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The correlation of ultrasonic attenuation, microstructure and ductile to brittle transition temperature in very low carbon steels

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A study of the frequency dependence of the ultrasonic attenuation and the ductile to brittle transition temperature as a function of microstructure has been carried out for a very low carbon (0.02 wt%) steel. The ultrasonic attenuation was found to be anomalously high when compared to normal low carbon (0.2 wt%) steels and could not be interpreted in terms of simple scattering models. This is thought to be due partly to large hysteresis losses (dislocation and magnetic domain-wall damping) and partly to large grain-size distributions. An empirical correlation between the ductile to brittle transition temperature and an ultrasonic attenutation parameter has been found for this particular steel.

1. Introduction

Some of the mechanical properties of metals show a distinct dependence on microstructural features such as mean grain diameter. It is well known [1] that for frequencies above a few MHz the attenuation of ultrasonic waves in polycrystalline metals and alloys is also mainly determined by the grain structure. Accordingly, attempts have been made to relate ultrasonic attenuation parameters directly with properties of engineering interest. If such a non-destructive technique can be reliably established it will become possible to carry out cheaper, quicker and more comprehensive assessment of both material quality and structural integrity.

Work along these lines has been described previously, [2, 3]. More recently [4] the frequency dependence of the attenuation in the 2 to 10 MHz range has been used to derive a mean grain size, d, for each of 46 different plain carbon steels. These grain sizes were then correlated with mechanical properties by the use of the Hall–Petch relationship.

$$\mu = \mu_0 + kd^{-1/2}, \qquad (1)$$

where μ is the value of the mechanical property of interest, μ_0 is a constant dependent on the composition, and k is a proportionality constant.

It was concluded that ultrasonic attenuation between 1 and 12 MHz could be used in combination with chemical analysis to predict yield strength, tensile strength and ductile to brittle transition temperature with a useful degree of precision.

A different approach was adopted by Vary [3], who took an empirical ultrasonic attenuation parameter based on high-frequency (20 to 50 MHz) data and correlated this with the measured fracture toughness. Good agreement was found for two grades of maraging steels and a titanium alloy. A heuristic theoretical basis for this correlation has been proposed [5].

The present work has been confined to samples of a very low carbon steel in which the only microstructural variable was the ferritic grain size. Correlation has been sought with the ductile–brittle transition temperature (DBTT) as measured by tests on sets of Charpy impact specimens.

TABLE I The raw material (M1 steel, 0.02 wt% C and 34 ppm O_2)

Billet	Forged at 1200° C to (mm)	Cold–rolled to (mm)	% reduction
M1/3	78	47	63
M1/5	68	47	43
M1/7	52	47	16

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TABLE II Heat treatment of the specimens

Specimen	Heat treatments (in vacuum)	
	Temperature (° C)	Time (h)
M1/3/1	700	1
M1/3/2	700	72
M1/5/1	700	96
M1/5/2	700	120
M1/7/1	700	24
M1/7/2	700	72

2. The specimens

The very low carbon (0.02 wt %) steel was produced from electrolytic iron, containing 34 ppm O_2, which was in the form of a 150 kg ingot and labelled M1. This ingot was sectioned into three billets (152 mm x 152 mm x 178 mm) labelled M1/3, M1/5 and M1/7. These billets were then forged and cold-rolled to produce uniform bars of 47 mm diameter (Table I). Each bar was then sectioned into two sets of discs (2 mm and 4 mm in thickness for the attenuation measurements) and Charpy specimens (for the transition temperature measurements) and then heat treated in vacuum to produce various microstructures (Table II).

After the ultrasonic attenuation measurements had been made, each disc was sectioned and micrographs taken. Similarly, after the transition temperature measurements had been made the Charpy specimen which had been tested at room temperature was sectioned and micrographed.

