THE EFFECT OF CARBON ON THE CHARPY V-NOTCH DUCTILE-BRITTLE TRANSITION CURVE

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ABSTRACT

The literature on the microstructures and Charpy V-notch ductile-brittle transition curves for normalized or annealed irons and plain carbon steels have been reviewed. Up to about 0.10 wt.% carbon the microstructure has grain and sub-grain structures with a grain boundary carbide and, towards the top of the range, some limited pearlite. From about 0.10 wt.% to about 4.5 wt.% the microstructure consists of pearlite colonies in a matrix of ferrite. From about 4.5 wt.% carbon to the eutectoid composition (0.80 wt.% carbon) the microstructure consists of grain boundary proeutectoid ferrite and pearlite in the rest of each grain. Each type of microstructure leads to a distinguishable type of ductile-brittle transition behavior.

A phenomenological model of the transition has been developed in which the Charpy V-notch impact energy is expressed as a function of carbon content and temperature. This model has been shown to describe the main features of the transition but has yet to be fully tested.

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INTRODUCTION

A summary of the history of impact testing has been published by Siewert, Manahan, McCowan, et al.[1]. They have shown that by the middle of the nineteenth century it was realized that the results of tensile tests on a steel could not be used to predict how that steel would perform in service where it was subjected to impacts. In 1857 Rodman devised a drop-weight machine to test for impact properties. Later, in 1892, LeChatalier realized the importance of using notched specimens.

The first pendulum hammer machine was developed in 1898 by Russell [2] and its design was improved by subsequent work of Charpy and others. Charpy became Chairman of a Commission of the International Association for Testing Materials which promoted the use of the design developed by Charpy [3,4]. Starting in 1923, the American Society for Testing and Materials developed an interest in pendulum hammer testing and this led, in 1933, to a tentative ASTM standard designated E23-33T[5]. There has been an ASTM standard relating to Charpy V-notch impact testing since that date.

Although there is a vast literature in which the results of Charpy V-notch tests carried out on irons and steels have been reported, we are still a long way from understanding fully what determines the shape of the impact energy versus temperature curve and its variation with factors such as composition, grain size, heat treatment and mechanical treatment. Also, there is no agreed definition of the term "ductile-brittle transition temperature". Sometimes it is defined as the temperature below which the metal is completely brittle, sometimes as the temperature below which more than half of the fracture surface appears to exhibit cleavage, and sometimes the temperature at which the impact energy is one half of the sum of the impact energy for a fully ductile specimen (upper shelf energy) and for a fully brittle specimen (lower shelf energy).

Many of the more important results on Charpy V-notch testing have been brought together in Vol. 1 of the ASM Metals Handbook [6]. Included in the ASM review is the work of Petch [7] who showed that the fracture appearance transition temperature decreases linearly with $\log_e d^{-1/2}$, where d is the grain diameter. Work of Burns and Pickering [8] shows that increasing the carbon content raises the ductile-brittle transition temperature, as defined by the transition to complete brittleness, stretches out the transition and reduces the upper shelf energy. Their results are shown, redrawn, in Figure (1).

In this paper all of the results from the literature are presented only in Joules, for impact energy, and °C, for temperature. The results shown in Figure (1) are for irons and steels in the normalized condition.

The ASM review also includes material on the effects of manganese, aluminum, nickel, niobium, sulfur and oxygen on the ductile-brittle transition temperature. Results on the effects of microstructure show that tempered martensite gives the lowest transition temperature, pearlite the highest, and bainite a transition temperature between those two. There are also results on the effects of normalizing temperature, tempering temperature and aging temperature. At present we are lacking a unifying theoretical treatment which correlates all of these results. Indeed, the construction of a theoretical framework to explain and model all of these results presents a formidable prospect and success in the immediate future does not seem likely.

In this paper we make a modest attempt to look at the simplest aspect of this problem we could find. We have chosen to examine the Charpy V-notch transition curves for normalized irons and steels containing just manganese, carbon and silicon. We will use the results of Burns and Pickering [8] even though the impact energy vs. temperature curves were presented without the experimental points on which they are based. We made this choice for two reasons. First, these results are part of a study which was detailed and thorough. Secondly, there is a second set of results obtained by Rinebolt and Harris [9] which agree well with those of Burns and Pickering. Thus, we are inclined to trust the Burns and Pickering work even in the absence of their experimental points. We have supplemented their work with the results of Allen, Rees, et al. [10] who have worked on very low carbon materials.

