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# CONCEPTS AND TECHNIQUES FOR ULTRASONIC EVALUATION OF MATERIAL MECHANICAL PROPERTIES



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## INTRODUCTION

Reliable performance of advanced, high-strength materials in critical applications depends on assuring that each part placed in service satisfies the conditions assumed in design and life prediction analyses. Reliability assurance requires the availability of nondestructive evaluation (NDE) techniques not only for defect detection but also for verification of mechanical strength and associated properties. Advanced NDE techniques are needed to confirm that metallic, composite, or ceramic parts will not fail under design loads due to inadequate or degraded mechanical strength. This calls for NDE techniques that are sensitive to variations in microstructure, extrinsic properties, and dispersed flaw populations that govern the ultimate mechanical performance of a structure.

The purpose of this paper is to review ultrasonic methods that can be used for material strength prediction and verification. Emergent technology involving advanced ultrasonic techniques and associated measurements is described. It is shown that ultrasonic NDE is particularly useful in this area because it involves mechanical elastic waves that are strongly modulated by morphological factors that govern mechanical strength and also dynamic failure modes. These aspects of ultrasonic NDE will be described in conjunction with advanced approaches and theoretical concepts for signal acquisition and analysis for materials characterization. It is emphasized that the technology is in its infancy and that much effort is still required before the techniques and concepts can be transferred from laboratory to field conditions.

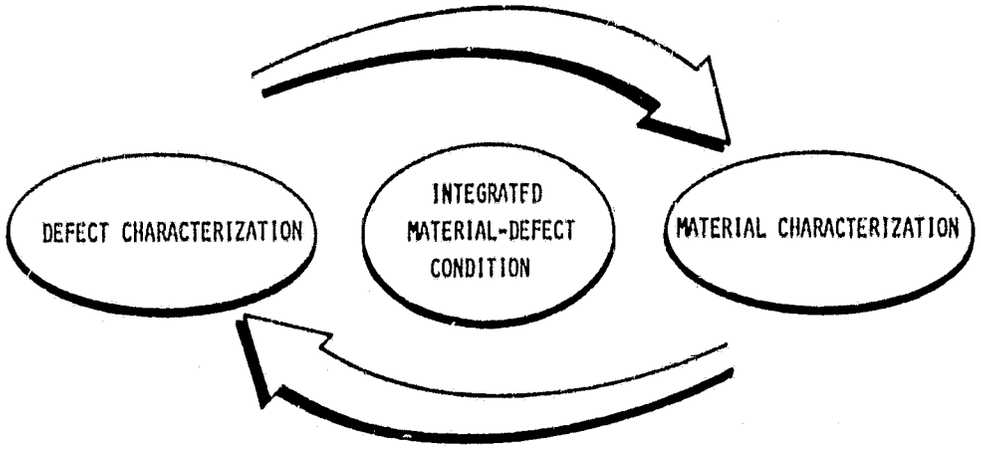


Fig. 1. Diagram illustrating the relation of defect and material characterization to defining the integrated effect of the material-defect state on structural integrity and life.

## PRELIMINARY CONSIDERATIONS

In its most general context, nondestructive evaluation (NDE) is a branch of materials science that is concerned with all aspects of the uniformity, quality, and serviceability of materials and structures. Therefore, NDE should not be defined solely by the current emphasis on the detection of overt flaws (Sharpe, 1976). Certainly, it is necessary to extend NDE technology to characterize discrete flaws according to their location, size, orientation, and nature. This leads to improved assessment of the potential criticality of individual flaws. Concurrently, it is necessary to develop NDE techniques for characterizing various inherent material properties. In this case, the emphasis is on evaluation of microstructural and morphological factors that ultimately govern mechanical strength and dynamic performance. As illustrated in Fig. 1, a holistic approach combines nondestructive characterization of defects and also material environments in which the defects reside. This leads to improved accuracy in predicting structural integrity and life upon exposure to service conditions, particularly in the presence of discrete flaws.

The specification of flaw criticality and prediction of safe life depend on the assumption of a realistic set of extrinsic properties and conditions, such as those listed in Fig. 2. Fracture and life prediction analysis models invariably presuppose flaw development and propagation in materials with well established moduli, ultimate strengths, fracture toughnesses, and fatigue and creep properties. It is within the province and capability of NDE technology to verify whether or not a structural part possesses the properties assumed in design analysis (Vary, 1980). There are numerous NDE

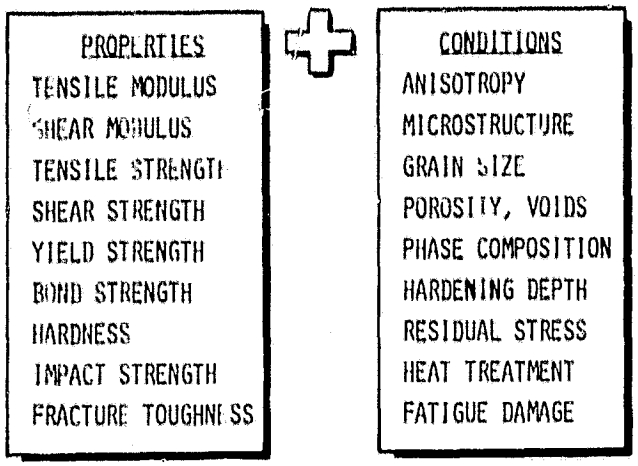


Fig. 2. Material properties and conditions that can be assessed by various nondestructive evaluation (NDE) techniques.

techniques that can be used for material properties characterization (e.g., radiometric, electromagnetic, ultrasonic)(McMaster, 1959; Green, 1973; Krautkramer, 1977; Hayward, 1978). Many of these are complementary and can be used to extend or corroborate measurements by other methods. This paper focuses on ultrasonic techniques that have demonstrated potentials for materials characterization. These techniques rely on physical acoustic properties of materials and the interaction of elastic stress waves with morphological factors in the ultrasonic regime (Mason, 1958; Kolsky, 1963; Kolsky, 1973).

