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Nondestructive Techniques for Characterizing Mechanical Properties of Structural Materials—An Overview

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NONDESTRUCTIVE TECHNIQUES FOR CHARACTERIZING MECHANICAL PROPERTIES
OF STRUCTURAL MATERIALS - AN OVERVIEW

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SUMMARY

An overview of nondestructive evaluation (NDE) is presented to indicate the availability and application potentials of techniques for quantitative characterization the mechanical properties of structural materials. The purpose of this brief survey is to review NDE techniques that go beyond the usual emphasis on flaw detection and characterization. This survey covers current and emerging NDE techniques that can verify and monitor intrinsic properties (e.g., tensile, shear, and yield strengths; fracture toughness, hardness; ductility; elastic moduli) and underlying microstructural and morphological factors. Most of the techniques described are, at present, neither widely applied nor widely accepted in commerce and industry because they are still emerging from the laboratory. The limitations of the techniques may be overcome by advances in applications research and instrumentation technology and perhaps by accommodations for their use in the design of structural parts.

INTRODUCTION

The usual emphasis in NDE is on detection and characterization of a variety of discrete hidden flaws that can impair structural integrity and reduce life (i.e., cracks in metals, delaminations in composites, inclusions in ceramics, etc.). In failure prevention schemes, the specification of flaw critically and prediction of safe life depend on the assumption of a realistic set of extrinsic properties. Fracture analysis models presuppose flaw development in materials with "known" moduli, ultimate strengths, fracture toughness, and fatigue and creep properties.

There are emerging NDE techniques that may be used to verify the mechanical properties mentioned above and also to assess their degradation in service. Ultimately, these techniques may be adapted for application to a variety of materials and actual structural parts and help circumvent sole reliance on handbook or representative values based on prior screening or sampling tests. A holistic approach to reliability assurance would combine nondestructive characterization of flaws with characterization of material environments in which the flaws reside (Ruud and Green, 1983; Buck and Wolf, 1981; Vary 1984). This approach would engender more realistic assessments of structural integrity and service degradation by providing a better information base for fracture analysis and life prediction. The development and adaptation of the types of techniques discussed is needed to assure structural reliability and safe service life of components made of advanced materials in systems that demand efficient performance under extreme operating conditions.

The need for nondestructive materials characterization is indicated where local properties are critical or where the presence, identity, and distribution of potentially critical flaws can only be assessed statistically. In the latter case, flaws can be so microscopic, numerous, and dispersed that it is impractical to resolve them individually. Large populations of nonresolvable flaws may interact with each other (e.g., surface versus volume flaws) or with morphological anomalies. These interactions would be manifested as degraded bulk properties, (e.g. deficiencies in strength, toughness). While a structure may be free of discrete critical flaws, it may still be susceptible to failure because of inadequate or degraded intrinsic mechanical properties. This can arise from faulty material processing and/or degradation under aggressive service environments. It is for these reasons, amplified by the examples given in table I, that it is important to have nondestructive methods for quantitatively characterizing mechanical properties.

Ultimately, mechanical properties are controlled by composition, microstructure, and morphology (Rice, 1977). These factors also influence various NDE probe media, e.g., ultrasonic waves, electric currents, magnetic fields, x-rays, etc. (McMaster, 1959; Green, 1973; Vary, 1973; Anon., 1973). Modulations of probe media by materials give quantitative measurements that correlate to differing degrees with strength, hardness, toughness, and other properties.

Examples of current laboratory techniques with potentials for field use are reviewed in this paper. Most of the techniques described are, at present, neither widely applied nor widely accepted in commerce and industry. Adaptation to practical use on actual structural parts is still emerging from the laboratory in most instances. Wide application of the types of NDE techniques described herein await advances in applications research and instrumentation technology and in many cases will require design accommodations for their effective use.

TECHNIQUES

General

Nondestructive materials characterization techniques may be divided into two major categories. The first category pertains to NDE measurements that correlate with moduli, strength, hardness, toughness, and other extrinsic properties. The second category pertains to NDE measurements that correlate with morphological and microstructural factors that govern the previously mentioned properties (e.g., grain size distribution, elastic anisotropy, second and tertiary phases, etc.).

