BASIC CONSIDERATIONS FOR ULTRASONIC NONDESTRUCTIVE CHARACTERIZATION OF MATERIALS

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Coupled with reliability and cost-effective manufacturing of industrial materials, the issue of quality has become extremely urgent to producers and users alike. In order to establish the quality parameters, no test method is better than nondestructive one. Underscoring the significance of materials quality, the science and technology of ultrasonic NonDestructive Characterization (NDC) have undergone a spectacular revolution during the last two decades.

Overt defect detection in primary metals by ultrasound is well-known. Proper applications of ultrasound, however, can provide further information about test material properties and microstructure, too. Furthermore, what is useful in metals testing may not be useful for other materials. For example, wet transducer coupling (popular in metals testing) is not reliable for the characterization of green, porous, or liquid-sensitive materials.

Microstructurally, metals do not vary as much as ceramics, powder metals, polymers, and their composites. Unlike these materials, most metals manufacturing does not go through green, sintering, or polymerization stages, yet it is highly desirable to analyze them nondestructively at these steps. For reliable ultrasonic NDC, new materials demand new techniques.

In this paper we illustrate the limitations of metals-NDT practice in light of modern characterization requirements, and provide "materials and objectives suitable"methodologies for the reliable NDC of a wide variety of advanced and conventional materials at various stages of their manufacture.

INTRODUCTION

Analogous to any materials characterization method that utilizes a wave as the characterizing vehicle, ultrasound can also provide significant information about a medium through which it is propagated. Ultrasonic waves travel by exerting oscillating pressure on particles of the medium, generally corresponding to the frequency of incident wave. In a solid medium - in which particles are tightly held together - oscillation of one particle generates corresponding vibrations in the adjecent particle, and so on, thus completing the mechanism of ultrasonic propagation. Magnitude of oscillations and the speed of ultrasound are directly dependent upon the composition and physical characteristics of the medium of ultrasound propagation. Therefore, the phenomena of ultrasound-material interaction - reflection, transmission, refraction, diffraction,

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interference, and scattering - can be applied to detect discontinuities, to evaluate microstructure, density, porosity, elastic and mechanical properties, and to produce other applications such as surface and internal imaging of materials. Investigation of time, frequency, and image domain analyses of transmitted signals sets the stage for ultrasonic NDC, Table I, modified after Vary.[1] Table II shows the summary of important relationships used for determining various ultrasonic parameters and materials properties.

TABLE I. Significance of ultrasonic NDC.

MEASUREMENT CATEGORY	MEASURED PARAMETERS	INFORMATION REVEALED
Time Domain	Velocities of longitudinal, shear, and surface waves	Direct correlation with density, porosity, defect detection, elastic and mechanical properties.
Frequency Domain	Frequency dependence of ultrasonic attenuation (Ultrasonic Spectroscopy)	Direct correlation with microstructure: grain size and grain boundary relationships, porosity, and study of any process/compositional parameter that results in microstructural or phase changes.
Image Domain	Time of flight, attenuation, or frequency domain monitoring of ultrasonic signals as functions of transducer location on test material.	Planar or 3D representation of surface and internal features of materials, including defects and microstructure.

Besides being nondestructive, the advantages of ultrasonic NDC are numerous:

1. ***It does not require special sample preparation.***
2. ***It can be adapted to on-line manufacturing environment.***
3. ***Unlike x-ray and γ-ray methods, ultrasound is non-hazardous.***
4. ***The equipment involved is relatively easy to transport.***
5. ***It can be used to test transparent or opaque materials.***

In fact, ultrasound can be used to characterize *any* medium through which it can be propagated. For example, with the exception of vacuum, all three states of matter - solid, liquid, and gas - can be analyzed by ultrasound. The key, however, is to propagate measurable quality ultrasound through the medium in such a manner that it (the medium) is unaffected by the mechanism through which ultrasound is propagated.

NDT vs. NDC

Since its inception,[2,3] ultrasonic NonDestructive Testing (NDT) has been preoccupied with *overt* flaw detection in primary metals.[4] Considering the fact that the theory and practice for materials characterization by ultrasound have been well-established,[5,6,7] it is rather disconcerting to note

TABLE II. Important relations used in ultrasonic characterization of materials.

