

## **General Disclaimer**

### **One or more of the Following Statements may affect this Document**

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

**NASA TECHNICAL  
MEMORANDUM**

**NASA TM-78905**

NASA TM-78905

**QUANTITATIVE ULTRASONIC EVALUATION OF MECHANICAL  
PROPERTIES OF ENGINEERING MATERIALS**

by Alex Vary  
Lewis Research Center  
Cleveland, Ohio 44135

TECHNICAL PAPER to be presented at the  
First International Symposium on Ultrasonic Materials Characterization  
cosponsored by the National Bureau of Standards and the  
American Society for Nondestructive Testing  
Gaithersburg, Maryland, June 7 to 9, 1978



1. Report No. <b>NASA TM-78905</b>	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle <b>QUANTITATIVE ULTRASONIC EVALUATION OF MECHANICAL PROPERTIES OF ENGINEERING MATERIALS</b>		5. Report Date	
		6. Performing Organization Code	
7. Author(s) <b>Alex Vary</b>		8. Performing Organization Report No. <b>E-9640</b>	
		10. Work Unit No.	
9. Performing Organization Name and Address <b>National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135</b>		11. Contract or Grant No.	
		13. Type of Report and Period Covered <b>Technical Memorandum</b>	
12. Sponsoring Agency Name and Address <b>National Aeronautics and Space Administration Washington, D. C. 20546</b>		14. Sponsoring Agency Code	
		15. Supplementary Notes	
16. Abstract <p>Current progress in the application of ultrasonic techniques to nondestructive measurement of mechanical strength properties of engineering materials is reviewed. A hitherto dormant concept in nondestructive evaluation (NDE) is invoked: Even where conventional NDE techniques have shown that a part is free of overt defects, advanced NDE techniques should be available to confirm the material properties assumed in the part's design. There are many instances where metallic, composite, or ceramic parts may be free of critical defects while still being susceptible to failure under design loads due to inadequate or degraded mechanical strength. This must be considered in any failure prevention scheme that relies on fracture analysis. This review will discuss the availability of ultrasonic methods that can be applied to actual parts to assess their potential susceptibility to failure under design conditions. It will be shown that ultrasonic methods will yield measurements of elastic moduli, microstructure, hardness, fracture toughness, tensile strength, yield strength, and shear strength for a wide range of materials (including many types of metals, ceramics, and fiber composites). It will also be indicated that although most of these methods have been shown feasible in laboratory studies, more work is needed before they can be used on actual parts in processing, assembly, inspection, and maintenance lines.</p>			
17. Key Words (Suggested by Author(s)) <b>Nondestructive evaluation; Ultrasonics; Materials characterization; Attenuation; Velocity; Frequency; Resonance</b>		18. Distribution Statement <b>Unclassified - unlimited STAR Category 38</b>	
19. Security Classif. (of this report) <b>Unclassified</b>	20. Security Classif. (of this page) <b>Unclassified</b>	21. No. of Pages	22. Price*

\* For sale by the National Technical Information Service, Springfield, Virginia 22161

QUANTITATIVE ULTRASONIC EVALUATION  
OF MECHANICAL PROPERTIES OF  
ENGINEERING MATERIALS

Alex Vary

National Aeronautics and Space Administration  
Lewis Research Center  
Cleveland, Ohio 44135

ABSTRACT

Current progress in the application of ultrasonic techniques to nondestructive measurement of mechanical strength properties of engineering materials is reviewed. A hitherto dormant concept in nondestructive evaluation (NDE) is invoked: Even where conventional NDE techniques have shown that a part is free of overt defects, advanced NDE techniques should be available to confirm the material properties assumed in the part's design. There are many instances where metallic, composite, or ceramic parts may be free of critical defects while still being susceptible to failure under design loads due to inadequate or degraded mechanical strength. This must be considered in any failure prevention scheme that relies on fracture analysis. This review will discuss the availability of ultrasonic methods that can be applied to actual parts to assess their potential susceptibility to failure under design conditions. It will be shown that ultrasonic methods will yield measurements of elastic moduli, microstructure, hardness, fracture toughness, tensile strength, yield strength, and

E-9640

shear strength for a wide range of materials (including many types of metals, ceramics, and fiber composites). It will also be indicated that although most of these methods have been shown feasible in laboratory studies, more work is needed before they can be used on actual parts in processing, assembly, inspection, and maintenance lines.

QUANTITATIVE ULTRASONIC EVALUATION OF MECHANICAL  
PROPERTIES OF ENGINEERING MATERIALS

Alex Vary

National Aeronautics and Space Administration  
Lewis Research Center  
Cleveland, Ohio 44135

INTRODUCTION

It is true that the most urgent problem in nondestructive evaluation (NDE) is usually that of flaw detection. Thus, the chief objective of ultrasonic NDE is the location and characterization of cracklike flaws and similar imperfections. However, the same ultrasonic waves that are used for flaw detection can also be used for indirectly measuring the inherent strengths of unflawed materials.

There is a growing consensus that the field of NDE encompasses a wider area than merely that of overt defect detection. Recent studies have shown that NDE methods can supplement and in some cases replace destructive methods for characterizing the properties of engineering materials. The need for nondestructive methods for determining engineering properties as well as actual flaw detection has been a theme in a number of previous papers<sup>1-4</sup>.

In many instances the NDE approach offers distinct advantages. In conjunction with traditional destructive tests, nondestructive techniques can be used to reduce the cost of materials testing. Accelerated testing of new

materials would benefit from NDE technology since there would be less need for large, specialized, or expensive test specimens. Moreover, once conventional nondestructive inspection has either detected or shown a particular part to be free of overt defects, advanced NDE can confirm the material properties assumed in the part's design. In this latter instance, NDE methods would verify material properties of an actual component rather than relying on tabulated values based on prior screening tests. Examples are the ultrasonic determination of bond strength in adhesive joints or fracture toughness of high strength structural components.