THE ROLE OF PEARLITE

The change in shape of the Charpy V-notch transition curve with carbon content must obviously be related to the changes in microstructure which occur in normalized irons and steels as the carbon contents change. These microstructures have been thoroughly documented in L. E. Samuels' book "Light microscopy of carbon steels" [11]. Figure (2a) shows schematically the microstructure of iron with 0.0026 wt.% carbon. It shows the grain structure but also a pronounced sub-grain structure made up of arrays of individual dislocations which at this magnification (X250) are not resolved. The microstructure also contains randomly distributed dislocations which, for clarity, are not shown. We propose calling this a “Type I" microstructure.

Figure (2b) shows a steel with 0.25 wt.% carbon at a magnification of X100. The light phase is ferrite and the dark areas the unresolved phase mixture pearlite. Note that the pearlite is in the form of islands in the ferrite. We shall call this a “Type II” microstructure. Finally, Figure (2c) shows a steel with 0.6 wt.% carbon at a magnification of X100. The ferrite is now the light colored phase at the grain boundaries and the dark areas making up the rest of each grain are pearlite. Figures (2a), (2b) and (2c) are all based on actual micrographs in Samuels’ book. We might reasonably expect that Types I, II and III microstructures will all have their own characteristic Charpy V-notch transition features.

To explore the significance of the transition from Type II to Type III microstructures a topographic map was constructed showing the variation of Charpy energy with carbon content and temperature. This is presented in Figure (3). It clearly shows that there are two surfaces, one for Type II and one for Type III. The break occurs at a carbon content of about 0.45 wt.% carbon.

In Figure (1) the curve for 0.8 wt.% carbon represents the behavior of a steel with 100% pearlite since 0.8 wt.% is the eutectoid composition. To be able to continue with our analysis we have to make two assumptions. These are:

(I) The impact energy for a given composition at a given temperature is made up of a contribution from pearlite and a contribution from ferrite.

(ii) For a composition C wt.% carbon the pearlite contribution is C/C_e times the contribution at the same temperature of a steel with the eutectoid composition C_e.

No proof is offered for either of these propositions. They are offered only for purposes of exploring their consequences.

THE UPPER SHELF ENERGY

The ferrite component of the upper shelf energy was calculated for each of the compositions shown in Figure (1) and these were plotted against carbon content (Figure 4a). Curve fitting showed that the ferrite impact energy varies linearly with the inverse square root of the carbon content

(Figure 4b) for Type II and Type III microstructures. The one point off the line is for the only Type I microstructure material in Figure (1). We may write the relationship between the carbon content, C, and ferrite impact energy, E_F, as

$$C^{-\frac{1}{2}} = C_0 + KE_F$$

Since the ferrite energy, E_F is zero when $C = C_e$, i.e. at the eutectoid composition, where we have 100% pearlite and no ferrite, we obtain $C_0 = C_e^{-1/2}$ and

$$E_F = \frac{1}{K}\left(C^{-\frac{1}{2}} - C_e^{-\frac{1}{2}}\right)$$

THE PEARLITE TRANSITION CURVE

Next, let us attempt to set up an equation to represent the contribution of pearlite to the impact energy for any carbon content and temperature. Let us deal first with the case of the eutectoid composition. We have a lower shelf energy, E_{0P}, at low temperatures and then a gradual transition to the upper shelf energy, E_{SP}, at higher temperatures. We need a function to represent the transition and we can use the simple expression

$$E_P = E_{OP} + E_{SP}\exp\left(-\frac{\lambda_P}{T - T_{OP}}\right)$$

where λ is a constant which determines the width of the transition and T_{0P} is the temperature at which the transition begins. For a composition other than C_e, this becomes

$$E_P = \frac{C}{C_e}\left[E_{OP} + E_{SP}\exp\left(-\frac{\lambda_P}{T - T_{OP}}\right)\right]$$

For equation (3) to fit the curve for 0.8 wt.% carbon in Figure (1) we have to have $E_{SP} \simeq 4.5$ Joules, $T_0 \simeq 10°C$ and $\lambda \simeq 60$.