3. Experimental procedure and results

The method and results of the ultrasonic attenuation measurements have been reported previously [6]. Figs 1 to 6 summarize the attenuation results for each sample and three significant features should be noted. Firstly, the attenuation is very high (1 to 2 dB mm^{-1} at 20 MHz) compared to normal steels which are usually an order of magnitude less. Secondly, the rate of increase of the attenuation with frequency is low. Thirdly, in two cases (M1/3/1 and M1/5/1) there is a notable difference in attenuation between the two disc specimens.

The ductile to brittle transition temperature (DBTT) was measured using the standard Charpy impact test. The results of these tests are shown in Fig. 7. It can be seen that the DBTT varies systematically across the series of specimens with the exception of M1/3/2 which shows an

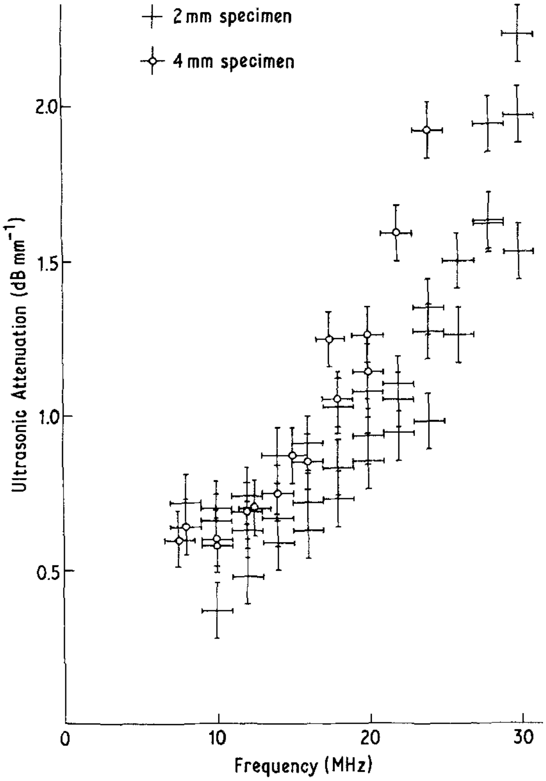


Figure 1 The frequency dependence of the ultrasonic attenuation in M1/3/1.

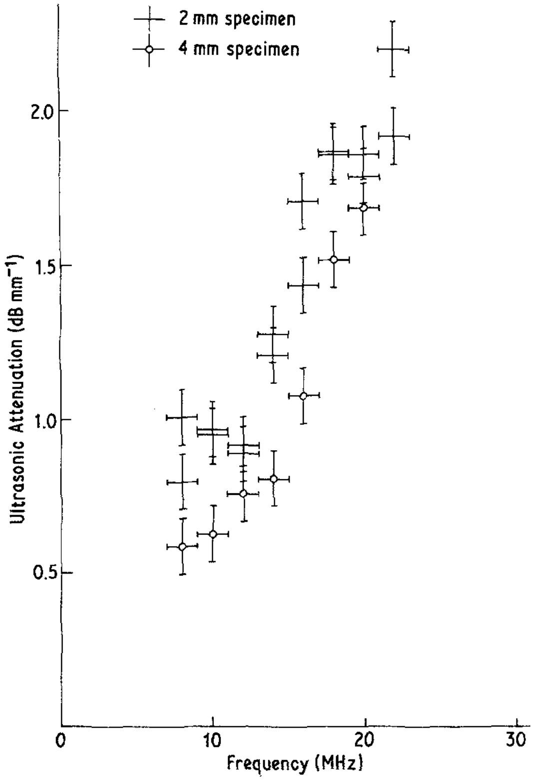


Figure 2 The frequency dependence of the ultrasonic attenuation in M1/3/2.