An inventory of NDE techniques that address the previously mentioned attributes of structural solids appears in table II. As indicated in table II, directly measured quantities include ultrasonic velocity and attenuation, electric current, magnetic flux, x-ray attenuation, and similar physical variables. The essential problem is that of evolving practical signal insertion/acquisition, processing, and analysis methods for relating NDE measurements to particular extrinsic properties exhibited by a material. Table II gives examples of extrinsic properties that can be directly measured by various NDE techniques. The following paragraphs elaborate on selected operational techniques

and methodologies in the principal areas of dynamic excitation, ultrasonic/acoustic, electromagnetic, penetrating and particle radiation, and photo-optical NDE.

Dynamic Excitation

Dynamic tests are among the oldest forms of NDE. The genera includes striking or coin tapping and listening to the sound produced (i.e., to determine if an object "rings true"). In modern versions of this acoustic "signature analysis" approach the vibrational frequencies are often beyond the audible range and require electronic instruments for signal acquisition and processing. These tests are nondestructive because amplitudes and mechanical strains are quite small and leave the material unaltered. They may be applied to simple laboratory specimens and also to structural parts having complex shapes. Automated acoustic signature analysis merits consideration for inferring the integrity and condition of a range of finished articles (McMaster, 1959; Vary, 1973).

Dynamic-sonic vibration techniques are suitable for studying microstructure-dependent properties (Nowich and Berry, 1973). Damping and resonant frequency measurements can be used to study phase transformations, plastic deformation, hardening, cold working, alloy composition effects, etc. (Uygur, 1980). Elastic moduli and dynamic constants of structural materials can be assessed for predicting dynamic response. Dynamic-sonic methods have been used to evaluate porosity and density in ceramics, fiber/resin ratio in composites, bond strength in laminates, and grain texture in metals (DiCarlo and Maisel, 1970; Papadakis and Kovacs, 1980).

Ultrasonic/Acoustic

Well established theory and experimental demonstrations underly ultrasonic velocity measurements of elastic constants such as longitudinal and shear moduli. Fundamental relations among elastic moduli and ultrasonic wave velocities are given in table III (Schreiber, et al., 1973; Green, 1973).

Measurement of elastic moduli are fundamental to understanding and predicting material behavior (e.g., bending moments, thermal expansion, strain under load, etc.). Since they are related to interatomic forces, elastic moduli indicate maximum attainable strength. In the case of brittle materials (e.g., ceramics) ultrasonic velocity measurements are preferred for measuring elastic moduli because of the minute strains usually exhibited by these materials under tension or compression. Magnitudes of elastic constants correlate directly with strengths for some classes of brittle materials. Combined ultrasonic longitudinal and transverse velocity measurements can form the basis for verifying the relative strengths of materials such as concrete, cast iron, and ceramics (Kraukramer, 1977).

Ultrasonic velocity measurements can form the basis for determining active and residual stress fields in a range of objects from bolts to railway tracks (Heyman, 1977; Bray, 1981). The underlying phenomenon for this is the variation of ultrasonic velocity with lattice strains (Noronha and Chapman, 1973). Ultrasonic birefringence, critical angle reflectivity, and combined ultrasonic/magnetic field measurements comprise auxiliary methods for residual stress evaluations (Namkung and Heyman, 1984).

Correlations between ultrasonic velocity and various other properties of solids also exist. For example, age hardening of aluminum and effects of carbon content in steels have been characterized by velocity measurements (Friant, et al., 1981; Heyman, et al., 1983). Empirical relations have been found that connect density (porosity) and velocity in monolithic ceramics (Klima, 1984; Klima and Baaklini, 1986). Combined velocity and attenuation measurements in metals correlate with microstructural factors like mean grain size, grain size distribution, and grain morphology (Vary, 1980; Generazio, 1986; Serabian, 1986).

