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THE FEASIBILITY OF RANKING MATERIAL FRACTURE TOUGHNESS BY ULTRASONIC ATTENUATION MEASUREMENTS

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ABSTRACT

A preliminary study was conducted to assess the feasibility of ultrasonically ranking material fracture toughness. Specimens of two grades of maraging steel for which fracture toughness values were measured were subjected to ultrasonic probing. The slope of the attenuation coefficient versus frequency curve was empirically correlated with the plane strain fracture toughness value for each grade of steel.

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SUMMARY

It is proposed that purely ultrasonic methods can be used to rank metals according to variations in their fracture toughness. Experimental verification was made of the expected correlation between ultrasonic attenuation parameters and fracture toughness measurements on a set of maraging steel specimens.

An empirical equation is proposed for relating the fracture toughness property K_c to the ultrasonic properties of a polycrystalline solid. The pertinent ultrasonic properties in this case involve the attenuation coefficient α and frequency f. This dependence is measured in terms of β, the slope of the α vs. f curve. The proposed relation has the form $K_c = \varphi\beta_f$. It predicts that the fracture toughness property K_c will be proportional to the attenuation slope β evaluated over an appropriate frequency range.

The results of this feasibility study with maraging steel specimens indicate that if various specimens of a given metal possess different fracture toughnesses, it is possible to rank them in order of increasing toughness by ultrasonic testing.

INTRODUCTION

There are strong incentives for developing alternative methods of making fracture toughness measurements. This is true because adherence to the current recommended practice of destructive testing is expensive and requires massive specimens in many instances (ref. 1). A possible alternative to mechanical testing is ultrasonic probing. The benefit would be twofold. First, a nondestructive technique would be available to complement and corroborate

mechanical destructive test results. Second, nondestructive techniques would be available for use on actual hardware to assess or verify material properties.

This paper attempts to show that a correlation exists between material fracture toughness and ultrasonic propagation parameters. Established theoretical foundations for the premise involved are unavailable. A functional relation is proposed as a basis for the expected correlation, and experimental results from a feasibility study on maraging steels are presented to support the proposed relation.

SYMBOLS

Units used in text are indicated when applicable. Fundamental SI dimensions appear in brackets.

b_1, b_2	ultrasonic echo amplitude relative to frequency
B	ratio of echo amplitudes relative to frequency
C	proportionality constant, eq. (7)
C_1	proportionality constant, [s/m]
d	specimen thickness, cm, [m]
D	average grain diameter, [m]
E	Young's modulus, $[N/m^2]$
E'	extensional modulus, $[N/m^2]$
f	frequency, MHz, $[s^{-1}]$
G_c	critical "driving force", eq. (1), [N/m]
K_c	critical stress intensity, $MN/m^{3/2}$, $[N/m^{3/2}]$
K_{Ic}	plane strain fracture toughness, $MN/m^{3/2}$, $[N/m^{3/2}]$
m	exponent, eq. (7)
R	reflection coefficient
R_c	Rockwell-C hardness

S_1	scattering factor, $[(s/m)^4]$
S_2	scattering factor, $[(s/m)^2]$
v	ultrasonic velocity, [m/s]
v_l	longitudinal ultrasonic velocity, [m/s]
v_t	transverse ultrasonic velocity, [m/s]
Z	acoustic impedance of solid, $= \rho v$, $[kg/m^2s]$
Z_w	acoustic impedance of water, $[kg/m^2s]$
α	attenuation coefficient, Np/cm, $[m^{-1}]$
α_a	absorption attenuation coefficient, Np/cm, $[m^{-1}]$
α_s	scatter attenuation coefficient, Np/cm, $[m^{-1}]$
β	attenuation slope, $= d\alpha/df$, [s/m]
β_f	attenuation slope evaluated at f, Np/(cm MHz), [s/m]
$\beta_{\alpha 1}$	attenuation slope evaluated at $\alpha = 1$, Np/(cm MHz), [s/m]
λ	wavelength, [m]
ν	Poisson's ratio
ρ	density, $[kg/m^3]$
σ_y	yield strength, MN/m^2, $[N/m^2]$
φ	parameter, eq. (6)

BACKGROUND

Fracture toughness is an intrinsic material property. It corresponds to a particular stress intensity at which a crack will propagate very abruptly. Fracture toughness is expressed as a critical stress intensity K_c. It is related to the extensional modulus and critical "crack driving force" G_c (refs. 1, 2),

$$K_c = \sqrt{E' G_c} \tag{1}$$

where, E' equals E for plane stress and $E/(1 - \nu^2)$ for plane strain.