All the material properties and conditions listed in Fig. 2 are amenable to ultrasonic evaluation to differing degrees (Vary, 1978a; 1980). The speed of wave propagation and energy loss by interaction with material microstructure and geometrical factors underlie ultrasonic determination of material properties. There is a well-established body of theoretical and experimental knowledge concerning the ultrasonic measurement of elastic moduli (Truell et al, 1969; Schreiber et al, 1973). Conversely, ultrasonic prediction of tensile and yield strengths, and fracture toughness are currently based on empirical correlations (Vary, 1978b).

Proposed models for explaining the above-mentioned empirical correlations invoke the concept of ultrasonic stress wave interactions with material microstructure to the degree where the stress waves actually promote plastic deformation and microcrack extension (van Elst, 1973; Vary, 1979a). This stress wave interaction concept forms the basis for an ultrasonic approach to defining material--defect interactions as a means for prediction of ultimate strength and dynamic reaction to applied loads. Illustrative examples of the concept are discussed hereinafter.

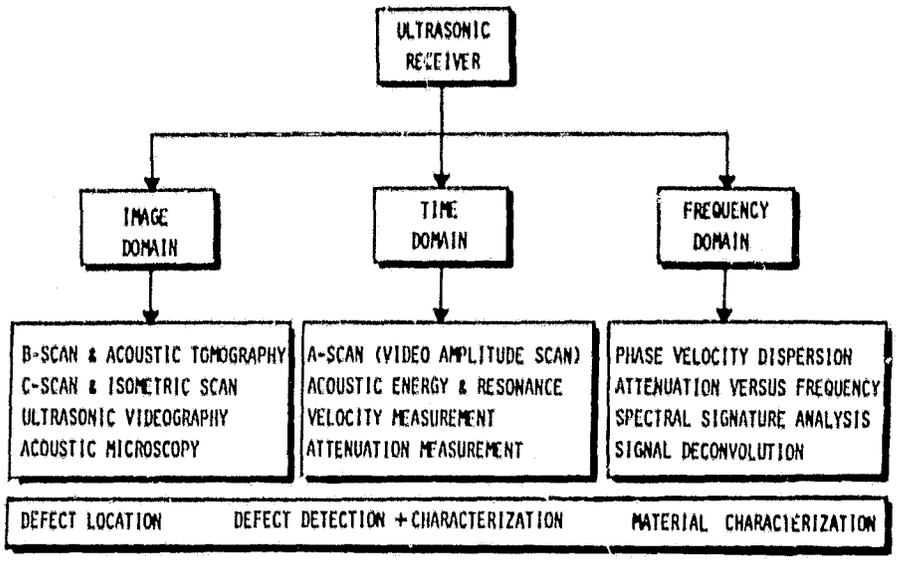


Fig. 3. Alternative data processing and analysis methods upon the acquisition of ultrasonic signals from a test article.

ULTRASONIC DOMAINS

There are three major domains for presenting, processing, and analyzing ultrasonic data: (i) image domain, (ii) time domain, and (iii) frequency domain. As indicated in Fig. 3, the detailed treatment of ultrasonic signals within each domain can be accomplished by various methodologies, e.g., acoustic tomography, acoustic microscopy, velocity and attenuation measurement, spectral signature analysis (Brown, 1973; Kessler and Yuhas, 1978; Krautkramer, 1977; Vary 1980). The end objectives range from defect detection to material property characterization.

Irrespective of the methodology used, the fundamental process in the image domain produces a representation of signal strength against spatial coordinates. An example is given in Fig. 4 wherein material quality variations associated with microvoids and fiber content in a composite laminate are revealed. In the image domain, the location and size of flaws or the extent of defective material become apparent. The chief advantage of ultrasonic imaging is in affording means for qualitative ranking of test articles relative to defect populations and material anomalies (Posakony, 1978).

The time domain methodologies all employ electrical analogs of ultrasonic echoes and transmitted waveforms that are displayed as signal amplitude versus time oscilloscope traces. Specific signals are selected for detailed examination and quantitative measurements of energy, velocity, or attenuation. Time domain measurements are currently predominant in defect and material characterization.

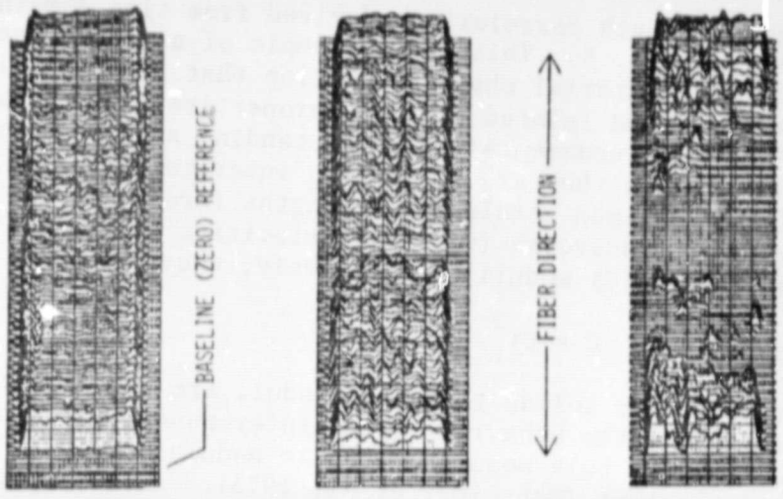


Fig. 4. Through transmission immersion ultrasonic amplitude scans (isometric scans) of graphite/polyimide composite laminate panels. Scans show variations of transmitted signal relative to zero transmission baseline reference at bottom. Although each panel was formed with the same cure pressure, it is evident that material quality and uniformity differ from panel to panel (Vary and Bowles, 1979).