THE FERRITE TRANSITION CURVE

The contribution of the ferrite to the impact energy as a function of temperature was calculated for each composition shown in Figure (1). This was accomplished by subtracting the pearlite contributions calculated using equation (4). In Figure (5) the full lines show the resulting curves for 0.20, 0.31 and 0.41 wt.% carbon. It was then assumed that the ductile to brittle transitions can be represented by an equation similar to equation (4), i.e. by

$$E_F = E_{OF} + E_{SF} \exp\left(- \frac{\lambda_F}{T - T_{OF}} \right)$$

where E_{0F} and E_{SF} are the lower and upper shelf energies for ferrite. Working with just a pocket calculator, values of λ_F, T_0 and E_{SF} were found which gave reasonable agreement with the results derived from Figure (1). The curves derived in this manner are shown as dashed lines in Figure (5). The values of λ_F, T_0 and E_{SF} used in obtaining the fits are shown in Table I.

RESULTS ON VERY LOW CARBON IRONS

Only one composition in the work of Burns and Pickering (Figure 1) lies in the range of Type I microstructures. The work of Allen, Rees, et al., however, included work on material with a carbon content as low as 0.05 wt.% [10]. Figure (6) shows some of their results redrawn to show impact energies in joules. These transition curves are significantly different to those for higher carbon contents. The transition to the upper shelf energy is sharp and, on the lower side of the transition, there is a large "tail". This tail can most likely be explained as due to the sub-structure made up of dislocations locked in place by carbon atoms. The locking is probably strong enough to inhibit dislocation movement and thus hinder the formation of the pile-ups needed to generate microcracks. Cottrell [12] has discussed the role of cooling rate in influencing dislocation locking and we see a pronounced effect of cooling rate in the results shown in Figure (6).

AN EQUATION DESCRIBING THE DUCTILE-BRITTLE TRANSITION

We now have equations describing the separate contributions of pearlite and ferrite to the Charpy impact energy. We are ready to put them together to get a phenomenological description of the Charpy V-notch transition curve but we have to resolve a small problem relating to the lower shelf energy. The lower shelf energy for the pearlite is the energy to fracture pearlite at low temperatures while the lower shelf energy for ferrite is the energy to fracture ferrite at low temperatures. At the eutectoid composition the correct lower shelf energy is that for pearlite. Where the carbon concentration is small the correct lower shelf energy is close to that for ferrite. In between it varies continuously from one to the other as the carbon content increases. In practice both are small and we do not have exact values for either. We will therefore use one value for all compositions and call it E_0.

The final equation describing the Charpy V-notch ductile-brittle transition becomes:

$$E = E_0 + \frac{C E_{SP}}{C_e} \exp\left(- \frac{\lambda_P}{T - T_{OP}} \right) + \frac{1}{K} \left(C^{-\frac{1}{2}} - C_e^{-\frac{1}{2}} \right) \exp\left(- \frac{\lambda_F}{T - T_{OF}} \right)$$

This equation should be capable of generating a complete set of Charpy V-notch impact curves. Since this project is a work in progress we expect to explore the validity of this equation by computer generating curves in the near future.

SUMMARY

The literature on the microstructure of normalized or slowly cooled irons and steels containing up to 0.80 wt.% carbon has been reviewed as has the literature on the Charpy V-notch ductile-brittle transition curves of the same materials. The purpose of this work was to try to grain a deeper understanding of the Charpy curves and to attempt a phenomenological model of the ductile-brittle transition.

With increasing carbon content, three types of microstructure are observed. Type I occurs with carbon contents up to about 0.10 wt.%. It exhibits grain and subgrain structures, grain boundary carbide and some limited pearlite colonies in the higher carbon part of the range. The Charpy curve has a sharp knee at the low temperature end of the upper shelf and a substantial tail before the lower shelf is reached.

Type II microstructure occurs with carbon contents in the range 0.10 to about 0.45 wt.% carbon. This microstructure consists of pearlite colonies in a ferrite matrix. The upper shelf energy falls off with increasing carbon content and the transition occurs over wider temperature ranges. Type III microstructure consists of grain boundary proeutectoid ferrite with the rest of each grain consisting of pearlite. The upper shelf energy continues to decrease with increasing carbon content and the transition continues to be more spread out. The dependence of Charpy energy on carbon content and temperature changes abruptly on going from Type II to Type III.