From the standpoint of ultrasonic assessment of K_c it is significant that E' in Eq. (1) is related to ultrasonic velocity v (ref. 3). It is known that K_c is related to a solid's microstructure. Because the attenuation of sound waves is likewise related to microstructure, it is reasonable to expect that K_c is related to ultrasonic attenuation properties. Therefore, one might expect that a correlation exists between fracture toughness and ultrasonic propagation properties of some types of solid materials.

Acoustic emission studies show that stress waves in metals are emitted by various disturbances, e.g., dislocation motions, microcracking (refs. 4, 5, 6). Acoustic emission studies appear to support the expectation that in high toughness materials the propagation and interaction of stress waves are inhibited by the attenuation properties of the material (ref. 7). Therefore, we might suppose that during rapid crack growth, the wave propagation properties of the material are significant. Ultrasonic attenuation measurements should then be expected to gauge factors that influence crack propagation and hence fracture toughness.

Some experimental support for the above-stated supposition is available. By using shock stressing techniques, it can be shown that sustained crack growth occurs at times corresponding to the presence of a stress wave front at the crack tip. It appears that terminal crack speed is bounded by the stress wave's propagation velocity. Since crack speeds are less than wave velocities, stress wave reflections interact with and influence the growth of a running crack (ref. 8).

Among the causes of ultrasonic attenuation in polycrystalline aggregates is scattering by the microstructure and absorption due to dislocation dampening and elastic hysteresis. Ultrasonic attenuation can be summarized in terms of the attenuation coefficient α, the average grain diameter D, frequency f, and wavelength λ (refs. 3, 9). The total attenuation coefficient is,

$$\alpha = \alpha_s + \alpha_a \tag{2}$$

where, for $\lambda \gg D$ (Rayleigh scattering domain),

$$\alpha_s = D^3 S_1 f^4 \tag{3}$$

and, for $\lambda \leq D$ (stochastic scattering domain),

$$\alpha_s = D S_2 f^2 \tag{4}$$

and (absorption domain),

$$\alpha_a = C_1 f \tag{5}$$

Generally, for most engineering materials, the dependence of the attenuation coefficient on frequency will not be governed by the exact exponents given in the previous equations. It should be expected instead that microstructural variations will produce corresponding variations in the slope of the α vs. f curve (refs. 9, 10).

APPROACH

Proposed equation. - According to the previous discussion, it is plausible that ultrasonic attenuation parameters will reflect fracture toughness variations of a material. I propose that this relation be tentatively expressed as,

$$K_c = \varphi \beta_f \tag{6}$$

where, $\beta_f = d\alpha/df$ evaluated at an appropriate frequency. The parameter φ incorporates the elastic properties of the material, e.g., E, ν, etc. Thus, in Eq. (6), φ is analogous to $\sqrt{E'}$ and β_f is analogous to $\sqrt{G_c}$ in Eq. (1).

An empirical basis for a direct relation between K_c and β_f can be inferred from the literature. For example, results reported in Ref. 11 show an inverse relation between Rockwell-C hardness and the slope of the attenuation versus frequency curve for steel specimens. On the other hand, Ref. 12 indicates an inverse relation between Rockwell-C hardness and plane strain fracture toughness. It is therefore reasonable to expect the relation of Eq. (6) to apply, at least in the case of materials similar to those investigated in the previously-cited studies. The empirical evidence also indicates

that the correlation sought depends not simply on the attenuation coefficient but upon the slope of the attenuation coefficient versus frequency curve.