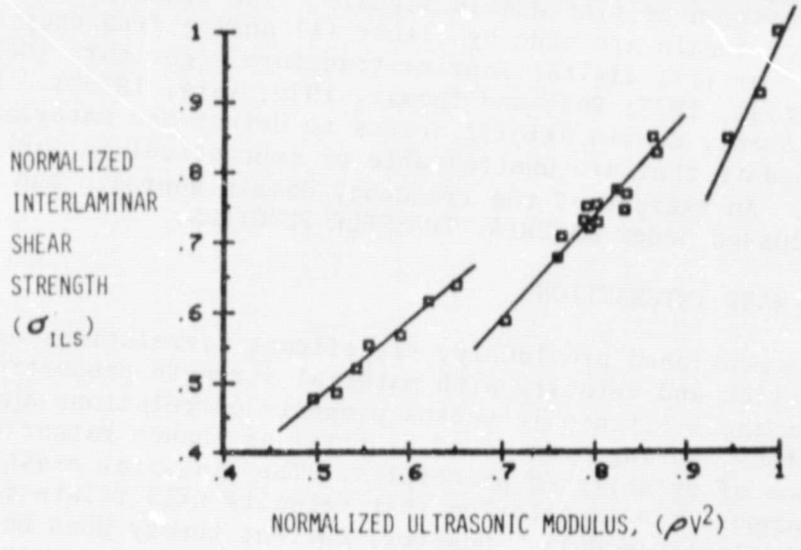


Fig. 5. Interlaminar shear strength of graphite/polyimide composite laminate specimens compared to ultrasonic modulus based on density and through-thickness velocity measurements. Three separate correlation curves that were obtained corresponded to different combinations of morphological factors that controlled fracture modes during short beam shear tests for interlaminar shear strength (Vary and Bowles, 1977).

Material strength correlations derived from time domain signals are indicated in Fig. 5. This is an example of a widely-used ultrasonic approach to material characterization that involves measuring elastic constants and related strength properties. Measurement of elastic moduli are fundamental to understanding and predicting material behavior. Since they are related to interatomic forces, elastic moduli indicate maximum attainable strengths (Green, 1973). Longitudinal ($v_l$) and transverse ($v_t$) wave velocities give the longitudinal (L) and shear (G) moduli, respectively, where,

$$L = \rho v_l^2 \quad \text{and} \quad G = \rho v_t^2 \tag{1}$$

For linear isotropic solids these two moduli are sufficient to completely define elastic behavior, given interconnecting relations with other moduli, e.g., bulk modulus, tensile modulus, Poisson's ratio and the Lamé constant (Schreiber et al, 1973). Anisotropic and most polycrystalline solids present a more complex situation since the principal moduli (L and G) will assume different values with different directions of ultrasonic wave propagation. Nevertheless, there exists an extensive literature that confirms the capabilities of various time domain measurements for predicting mechanical strength for materials ranging from cast iron to concrete (Vary, 1980).

Frequency domain methodologies begin with the acquisition and transformation of time domain signals. The transformations to the frequency domain are made by either (i) analog frequency spectrum analysis or (ii) digital Fourier transform algorithms (Gericke, 1970; Adler et al, 1977; Rose and Thomas, 1979; Vary, 1979b). Working in the frequency domain affords access to defect and material characterization data that are unattainable or impractical to seek in the time domain. An example of the frequency domain approach and methodology is discussed under MATERIAL TRANSFER FUNCTION.

## STRESS WAVE INTERACTION

As mentioned previously, significant correlations of ultrasonic attenuation and velocity with material strength properties exist. Many of these ultrasonic versus property correlations appear to be fortuitous, having been found by trial or chance rather than by extentions of established principles. The classical elastic wave model does support the expectation that velocity will relate to strength through elastic moduli. However, current theory does not adequately account for the strong correlations of ultimate strengths and fracture toughness with attenuation. It is proposed that this lack can be remedied by considering fracture models in which ultrasonic stress waves interact with material morphological factors to the extent that they actually promote microcracking and also catastrophic crack extention. This point of view coincides with dynamically-based models for fracture behavior (Kolsky, 1973; Curran et al, 1977).

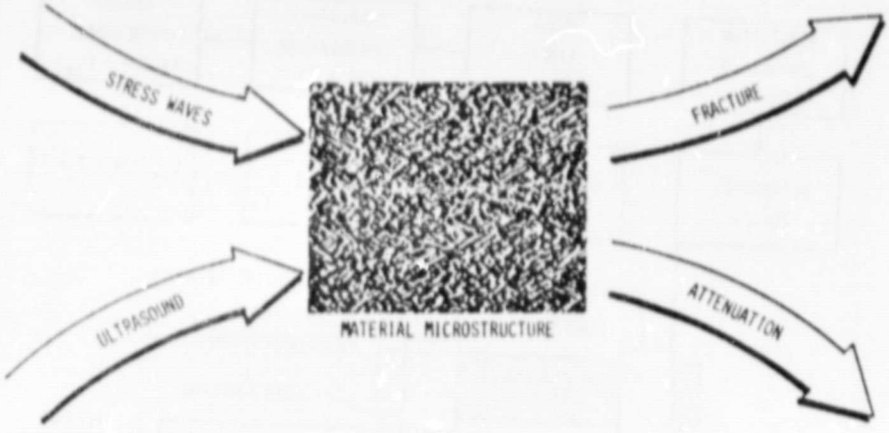


Fig. 6. Depiction of the equivalence of ultrasound and stress wave propagation under linear elastic conditions wherein material microstructure governs ultrasonic attenuation and fracture phenomena.

The stress wave interaction concept stated above can be used for developing a theoretical basis for correlations found between ultrasonic attenuation and material strength and toughness. The working hypothesis is that given linear elastic conditions, propagation of probe ultrasound is governed by the same material morphological factors that govern stress waves generated during fracture, Fig. 6. The importance of microstructure in controlling mechanical behavior is, of course, well established (MacCrone, 1977; Froes et al, 1978). The use of probe ultrasound, as depicted in Fig. 7, would be expected to define material transfer functions that determine stress wave interactions such as redirection and energy loss due to scattering and absorption, for example. Considering material microstructure as a filter with a transfer function definable in terms of the ultrasonic attenuation coefficient proves to be a useful concept, as indicated by results cited under FRACTURE TOUGHNESS AND ATTENUATION.