Measurements of energy loss of ultrasonic waves interacting with material microstructures underly empirical correlations with mechanical properties. A fundamental equation, given in terms of energy intensity I at distance d from a source I_0 of ultrasound, is $I = I_0 \exp(-\alpha d)$, where α is the frequency-dependent attenuation coefficient. The attenuation coefficient includes effects of absorption and scattering of ultrasonic waves (e.g., by grains, second phase particles, etc. in polycrystalline solids). Attenuation measurements are most useful when made over a broad range of frequencies. In polycrystalline solids the frequency dependence of the attenuation coefficient correlates with a variety of extrinsic properties (e.g., strength, toughness) via the attenuating effects of microstructural factors on ultrasonic wave propagation (Vary, 1980; 1984).

Theoretical dependences of attenuation coefficient on frequency are indicated in table IV for polycrystalline aggregates (Serabian, 1980; Vary and Kautz, 1986). Functional relations between the attenuation coefficient and ultrasonic frequency for the various loss mechanisms indicated in table IV have been confirmed for a range of engineering solids (Mason and McSkimmin, 1947, 1948; Truell, et al., 1969). These relations form bases for ultrasonic evaluation, verification, and monitoring of mechanical properties governed by the microstructural factors involved. An example concerning the use of ultrasonic attenuation for determining fracture toughness is highlighted at a later point in this paper.

Assessments of mean grain size, morphological anomalies, anisotropies, laminations, inclusions, and debris in coarse grained, multiphase, or composite materials can apparently be accomplished by backscatter analysis. The procedures involve time domain analysis and/or frequency domain spectral analysis of backscatter echoes.

Time domain backscatter measurements have been shown to correlate quite well with metallographic measurements of grain size in steels (Goebbels, 1980). Frequency domain analysis of backscatter spectra have been used to characterize microstructural variations in a nickel base powder metal alloy (Tittmann, et al., 1986). Broadband spectroscopy has also been investigated for coarse grained and layered media (Bilgutay and Sanjie, 1984; Haines, et al., 1978). Broadband spectral analysis of either back or forward-scattered signals can result in spectral signatures that are peculiar to the material macro and/or micro-structure examined. Material variations might be monitored by comparison with standard signatures.

Thus far, only signal analysis, as opposed to image generation and analysis, methods have been discussed. Obviously, methods that produce images of material microstructures and morphological anomalies can convey essential information needed to characterize a material. Photomicrographs serve this

need but are obtained only by essentially destructive methodology. Nondestructive ultrasonic (and radiographic methods, discussed later) offer a means for imaging the internal constitution of materials. Moreover, images produced by ultrasonic waves will render additional information that differs from that produced by photo-optics (e.g., metallography). Ultrasonic imaging methods range from mechanical macroscans (Kraukramer, 1977; Jacobs, 1970) to acoustic microscopy (Kessler, 1977; Rosencwaig, 1979; Lemons and Quate, 1973).

A common operational macroscanning technique, the "immersion scan," produces a mapping of ultrasonic signal amplitude or velocity against spatial coordinates of the part being examined. On a smaller scale, acoustic microscopy produces images of only minute portions of test specimens. In either case, an image is rendered that shows spatial variations of elastic properties, grain structure and texture, density and porosity, and similar factors that affect the velocity, attenuation, diffraction, refraction, etc. of ultrasound. The spatial resolution of microstructural features depends on the ultrasonic frequencies that are used.

Acoustic emission is a passive technique that relies on spontaneous, transient, and usually inaudible ultrasonic signals generated by rapid release of energy (e.g., during mechanical deformation or thermal stressing). Acoustic emissions can arise when a material undergoes metallurgical transformations, dislocation movements (plastic yielding), microcracking, crack growth, etc. (Matthews, 1983).

The spontaneous stress waves that constitute acoustic emission can be analyzed to obtain information concerning the nature, locations, abundances, distributions, etc. of the various sources activated, as during the loading or proof testing of structures (Spanner, 1974; Liptai, et al., 1971). Operational methods include event counts, ringdown counts, energy or amplitude distribution analysis, and frequency spectrum analysis. The acoustic emission technique offers a means for monitoring structural integrity and dynamic response and for inferring the current internal condition or state of degradation of structural components.