Verification method. - When Rayleigh or stochastic attenuation predominate, the form of the attenuation coefficient versus frequency relation will be,

$$\alpha = C f^{m} \tag{7}$$

For the ultrasonic measurements in this study, it is reasonable to assume that Eq. (7) applies and that m and C are constants for a given specimen in the pertinent frequency regime (refs. 13-15). The α vs. f plot can thus be used to evaluate m and C. Since $\beta = d\alpha/df$, we have

$$\beta = m C f^{(m-1)} \tag{8}$$

Let β be evaluated at the frequency where $\alpha = 1$, then,

$$\beta_{\alpha 1} = m C^{\frac{1}{m}} \tag{9}$$

The quantities m and C are evaluated by using that part of the α vs. f curve where its trend is well established, i.e., assumes a fixed slope. This can be determined by inspection. Note that α can be a constant other than 1. The choice depends on the properties of the α vs. f curves for a given material.

The form for β given in Eq. (9) will be used to test Eq. (6). This is a reasonable choice since the α vs. f curves in this study are in the domain where $\alpha = 1$.

To demonstrate the assumed relation in Eq. (6), it is necessary to ultrasonically probe specimens of materials for which fracture toughness values have been measured. These measurements are conventionally made under conditions that yield plane strain fracture toughness K_{Ic} values (ref. 16). The validity of fracture toughness measurements depend on the use of appropriate test and specimen parameters. These vary with the material being tested to ensure that plane strain conditions prevail. The quantity K_{Ic} thus implies a particular type of K_c value. Therefore, the procedure used herein was to examine the correlation between K_{Ic} and $\beta_{\alpha 1}$.

EXPERIMENTAL PROCEDURE

Specimen materials. - The materials used in this study were specimens of two maraging steels for which plane strain fracture toughness values had been measured. There were five 200-grade specimens each aged at different temperatures to obtain a range of fracture toughnesses. A second set consisted of four specimens with a 250-grade composition. This second set was selected because the specimens spanned a wide difference in K_{Ic} values while having virtually identical yield strengths. Pertinent data on the two sets of specimens are given in tables I and II. The data include Rockwell-C hardness, yield strength, and plane strain fracture toughness values. The values of K_{Ic} cover the range from 92 to 146 $MNm^{-3/2}$ (84 to 133 ksi $\sqrt{in.}$).

Fracture toughness measurements quoted herein were made by the Lewis Research Center, Fracture Branch, in conformance with plane strain criteria defined in ASTM E 399-70T, 4.2 (ref. 16). For two specimens the conditional value K_Q defined in ASTM E 399-70T, 8.1 (ref. 16) is given in place of K_{Ic} in table I. For the two specimens involved, only the conditional values were available. It can be assumed that the K_Q value is close to the actual K_{Ic} value but it ranks lower in validity.

The original fracture toughness specimens were sectioned and a representative rectangular segment was cut from each and ground to size. These segments constituted the ultrasonic specimens. This procedure ensured that the attenuation properties measured were related specifically to objects that were actually subjects of previous fracture toughness tests. The ultrasonic specimens had smooth ground surfaces (32 rms, approximately) and were 1.0 cm thick.

Procedure. - Ultrasonic velocity and attenuation measurements were made on the previously- described ultrasonic specimens. In making the measurements, the ultrasound was directed into the specimens along an axis parallel to the fracture surface of the original fracture toughness specimen. Thus, relative to the microstructure, the probe ultrasound propagated in the same direction as the crack did in the original K_{Ic} tests.

As indicated in Figs. 1 and 2, the ultrasonic measurements were made using a water-buffered pulse-echo method. Velocity measurements were made to determine the water-to-specimen interface reflection coefficient R,

$$R = (Z - Z_w)/(Z + Z_w) \tag{10}$$

This value of R was then used in a formula for calculating the attenuation coefficient α.

The formula used to calculate α is based on the frequency spectrum analysis method for measuring attenuation. The method is described in Refs. 17 and 18. In the present case, it involved spectral analysis of the first two surface echos b_1 and b_2 from the back (free) surface of the specimens, (see Fig. 2). The amplitude ratio of the echos $B = (b_1/b_2)$ was determined for a set of frequencies over the range from 5 to 40 MHz. These values for B were used with the measured values of R to compute α from,

$$\alpha = \ln(R/B)/2d \tag{11}$$

where, d is the specimen thickness.

A plot of α vs. f was made for each specimen. It was found that above approximately 15 MHz each of the curves exhibited essentially fixed slopes. Using the slope-intercept method an equation was determined for the α vs. f characteristic of each specimen in the range from 15 to 40 MHz. This yielded values for m and C Eq. (7) for use in calculating values for $\beta_{\alpha 1}$ Eq. (9). A typical α versus f plot is shown in Fig. 3.