The chief purpose of this paper is to indicate recent advances in the application of ultrasonics to the nondestructive evaluation of material properties. A second purpose is to set forth a rationale for increased study and use of ultrasonics to characterize material properties. It will be seen that ultrasonic methods have demonstrated capabilities both for direct assessment of mechanical strength and for use in materials selection and development activities. The reviews given herein include brief accounts of recent and ongoing work at the NASA Lewis Research Center in the areas of ultrasonic evaluation of fiber composite strength and metal fracture toughness properties.

## BACKGROUND

A consideration of fracture prevention principles and an analysis of failure causes leads to the recognition of the vital role of NDE in assuring the reliability of high performance materials<sup>5-7</sup>. Table I lists material deficiencies that can reduce strength or performance. Table II lists material properties that can be evaluated nondestructively in efforts to reduce failure causes listed in table I.

To appreciate the role of NDE in material properties determination, it is necessary to distinguish between two kinds of flaws: First, there are those overt flaws that can be individually detected and characterized (e.g., cracks in metals, delaminations in composites). Second, there are those flaws that are so numerous, microscopic, and dispersed that their presence is detected only in their effect on bulk properties (e.g., toughness, strength). Overt flaws or flaws of the first type are typically stress raisers and fracture nuclei. Dispersed flaws or flaws of the second type are those that predispose a material part to failure even under design conditions.

An example of the utility of ultrasonic NDE is provided by the requirements for determining and verifying the fracture toughness of high strength alloys<sup>8-9</sup>. The need for rapid and inexpensive tests for determining fracture toughness has led to the investigation of ultrasonic correlations with fracture toughness factors<sup>10</sup>. The



correlations that have been developed indicate that purely ultrasonic methods can be used to verify a material's plane strain fracture toughness. In its present form, ultrasonic toughness testing is geared primarily to laboratory tests of small metal specimens. Were the method adapted for field applications, ultrasonic toughness testing could become an important inspection tool in addition to the detection of voids and cracks in fracture-prone components.

In the past, material property characterization has been the province of those branches of materials science that employ destructive test techniques or nondestructive tests on highly specialized specimens. The relation of NDE to destructive testing (DT) and nondestructive testing (NDT) is illustrated in table III. Given the perspective of table III, NDE is seen as a bridge between materials research and hardware inspection. Underlying sciences are also indicated for the major areas in table III. Physical acoustics, the scientific basis for ultrasonic NDE and NDT, is pivotal in the measurement of the material properties given in table II. An overview and illustrative cases of practical applications of physical acoustics in ultrasonic NDE are given below.

#### TECHNOLOGY OVERVIEW

There are, of course, numerous techniques other than ultrasonic ones (e.g., radiometry, eddy current, etc.) that can be used for material properties evaluation<sup>11</sup>. Many of these are alternatives that can complement or corroborate

ultrasonic measurements. A review of existing ultrasonic techniques shows that considerable advances have been made in the sophistication of flaw detection and characterization methods<sup>12-20</sup>. In addition, there is an emerging literature concerned with materials characterization through the ultrasonic assessment of microstructure and elastic moduli. It will be clear presently that ultrasonic signals recovered from material specimens can be a rich source of information relative to physical properties and material strength of engineering components. Table IV summarizes the current capabilities of ultrasonics for properties and strength characterizations.

Progress in the use of ultrasonics for evaluation of material strength related properties may be categorized into three overlapping stages:

- (1) Ultrasonic measurement of elastic constants
- (2) Ultrasonic measurement of microstructure
- (3) Ultrasonic measurement of mechanical strength

The last mentioned stage is the least developed and comprises the main focus of this report. The second stage will be discussed in relation to practical applications of ultrasonic attenuation theory. The first stage has usually involved physical acoustics applied to crystalline and atomic-scale phenomena. However, it will be evident that ultrasonic moduli (formed by the product of velocity squared and density) are related to elastic moduli and hence strengths of polycrystalline and composite materials.

Physical acoustics generally encompasses the study of wave propagation and the interpretation of velocity and attenuation effects in solids<sup>21-23</sup>. Among the objectives of physical acoustics are the investigation of crystal imperfections, dislocation motions, internal friction, and elastic wave motions. The practical applications of physical acoustics involve the following ultrasonic measurements which are prominent in NDE:

- (1) Velocity - involving the analysis of longitudinal, transverse, and surface waves, and frequency dispersion<sup>12, 14</sup>
- (2) Attenuation - involving the analysis of absorption, scatter, and frequency dispersion<sup>12, 14, 20</sup>
- (3) Resonance - involving the analysis of continuous wave interactions<sup>13</sup>
- (4) Spectrum analysis - involving pattern analysis of frequency spectra<sup>15-17</sup>
- (5) Acoustic emission - involving analysis of simulated or spontaneous signals emitted during strain or fracture<sup>18</sup>
- (6) Acoustic microscopy - involving direct imaging of microstructure, wave interferometry<sup>12, 19</sup>

The above six measurement methods form the basis of ultrasonic evaluation of physical properties and material strength. Most of the cases to be cited below involve recent efforts that illustrate feasibility rather than current practice.

## ILLUSTRATIVE CASES

## Elastic Moduli

The earliest applications of ultrasonics to materials characterization involved the study of elastic constants, usually with specialized specimens such as single crystals. This work laid the foundations for ultrasonic characterization of polycrystalline, amorphous, and heterogeneous materials.

Physical acoustics theory indicates that the elastic behavior of solids can be determined by measurement of ultrasonic wave propagation. The measurement of longitudinal ( $v_l$ ) and transverse ( $v_t$ ) velocities yield the longitudinal (L) and shear (G) moduli, respectively, where,

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

For linear elastic, isotropic solids these two moduli are sufficient to completely describe elastic behavior, given interconnecting relations with other moduli, e.g., bulk modulus, Young's modulus, Poisson's ratio<sup>21</sup>. These relations provide a basis for ultrasonic correlations with mechanical strength properties even for less ideal materials.