Electromagnetic

Electromagnetic methods for material characterization are generally restricted to assessment of nearsurface features. Applicability is further restricted to electrically conductive or ferromagnetic solids. Eddy-current probes induce small subsurface electric currents with intensities and depths of penetration that depend primarily on frequency and material conductivity and permeability. Factors such as alloy composition, impurities, and grain structure will affect the probe reactance (Libby, 1971; Lord, 1980). Eddy-current methods have proven viable for hardness and porosity measurements in materials ranging from grey cast iron to carbon fiber reinforced plastics (Giza and Papadakis, 1979).

Magnetic field methods generally depend on flux leakage or eruptions of externally induced fields. Passive probes are used to sense variations in natural magnetic domains to measure ferroalloying content, distribution, and anisotropies. Degrees of aging and case hardening have been measured by magnetic field probes (McMaster, 1959). Potentials exist for magnetic flux

leakage methods for measurements of microstructural gradients, plastic damage, and stress fields (Dobmann and Holler, 1980; Davis, 1974).

Penetrating and Particle Radiation

Radiography and radiometry cover a wide range of operational techniques that are suitable to differing degrees for materials characterization. Penetrating radiation involving x-rays and gamma rays and penetrating particle radiation involving neutrons can be used to cast images of grain structure, density variations, porosity, and contamination (Bryant and McIntire, 1985; Berger, 1965).

Images with high spatial resolution can be achieved with projection micro-radiography (Baaklini and Roth, 1985) while high sensitivity can be achieved with radiometry. The latter is a nonimaging, metrological method useful for quantifying degrees of porosity and density gradients (Halmshaw, 1968; 1982).

Radiation scattering analysis methods may provide means for characterizing grain structure and other morphological factors associated with thermal and mechanical processing effects (e.g., plastic deformation, precipitates, inclusions, porosity, creep, etc.) in engineering solids (Walther and Pizzi, 1980; Berk, 1966). Small angle neutron scattering is a method similar to x-ray scattering for characterizing microstructure. The method is a potential analytical tool for assessing thermal treatments; microvoid populations; and degradation due to fatigue, creep, deformation, and irradiation (Oien, 1983).

X-ray diffraction measurement is used routinely for determining residual stress although the method is ineffective at depths greater than about 20 Å (Bryant and McIntire, 1983). Nevertheless, x-ray diffraction instrumentation has been deployed in industrial environments for assessing residual stresses and characterizing damage in polycrystalline materials subjected to mechanical processing (i.e., cold working, etc.) (Ruud, 1983).

Photo-Optical

Laser holography is predominant among techniques for materials characterization by visible light optics. Holographic methods can be used to image microstrain deformations. When used in conjunction with mild thermal or mechanical stressing holography can reveal material anomalies and morphological variations through their effect on local strain patterns (Collier, et al., 1971; Ennos, 1970).

Moire and holographic interferometry are currently laboratory techniques that are largely unexplored regarding their potentials for field applications for materials characterization and degradation assessment (Sigler and Haworth, 1981; Post, 1980). These techniques have been shown applicable to the study of early stages in fatigue damage and to assess variations in elastic properties of metals and composites (Govada, et al., 1985; Duke, et al., 1983).

EXAMPLE

Ultrasonic waves are probably the most important probe media for assessing mechanical properties. A strong case can be stated for expecting ultrasonic velocity and attenuation measurements to correlate with mechanical properties that are governed by material microstructures (Vary, 1980, 1984). Indeed, the ultrasonic waves interact with and are modified by microstructural features that govern extrinsic properties such as yield strength, hardness, ductility, and toughness (Rice, 1977; Vary, 1986).

Fracture toughness is a material property that is determined by factors like mean grain size, grain interface characteristics, grain aspect ratios, second phase constituents, precipitates, etc. The fracture toughness of a material is a measure of its resistance to catastrophic fracture when minor cracks are activated by stress.