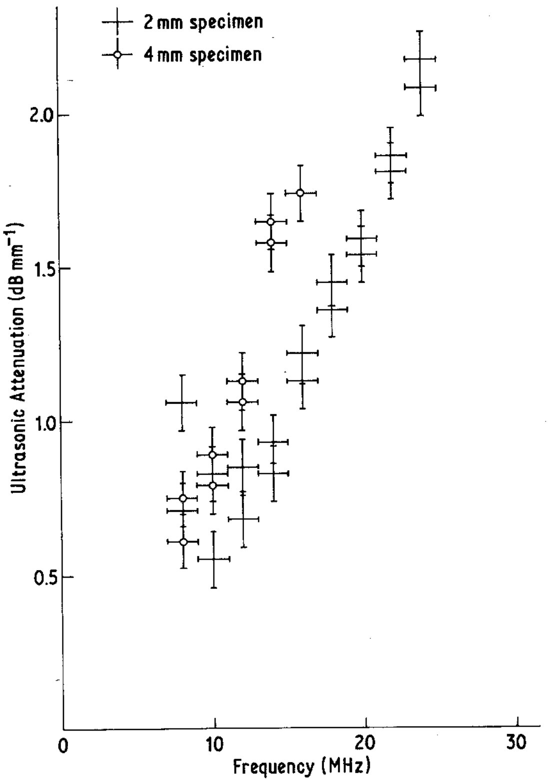


Figure 3 The frequency dependence of the ultrasonic attenuation in M1/5/1.

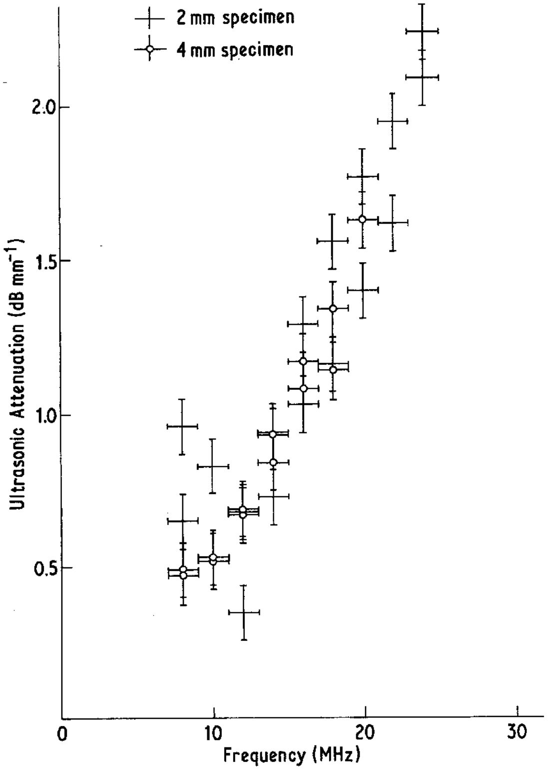


Figure 4 The frequency dependence of the ultrasonic attenuation in M1/5/2.

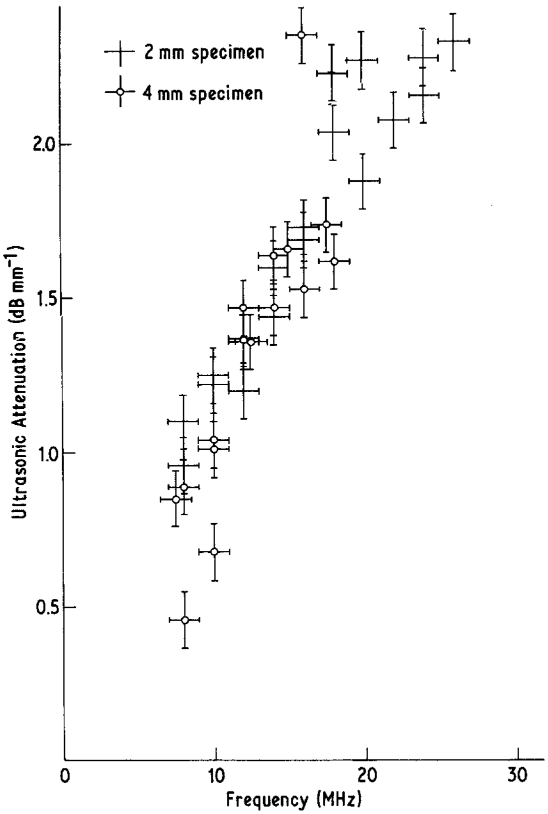


Figure 5 The frequency dependence of the ultrasonic attenuation in M1/7/1.