The magnitudes of elastic constants are related directly to the strengths of some groups of brittle materials, e.g., concrete, ceramics, cast iron. Because the elastic modulus may be determined on the basis of longitudinal velocity, ultrasonic measurements can form the basis for determination of the tensile strength of

high-quality cast iron, for example<sup>13</sup>. To reduce the tensile strength in this case also requires the determination of Brinell hardness. Thus, by making two nondestructive measurements on a finished article an important strength property can be verified.

#### Microstructure

There is a considerable literature built on the ultrasonic study of grain size in metals<sup>14-20</sup>. Some of this literature grew from the need to understand the effects of grains, boundaries, and inclusions on flaw detection. Detection of small, critical flaws in many metals is hampered by "grain noise". Thus, attenuation and velocity variations associated with grain size variations in various metals have been studied in conjunction with determining limitations on ultrasonic flaw detection. In the process, strong correlations were discovered among ultrasonic wave transmission and material microstructure variations due to hardening, annealing, quenching, and cold work.

Ultrasonic velocity and attenuation measurements have been conducted with the object of verifying microstructure<sup>21-26</sup>. The coarseness and quantity of graphite in lamellar cast iron, for example, has been found to influence the velocity of longitudinal waves<sup>13</sup>. Since the amounts and forms of graphite affect the tensile strength of cast iron, velocity measurements can serve as a quality check for acceptance purposes.

Ultrasonic velocity and attenuation measurements can

also provide quality checks for light metals such as aluminum, magnesium, titanium, and their alloys. The mechanical strengths of these materials are influenced by segregations, precipitates, impurities, dispersoids, alloy concentrations, and so forth, which can be assessed by ultrasonic methods<sup>13</sup>.

Relative differences in microstructure of polycrystalline and amorphous solids can be determined by ultrasonic spectrum analysis<sup>15</sup>. The influence of grain size on frequency spectra has been demonstrated<sup>16</sup>. It is possible, for example, to ascertain the structural differences generated in carbon steels by different heat treatments by comparison with spectra obtained with reference samples. Heat treatments given to forged articles can be verified during the fabrication process. This capability meets a quality control requirement frequently expressed by steel processors.

Measurements of ultrasonic diffraction, dispersion, and scattering can contribute to material property assessment<sup>17</sup>. Some progress in this direction has been made by precise measurements of the frequency dependence of velocity and attenuation<sup>18, 25</sup>. It appears that indirect determinations of grain size in polycrystalline metals are possible through the measurement of the scatter attenuation coefficients  $\alpha_r$  and  $\alpha_s$ , where,

$$\alpha_r = D^3 f^4 S_r \quad \text{and} \quad \alpha_s = Df^2 S_s$$

The subscripts r and s pertain to Rayleigh and

stochastic scattering, respectively, while  $D$  is grain diameter,  $f$  is frequency, and  $S$  is an experimentally determined scattering factor. (Rayleigh scattering occurs when ultrasonic wavelength is  $>D$  and stochastic scattering when wavelength is  $<D$ , approximately.)

Acoustic microscopy affords advantages of direct microstructure imaging in the case of small articles. The technique visually reveals localized variations in the elastic properties of materials<sup>19, 27</sup>. Therefore, microstructural features that govern sound propagation will appear in acoustic micrographs. The technique permits examination and characterization of microelastic variations, grain structure, and micro-inclusions. Both qualitative and quantitative assessments of a wide range of ultrasonically transparent articles are possible.

#### Hardness

The nondestructive measurement of hardness in metals is routinely accomplished chiefly by indentation test methods. Ultrasonic methods for hardness determination have been studied as a key to rapid, on-line product verification<sup>28-29</sup>.

It has been found that ultrasonic velocity hardness measurements offer advantages over other methods in the rapid sorting of malleable cast iron<sup>28</sup>. The relationship between hardness and ultrasonic attenuation has also been demonstrated for some steels<sup>29</sup>. Direct correlations were found between Rockwell-C hardness and the attenuation

coefficient.

In the previously cited cases ultrasonic hardness tests were applied to the examination of bulk microstructural changes due to variations in heat treatment, density, and so forth. Recent studies have focused on hardness gradients associated with surface treatments<sup>30-31</sup>. Ultrasonic surface waves are promising in the measurement of variations with depth of properties such as density, case hardening, mechanical deformation, and gas diffusion in metals. For example, hardness gradients in quench hardened steel have been shown to correlate with the frequency dependence of the velocity of ultrasonic surface waves<sup>30</sup>.

#### Fracture Toughness

The investigation of ultrasonic attenuation as a function of frequency has led to useful correlations with a variety of material properties<sup>14, 20</sup>. The previous examples (under Microstructure and Hardness) emphasized nondestructive evaluations of material factors that are indirect indicators of strength. In the case of metals there have been some indications of the potentials of ultrasonic measurement of actual yield strength, impact strength, and fracture toughness<sup>32-34</sup>.

There are strong incentives for ultrasonic toughness tests<sup>8-9</sup>. One of the major cost drivers in using fracture controlled materials in aircraft is the requirement to verify toughness levels of materials at receiving inspection and after any processing that may adversely affect fracture



toughness. The major drawback of existing mechanical destructive tests for determining  $K_{Ic}$ , plane strain fracture toughness, is the high costs of machining and testing suitable specimens.