An equation has been developed to describe phenomenologically how the Charpy energy depends on carbon content and temperature for types II and III behavior. It is as follows:

$$E = E_0 + \frac{CE_{SP}}{C_e} \exp\left(- \frac{\lambda_P}{T - T_{OP}} \right) + \frac{1}{K}\left(C^{-\frac{1}{2}} - C_e^{-\frac{1}{2}} \right) \exp\left(- \frac{\lambda_F}{T - T_{OF}} \right)$$

where E = Charpy impact energy

E_0 = lower shelf energy

C = carbon content in wt.%

C_e = eutectoid composition in wt.%

λ_P = transition width parameter for pearlite

T = temperature in °C

T_{0P} = temperature above which the transition occurs in pearlite

K = constant in the relationship between carbon content and upper shelf energy

λ_F = transition width parameter for ferrite

T_{0F} = temperature above which the transition occurs in ferrite

To obtain the best fit, separate values of T_{0P} and λ_F will have to be developed for Types II and III behavior.

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Table 1 - Values of λ_F, T_0 and E_F used in fitting theoretical curves to experimentally derived results.

wt.% carbon	λ_F	T_0	E_F
0.20	10	-25°C	160
0.31	35	-40°C	95
0.41	30	0°C	75

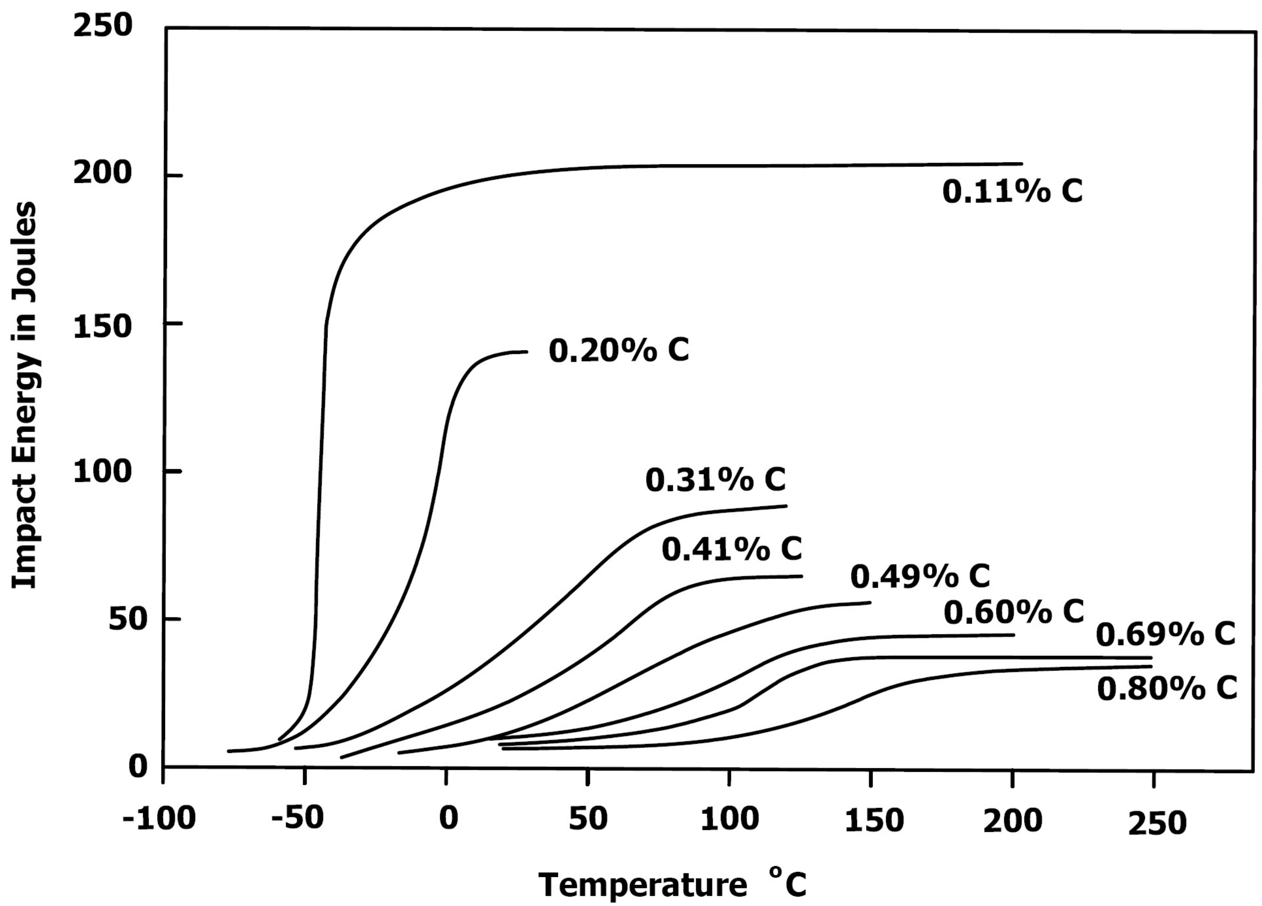

Figure (1) - The Charpy V-notch ductile-brittle transition curves for several normalized irons and steels (redrawn from Rinebolt and Harris [9]).

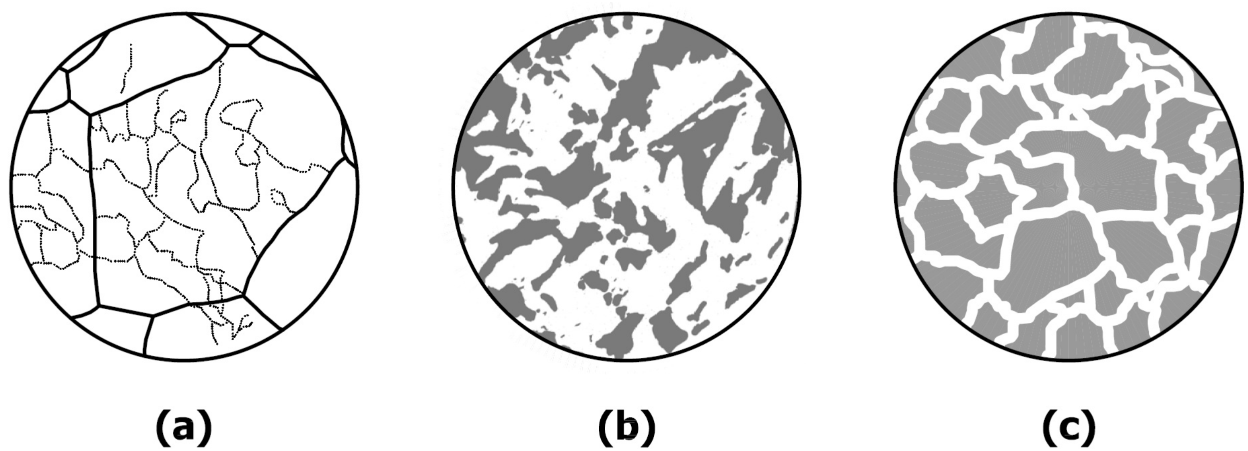

Figure (2) - The microstructures of (a) a high purity iron with 0.0026 wt.% carbon (X250), (b) an annealed 0.25 wt.% carbon steel (X100), and © an annealed 0.60 wt.% carbon steel (X100). (Based on microstructures reported in Samuels [11].)