RESULTS AND DISCUSSION

In accordance with the approach adopted herein, the constants m and C were evaluated and the quantity $\beta_{\alpha 1}$ was calculated for each of the previously-described specimens. The results appear in table III. Note that m and C should be considered valid only in the range from approximately 15 to 40 MHz. Also, the values for $\beta_{\alpha 1}$ are subject to the error ranges indicated in table III.

Figure 4 is a plot of $\beta_{\alpha 1}$ vs. K_{Ic} in which each datum point is labeled with the corresponding specimen's identifying designation. Representative micrographs for some of the specimens appear in Fig. 5.

The experimental results in Fig. 4 show that it is apparently possible to ultrasonically rank the fracture toughness variations of a metal. Moreover,

as indicated in Fig. 4, the relation between $\beta_{\alpha 1}$ and K_{Ic} (i.e., between β_f and K_c) is apparently linear for a given class of material or microstructure as suggested by Eq. (6).

As indicated by the lines drawn in Fig. 4, the data points should be grouped into two distinct populations corresponding to the steel grade or classification. It is likely that the alignments of the two groups are influenced by microstructure factors such as grain size, and rolling direction peculiar to the materials examined. Micrographs of the two maraging steels reveal subtle differences in microstructure (see Fig. 5). It is difficult to correlate microstructural variation in these specimens with either K_{Ic} or $\beta_{\alpha 1}$. However, between the 200- and 250-grade specimens differences in grain morphologies exist. For the specimens examined, microstructures with fewer scattering centers were less attenuating and hence less fracture resistant. This does not necessarily imply that the abundance of scattering centers due to precipitates, inclusions, and the like might not also be associated with lower fracture resistance. Thus, these preliminary results must be viewed as relevant only for the material morphology class actually studied.

There is a tacit assumption involved in the approach used herein. It was assumed that the equations for attenuation curves in the frequency range from 15 to 40 MHz applied equally in the higher frequency domain associated with crack extension stress waves. This implicit "extrapolation" was needed to overcome the frequency limitation of the ultrasonic equipment used. However, I believe that ultrasonic probing in this lower frequency domain yields an indirect measure of the energy that is potentially transferable to crack extension involving higher frequency stress waves. The frequencies of the stress waves associated with cracking could range from roughly 100 MHz for grain cleavage to 1000 MHz for dislocation vibrations (refs. 4, 13).

The limited amount of data obtained thus far scarcely justifies generalizations. However, it should be noted that the choice of specimen materials was not predicated on fulfilling a particular qualification other than to include an adequate range of K_{Ic} values. Therefore, I believe that the resultant correlations are not simply fortuitous. For example, it is significant that two pairs of specimens having virtually identical yield strengths but greatly different K_{Ic} values (specimens 15A-1, 22A-1 vs. 26-1, 33-2) exhibited the

expected relation between K_{Ic} and $\beta_{\alpha 1}$. Thus, the correlations obtained thus far probably reflect that the presence of certain microstructural fractures permits one to ultrasonically evaluate fracture toughness variations.

CONCLUSION

Nine specimens of two maraging steels (a 200- and a 250-grade) with a range of measured plane strain fracture toughness values were probed ultrasonically. The ultrasonic attenuation properties of the specimens appeared to correlate well with plane strain fracture toughness values. Thus, it seems reasonable to conclude that if a given material can be treated to achieve a range of fracture toughness values, it is feasible to rank fracture toughness with this nondestructive, ultrasonic technique.

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TABLE I. - 200-GRADE MARAGING STEEL SPECIMENS[a]

Specimen	Aging temperature[b] °K	(R_c) Rockwell-C hardness	(σ_y) Yield strength[c] MN/m^2	(K_{Ic}) Fracture toughness[d] $MN/m^{3/2}$
RW2	700	39.9	132 × 10	(113.5)
RW5	728	42.9	143 × 10	98.1
RW9	756	43.2	143 × 10	92.3
RW11	783	42.8	133 × 10	103.1
RW15	811	40.9	121 × 10	(109.8)

[a]Cold rolled 50 percent and aged as indicated.
[b]Aged 8 hours at temperature indicated.
[c]At 0.2 percent elongation.
[d]Conditional (K_Q) values in parentheses.