Correlations between ultrasonic measurements, fracture toughness, and also yield strength have been demonstrated. Moreover, a theoretical basis for predicting the empirical correlations has been developed (Vary, 1978, 1979). Results are shown in figures 1 and 2 for two maraging steels and a titanium alloy. In these metals the correlations appeared to be influenced by grain size and morphology. The "characteristic length" factor in figure 1 (comprised of the ratio of plane strain fracture toughness and yield strength) is a measure of toughness. This characteristic length (microcrack blunting zone) apparently depends on the ultrasonic attenuation properties of a material. At least in the case of the metals studied thus far, it appears that toughness increases when more ultrasonic stress wave energy can be retained and absorbed in localized plastic deformation zones (via dislocation movements) (Vary and Hull, 1982).

LIMITATIONS

The purpose of the previous example is to illustrate the viability of ultrasonics for nondestructive characterization of an important mechanical property. The example presages potential advantages to be gained by its use in materials research and testing and adaptations to actual parts. However, like many of the previously discussed NDE methods, ultrasonics for laboratory characterization of mechanical properties and subsequent technology for field applications is essentially undeveloped.

Even in a laboratory environment materials characterization NDE techniques (as in the case of the previous example) can usually be accomplished only under strict constraints. Satisfactory signal insertion and acquisition, accurate measurements, and valid analysis and interpretations require sample preparation and specific constraints on size, shape, surface finish, etc. The complexity of preparation and incurred expense may be less than for destructive test samples for similar purposes. By adapting probes and instrumentation to them, objects for NDE may be simpler, smaller, or may just consist of selected regions of actual parts.

Table V lists general requirements for good signal processing and accurate measurements by most of the NDE techniques described herein. Design accommodations or adaptations for NDE probes and probe media may be necessary to optimize technique sensitivity and precision in applications to actual parts.

Sophisticated NDE techniques may be useless if reasonable provisions for their use are not included in the design of critical structural components.

CONCLUSION

The techniques reviewed herein suggest possibilities for the nondestructive evaluation of a wide range of mechanical properties and underlying microstructural factors. Most are advanced techniques that require development for complementing conventional NDE for flaw detection and characterization. Apart from this, the techniques reviewed present possibilities for verification of mechanical properties and assessment of service degradation of critical structures. Development and adaptation of the techniques discussed is needed to assure structural reliability and safe service life of components made of advanced materials in systems that demand efficient performance under extreme operating conditions.

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TABLE I. - TYPICAL STRENGTH-
 REDUCING DEFICIENCIES
 REQUIRING NONDESTRUC-
 TIVE MATERIAL CHAR-
 ACTERIZATION

Improper processing
Wrong alloy composition Inclusions, debris Embrittling impurities Excessive grain growth Wrong grain morphology Faulty heat treatment Faulty case hardening Faulty surface treatment High residual stresses Incomplete polymerization Wrong fiber fraction High microvoid content Poor bonding integrity
Service degradation
Altered microstructure Corrosion/chemical attack Excess deformation Local overheating effects Fatigue/creep damage Internal oxidation Decarburization Stress corrosion Radiation damage Gas embrittlement Moisture damage absorption Matrix softening/crazing Impact/shock damage

TABLE II. - QUANTITATIVE NONDESTRUCTIVE EVALUATION TECHNIQUES FOR INDIRECT CHARACTERIZATION OF MATERIAL STRENGTH AND RELATED PROPERTIES

