral for all steels except the stainless steel where a 50/50 mixture of 5g of picral acid and 5ml HCL per 100ml methanol was used in order to highlight grain boundary carbides. Although the optical microscope cannot be used to resolve the thickness of gbc, with oil immersion their presence can be clearly revealed. A linear traverse was carried out over 5 mm for the low alloy and C-Mn steels and 50 mm for the stainless steel and the number of carbides intercepted per given length is the gbc density. The carbides intersected at the boundaries where either at the tails of pearlite colonies or isolated carbides. Gbc delineating the pearlite colonies and which were generally finer were not counted.

Two parameters were chosen to relate to the ITT, N - the number of carbides per mm and Nd*[1] - the probability of finding a carbide at a grain boundary.

RESULTS

Pearlite Containing Steels

The curves of number of carbides per mm (N) against grain size are given in Fig. 2. It can be seen that as the grain size becomes finer the number of carbides intersected increases. However, the steels clearly fall into two groups. At the same grain size, Ti and Nb containing steels have a greater carbide density than the plain C-Mn, the C-Mn-Al and the C-Mn-V steels. Insufficient data is available to be able to group the C-Mn-V-Nb steels.

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[1] d* is the adjusted mean linear intercept allowing for the pearlite.

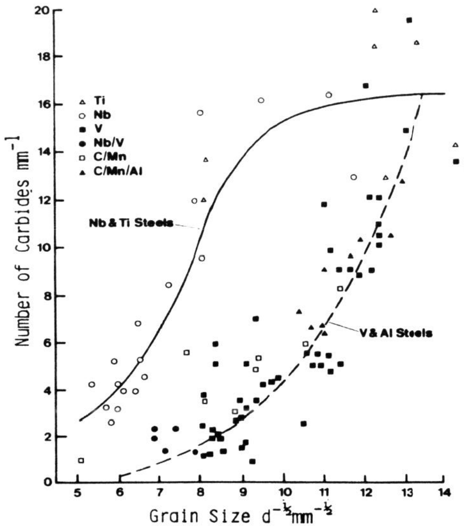


Fig.2

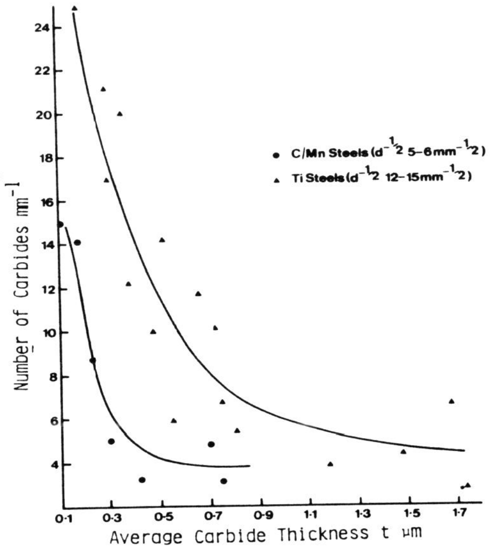


Fig.3

Pearlite Free Steels

The curves of carbide density against average carbide thickness for the C-Mn, Ti - containing steels, and ferritic stainless steels are given in Fig. 3. The very coarse gain size of the ferritic stainless steel determined that the carbide density could only be very low. The finer grained Ti steels can be seen to have the greatest carbide density although it is not clear whether this is a consequence of the finer grain size or the Titanium additions. The general trend as can be seen from Fig.3 for the low C-Mn and titanium containing steel is for the carbide thickness to increase as the carbide density decreases. In comparison the ferritic stainless steel gave the opposite behaviour, although changes were very small.

DISCUSSION

With this type of work it is very difficult to alter one variable independently of the other. Thus it can be seen from Figs. 2 and 3 that altering the carbide density generally results in either a change in the carbide thickness or a change in grain size. The difficulty in keeping the grain size and carbide thickness constant whilst altering the carbide density means that a linear regression approach has had to be taken in an attempt to isolate the individual effects.

Previous work (3) on the pearlite containing steels has given the following linear regression equation for the 27J ITT:-

$$27J\ ITT,\ {}^{o}C = 173\ t^{\frac{1}{2}} - 8.3d^{-\frac{1}{2}} + 0.37\ \Delta y - 42 \qquad (1)$$

where t is the average carbide thickness, μm, d is the grain diameter Nmm^{-2}, and Δy,Nmm^{-2} is the precipitation and solid solution strengthening contribution.

Strictly this equation can only be used for the conditions under which it was derived, i.e. for the pearlite containing steels. However, it is reasonable to assume that although it cannot be used to calculate the absolute values of ITT's for the pearlite free steels it can be used to obtain changes in ITT. The approach in this work has been to calculate the 27J ITT using equation (1) for the steels examined and to subtract these calculated values from the observed 27J ITT's. Carbide density can then be plotted against this difference to ascertain whether the density has any influence on ITT.