TABLE II. - 250-GRADE MARAGING STEEL SPECIMENS[a]

Specimen	Aging temperature[b] ^{o}K	R_c Rockwell-C hardness	σ_y Yield strength[c] MN/m^2	K_{Ic} Fracture toughness $MN/m^{3/2}$
15A-1	672	45.7	140 × 10	118
22A-1	672	45.7	140 × 10	117
26-1	838	46.1	140 × 10	139
33-2	838	46.1	140 × 10	146

[a]Annealed at 1090 ^{o}K, air cooled and aged as indicated.
[b]Aged 6 hours at temperature indicated.
[c]At 0.2 percent elongation.

TABLE III. - ULTRASONIC ATTENUATION CHARACTERISTICS OF MARAGING STEEL SPECIMENS

Maraging steel grade	Specimen	Attenuation constants[a]		Attenuation slope	
		Exponent[b] m	Coefficient[c] C, $\times 10^4$	Slope[d] $\beta_{\alpha 1}$ Np/cm MHz	Error[e] Np/cm MHz
200-grade	RW2	1.86	29.5	.081	±.003
	RW5	1.34	93.6	.041	±.002
	RW9	1.19	120.0	.029	±.001
	RW11	1.93	13.4	.063	±.002
	RW15	2.09	9.50	.075	±.002
250-grade	15A-1	2.92	0.220	.074	±.002
	22A-1	2.67	0.595	.070	±.002
	26-1	2.86	0.449	.086	±.002
	33-2	3.00	0.253	.088	±.002

[a]Based on eq. (7) valid from 15 to 40 MHz, approximately.
[b]Slope of log-log α vs. f curve.
[c]Intercept of log-log α vs. f curve.
[d]Calculated from eq. (9) using tabulated m and C values.
[e]Based on estimated errors in tabulated m and C values.

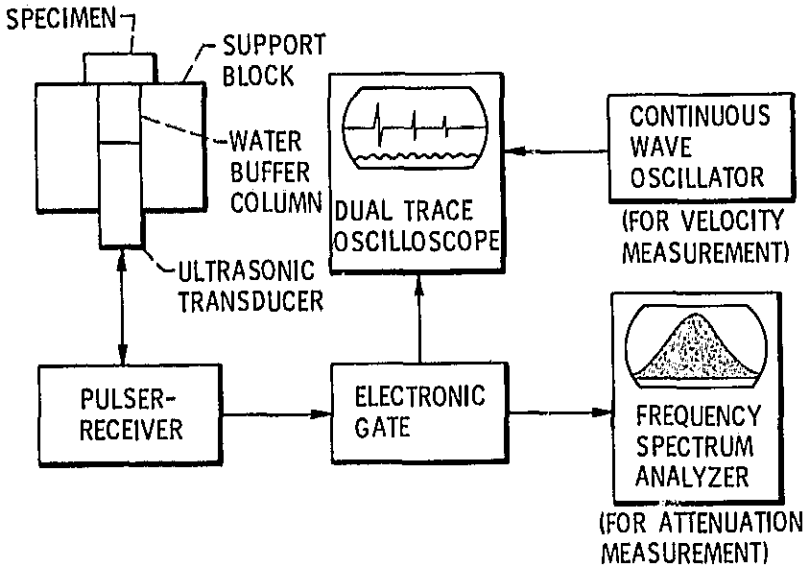


Figure 1. - Block diagram of ultrasonic velocity and attenuation measuring apparatus.

FS IS THE FRONT SURFACE (WATER INTERFACE) ECHO
b_1 IS THE FIRST BACK (FREE) SURFACE ECHO
b_2 IS THE SECOND BACK (FREE) SURFACE ECHO
THE INTERVAL BETWEEN ECHOS IS USED FOR VELOCITY MEASUREMENT BY OSCILLATION COUNTS
ECHOS b_1 AND b_2 ARE ELECTRONICALLY GATED FOR FREQUENCY SPECTRUM ANALYSES FOR CALCULATING ATTENUATION