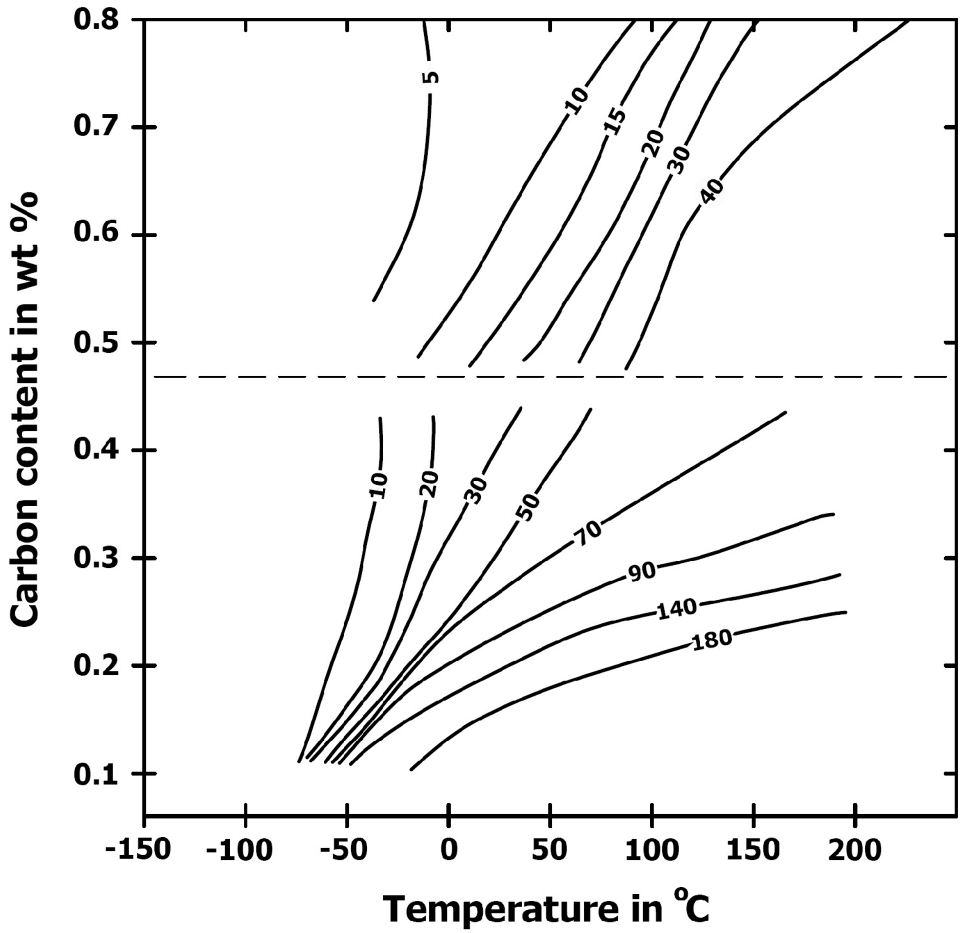

Figure (3) - The dependence of the Charpy V-notch impact energy of irons and plain carbon steels on carbon content and temperature.