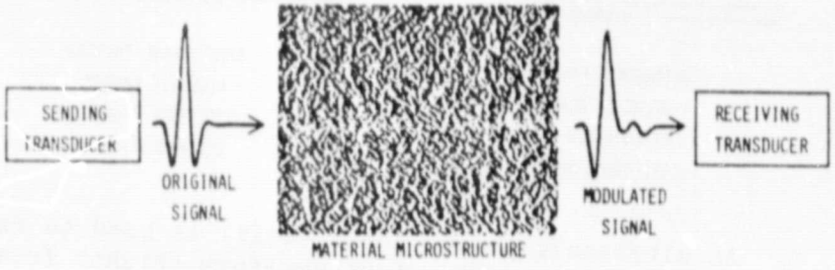


Fig. 7. Depiction of material microstructure as an ultrasonic wave filter in which a standard reference signal becomes modulated according to a definable transfer function.

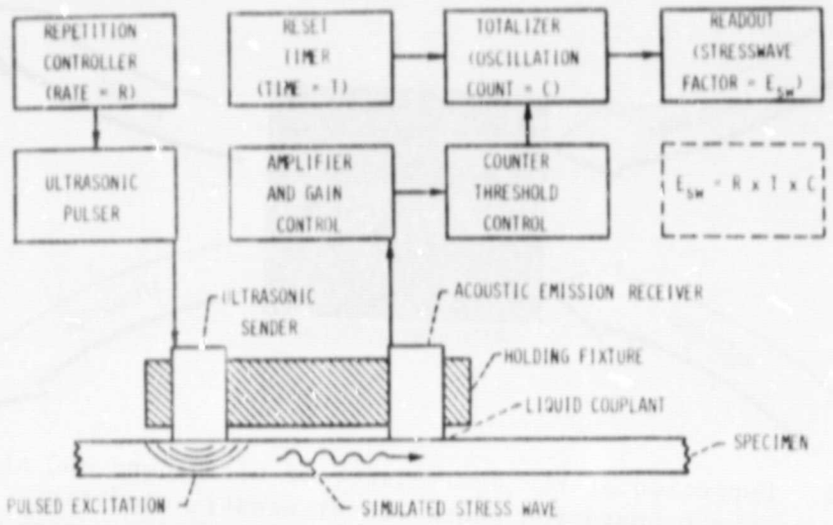


Fig. 8. Diagram of acousto-ultrasonic apparatus for measurement of the stress wave factor $E_{sw} = R \cdot T \cdot C$. The quantity C is the number of time domain "ringdown" oscillations exceeding a threshold voltage as in the acousto-ultrasonic waveform shown in Fig. 9 (Vary and Bowles, 1977; 1979).

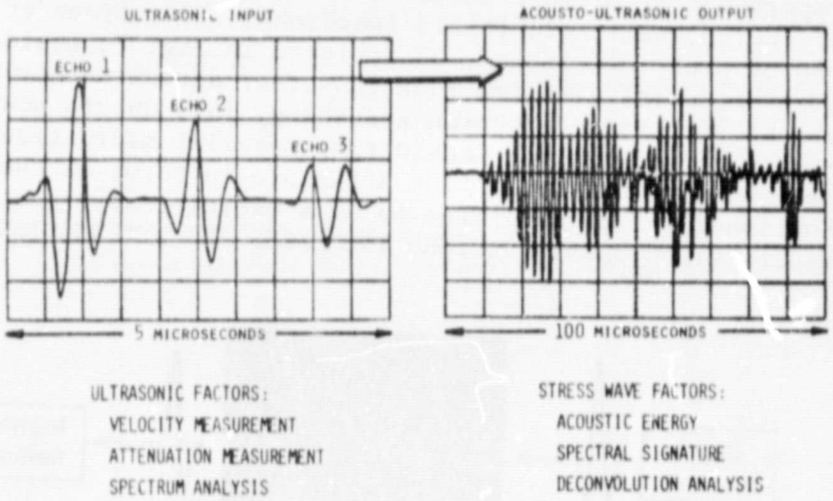


Fig. 9. An ultrasonic pulsed input (left) is used to excite the acousto-ultrasonic output waveform (right) from which the stress wave factor, $E_{sw}$, is measured. Both the ultrasonic input pulse echoes and acousto-ultrasonic output can be measured by the alternative factors indicated in order to determine the material modulation transfer function.

## STRESS WAVE FACTOR

An illustrative example of the application of the stress wave interaction concept is given herewith. The application involves a novel approach that was developed to evaluate fiber composite panels for mechanical strength properties and in-service strength loss. The approach combines instrumentation from two previously separate technologies: (i) acoustic emission and (ii) pulse ultrasonics (Liptai and Harris, 1971; Spanner, 1974; Krautkramer, 1977). The usual procedure with acoustic emission involves the detection and analysis of spontaneous stress wave emissions due to material deformation and flaw growth. The "acousto-ultrasonic" procedure employs ultrasonically excited elastic waves that simulate acoustic emission events, as indicated in Figs. 8, 9 (Vary and Bowles, 1977; 1979).

The object is to generate a repeating, controlled set of elastic waves that will interact with material morphology and boundary surfaces in a manner similar to spontaneous stress waves that arise at the onset of fracture. The resultant output waveform resembles "burst" type acoustic emission both in the time and frequency domains. Like spontaneous acoustic emission waveforms the acousto-ultrasonic waveform carries substantially more information on the material in which it runs than on the signal source. It is a mixed function of multimode velocities, attenuations, dispersions, and reflections. It has been demonstrated that, in the restricted case of fiber composite laminates, the acousto-ultrasonic waveform will yield correlations with ultimate tensile and interlaminar shear strengths, Figs. 10, 11.