As has been mentioned, at constant grain size there is an upper limit to the gbc thickness above which it has no further effect on ITT. This limiting value has been shown to be dependent on grain size, the finer the grain size the lower its value. However, as can be seen from Fig.4, which has been taken from previous work, (Ref. 3), it also appears as if there is a lower limit of gbc thickness. The region in which the $t^{\frac{1}{2}}$ relationship in equation (1) applies is therefore clearly restricted and has been contained for the purpose of this work between the limits $.25\ \mu m < t^{\frac{1}{2}} < 0.80\ \mu m$.

The curves of carbide density (N) and the probability of finding a gbc carbide at the boundary (Nd*) against the difference in 27J ITT between the observed and calculated values are given in Figs. 5 and 6 for the pearlite containing steels respectively and Figs. 7 and 8 for the pearlite free steels. Although there is considerable scatter it is clear that increasing N or Nd* results in an increase in ITT. An increase in N by 20 produces a 20 to 30°C rise in the ITT for both pearlite free and pearlite containing steels. The co-relation coefficients (r) for the data in Figs. 5 and 6 for the pearlite containing steels which come from a variety of sources with very different compositions were 0.4 and 0.38 respectively. Much better co-relation coefficients were obtained for the pearlite free steels, Figs. 7 and 8, 0.78 and 0.84 respectively. In the latter steels an attempt had been made to keep the base compositions the same and to alter the carbide distribution by heat treatment alone.

A feature of the work on the pearlite containing steels at the 1% Mn level (Ref. 3) was the poor impact properties shown by the Ti and Nb containing steels compared to the plain C-Mn, C-Mn-Al and C-Mn-V steels. The Ti and Nb containing steels gave ITT's which were on average 20°C higher than expected after taking all other variables in equation (1) into account. The points from these steels are shown in Fig.5 and it would seem likely that these higher ITT's are probably due to their higher gbc density (15 carbides per mm compared to 5 carbides per mm). It should be noted that as well as having higher gbc density these steels also exhibit thicker gbc's (Ref.3). It is reasonable that Nb and Ti actively encourage both precipitation of gbc as well as their growth.

Of the two factors - gbc thickness and gbc density, the effect of carbide thickness on ITT would appear to be dominant. Whereas an increase in carbide thickness can produce a 60°C rise in ITT, Fig. 4, increasing carbide density within the normal range encountered gives only a 20-30°C rise in ITT, for both pearlite free and pearlite containing steels.

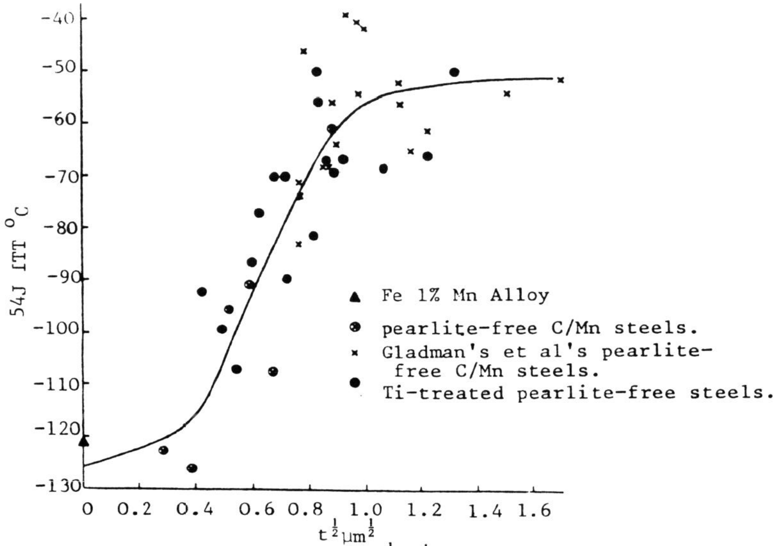


Fig.4 Curve of 54J^{o}C vt$^{\frac{1}{2}}\mu m^{\frac{1}{2}}$ for pearlite-free steels. After Mintz et al (3)

Influence of Nd* on the ITT of Pearlite Containing and Pearlite Free Steels

The probability of finding a carbide at a grain boundary Nd* can be high, and up to 1 in 2 has been recorded for the ferritic stainless steel. For the ferrite/pearlite steels the chances of finding a carbide at a grain boundary varied between 1 in 20 to 1 in 5.

As with N increasing Nd* also increases the ITT (Figs. 6 and 8). It is not however possible to separate the individual influence of the N and Nd* parameters on ITT. Although the effect of increasing carbide density on raising the ITT is understood it is not clear why increasing the probability of finding a carbide at a grain boundary should have a similar effect. The quantity Nd* (note also the effect of grain size on ITT will already have been taken account of in the regression equation as $d^{-\frac{1}{2}}$) might only be expected to be important if it influences the ability of a crack to cross a grain boundary. It could be imagined that if a carbide cracks and the crack propagates to the other side of the grain, its propagation over the boundary into the next grain will be easier if there is another brittle or low energy adhesion gbc situated at this grain boundary directly in front of the crack path. Grain boundaries are likely to be obstacles to crack propagation only when the carbides are relatively coarse which is not generally the case in the steels examined. The importance of the term Nd* may be a consequence of the Charpy test itself where an energy criterion is used rather than a fracture stress criterion, and part of the energy recorded is related to the crack propagating through the sample.