The feasibility of ultrasonic measurement of  $K_{Ic}$  has been demonstrated for two maraging steels and a titanium alloy<sup>33</sup>. Empirical correlations were found between ultrasonic attenuation factors and  $K_{Ic}$  and  $\sigma_y$ , the 0.2 percent yield strength, see fig. 1. The equation for fig. 1 is,

$$K_{Ic}^2 / \sigma_y = \psi (v \beta_\delta)^e$$

where,  $v$  is velocity,  $\beta_\delta$  is an ultrasonic attenuation factor, and  $\psi$  and  $e$  are experimental constants. In addition, figure 2 shows recent data that suggests a linear empirical relation of the form,

$$\sigma_y + AK_{Ic} + B\beta_1 = C$$

where,  $\beta_1$  is an ultrasonic attenuation factor and  $A$ ,  $B$ , and  $C$  are experimental constants that depend on the material involved<sup>33</sup>. Given the previous equations, it appears that the essential measurements for deducing fracture toughness and yield strength can be made by purely ultrasonic techniques once calibration curves have been established for a (polycrystalline) material<sup>34</sup>.

#### Bond Strength

The question of adhesive bond strength arises most frequently in aerospace structures which employ metal and composite laminated joints<sup>35-36</sup>. Ultrasonic resonance

methods are widely used in assessing the integrity of metal-to-metal adhesive bonds<sup>37</sup>. The nondestructive estimation of bond shear strength is based on a formula that incorporates the resonance frequency,  $f$ , adhesive thickness,  $t$ , metal thickness,  $d$ , and elastic modulus,  $L_t$ , of the adhesive layer,

$$f = \frac{1}{2\pi} \sqrt{2L_t / \rho t d}$$

The above equation is derived from the relation between velocity and longitudinal modulus given earlier:  $L = \rho v_l^2$ . Strength correlation obtained by resonance tests are, therefore, ultimately dependent on ultrasonic velocity in the adhesive layer. Application of the resonance method requires the establishment of calibration curves for each individual joint configuration and adhesive system.

Improved methods are being sought to evaluate the actual strength of bond in layered structures<sup>38-40</sup>. The assessment of bond strength is currently being pursued by means of frequency spectrum analysis methods that are considerably more sophisticated than the previously mentioned resonance method. The resultant correlations of spectral patterns with bond strength are encouraging. Interconnecting relations between velocity and attenuation in adhesive materials are being studied in efforts to evolve purely ultrasonic methods for predicting adhesive bond strength<sup>40</sup>.

#### Composite Strength

Effective design and reliability assurance of composite

materials depend on nondestructive methods for measuring mechanical properties before use and strength degradation during use. (In some fiber composites, for example, strength degradation can follow moisture absorption and matrix crazing.)

One approach for inferring strengths of fiber reinforced composites is that of velocity measurements to determine elastic moduli<sup>11-12</sup>. This approach is based on the familiar relations,  $L = \rho v_l^2$ , and  $G = \rho v_t^2$ . Another approach is that of measuring ultrasonic attenuation<sup>13-14</sup>. This latter approach is similar to that of ascertaining grain size in metals except that the emphasis usually is on determining microvoid content. Microvoids in fiber composites are known to be serious strength reducing factors.

Ultrasonic attenuation measurements afford a means of assessing microvoid content and hence (indirectly) material strength. The total attenuation coefficient,  $\alpha_c$ , of a microvoid containing material is given by,

$$\alpha_c = \alpha_b + \alpha_v$$

where,  $\alpha_b$  is attenuation coefficient under void-free conditions and  $\alpha_v$  is attenuation coefficient due to microvoids. (Both  $\alpha_b$  and  $\alpha_v$  may be frequency dependent.)

A problem peculiar to many fiber reinforced composites is the high degree of anisotropy due to fiber orientation. Ultrasonic methods for determining elastic constants must adapt to this situation. The effect of fiber orientation on

elastic properties has been studied by use of special ultrasonic transducer arrangements<sup>45-46</sup>. The empirical equation,

$$\rho v_{\theta}^2 = \gamma L_{\theta}$$

was found to describe seven composite materials ranging from glass/epoxy to boron/aluminum<sup>3</sup>. The subscript  $\theta$  refers to fiber angle in a series of laminate specimens. Velocity,  $v_{\theta}$  was measured in-plane, i.e., parallel to the major surfaces of the lamina. Good correlations were obtained between destructively measured tensile strength and the ultrasonic modulus,  $L_{\theta}$ .

Correlations between ultrasonic attenuation and interlaminar shear strength (as measured by short beam shear tests) have also been demonstrated<sup>44,47</sup>. In these instances, the attenuation coefficient was determined by introducing pulsed ultrasound perpendicular to the major surfaces of the lamina. Increased attenuation corresponded to lower interlaminar shear strength.

An acoustic-ultrasonic method for fiber composite strength evaluation was reported recently<sup>48-50</sup>. The method differs from those described above in its use of simulated acoustic emissions which are introduced into the composite laminate specimens. The simulated acoustic emission signals are analyzed to determine a "stress wave factor",  $\epsilon$ . The stress wave factor is a mixed function of attenuation, velocity, and resonance in the laminates. The method for measuring  $\epsilon$  produces a numerical value that can rank

specimen laminates according to strength. Correlations of  $\epsilon$  with composite shear strength have been found for graphite/polyimide laminates. Using the stress wave factor in conjunction with velocity demonstrated the feasibility of purely ultrasonic methods for indirect measurement of the interlaminar shear strength of fiber composite laminates<sup>10</sup>. For example,  $\tau$ , interlaminar shear strength, correlated with  $\epsilon$  and  $v$  through,

$$\tau' = \zeta (v - a) / (b - \epsilon)$$

where,  $\tau'$  is an estimator for  $\tau$  and  $\zeta$ ,  $a$ , and  $b$  are experimentally determined constants for a particular composite material, see fig. 3. (Both  $\epsilon$  and  $v$  were, in this case, measured with waves propagating in-plane and perpendicular to the fibers which were unidirectional.)

#### Ceramic Strength

The ultrasonic evaluation of ceramic materials of current technological importance presents special demands. Silicon nitrides and carbides are examples of candidate materials for use in future high temperature engines. Micron-size voids and inclusions can constitute serious flaws in these ceramics. Advanced high frequency ultrasonic techniques are needed simply to detect flaws of this nature. On the other hand, these minute flaws may be distributed in large numbers throughout the bulk of a ceramic article and thus affect bulk properties that can be ultrasonically determined without the need to detect individual flaws.