The correlations were obtained by measurement of a "stress wave factor" (see Fig. 8). The stress wave factor may be described as a measure of the efficiency of stress wave energy transmission. This factor apparently provides a means for rating the efficiency of the dynamic strain energy transfer in the composites tested heretofore (Vary and Lark, 1979). Once microcracking starts in the brittle matrix or fibers, it is to be expected that prompt dissipation of stress wave energy away from the crack initiation sites contributes to dynamic integrity and ultimate strength. In unidirectional composites, the stress wave factor is greatest along the fiber direction which is also the direction of maximum strength. Regions of small values of stress wave factor are regions of higher ultrasonic attenuation (Williams and Lampert, 1980). These regions are also observed to be regions of weakness where dynamic strain energy is likely to concentrate and promote further microcracking failure.

The preceding discussion leads to a point made previously with regard to the phenomenon of stress wave interactions and their relation to failure dynamics. The fundamental argument being advaned is that spontaneous stress waves that arise during microcracking can interact with other potential crack sites leading to either cleavage

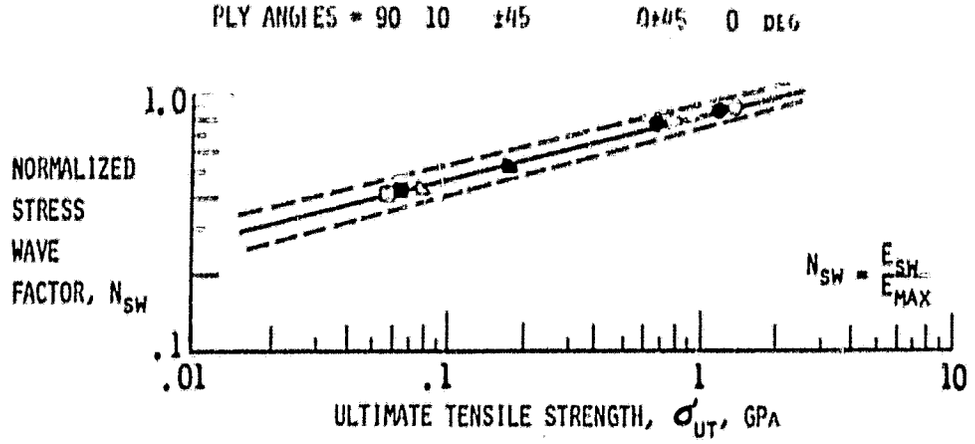


Fig. 10. Stress wave factor as a function of ultimate tensile strength for graphite/epoxy fiber composite. The stress wave factor is normalized relative to its maximum value for the specimen materials. The ply angles given are relative to the loading axis (Vary and Lark, 1979).

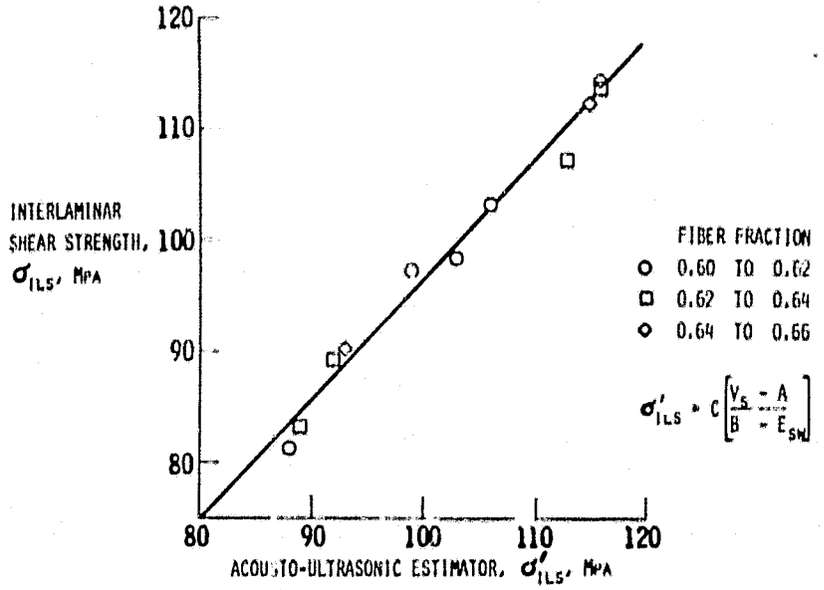


Fig. 11. Correlation of graphite/polyimide fiber composite interlaminar shear strength with acousto-ultrasonic estimator. The estimator is derived from stress wave factor and velocity measurements, $E_{SW}$ and $V_S$, respectively. A, B, and C are experimental constants (Vary and Bowles, 1977).

or void coalescence and thence large-scale abrupt failure, provided an initiating excess strain has been applied (Vary, 1979a). Since the stress waves are ultrasonic in nature and subject to modulation by the material microstructure, it should be possible to determine a modulation transfer function by ultrasonic means. Measurement of a stress wave factor as described herein affords only a relative means. Time domain attenuation measurements provide alternative means if the material sample geometry permits access along appropriate directions. However, the more appropriate approach is to work in the frequency domain wherein signal deconvolution is readily accomplished and the material transfer function can be precisely defined.

## MATERIAL TRANSFER FUNCTION

The conditions under which the material transfer function can be defined are restricted. An isotropic polycrystalline aggregate is assumed for the purposes of this discussion. It is also assumed that the sample has flat, parallel opposing surfaces and satisfies the conditions necessary to obtain two back surface echoes as indicated in Fig. 12 (Truell et al, 1969). Signal acquisition and processing would be accomplished as indicated in Fig. 13 (Vary, 1979b).