PROPERTY/PARAMETERS	RELATION
Velocity (V), Distance (d), & Time (t)	$V = d/t$
Frequency (f), Wavelength (λ), Velocity (V) & Period (P)	$\lambda = V/f$ $P = 1/f$
Acoustic Impedance (Z), Density (ρ), & Velocity (V)	$Z = \rho . V$
Reflection (R) & Transmission (T) Coefficients	$R = ((Z_2 - Z_1)/(Z_2 + Z_1))^2$ $T = 4Z_1Z_2/(Z_1 + Z_2)$ Z_1 and Z_2 are impedances of propagating & transmitted media.
Resolution (d_{min}), Number of wavelengths (n), Pulse width (p), & Material time of flight (M_{tof})	$d_{min} = n\lambda/2$ (general) d_{min} =/> p (real) $p < M_{tof}$ (optimum) "p" is also expressed in length units, corresponding to time of flight in test material.
Detectability (ϕ_{min}), Wavelength (λ), & Numerical Aperture (na)	$\phi_{min} = 2(K(0.003\ \lambda^2/na))^{1/2}$ K, a proportionality constant, >1
Elastic Properties: Young (E), Shear (G), Bulk (K), & Surface (S) modulii, and Poisson's Ratio (σ)	$E = V_l^{\,2} . \rho . (1 + \sigma)\ (1 - 2\sigma)/(1 - \sigma)$ $G = V_t^{\,2} . \rho$ $K = E/3(1 - 2\sigma)$ $S = V_s^2 . \rho_s$ $\sigma = 1\text{-}2b^2/2\text{-}2b^2$ $b = V_t/V_l$ V_l, V_t, & V_s are longitudinal, shear, & surface wave velocities; ρ, bulk density & ρ_s, surface density.
Attenuation, (α)	$\alpha = -\log 20\ A_o/A_i$ A_o and A_i are amplitudes of transmitted and applied ultrasonic energy in volts.

that this important subject did not receive the attention of the materials community until recently. Some thoughts on the late entry of ultrasonic NDC into materials manufacture and development are given by Bhardwaj.[8]

Meanwhile, the works of Vary,[9,10] Papadakias,[11] Green,[12] Brown,[13] Sharpe,[14] and Serbian,[15] in time and frequency domain analyses of metallic and some non-metallic materials for density/porosity and microstructure evaluation, and of Kino,[16] Kessler,[17] Quate,[18] and Nokoonahad[19] in acoustic microscopy clearly suggest the widespread significance of ultrasound in modern materials characterization needs.

Recently interest in nondestructive characterization has increased tremendously at both R&D and QC/QA levels of materials laboratories and industries. This unprecedented flux of NDC into the world of materials is directly proportional to the current and potential uses of components manufactured from porous and dense ceramics, powder metals, and their composites, fiber glass and graphite fiber reinforced plastic, and carbon-carbon composites in the critical applications of aircraft/aerospace, nuclear, electronic, biomedical, and automotive industries. Nearly all professional societies related to materials science, technology, manufacturing, and applications today specifically address the issues of materials quality and their process control through NDC. Concurrent with the demand of NDC, ultrasonic technqiues have undergone substantial modifications and developments for their applications into surface, subsurface and bulk defect, properties, and microstructure characterization of materials.

Maxfield and Fortunko,[20] and Alers,[21] have developed noncontact electromagnetic transducers for ambient and high temperature evaluation of ferro-magnetic materials. Palmer, et.al.,[22] have developed contactless generation and laser detection of acoustic waves, using a laser generation and laser interferometric detection system which has been applied for the characterization of phase transformation in alloys by Rosen.[23] Through the development of dry or self transducer coupling, density and elastic properties of porous and dense ceramics, and anisotropicity in 2D carbon-carbon composites have been characterized by Bhardwaj,[24] and Bhardwaj and Trippett.[25] Innovated transducer designs such as half wavelength impulse now facilitate very high resolution and investigation of thinner materials sections without the use of very high frequencies, Bhardwaj.[26] Through the combination of dry coupling and near white frequency incident ultrasonic spectra, wideband ultrasonic spectroscopy delineating the microstructure of environment-sensitive ceramic superconductors has been reported by Bhardwaj, et.al.[27] Wave-material interaction based geometrical acoustics concepts and their high resolution and detectability applications in NDC have been described by Kino.[28]