The literature on ultrasonic evaluation of ceramic

materials is dominated by studies of elastic wave propagation in fused silica, quartz, and other glasses<sup>2,3</sup>. Recent work on ultrasonic inspection of ceramics has generally dealt with microcrack detection and acoustic emission monitoring of crack growth. Some attempts have been made to apply ultrasonics to measure strength related properties of ceramics intermetallics<sup>2, 51</sup>. There is a gap in NDE technology applicable to the evaluation of ceramic components. Ultrasonic methods for verification of the density and microstructure of sintered and reaction bonded ceramics await development. Measurement of ultrasonic moduli in conjunction with destructive tests are needed to confirm material properties in actual ceramic parts. Ultrasonic methods would be most useful for measuring elastic constants of ceramic and other brittle and semi brittle materials (e.g., graphite) where other methods produce either poor or no results<sup>2</sup>.

#### ADDITIONAL CASES & CONSIDERATIONS

There are two major considerations that should guide the development of NDE technology for material strength evaluation:

- (1) Verification and control of material strength properties in actual parts.
- (2) Investigation and characterization of factors governing material strength properties.

The first consideration is a self evident counterpart of material specification, reliability assurance, and

inspection practices. The second consideration requires adoption of the view that NDE should be an integral part of materials testing practices.

In the usual conduct of destructive mechanical tests, specimens are inspected for dimensional conformity and overt flaws. However, little thought is given to the application of NDE methods to confirm the uniformity or quality of material specimens. Data scatter of over  $\pm 2$  percent is often accepted as an inherent consequence of test procedures. The opportunity to reduce this scatter and to gain more information is available with the ultrasonic techniques cited previously in this paper. In particular, ultrasonic technology has demonstrated capabilities for direct assessment of strength related properties such as elastic moduli, microstructure, hardness, toughness, etc.

In addition to pretest material characterization or property prediction, ultrasonics has proven utility for in situ monitoring as, for example, during fracture toughness testing<sup>52-53</sup>. In situ applications of ultrasonics can afford continuous monitoring of materials undergoing thermal or mechanical processing<sup>2</sup>. For example, velocity measurements during sintering of ceramics can serve to follow the process of pore formation. Distinct velocity changes observed during the process of polymer hardening can be utilized for process control. Controlling the melting process and phase formation in metallurgy can be accomplished by monitoring changes in ultrasonic velocity

and stopping the process at a critical stage.

A case for the addition of ultrasonic measurements to destructive test procedures is illustrated in fig. 2. By comparing the plots therein, it is evident that the addition of an ultrasonically measured factor  $\beta_1$  introduced considerably more coherence to the relation between fracture toughness and yield strength. Accordingly, it may be concluded that fracture toughness and yield strength are linked to ultrasonic stress wave propagation properties of polycrystalline materials. It appears that in addition to determining these material properties ultrasonic measurements can be significant in indicating factors that govern toughness and strength<sup>30</sup>.

The above examples suggest that ultrasonic interrogation of materials provides more than merely an assessment of static characteristics but provides an indication of dynamic response. That is, ultrasonic probing can apparently aid in studies of stress wave propagation factors that govern material response under static, quasi-static, and dynamic loading conditions<sup>54-55</sup>. It has been observed, for example, that polycrystalline, heterogeneous materials exhibit a distinct velocity dispersion (i.e.,  $v$  as a function of  $f$ ). From this it can be inferred that the elastic modulus will increase as velocity increases with frequency<sup>2</sup>. Knowledge of dynamic moduli would be of considerable importance in materials subjected to severe dynamic loads, e.g., composite fan



blades.

The above-discussed factors ultimately converge to enhance material specification, reliability assurance, and inspection. The availability of NDE to ascertain yield strength, hardness, microstructure, etc., can become a prime element in assuring that a structure meets stringent strength specifications when necessary. NDE for material grading and reliability assurance would certainly generate cost and safety benefits that outweigh the cost of method development and adaptation.

#### SUMMARY AND CONCLUSION

Applications of ultrasonics to direct nondestructive evaluation (NDE) of material strength properties were reviewed. It was shown that probing with ultrasonic waves will yield measurements of elastic moduli, microstructure, hardness, toughness, tensile strength, and shear strength for a wide range of materials (including many types of metals, ceramics, and fiber composites). The review also indicated that:

- (1) Reliability assurance should begin with NDE to verify material strength even in the absence of overt flaws particularly in critical high strength components.

- (2) Failures caused by processing errors, inherent material deficiencies, or strength degradations in service can be reduced by application of advanced ultrasonic methods.

(3) Materials screening and accelerated testing of new materials would benefit from ultrasonic NDE technology since there would be less need for large, specialized, and expensive test specimens.

(4) Improved quality control during thermal and mechanical processing can be accomplished by ultrasonic monitoring of microstructural changes.

In order to implement the above concepts, advanced technique development is required to assure the availability of ultrasonic methods and devices for strength evaluations of critical articles of high strength alloys, high temperature ceramics, and advanced fiber composites. Research reports on these topics are scarce. The greatest current need, therefore, is the development of theory and empirical correlations that will further establish and confirm ultrasonic capabilities for direct evaluation of material strengths. In particular, development of relationships based on solid state and physical acoustics theory would be of great benefit and would probably extend the usefulness of these techniques. Although some advanced ultrasonic methods have been created and shown feasible in laboratory studies, more work is needed before these methods can be used on actual parts in processing, assembly, inspection, and maintenance lines.