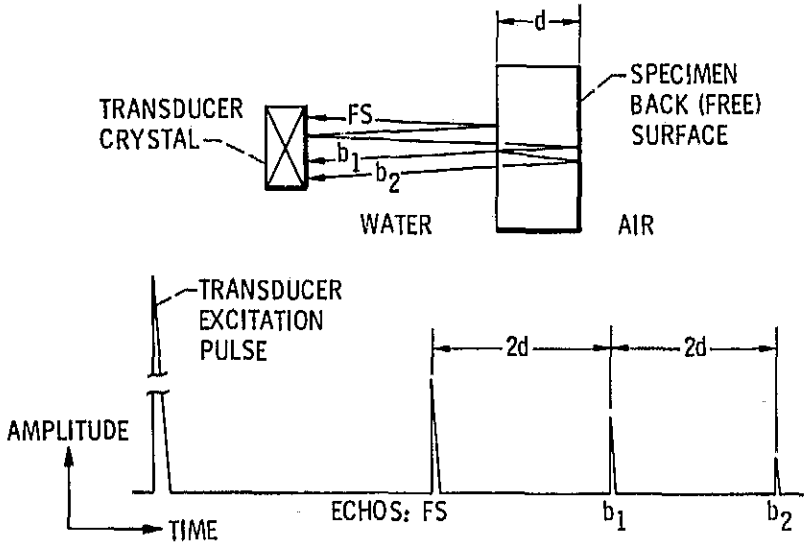


Figure 2. - Representation of ultrasonic echos used for velocity and attenuation measurements.

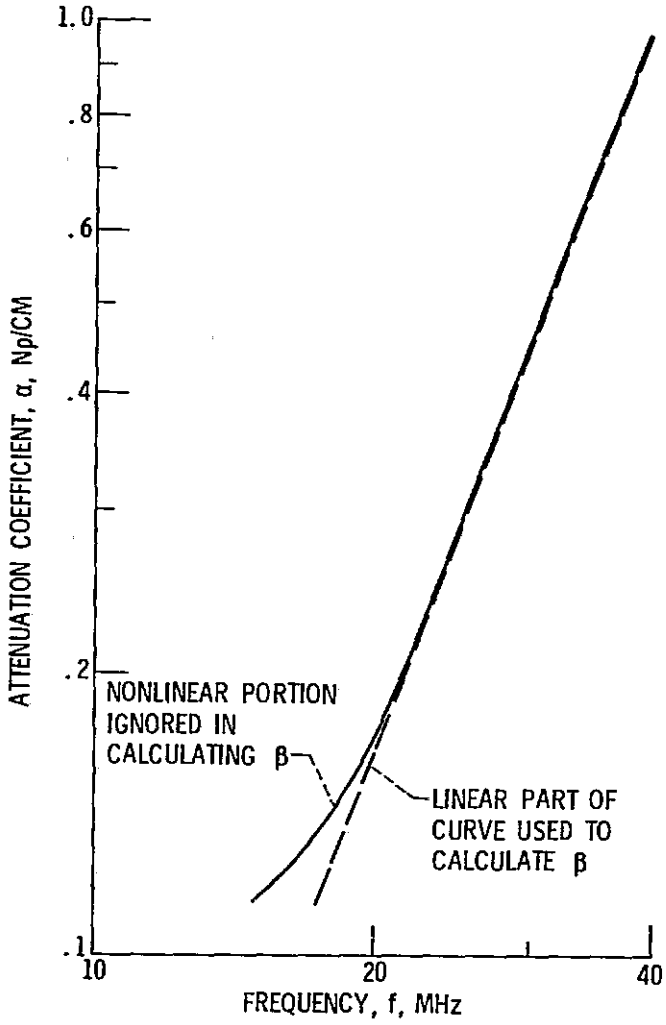


Figure 3. - Typical relation between attuation coefficient and ultrasonic frequency for maraging steel specimens.