Principal techniques	Operational techniques	Directly-measured quantities	Indirectly-measured quantities	Bibliographic references
Dynamic excitation	Sonic vibration, eddy sonic	Natural frequencies, forced frequencies	Dynamic moduli, elastic constants, density, morphology, bond strength	DiCarlo, Maisel 1979 Papadakis, Kovacs 1979
	Forced flexure, torsion	Amplitude, energy dissipation	Damping capacity, density, texture, hardness, alloying effects, cold work	Nowick, Berry 1974 Uygur 1980
Ultrasonic, acoustic	Continuous wave, transmission, resonance	Phase/group velocities, dispersion, damping, resonance frequencies	Elastic constants, moduli, anelasticity, microstructure, grain/phase morphology, residual stress state/distribution	Schreiber et al. 1973 Kraukramer 1977 Noronha, Chapman 1973
	Broad pulse-echo, spectrum analysis	Rayleigh/phase/diffuse scatter, attenuation coefficients	Hardness, tensile/shear yield strengths, fracture toughness, microstructure, texture, grain/phase size/morphology	Truell et al. 1969 Vary 1978, 1979, 1980 Goebbels 1980
	Mechanical scan imaging	Signal intensity, diffraction effects	Macro/micro-structural variations/anomalies, bond/weld integrity/strength	Jacobs 1970 Segal, Rose 1980
	Acoustic microscopy	Spatial frequency image, interference fringes	Elastic/anelastic micro-structural variations, grain texture, porosity, stress	Kessler 1973, 1979 Lemons, Quate 1973
	Acoustic emission	Emission rate, amplitude distribution, spectrum	In situ metallurgical transformation, creep, fatigue damage, micro-cracking	Spanner 1974 Liptai et al. 1971
Electro-magnetic	Eddy current	Electrical conductivity, magnetic permeability	Polycrystalline grain/domain anisotropies, alloy composition, hardness, porosity	Libby 1971 Giza, Papadakis 1979
	Magnetic field	Coersive force, flux leakage/signature	Ferro-alloying content/distribution, age/case hardening, stress fields	Davis 1973 McMaster 1959 Dobmann, Höller 1980
Penetrating and particle radiation	X, gamma, neutron radiography and radiation gaging	Absorption and scatter radiation/attenuation, backscatter	Macro/micro-structural variations/anomalies, density, porosity, grain texture, chemistry, moisture ingress, corrosive/chemical attack	Halmshaw 1968 Berger 1965 Berk 1966 Walther, Pizzi 1980
	X-ray diffraction	Scatter goniometry	Residual stress state, lattice spacing	McMaster 1959 Anon 1971
	Mossbauer method	Gamma-Doppler velocity	Subsurface gradients, corrosion products	Wertheim 1964
	Position annihilation	Annihilation event count	Fatigue microcracking, plastic deformation, grain boundary voids, strain hardening	Coleman, Hughes 1977
	Exo-electron emission	Emission current, photoemission image	Fatigue damage, plastic strain/deformation	Baxter 1977
Photo-optical	Neutron activation	Gamma spectrum analysis	Alloy/chemical content, impurities	Koch 1960
	Induced strain laser holography	Interference fringe spatial frequency	Stress/strain condition, deformation, macro/micro-structural anomalies	Collier et al. 1971 Ennos 1970

TABLE III. - RELATIONS AMONG ELASTIC
CONSTANTS AND PRINCIPAL ULTRASONIC
WAVE VELOCITIES FOR LINEAR
ELASTIC ISOTROPIC
SOLIDS

Elastic constant	Relation
Longitudinal modulus	$L = \rho v_l^2$
Shear modulus	$G = \rho v_t^2$
Bulk modulus	$= L - \frac{4}{3} G$
Young's modulus	$= \frac{G(3L - 4G)}{L - G}$
Lamé constant	$= L - 2G$
Poisson's ratio	$= \frac{L - 2G}{2(L - G)}$

v_l is longitudinal velocity, v_t is transverse velocity, ρ is density, other quantities are defined in terms of longitudinal modulus L and shear (transverse) modulus G .

TABLE IV. - THEORETICAL ULTRASONIC ATTENUATION
COEFFICIENTS FOR LINEAR ELASTIC
POLYCRYSTALLINE SOLIDS

Wavelength range	Attenuation mechanism	Attenuation coefficient
Independent	True absorption	$\alpha_a = C_a f$
$\lambda > D$	Rayleigh scattering	$\alpha_r = C_r D^3 f^4$
$\lambda \leq D$	Phase scattering	$\alpha_p = C_p D f^2$
$\lambda \ll D$	Diffusion scattering	$\alpha_d = C_d / D$

D is "nominal" grain size, λ is wavelength, f is frequency, α is attenuation coefficient, and the C 's are experimental constants.