Indeed, modern diagnostic ultrasonics little resembles yesteryear's NDT of primary metals. In order to improve the perception of diagnostic applications of ultrasound we offer two analogies. Soon after the discovery of x-rays in 1895 by Roentgen, they were quickly applied to the detection of cracks in bones. Radiography was thus initiated without any precise understanding of the radiation used since only in 1912 was the exact nature of x-rays established through the discovery of x-ray diffraction phenomenon.[29] Although radiography revealed details of the order of submillimeter region, x-ray diffraction increased detectability into the Angstrom region. Less than 30 years ago, x-ray diffraction techniques were still being developed and used primarily at research laboratories, yet, today this method is widely used for compositional characterization in various materials manufacturing functions. Similarly, since the conception of electron probe microanalysis in 1955 by Castaing and Descamps,[30] this method also has come a long way in establishing itself as a routine and reliable tool for surface characterization in the modern materials industry. Perhaps the status of ultrasonic NDT can be correlated to radiography, and NDC to x-ray diffraction, highlighting the fact that characterization provides a wide range of information about a material for its use producibility. We believe that the process of understanding, development, and applications of ultrasonic characterization method is no different from the two examples cited here. For example, during the 1960s, ultrasonic resolution and defect detectability in steel were approximately 1mm and 0.5mm, respectively. Today they are better than 50μm and 5μm, and improving!

ULTRASONIC NDC AND ITS HORIZONS

Underscoring the significance of materials characterization in industry, in 1967 a panel of distinguished scientists from educational institutions, government, and industrial laboratories described the status of this important subject.[31] This panel made important recommendations for the systematic development of *modii operandi*, and education and training in the various characterization methods, now used routinely. Although this panel only made a passing reference to the need for nondestructive testing techniques, but its visionary and practical recommendations can be used as important guidelines for NDC development for the benefitting industry and society.

Independent of the method, ***"characterization describes those features of the composition and structure (including defects) in a material that are significant for a particular preparation, study of properties, or use, and suffice for reproducibility of the materials."***[31] Nondestructive characterization should provide the same information (that is only restricted by the limitations of a given method), without destroying or altering the original characteristics of the material during the analytical process. As we noted earlier in Table I, if ultrasound can be propagated in a material, then investigation of its transmitted signal can provide valuable information about it. For example, for a given material,

1. ***Variations in its density cause corresponding variations in its longitudinal, shear, and surface wavevelocities, from which all elastic properties, including surface modulus, can be determined.***[24]

2. ***Variations in particle size introduce scattering as a function of frequency-dependence of ultrasound attenuation, from which microstructurecan be evaluated.***[15,27]

3. ***Anisotropic characteristics can be established by measuring direction-dependent velocities***[25]***. Applied and residual stresses can also be determined by investigating the behavior of polarized ultrasound such as through shear wave polariscopy,analogous to polarizing petrographic microscopy.***

4. ***Manipulation of reflected or transmitted signals can be used to image surfacial and internal imaging.***[16,17,18,26]

In fact, any process or compositional parameter that introduces measureable changes in ultrasonic time and frequency domains can be used to characterize phenomena such as crystallization, polymerization, phase transformation, etc.[32]

The fact that ultrasound can be transmitted into all three states of matter allows one to characterize them from the standpoint of simple curiosity to real practical value. For example, investigation of frequency-dependence of ultrasound attenuation through gases can be used to study their inter-molecular and elastic behavior as functions of temperature and pressure. Ultrasound propagation through air can be used for liquid level measurements and remote sensing. Similarly, significant practical process and applications related knowledge can be developed by studying the behavior of longitudinal and shear ultrasound through liquids. This is particularly applicable to those liquids which polymerize or crystallize, either as a function of time, or through the additions of catalysts ond activators. Doppler frequency shift in liquids is already used for blood flow measurements.