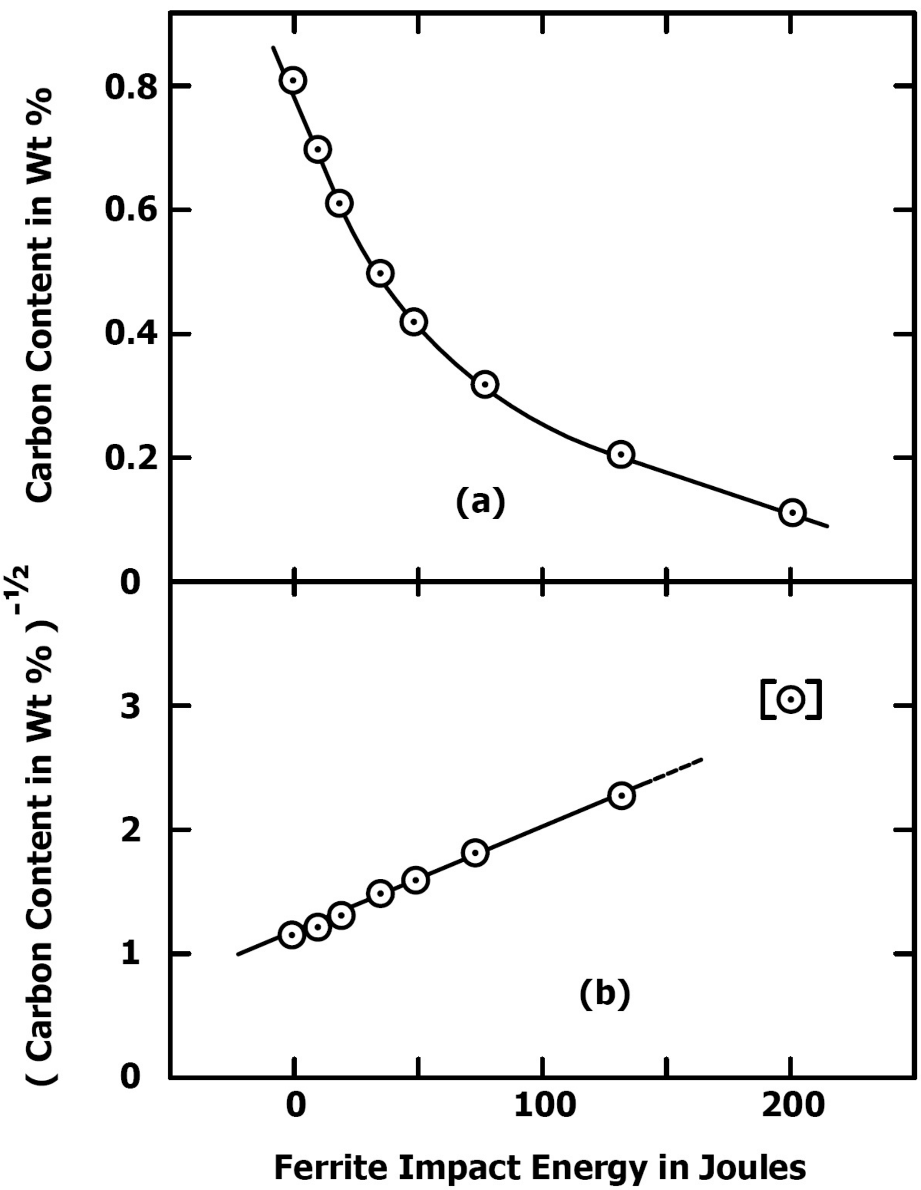

Figure (4) - (a) The effect of carbon content on the ferrite component of the upper shelf energy, and (b) The functional relationship between carbon content and ferrite shelf energy.

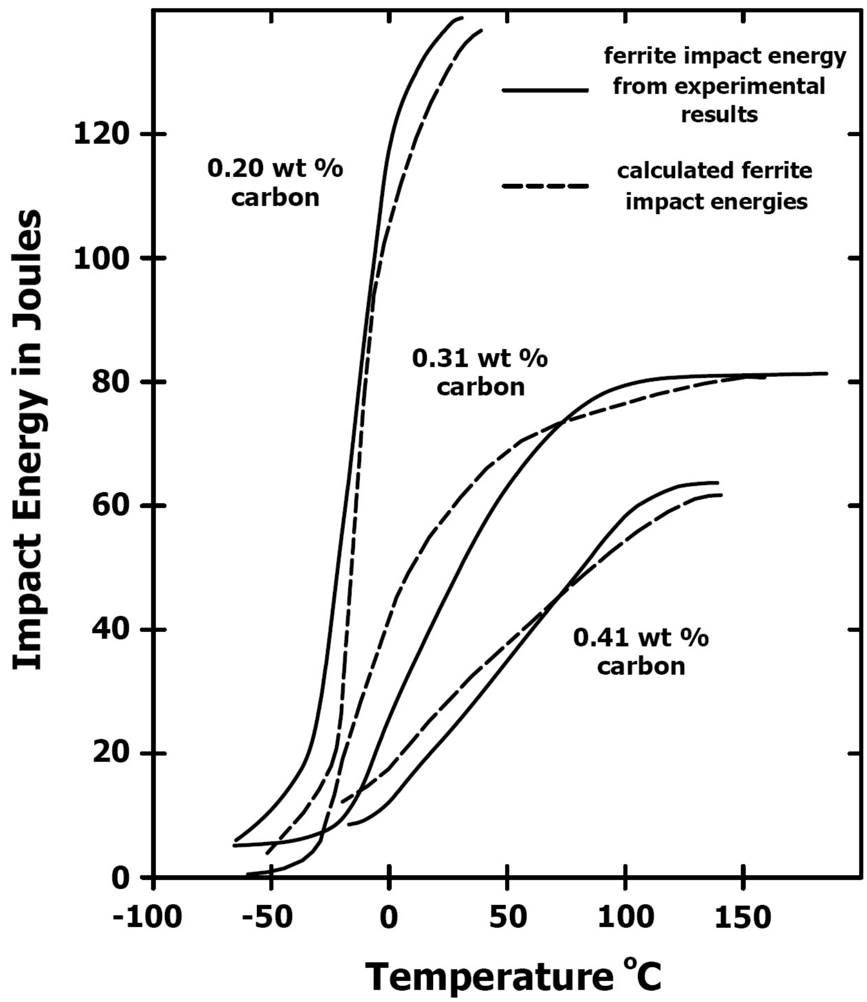

Figure (5) - Ferrite impact energies derived from experimental results (full line) and from equation (5) (dashed line).