## REFERENCES

1. Sharpe, R. S. "Innovation and Opportunity in NDT," British Journal of Non-Destructive Testing, 18, no. 4 (1976): 98.
2. Malecki, I. "Application of Ultrasonic Physics in Material Technology", Archives of Acoustics 2, no. 1 (1977): 3.
3. Zurbrick, J. R. "Direct Nondestructive Prediction of Engineering Properties," Journal of Testing and Evaluation 1, no. 1 (1973): 13.
4. McSkimin, H. J. Proc. of the Symposium on Physics and Nondestructive Testing, W. J. McGonnagle, ed., San Antonio, Texas: Southwest Research Institute, 1962, pp. 83-111.
5. "Application of Fracture Prevention Principles to Aircraft," National Materials Advisory Board, Washington, D.C., NHAB-302, Feb. 1973.
6. Grover, H. Sourcebook in Failure Analysis. Metals Park, OH: American Society for Metals, 1974, pp. 31-39.
7. Dolan, T. J. Sourcebook in Failure Analysis. Metals Park, OH: American Society for Metals, 1974, pp. 31-39.
8. "Rapid Inexpensive Tests for Determining Fracture Toughness," National Materials Advisory Board,

- Washington, D.C., NMAB-328, 1976.
9. Berryman, R. G., Chesnutt, J. C., and Proes, P. H. "A New Cost-Effective Titanium Alloy with High Fracture Toughness," Metal Progress 112, no. 8 (1977): 40.
  10. Vary, A. "Ultrasonics Takes on Fracture Toughness Testing," Machine Design, 49, no. 25 (1977): 145.
  11. Vary, A. "Nondestructive Evaluation Technique Guide," NASA SP-3079, 1973.
  12. Silvas, H. S., Jr. "Advanced Ultrasonic Testing Systems: A State-of-the-Art Survey," Southwest Research Institute, San Antonio, Texas, NTIAC-77-1, Sep. 1976.
  13. Krautkramer, J., and Krautkramer, H. Ultrasonic Testing Of Materials. 2nd ed., New York: Springer-Verlag, 1977.
  14. Papadakis, E. P. Physical Acoustics. Vol. XII, W. P. Mason and R. N. Thurston, eds., New York: Academic Press, 1976, pp. 277-374.
  15. Gericke, O. R. Research Techniques in Nondestructive Testing. R. S. Sharpe, ed., London: Academic Press, 1970, pp. 31-61.
  16. Canella, G., and Monti, F. "Spectrum Analysis: A New Tool for Quality Control by Ultrasonics," Non-Destructive Testing International 9, no. 4 (1976): 187.
  17. Brown, A. F. "Materials Testing by Ultrasonic Spectroscopy," Ultrasonics 11, Sep. (1973): 202.

18. Liptai, R. G., Harris, D. O., Engle, R. B., and Tatro, C. A. "Acoustic Emission Techniques in Materials Research," International Journal of Nondestructive Testing 3 (1971): 215.
19. Kessler, L. W., and Yuhas, D. E. "Structural Perspective," Industrial Research 20, no. 1 (1978): 52.
20. Rogers, E. H. "A Report Guide to Ultrasonic Attenuation Literature," Army Materials Research Agency, Watertown, Mass., AMRA-MS-65-09, Dec. 1965. (AD 627565.)
21. Schreiber, E., Anderson, O. L., and Soga, N. Elastic Constants and Their Measurement. New York: McGraw Hill, 1973.
22. Green, F. E., Jr. Ultrasonic Investigation of Mechanical Properties. New York: Academic Press, 1973.
23. Mason, W. P. Physical Acoustics and the Properties of Solids. New York: D. van Nostrand Co. Inc., 1958.
24. Papadakis, E. P. "Revised Grain-Scattering Formulas and Tables," Journal of the Acoustical Society of America 37, no. 4 (1965): 703.
25. Papadakis, E. P. "Variation of Ultrasonic Grain-Scattering Factors with Velocity," Journal of the Acoustical Society of America 43, no. 4 (1968): 876.
26. Papadakis, E. P. "Ultrasonic Attenuation Caused by Scattering in Polycrystalline Metals," Journal of the Acoustical Society of America 37, no. 4 (1965): 711.

27. Szilard, J., and Scruton, G. 1974 Ultrasonic Symposium Proceedings. New York: IEEE, 1974, pp. 707-710.
28. Tamburelli, C., and Quaroni, A. "Ultrasonic Velocity Measurement to Inspect Malleable Iron Casting," Non-Destructive Testing 8, no. 3 (1975): 152.
29. Roderick, R. L., and Truell, R. "The Measurement of Ultrasonic Attenuation in Solids by the Pulse Technique and Some Results in Steel," Journal of Applied Physics 23, no. 2 (1952): 267.
30. Tittmann, B. R., and Thompson, R. B. Ninth Symposium on Nondestructive Evaluation. San Antonio, Texas: Southwest Research Institute, 1973, pp. 20-28.
31. Tittmann, B. R., Alers, G. A., Thompson, R. B., and Young, R. A. 1974 Ultrasonic Symposium Proceedings. New York: IEEE, 1974, pp. 561-564.
32. Papadakis, E. P. "Ultrasonic Attenuation in SAE 3140 and 4150 Steel," Journal of the Acoustical Society of America 32, no. 12 (1960): 1628.
33. Vary, A. "Correlations Among Ultrasonic Propagation Factors and Fracture Toughness Properties of Metallic Materials," NASA TM X-71889, 1976.
34. Vary, A. "Correlations Between Ultrasonic and Fracture Toughness Factors in Metallic Materials," NASA TM-73805, 1978.
35. Forney, D. M., Jr. "NDI in the United States Air Force," The British Journal of Non-Destructive Testing