It will be seen that frequency domain analysis yields an ultrasonic transfer function, T, for the material in terms of its attenuation coefficient, $\alpha$, and reflection coefficient, R. The quantities B1, B2, E1, E2, T, and R are taken as Fourier transforms of corresponding time domain quantities (Bracewell, 1978). This puts the aforementioned quantities into the frequency domain where signal deconvolution and transfer function definition can proceed with simple mathematical manipulations. The attenuation coefficient, being a function of frequency, is likewise defined in the frequency domain,

$$\alpha = cf^m \qquad (2)$$

where, f is frequency and c and m are experimental constants (Vary, 1978b; Serabian, 1980), given that scatter attenuation prevails.

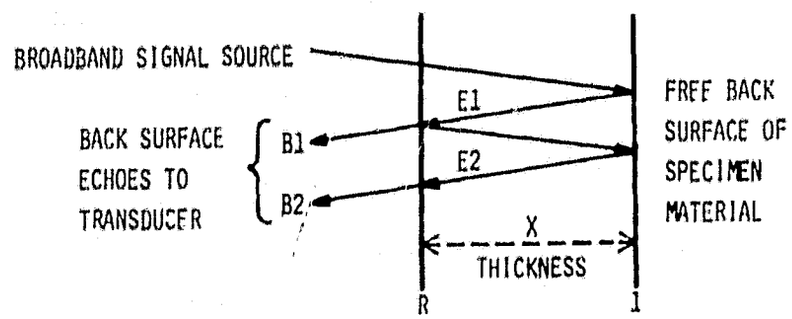


Fig. 12. Diagram of echo system showing quantities involved in the definition of the material ultrasonic transfer function.

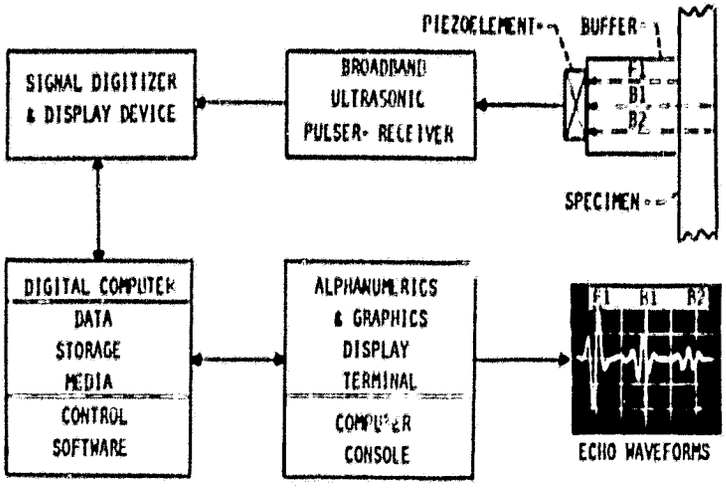


Fig. 13. Diagram of system for ultrasonic signal acquisition and analysis in time and frequency domains (Vary, 1979b).

As indicated in Fig. 12, a broadband ultrasonic pulse signal produces a series of back surface echoes in the material specimen. The first two back surface echoes B1 and B2 re-enter the ultrasonic transducer which acts as sender and receiver, Fig. 13. It is appropriate to take the internal echo E1 as the source signal for B1, thus,

$$B1 = (1+R)E1 \tag{3}$$

where, (1+R) is the transmission function at the specimen-transducer interface (Truell, et al, 1969). A portion of the energy of E1 is reflected and appears as the second internal echo E2, giving,

$$B2 = TR(1+R)E1 \tag{4}$$

where, the transfer function T incorporates signal modulation factors associated with the material microstructure (e.g., grain scattering, absorption, etc.) and interface effects. Combining the two preceding equations,

$$T = B2/RB1 \tag{5}$$

The transfer functions associated with coupling and other factors of signal transduction were ignored as they cancel out just as the term (1+R)(E1) vanishes upon combining Equations (3) and (4) to get (5). It has been shown by Papadakis (1976) that the attenuation coefficient can be measured by frequency spectrum analysis and that,

$$\alpha = (1/2x)\ \ell n(RB1/B2) \tag{6}$$

where, x is specimen thickness.

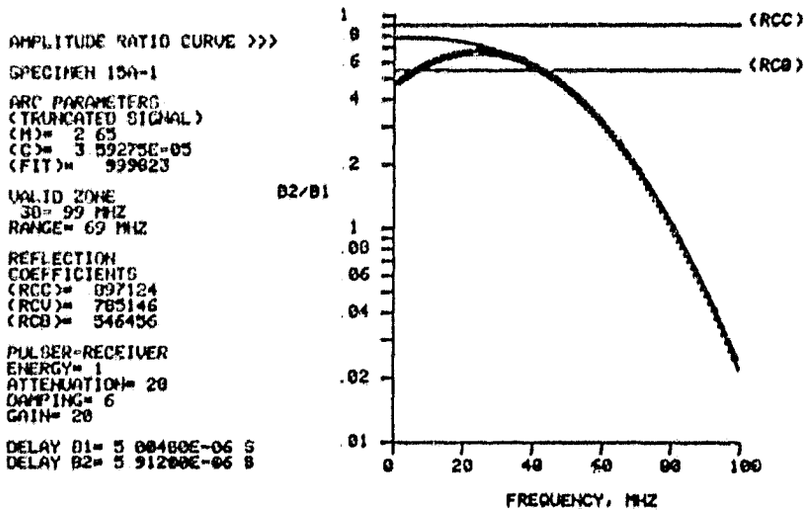


Fig. 14. Computer documentation of amplitude ratio curve and data associated with signal acquisition and analysis. The ratio B2/B1 as a function of frequency is the ultrasonic transfer function of the specimen material (Vary, 1979b).