anomalously high value. The transition temperature was measured using the average energy criterion T_{av}, i.e., at the mean of the energy needed to fracture a completely ductile specimen and that needed to fracture a complete brittle specimen. The values obtained for the transition temperatures are given in Table III.

From the section micrographs taken, it was found that the mean grain sizes obtained from the ultrasonic tests-pieces used previously [6] were not completely typical of the impact test specimens although the important observation, that there was a large grain-size distribution present in all the

TABLE III The ductile to brittle transition temperature

Specimen	Ductile to brittle transition temperature, T_{av} (° C)
M1/3/1	26
M1/3/2	50
M1/5/1	32
M1/5/2	34
M1/7/1	41
M1/7/2	44

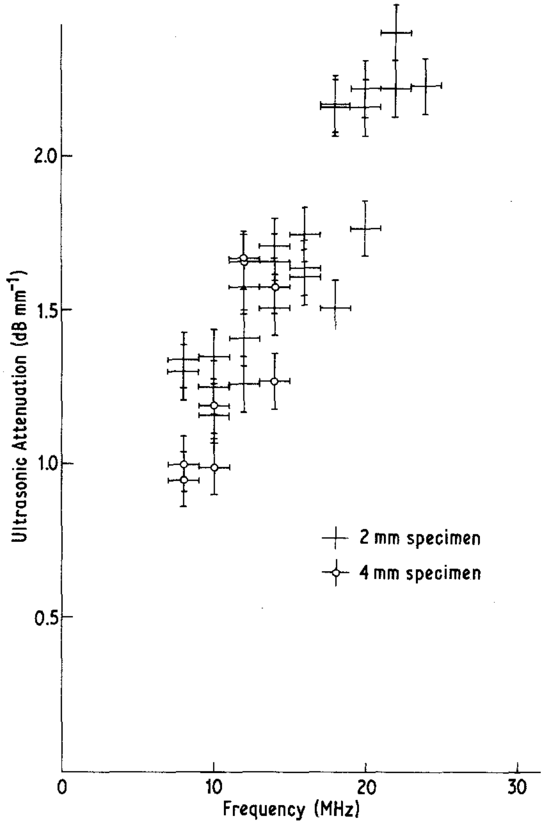


Figure 6 The frequency dependence of the ultrasonic attenuation in M1/7/2.

TABLE IV Mean grain sizes from line intercept method

Specimen	Mean grain size (μm)		
	2 mm disc	4 mm disc	Charpy
M1/3/1	28	44	29
M1/3/2	50	53	50
M1/5/1	58	79	52
M1/5/2	51	57	55
M1/7/1	94	98	80
M1/7/2	98	96	101

specimens, was confirmed. Fig. 8 shows the section micrographs that were taken for the M1/5/1 specimens. Mean grain sizes were obtained using the line intercept method for each specimen and they are given in Table IV. These values give only a rough guide to the microstructure of each specimen but clearly illustrate that there was a significant difference in the microstructure of the two discs used for the attenuation measurements on the materials M1/3/1 and M1/5/1 (Fig. 8). These differences were apparent from the ultrasonic attenuation measurements (Figs 1 and 3). In all cases the microstructure of the Charpy specimens correlates well with those of the 2 mm thick discs that were used for the attenuation measurements.