- 19, no. 3 (1976): 72.
36. Schliekelmann, R. J. "Nondestructive Testing of Adhesive Bonded Metal-to-Metal Joints," Non-Destructive Testing 5, no. 3 (1972): 129.
37. Van der Schee, E. J., and Bijlmer, P. F. A. "Non-Destructive Inspection Practices," E. Bolis, ed., Vol. 1, AGARD-AG-201, Brussels: North Atlantic Treaty Organization, 1975, pp. 91-128.
38. Alers, G. A. "Proceeding of the ARPA/AFML Review of Progress in Quantitative Non-Destructive Evaluation," Air Force Materials Labs., AFML TR-77-44, Sep. 1977, pp. 52-58.
39. Buckley, M. J., and Raney, J. M. "Proceeding of the ARPA/AFML Review of Progress in Quantitative Non-Destructive Evaluations," Air Force Materials Lab., AFML TR-77-44, Sep. 1977, pp. 66-73.
40. Flynn, P. L. "Proceedings of the ARPA/AFML Review of Progress in Quantitative Non-Destructive Evaluation," Air Force Materials Lab., AFML TR-77-44, Sep. 1977, pp. 59-65.
41. Dean, G. D., and Lockett, F. J. Analysis of Test Methods for High Modulus Fibers and Composites. ASTM STP-521, Philadelphia: ASTM, 1973, pp. 326-346.
42. Martin, G. Metal and Ceramic Matrix Composites. L. W. Davis and S. W. Bradstreet, eds., Boston: Cahners Publ. Co., 1970, pp. 133-173.
43. Martin, G. "Ultrasonic Attenuation Due to Voids in

Fiber-Reinforced Plastics," Non-Destructive Testing International, 9, no. 5 (1976): 242.

44. Stone, D. E. W., and Clarke, B. "Ultrasonic Attenuation as a Measure of Void Content in Carbon-Fibre Reinforced Plastics," Non-Destructive Testing 8, no. 3 (1975): 137.
45. Hastings, C. H., Olster, E. F., and Lopilato, S. A. "Development and Application of Nondestructive Methods for Predicting Mechanical Properties of Advanced Reinforced Nonmetallic Composites," Air Force Materials Lab., AFML TR-73-157, May 1973.
46. Schultz, A. W. "The Development of Nondestructive Methods for the Quantitative Evaluation of Advanced Reinforced Plastic Composites," Air Force Materials Lab., AFML TR-70-20, Aug. 1970. (AD-875229.)
47. Hayford, D. T., Hennecke, E. G. II., and Stinchcomb, W. W. "The Correlation of Ultrasonic Attenuation and Shear Strength in Graphite/Polyimide Composites," Journal of Composite Materials 11, Oct. (1977): 429.
48. Vary, A., and Bowles, K. J. "Ultrasonic Evaluation of the Strength of Unidirectional Graphite/Polyimide Composites," NASA TM X-73646, 1977.
49. Vary, A., and Bowles, K. J. "Use of an Ultrasonic Acoustic Technique for Nondestructive Evaluation of Fiber Composite Strength," NASA TM-73813, 1978.
50. Vary, A., and Lark, R. P. "Correlations of Fiber Composite Tensile Strength with the Ultrasonic Stress



- Wave Factor," NASA TM-78846, 1978.
51. Papadakis, E. P. "Sonic and Ultrasonic Methods for Nondestructive Testing of Catalytic Converter Substrates," Materials Evaluation 34, no. 2 (1976): 25.
  52. Tetelman, A. S., and Chow, R. Acoustic Emission. ASTM STP-505, Philadelphia: ASTM, 1972, pp. 30-40.
  53. Klima, S. J., Fisher, D. M., and Buzzard, R. J. "Monitoring Crack Extension in Fracture Toughness Tests," Journal of Testing and Evaluation 4, no. 6 (1976): 397.
  54. Curran, D. R., Seaman, L., and Shockey, D. A. "Dynamic Failure in Solids," Physics Today 30, no. 1 (1977): 46.
  55. Kolsky, H. Stress Waves in Solids. New York: Dover Publishing, 1963.

**TABLE I. - FAILURE CAUSES THAT  
GENERATE THE NEED FOR NON-  
DESTRUCTIVE EVALUATION OF  
MATERIAL PROPERTIES**

<p><b>Faulty processing</b></p> <p>Wrong composition Inclusions Embrittling impurities Wrong material properties Casting defects Segregations Porosity Faulty heat treatment Faulty case hardening Residual stress Faulty surface treatment Excessive grain growth</p>
<p><b>Deterioration</b></p> <p>Microstructural changes from: local overheating, friction, grinding Corrosion or chemical attack Decarburization Internal oxidation Stress corrosion Corrosion fatigue Vibrational fatigue Radiation damage Excess deformation Atmospheric contamination Gas embrittlement</p>

TABLE II. - EXAMPLES OF  
MATERIAL PROPERTIES AND  
CHARACTERISTICS THAT  
CAN BE NONDESTRUCTIVELY  
EVALUATED

<b>Mechanical properties</b>
Tensile modulus
Shear modulus
Tensile strength
Yield strength
Shear strength
Fracture toughness
Hardness
<b>Metallurgical factors</b>
Microstructure
Grain size
Phase composition
Porosity
Inclusions
Hardening depth
Residual stress
Heat treatment
Anisotropy

ORIGINAL PAGE IS  
OF POOR QUALITY

TABLE III. - RELATION OF NONDESTRUCTIVE  
EVALUATION TO DESTRUCTIVE TESTING AND  
NONDESTRUCTIVE TESTING

← Materials research →		
← Hardware inspection →		
Destructive testing	Nondestructive evaluation	Nondestructive testing
Materials characterization, verification of properties, strength measurement, screening		
	Flaw detection and characterization, process and fabrication control, preservice and inservice inspection	
Underlying sciences		
Solid state physics dislocation theory metallography	Physical acoustics elastic wave theory ultrasonics	