TABLE V. - TYPICAL CONSTRAINTS FOR ASSURING
 SENSITIVE AND PRECISE QUANTITATIVE
 NONDESTRUCTIVE MATERIAL
 CHARACTERIZATION

Recommended constraints	Ambiguities eliminated
Clean, smooth surfaces Flat, parallel surfaces, or Geometrically simple shapes Accessibility of key areas Minimum thickness, length Precise physical dimensions Large part-to-probe area Absence of overt flaws and gross nonuniformities	Poor probe coupling Signal path uncertainties Signal in/output relations Excess attenuation losses Variable miscalculations Edge and sidewall effects Spurious, false signals

- ◇ 200-GRADE MARAGING STEEL
- 250-GRADE MARAGING STEEL
- TITANIUM (8Mo-8V-2Fe-3Al)

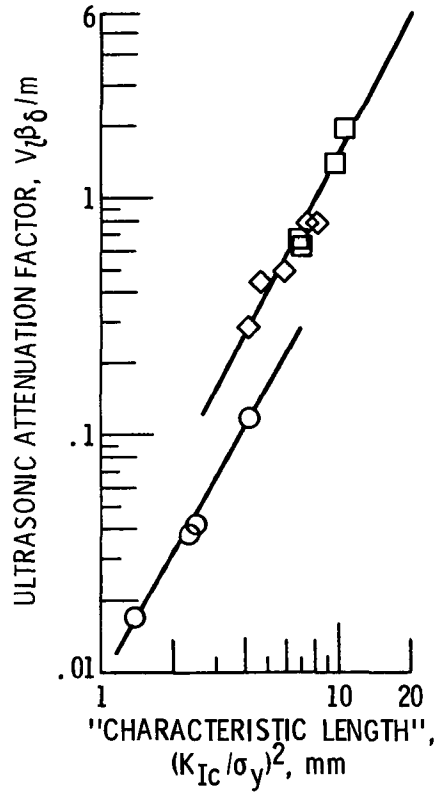


Figure 1. - Correlation of ultrasonic attenuation factor and fracture toughness "characteristic length" factor for three polycrystalline metals. K_{IC} is plane strain fracture toughness, σ_y is yield strength, v_l is longitudinal velocity, m is the frequency exponent in $\alpha = cf^m$, where α is attenuation coefficient, f is ultrasonic frequency, and β is $d\alpha/df$ evaluated at a critical wave-length related to the mean grain boundary spacing δ (from Vary 1979, p. 573).

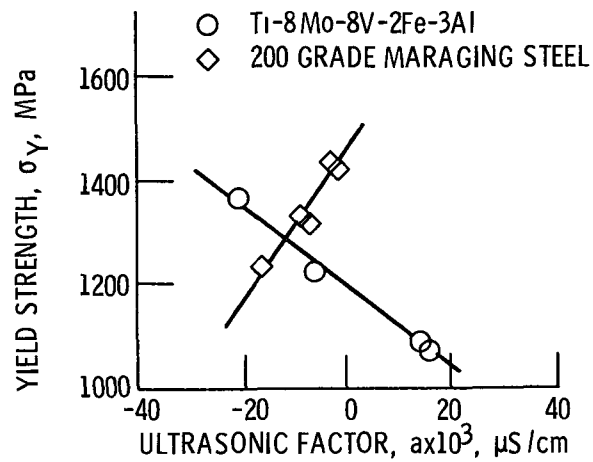


Figure 2. - Correlation of yield strength σ_y with the ultrasonic factor a for two polycrystalline metals. Factor a equals $+10^{-3}K_{IC} + \beta_1$, where K_{IC} is plane strain fracture toughness and β_1 is da/df evaluated at $\alpha=1$ (from Vary 1979, p. 574).

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16 Abstract An overview of nondestructive evaluation (NDE) is presented to indicate the availability and application potentials of techniques for quantitative characterization the mechanical properties of structural materials. The purpose of this brief survey is to review NDE techniques that go beyond the usual emphasis on flaw detection and characterization. This survey covers current and emerging NDE techniques that can verify and monitor entrinsic properties (e.g., tensile, shear, and yield strengths; fracture toughness, hardness; ductility; elastic moduli) and underlying microstructural and morphological factors. Most of the techniques described are, at present, neither widely applied nor widely accepted in commerce and industry because they are still emerging from the laboratory. The limitations of the techniques may be overcome by advances in applications research and instrumentation technology and perhaps by accommodations for their use in the design of structural parts.			
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