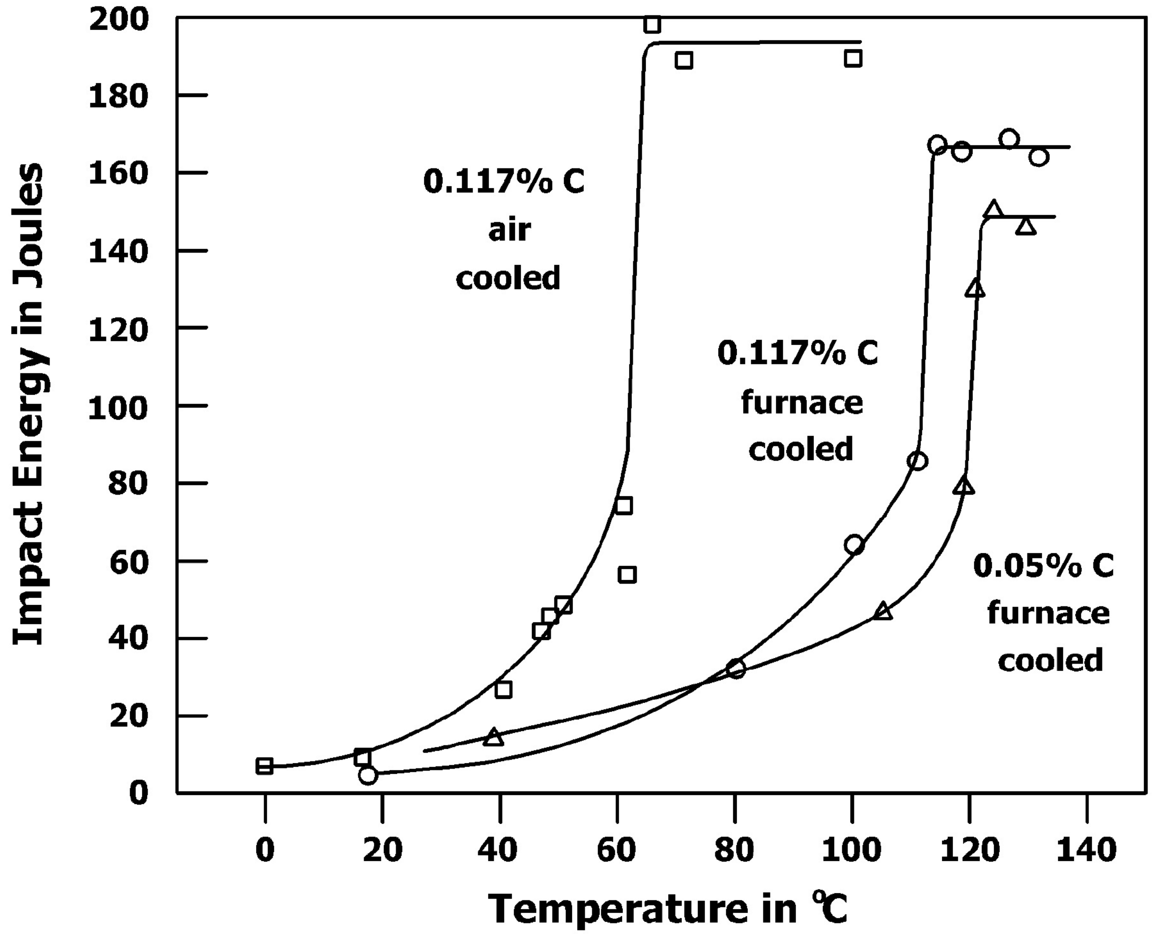

Figure (6) - Charpy V-notch ductile-brittle transition curves for low carbon irons. (Redrawn from Allen, Rees, et al. [10].)