The horizons of diagnostic ultrasound are virtually limitless! However, from a practical standpoint, ultrasound-material interaction needs to be understood in light of modern NDC requirements as pointed out by McCauley.[33]

MATERIAL-DEPENDENCE OF ULTRASONIC ATTENUATION AND ITS SIGNIFICANCE

A cursory glance at the literature on diagnostic uses of ultrasound is enough to suggest its widespread applications for overt flaw detection in primary metals and their alloys, such as those of steel and aluminum. Presumably, due to this reason, those interested in the NDC of polymers, ceramics, powder metals, etc., resort to the *metals-NDT* practice. Thus it is not unusual to find serious errors caused by misinterpretation in the incident frequency versus transmitted frequency with respect to non-metallic materials applications. For example, whereas a 10MHz incident frequency may yield the same transmitted frequency response from carbon steel, it may not do so if the test material is an acrylic plastic as long as the test conditions are the same in both cases. In fact, in the latter case the transmitted response is ~7MHz. A similar argument can be made if the test material is porous zirconia, alumina, cordierite, powder metal, etc. Distortion of incident frequency by the medium of its propagation causes adverse or unexpected effects upon desired resolution, detectability, and accuracy of time of flight measurements. In order to illustrate this phenomenon an experiment was performed by analyzing the transmitted response of a selected incident frequency of ultrasound as a function of varying materials compositions.

TABLE III. Transmitted frequency response of a nominal 25MHz incident ultrasound through a variety of 12.7mm thick materials. All observations were made by water immersion technique where transducer to test sample distance was maintained at 12.7mm. Transducer was excited with a 5ns -ve pulse and amplification of the transmitted signal performed with a broadband receiver, 100Hz to 35MHz at -3dB.

SAMPLE	TRANSMITTED FREQUENCY (MHz)[1]	BANDWIDTH % at -6dB[2]	INSERTION LOSS[3]
Clear Fused Quartz	*25.0*	56	-46
Carbon Steel	*22.5*	71	-64
#303 Stainless Steel	*13.0*	100	-120
Polystyrene (plastic)	*20.0*	80	-60
Acrylic (plastic)	*12.5*	115	-140
MACOR (machinable ceramic)	*23.5*	64	-58
CERAMIC FOAM		*No Transmission at all!*	

[1]***Determined by averaging the high and low values at -6dB of the frequency spectrum.***
[2]***Reported as percentage of center frequency at -6dB level.***
[3]***Sensitivity = -20 log A_o/A_i, where A_o is the amplitude of the transmitted signal in volts, and A_i is the amplitude of the excitation voltage.***

Assuming that incident characteristics of ultrasound can be established from a reference material such as an acoustically transparent (over a wide frequency range) clear fused quartz or synthetic sapphire, Table III shows the material-dependence of ultrasonic attenuation. Here the transmitted response of a nominally 25MHz ultrasound has been investigated on 12.7mm thick specimens of carbon steel, #303 stainless steel, polystyrene and acrylic plastics, MACOR (Corning's machinable glass ceramic), and a porous ceramic foam (Lockheed space shittle tile). These observations clearly exhibit strong frequency-dependence of ultrasound attenuation as a function of varying materials compositions and microstructure. It is also observed that as the transmitted frequency response decreases as a function of incident frequency, the insertion loss of the transmitted ultrasonic signal increases correspondingly, Fig. 1. From the standpoint of frequency suitability, it can be concluded that materials such as clear fused quartz, carbon steel, and MACOR can be