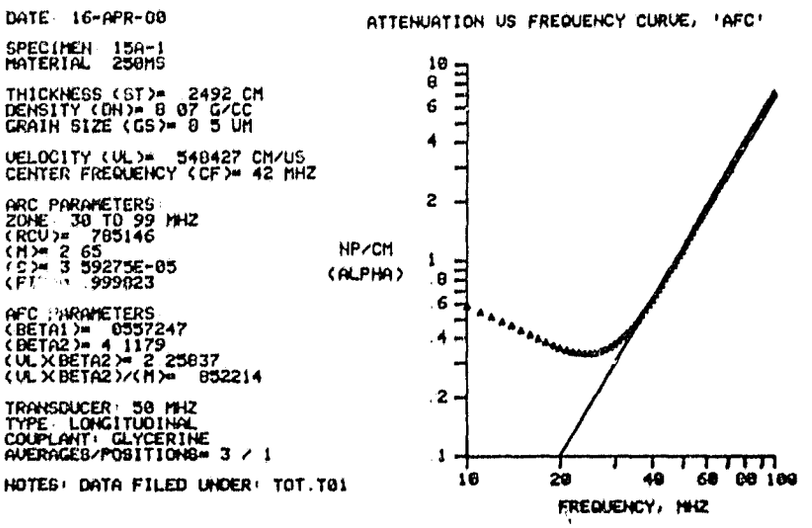


Fig. 15. Computer documentation of attenuation as a function of ultrasonic frequency and associated data. The straight line (through the raw data derived from Fig. 14) is the computed attenuation vs. frequency curve for the specimen material (Vary, 1979b).

By noting that the ratios, B2/B1, appearing in Equations (5) and (6) are identical functions of ultrasonic frequency, we have,

$$T = \exp(-2x\alpha) \tag{7}$$

that is, the material transfer function or ultrasonic wave filtering characteristic is defined in terms of the attenuation coefficient and reflection coefficient. For nondispersive materials, the reflection coefficient R is independent of frequency. It is a function of material velocity and density (Truell et al, 1969; Papadakis, 1976). Recalling that B1 and B2 were taken as Fourier transforms of corresponding time domain echoes, it is clear that Equation (5) gives the transfer function T as the ratio of the frequency spectra of time domain waveforms. Therefore, in complex polar form,

$$T = (1/R)(a2/a1)\exp(i\phi) \tag{8}$$

where, a1 and a2 are the amplitude spectra for signals B1 and B2, respectively, while $\phi$ is the difference in phase spectra ($\phi 2$-$\phi 1$). Here, T represents the deconvolution of the time domain counterparts of B1 and B2 (Newhouse and Fugason, 1977; Bracewell, 1978).

Equations (7) and (8) are a basis for determining material properties by means of ultrasonic spectrum analysis and associated ultrasonic attenuation measurement. The essential operations for accomplishing this, as implemented by a computer system, are illustrated in Figs. 14 and 15. A number of ultrasonic factors derived from material transfer function and attenuation curves have proven to correlate well with microstructure, fracture toughness, and yield strength in metals, as discussed in the following section.

## FRACTURE TOUGHNESS AND ATTENUATION

The feasibility of ultrasonic measurement of plane strain fracture toughness has been demonstrated for two maraging steels and a titanium alloy (Vary, 1978b). A principal ultrasonic factor that correlates with fracture toughness is $\beta$ which is the slope, $d\alpha/df$, of the attenuation versus frequency curve, Equation (2). The constants c and m for the material microstructure are established by the frequency domain analyses represented in Figs. 14 and 15. The correlations that have been found are shown in Figs. 16, 17, and 18.

Fracture toughness, yield strength, and related microstructural factors are apparently intimately connected with ultrasonic and hence (stress) wave propagation factors in polycrystalline metallic materials. The empirical correlations that are exhibited in Figs. 16 through 18 imply that stress wave interactions are important during rapid (catastropic) crack extension, as under the conditions for determining fracture toughness (Brown and Srawley, 1966).

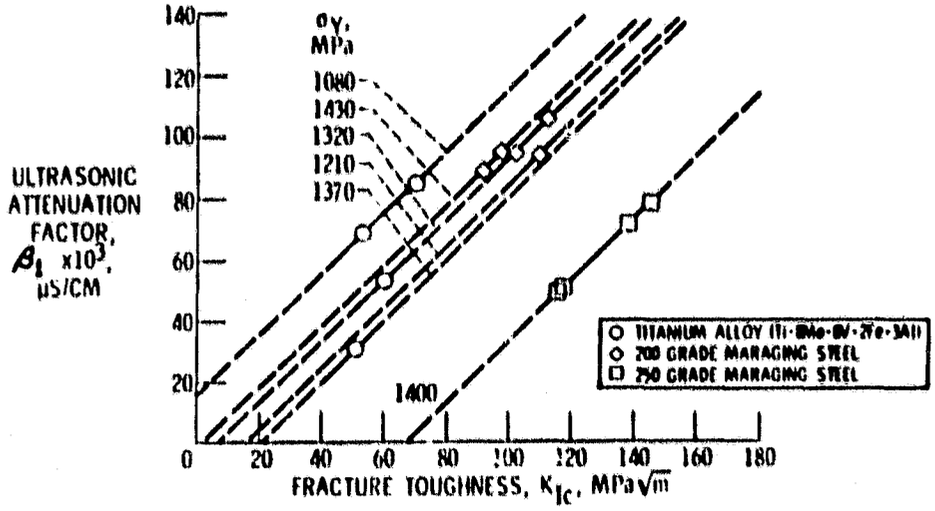


Fig. 16. Ultrasonic attenuation factor $\beta_1$ as a function of fracture toughness $K_{Ic}$ and yield strength $\sigma_Y$ for three metals. The material specimens that share the same yield strength are represented on the same line, for example, the 250-grade maraging steels with $\sigma$=1400 MPa (Vary, 1978b).