Comparative ultrasonic attenuation measurements were made on the Charpy specimens but

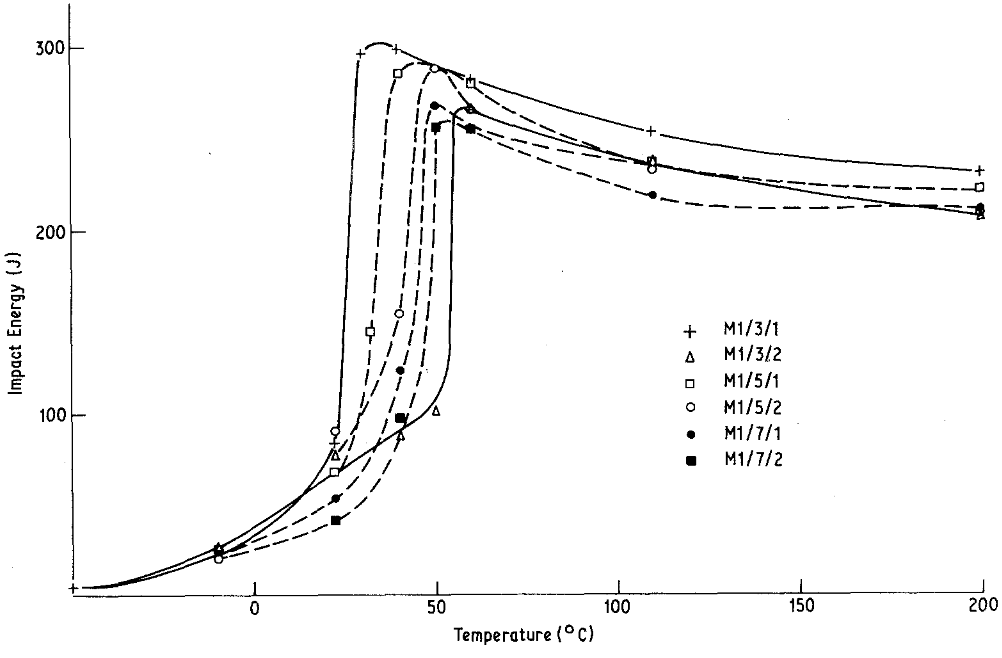
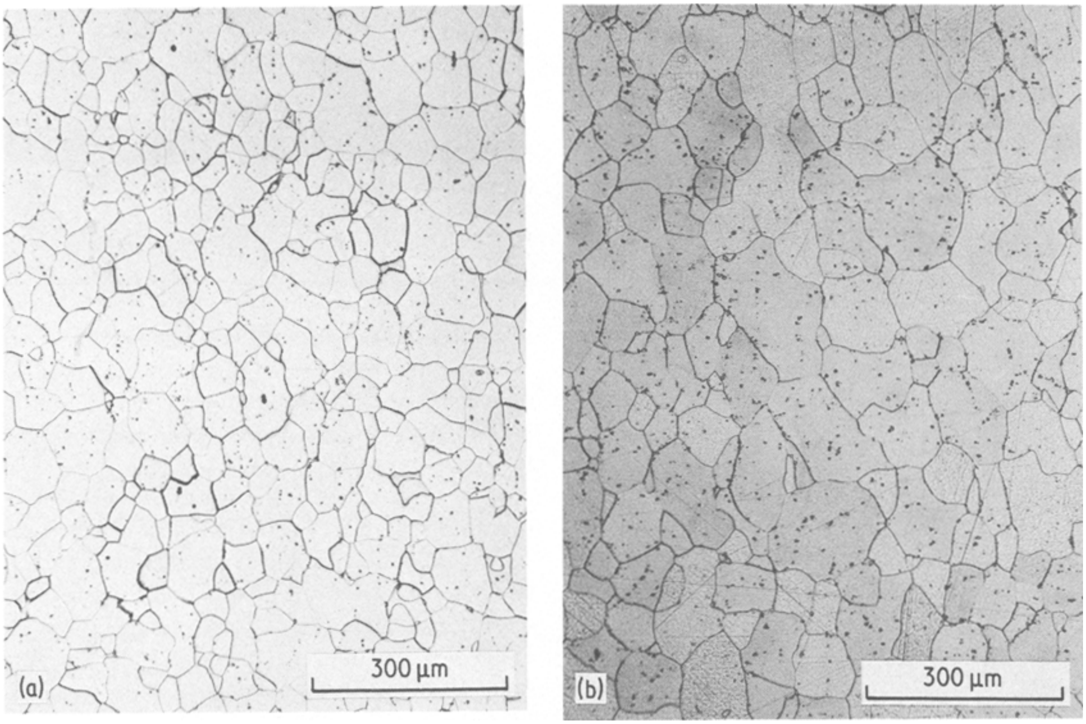