TABLE IV. - CAPABILITIES OF ULTRASONICS FOR NONDESTRUCTIVE EVALUATIONS OF MATERIAL PROPERTIES

Material property	Ultrasonic measurement	Applicable materials	References
Longitudinal modulus	Longitudinal velocity	Most engineering solids	2, 13, 21
Shear modulus	Transverse velocity	Most engineering solids	2, 13, 21
Grain size, microstructure	Attenuation, acoustic microscopy	Polycrystalline metals, ceramics	13, 20, 24, 26, 27
Porosity, void content	Velocity, attenuation	Fiber composites, ceramics	44, 48, 51
Hardness or hardness gradient	Velocity, velocity dispersion	Polycrystalline metals	28, 29, 30, 31
Tensile strength	Velocity, stress wave attenuation	Brittle metals, ceramics, fiber composites	2, 13, 45, 46, 50
Yield strength	Frequency-dependent attenuation	Polycrystalline metals	33, 34
Fracture toughness	Frequency-dependent attenuation	Polycrystalline metals	33, 34
Bond shear strength	Resonance, spectrum analysis	Metal-metal adhesive bonds	37, 39, 40
Interlaminar shear strength	Attenuation, stress wave attenuation	Fiber composites	44, 47, 48

ORIGINAL PAGE IS  
OF POOR QUALITY

ORIGINAL PAGE IS  
OF POOR QUALITY

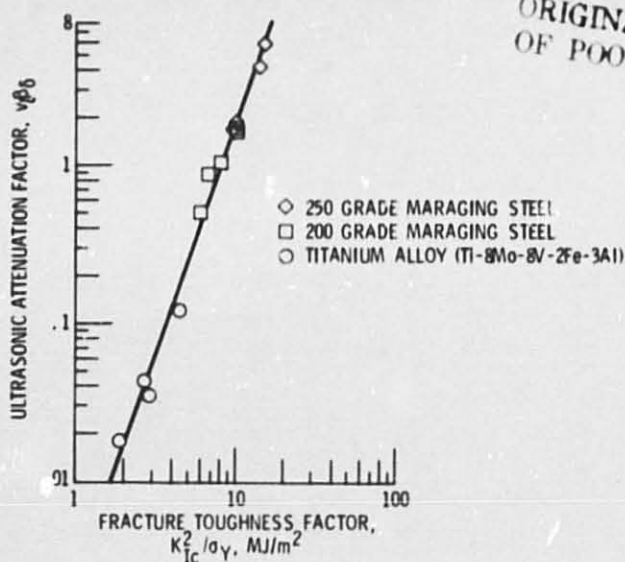


Figure 1. - Correlation of ultrasonic and fracture toughness factors. The ultrasonic attenuation factor  $v\beta\delta$  is based on measurements of longitudinal velocity,  $v_l$ , and the slope of the attenuation versus frequency curve,  $\beta\delta$ .  $K_{IC}$  and  $\sigma_y$  are the plane strain fracture toughness and 0.2 percent yield strength, respectively, as measured by destructive test methods (fig. from ref. 33).

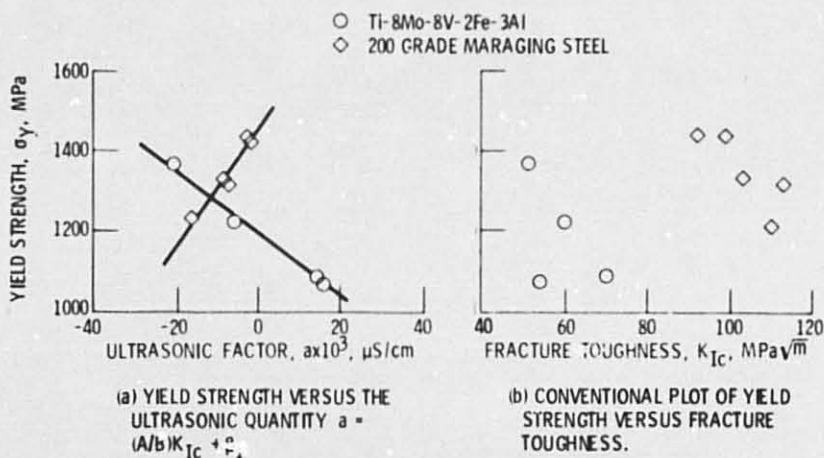


Figure 2. - Correlation of yield strength with fracture toughness via an ultrasonic factor. The ultrasonic quantity  $\beta_1$  is determined by the slope of the attenuation versus frequency curve evaluated at unit attenuation. The quantities A and B are experimentally measured ultrasonic constants for a given material.  $K_{IC}$  and  $\sigma_y$  are plane strain fracture toughness and 0.2 percent yield strength, respectively, as measured by destructive tests (fig. from ref. 33).

ORIGINAL PAGE IS  
OF POOR QUALITY

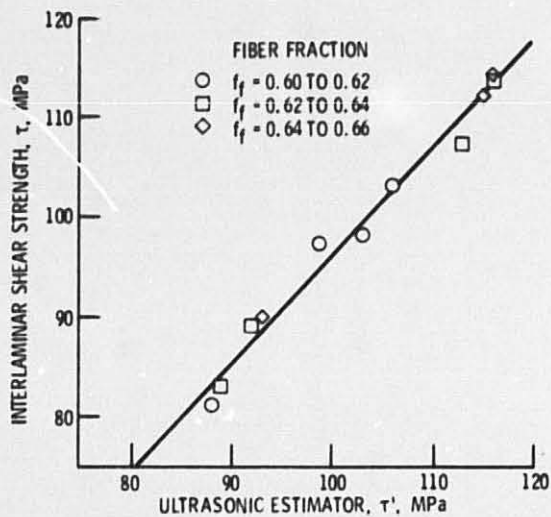


Figure 3. - Correlation of interlaminar shear strength and ultrasonic shear strength estimator. The above calibration curve was developed for graphite/polyimide fiber composite laminates. The ultrasonic shear strength estimator,  $\tau'$ , is based on velocity and stress wave attenuation measurements. The interlaminar shear strength,  $\tau$ , was obtained from short beam shear destructive tests (fig. from ref. 48).