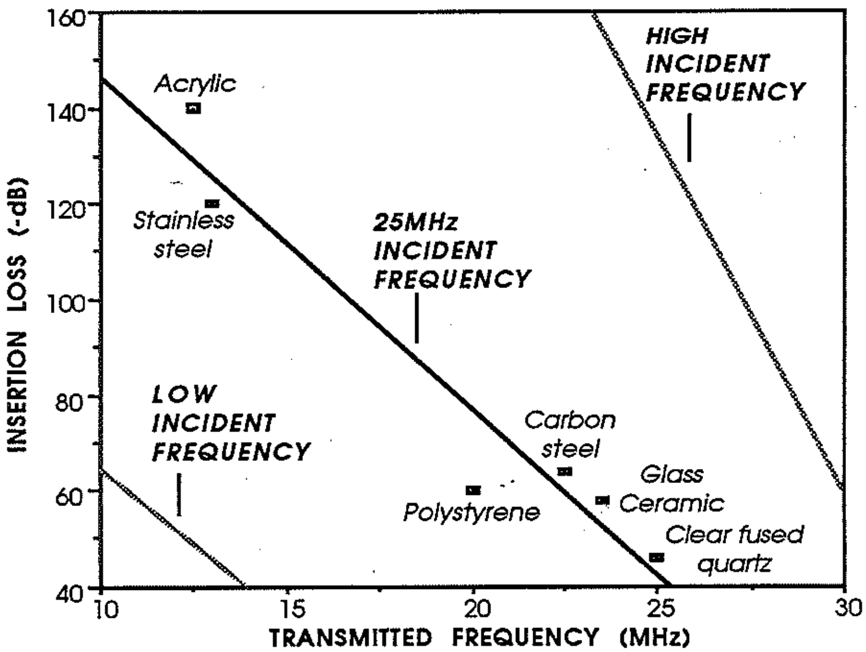

Fig. 1. Material-dependence of frequency attenuation. Relationship in the middle graph was generated by exciting the test samples with 25MHz incident frequency. Top and Bottom graphs are idealized transmitted frequency vs. insertion loss relations, if similar materials were excited by relatively high and low frequency ultrasound, respectively.

adequately analyzed by 25MHz frequency. On the other hand, if 25MHz incident frequency is used for the analysis of stainless steel, polystyrene and acrylic plastics, it may *appear* that analysis is being performed at higher 25MHz frequency, but *in reality* the investigating frequencies for these materials is much lower. Fig. 1 also shows *idealized* transmitted frequencies (as functions of varying materials) when excited by certain "high" and "low" incident frequencies.

From the foregoing discussion it is apparent that if a particular frequency is suitable for the NDC of a given material, it may not be so for another material. Therefore, it is desirable to establish "optimum" frequency response of a given test material with respect to its physical dimensions and microstructure. Optimum frequency is a particular high frequency beyond which it is attenuated "dramatically" by a the test material. For critical NDC applications it is highly desirable that optimum frequency of ultrasound be established with respect to characteristics, and shape and size of test components. This task can be accomplished by investigating the response of a test material by a wide range of frequencies such as by exciting it with near *white* frequency ultrasonic spectra. Fig. 2 shows such an analysis for a coarse grained #316 stainless steel. Since the attenuation of frequencies between ~10 to 15MHz is minumum, it is suitable to examine this material within this range.

Exceptions to this rule also apply. Since frequency attenuation is a linear function of distance traveled by ultrasound (it increases with greater material thickness), frequencies much higher than "optimum" can be used to investigate thinner materials sections. Also, while optimum frequency is desirable, certain factors such as material shape, size, and surface roughness, and transducer producibility, may limit its application. While performing an NDC application an alert transducer designer carefully takes these factors into account. Significance of these and other acoustic parameters for NDC have been described in detail by Bhardwaj.[8]