Figure 7 The ductile to brittle transition temperatures.



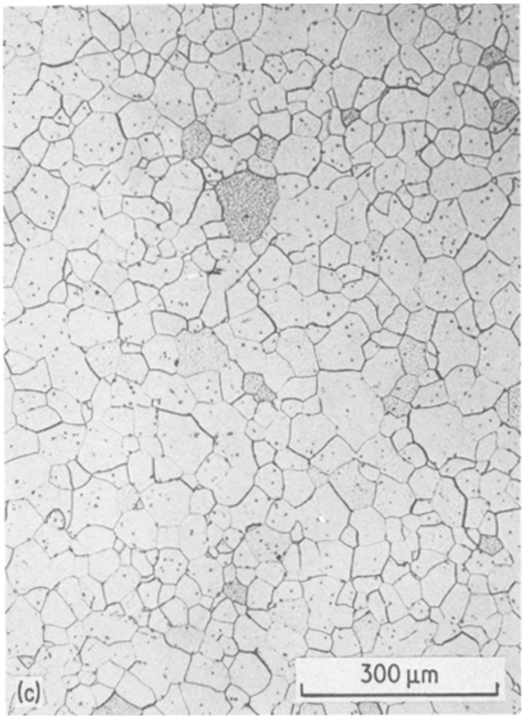


Figure 8 Micrographs of Specimen M1/5/1: (a) 2 mm disc, (b) 4 mm disc and (c) Charpy specimen.

absolute measurements were not possible because of the unsuitable geometry. These measurements produced an anomalous result for specimen M1/3/2, giving an attenuation of the order of 1 dB mm^{-1} at 7.5 MHz which was more than double that found in any of the other specimens at this frequency. Examination of the micrographs gave no indication of the cause of the very high attenuation but the material M1/3/2 did also give an anomalous DBTT (Fig. 7).

4. Discussion

The ultrasonic attenuation in the very low carbon steels studied here cannot be interpreted using only a simple grain scattering model (e.g. Rayleigh, stochastic and/or diffuse scattering) because of the wide grain-size distribution in the specimens. This can be shown in itself to alter the frequency dependence of the ultrasonic attenuation [7]. The high absolute values of the attenuation in these samples would indicate that the hysteresis losses, which are always present but usually assumed to be small compared to the grain scattering, are a major contribution to the total attenuation. The two most likely sources of hysteresis loss are dislocation damping and magnetic domain wall damping. It has been shown [8] that the ultrasonic attenuation in these specimens can be reduced by approximately 10% by magnetic saturation. The contribution of dislocation damping