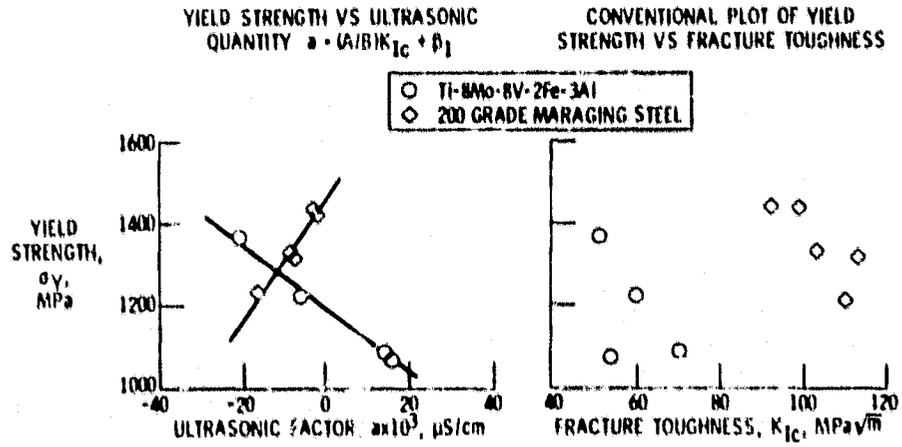


Fig. 17. Correlations of yield strength to fracture toughness for a titanium alloy and a maraging steel. The lefthand graph is based on data from Fig. 16 and combines the ultrasonic factor $\beta_1$ with fracture toughness $K_{Ic}$ in the quantity a as defined above the figure (Vary, 1978b).

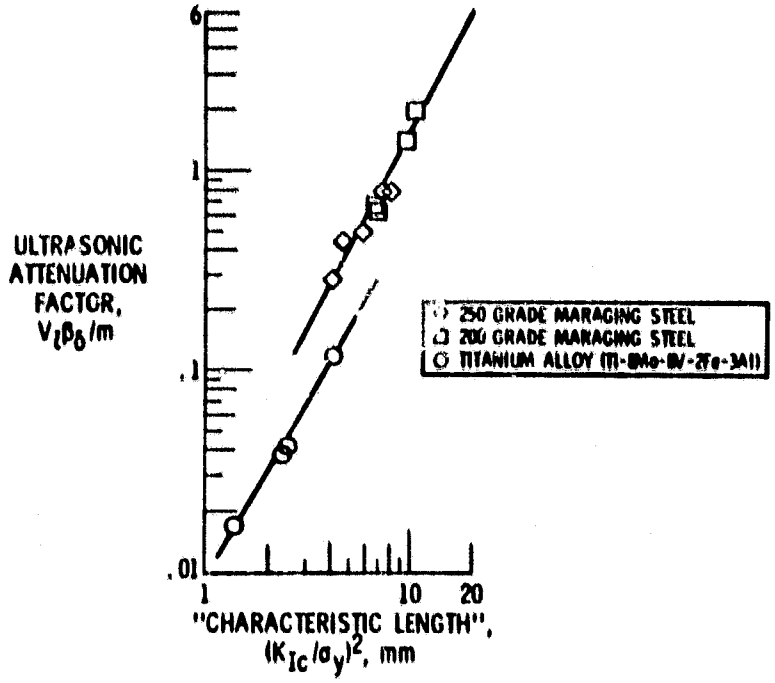


Fig. 18. Experimental correlation of ultrasonic attenuation factor and fracture toughness "characteristic length" factor for three metals. The experimental data agree with theoretical relation given by Equation (9) (Vary, 1979a).

It can be inferred that spontaneous stress waves generated during crack nucleation will contribute to promoting the onset of rapid unstable crack extension. A stress wave interaction model based on this idea was used to derive equations that predict the empirical correlations shown in Figs. 17 and 18 (Vary, 1979a). For the polycrystalline aggregates for which the equations were derived there exists a close relation between fracture toughness and yield strength. This accounts for the appearance of yield strength $\sigma_y$ in the equations connecting plane strain fracture toughness $K_{Ic}$ and the ultrasonic attenuation factor $\beta$,

$$(K_{Ic}/\sigma_y)^2 = M(v_\ell\beta_\delta/m)^{\frac{1}{2}} \qquad (9)$$

$$\sigma_y \mp AK_{Ic} \pm B\beta_1 = C \qquad (10)$$

where, $v_\ell$ is velocity and A, B, C, and M are experimental constants that are related to material microstructural factors. The quantity $\beta_1$ is the derivative $d\alpha/df$ evaluated at an attenuation coefficient $\alpha=1$, while $\beta_\delta$ is $d\alpha/df$ evaluated at a particular threshold frequency that corresponds to a critical ultrasonic wavelength in the material. This wavelength is related to the mean grain boundary spacing. Equation (9) describes the lines through the data in Fig. 18 while equation

(10) describes the lines through the data in Fig. 17. The empirical coefficient A and B in Equation (10) carry opposite algebraic signs that appear to depend on the mode of fracture. Thus, if these coefficients are experimentally determined for a material that fractures in a predominantly brittle manner, A assumes a negative sign, giving a negative slope as for the line for titanium in Fig. 17. The coefficients and associated quantities in Equation (10) apparently relate to modes of stress wave energy dissipation, residual strain in crack nucleation sites, and whether the nucleation sites are energy "sinks" or "sources" during fracture. The coefficient M in Equation (9) appears to be related to microstructural factors such as grain size, lath spacing, ligament length (Hahn et al, 1972). The quantity m in Equation (9) is the exponent on frequency in Equation (2). Once these experimental constants have been determined for a material, Equations (9) and (10) can be taken as simultaneous relations to solve for $K_{Ic}$ and $\sigma_y$ in terms of the ultrasonic factors.

## CONCLUDING REMARKS

The ultrasonic NDE approaches and results that have been highlighted herein indicate potentials for material characterization and property prediction. Stress wave interaction and material transfer function concepts were cited as bases for explaining correlations between material mechanical behavior and ultrasonically-measured quantities. It is observed that the criticality and effect of any discrete flaw (crack, inclusion, or other stress raiser) is definable only in terms of its material microstructural environment. This underscores the importance of ultrasonic techniques that can characterize stress wave energy transfer properties of a material.

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