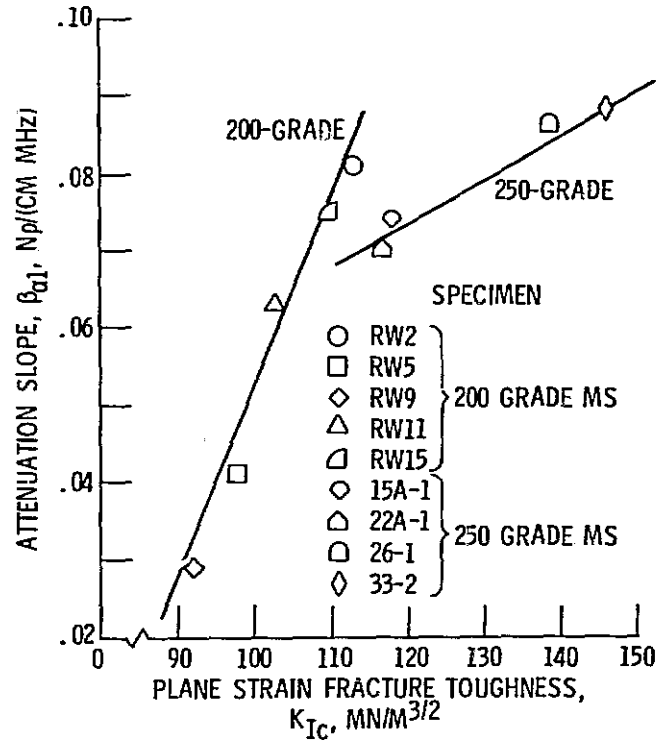
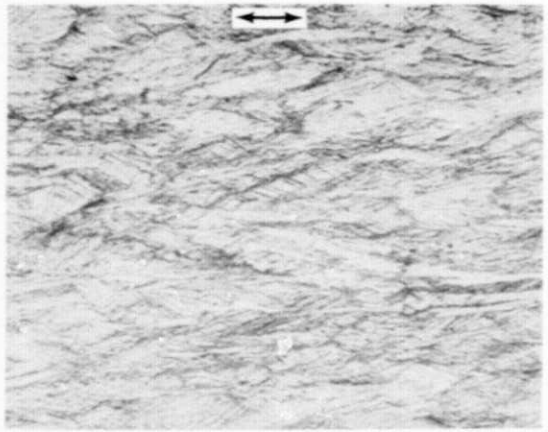


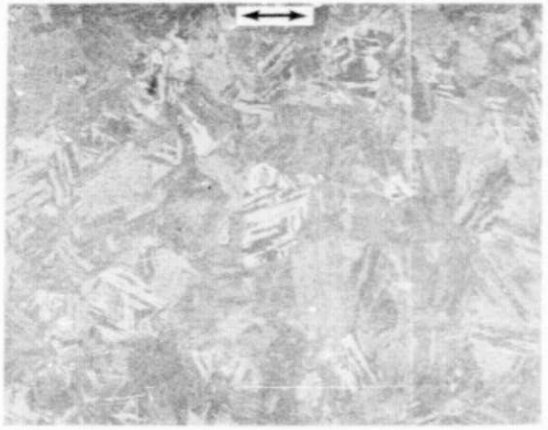
Figure 4. - Correlation of attenuation slope with fracture toughness for maraging steel specimens.



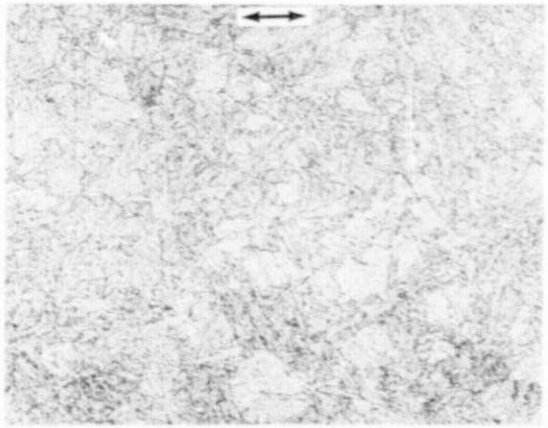
(a) SPECIMEN RW 2 (200-GRADE MARAGING STEEL). X250

(b) SPECIMEN RW 9 (200-GRADE MARAGING STEEL). X250

Figure 5. - Micrographs of maraging steel specimens. (Etchant used was Nital; double arrow shows direction of probe ultrasound and crack propagation relative to the microstructure.)



(c) SPECIMEN 22A-1 (250-GRADE MARAGING STEEL). X250



(d) SPECIMEN 26-1 (250-GRADE MARAGING STEEL). X250

Figure 5. - Concluded.

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