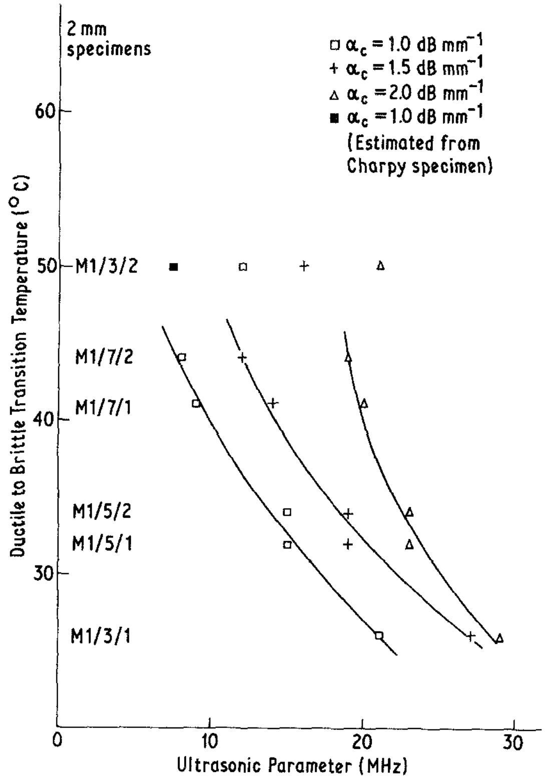


Figure 9 Correlation of the DBTT with the ultrasonic attenuation parameter.

is difficult to estimate but large dislocation loop lengths could exist in these materials with few pinning centres such as carbon inclusions.

For these reasons both the ultrasonic attenuation and the DBTT can be seen to vary in general with the mean grain size but interpretation in terms of the Hall–Petch relations as used in [4] is not possible and only a rough correlation is found if the DBTT is plotted against the ultrasonic attenuation at a particular frequency. Following the ideas in [3] however, and using the attenuation measurements from the 2 mm dics only, a graph such as Fig. 9 can be constructed, in which the DBTT is plotted against the frequencies at which the attenuation attains successively critical values, α_c, of 1, 1.5 and 2 dB mm^{-1}. These values are arbitrary and have been chosen merely for the convenient availability of data. The significance of such a parameter is that it depends not only on the mean grain size but also on the grain-size distribution and the hysteresis losses. It can be seen that there is a reasonable correlation between the DBTT and each value of α_c, the ultrasonic attenuation parameter, with the exception of specimen M1/3/2, in which as already noted the Charpy specimens showed exceptionally high values of both DBTT and ultrasonic attenuation. It is therefore suggested that the value of the attenuation determined from the disc specimens does not relate to the Charpy specimen.

As shown in Fig. 9, if the DBTT is plotted against the estimated critical attenuation frequency for the impact specimen the correlation is no longer inconsistent with that suggested by all the other specimens.

5. Conclusions

It has been shown that both the ultrasonic attenuation and ductile to brittle transition temperature can be varied systematically by altering the microstructure in a series of very low carbon steels. The microstructure variation used was the ferrite grain size which changed both in its mean value and its distribution. A simple model relating the ultrasonic attenuation to the microstructure and DBTT to the microstructure could not therefore be used. However, an empirical correlation between the DBTT and an ultrasonic attenuation parameter has been found for these steels.

This parametric relationship can be expressed conveniently as follows:

(a) The lower the frequency, α_c, at which a convenient attenuation (about 1.5 dB mm^{-1}) is reached, the higher the ductile to brittle transition temperature.

(b) The higher the frequency at which α_c is reached, the lower the general level of attenuation.

(c) The lower the general attenuation, the smaller the mean grain size or the maximum grain size.

Thus, our results suggest the following general relationship for these materials:

(i) The higher the overall attenuation, the higher the ductile to brittle transition temperature and the more brittle the material at room temperature.

(ii) Apart from grain-size effects, increasing attenuation and brittleness can arise from a hysteresis mechanism perhaps associated with dislocations.

The association of increasing grain size with higher DBTT is consistent with previous results [4] and has the implication that larger grains lead to embrittlement at room temperature as implied by the Hall–Petch relationship. However, the effects of variations in the grain-size distribution cannot yet be quantified in terms of the rather complex processes involved in the fracture of low carbon steels, which have recently been discussed [9].

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