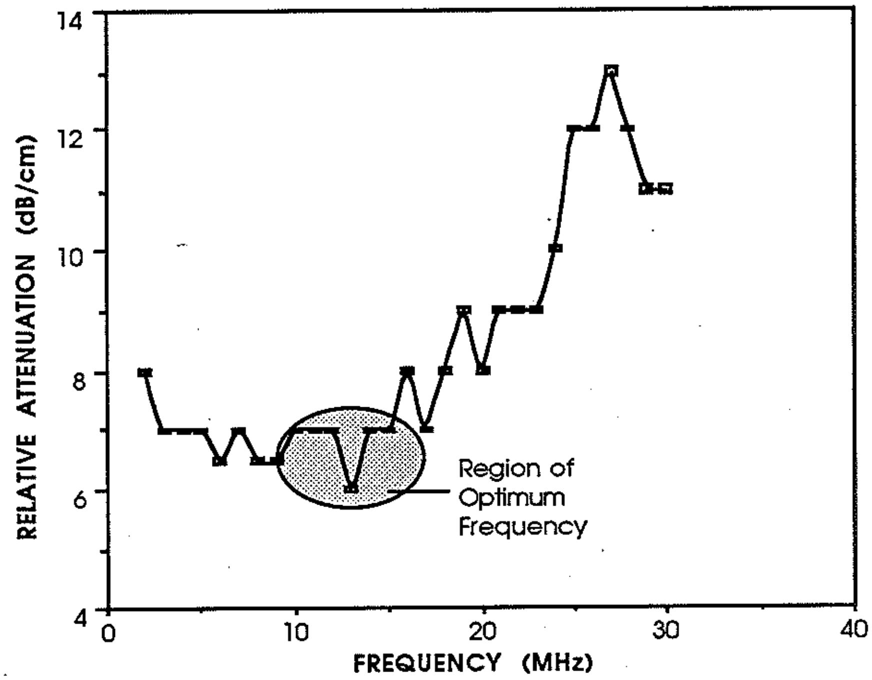

Fig. 2. Determination of "optimum" frequency for the characterization of a specific material. Example shown is for a microstructurally complex stainless steel. The shaded region shows the frequency range suitable for the evaluation of this material on account of its "minimum" attenuation.

The mechanism of optimum frequency determination, shown in Fig. 2, can also be used to conduct ultrasonic spectroscopy (frequency domain analysis) by establishing frequency-dependence of ultrasonic attenuation as a function of a given test material's composition and microstructure.

NEW MATERIALS DEMAND NEW NDC TECHNIQUES

Relative to most conventional and modern materials (including powder metals), processing techniques of primary metals and their common alloys are simple and well-established, and they are compositionally homogeneous, isotropic, and impervious compared to most non-metallic materials. Processing of ceramics, powder metals, polymers, and their composites undergoes complex cycles of liquid-solid preparation, powder compaction, sintering, polymerization, second or third phase impregnation, etc. Materials composition and microstructure variations introduce corresponding effects upon ultrasonic parameters, thereby limiting the use of metals-NDT practice for their reliable characterization.

Compositional and microstructural diversity and their effects upon ultrasonic parameters

Complex processing technqiues, heterogeneous compositions, and unusual combinations of matrix, fiber and particulate materials, are required for advanced high strength aircraft/aerospace composites, high temperature resistant coatings, multilayer electronic, biomedical, and structural materials, superconductors, etc. These steps are necessary in order to achieve desired characteristics of final products and devices. Simply stated, the world of non-metallic materials may range from one extreme to another. For example, they may vary from extremely porous (feather weight) to extremely dense microstructures (rigid ceramic foams in space shuttle tiles to dense ceramic inserts and diamond coatings), from isotropic to highly anisotropic grain and fiber orientations (medical grade isotropic graphite to 2D and 3D carbon-carbon composites), from transparent to opaque atomic structures and compositions (glasses and single crystals in optical devices to graphitized carbon), from extremely simple to extremely complex chemical compositions (sodium chloride to superconductors), and from extremely fragile to extremely strong physical conditions (green vs sintered stages), etc.

Acoustically, metals fall within a narrow velocity range, i.e., from ~5,000 to 6,500m/s). Advanced ceramics and composites, are characterized by an enormous range of velocities, e.g. from<400m/s for the ceramic rigid foam to >18,000m/s for diamond. Similarly, while the acoustic impedances of metals range from 20 to 50 x 10^5 g/cm^2.s, those of nonmetallic industrial materials vary from <0.05 to >115 x 10^5 g/cm^2.s. Table IV provides the summary of acoustic characteristics of a variety of green and sintered materials as determined in our laboratory. From these observations it is obvious that this massive compositional and microstructural diversity of non-metallic materials is no match for *metals-NDT* practice! In short, NDT methodology has limited value for materials characterization by ultrasound. In order to perform reliable and meaningful NDC of modern materials (at various stages of their processing and manufacture), special attention needs to be given.