Although it can be inferred from this work that both carbide thickness and density are significant factors in determing the ITT, metallographic examination on broken Charpy samples to confirm these observations has

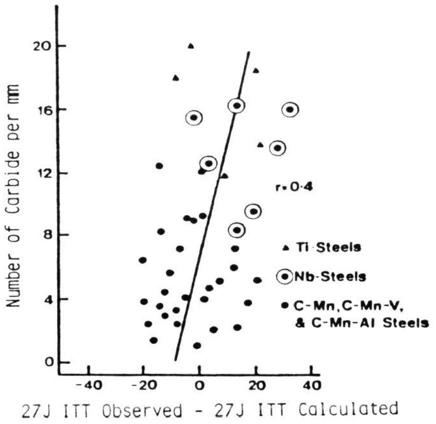


Fig. 5

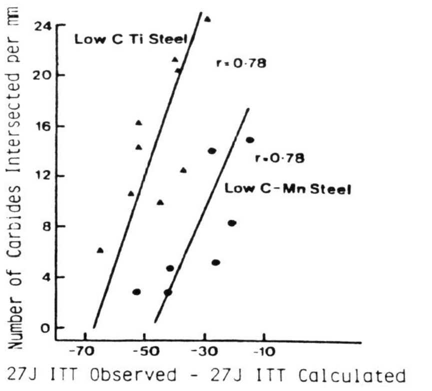


Fig. 7

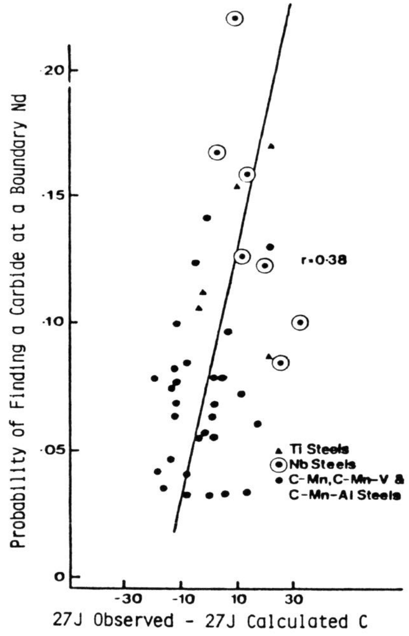


Fig. 6

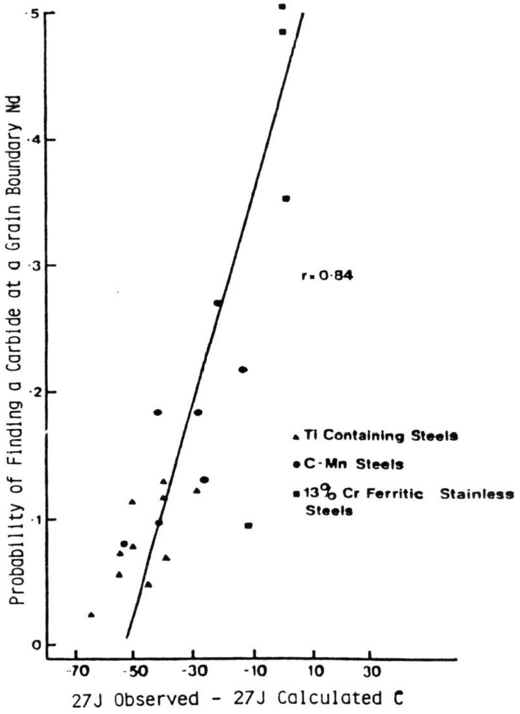
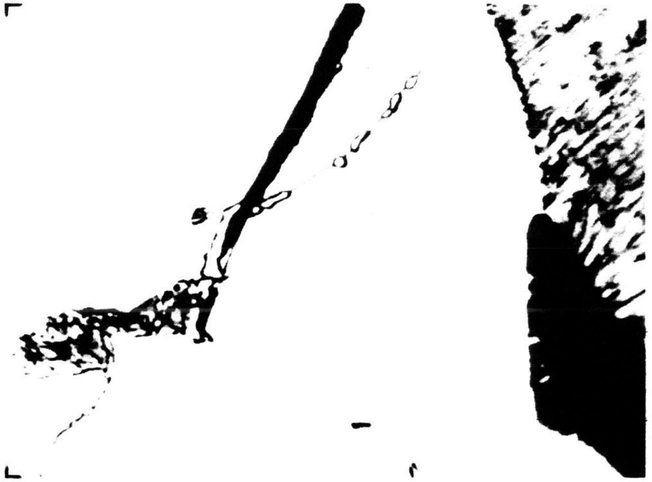


Fig. 8

proved difficult. Many examples of cracks going through carbide particles can be found, e.g. Fig.9, but rarely can their source be unambiguously traced to the carbide particles. This is an area for further work.



x 3,200

Fig.9 Example of a microcrack associated with a grain boundary carbide.

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