MATERIALS-SUITABLE ACOUSTICS

Materials-suitable acoustics defines critical ultrasonic parameters (incident frequency, bandwidth, pulse shape and its size in time domain) applicable to the inherent characteristics (composition and microstructure) and physical dimensions of a given test material. For example, while a 1MHz frequency may be adequate for the analysis of a 20mm coarse-grained fused SiO_2, it is too small for the interrogation of a 1mm dense SiC. The wavelength at 1MHz is ~4.0mm for fused SiO_2, and ~12mm for dense SiC. Considering that the pulse width of a 1MHz frequency is one wavelength, it is equal to 1μs in the time domain envelope (see Bhardwaj[8] for the importance of pulse width and other acoustic parameters in NDC). The round-trip Time of Flight (ToF) in 20mm fused SiO_2 is 9.3μs, while in dense 1mm SiC it is only 85ns when the direct reflection technique is used. Obviously, the pulse width of a 1MHz ultrasound (1μs) is too large for successful interrogation of dense 1.0mm SiC. Table V shows the suitability and unsuitability of 1MHz and 20MHz incident frequency for the characterization of these materials by assuming that the pulse width of interrogating ultrasound is equal to one wavelength for both frequencies. In summary, the higher the velocity of a given material, the higher the applicable frequency (or shorter pulse width), and vice versa. While developing optimum acoustics parameters for a given material, its physical dimensions (particularly the thickness through which ultrasound needs to be transmitted) and frequency-dependence of ultrasound attenuation also need be considered.

MATERIAL-SUITABLE TECHNIQUE

This refers to the applicable physical technique by which a given test material is coupled to an ultrasonic transducer. An impervious material can be coupled by applying a thin layer of water oil, grease, or glycerene between the longitudinal wave transducer and test material surface. Similarly, shear wave transducers can be coupled to impervious and liquid-insensitive materials by a very thin layer of viscous liquid such as ordinary honey or polymer resin. However, the same cannot be said if the test materials are green, porous, or liquid-sensitive (superconductors, ceramic electrolytes, salt-based compositions, green materials, etc.). Obviously, a portion of liquid couplant will penetrate inside the porous material, thereby altering the original state of the test material, or damaging the fragile green material. Conventional liquid coupling is not a desirable ultrasonic technique for the characterization of such materials. The wet coupling limitation of *metals-NDT* practice has been successfully alleviated since the development of dry coupling longitudinal and shear wave devices ranging in frequency from <100KHz to >20MHz. Bhardwaj has described time and frequency domain applications of this technique for the NDC of variable porosity ceramics, superconductors, and green materials.[24,27,34] Table VI shows the suitable

TABLE IV. Diversity of acoustic characteristics of selected conventional and advanced materials as a function of composition and microstructure.

MATERIAL	PREPARATION/ CONDITION	POROSITY %	LONGITUDINAL VELOCITY (m/s)	ACOUSTIC IMPEDANCE ($x10^5 g/cm^2 . s$)
Al_2O_3 (dense)	*GREEN* *SINTERED*	<1	1,600 11,000	2.4 43.5
Al_2O_3 (porous)	*GREEN* *SINTERED*	30 20	1,300 7,100	1.7 19.9
Fused Silica (refractory)	*FUSED*		4,100	10.25
ZrO_2 (refractory)	*GREEN* *SINTERED*	15	2,900 5,500	11.0 35.5
Ceramic Ferrite	*GREEN* *SINTERED*	2	1,100 6,800	2.0 37.0
WC	*GREEN* *SINTERED*	<1	1,400 9,500	2.8 114.0
YBC Superconductor	*GREEN* *SINTERED*	<10	1,100 4,500	1.9 29.0
SiC (single phase)	*SINTERED*	<1	12,000	37.5
SiC (composite)	*SINTERED*	<5	7,500	18.0
Si_3N_4 (single phase)	*SINTERED*	<1	11,000	33.5
Si_3N_4 (composite)	*SINTERED*	<5	6,500	15.3
Ceramic Foam	*SINTERED*	>80	400	0.04
AZS (refractory-"skin")	*FUSION CAST*	~5	7,100	46.0
AZS (refractory-"interior")	*FUSION CAST*	~7	6,700	43.5
Diamond	*INDUSTRIAL*	0	18,500	64.7
Graphite (isotropic)	*GRAPHITIZED*	<2	2,900	4.9
2D C-C composite (along planes)	*GRAPHITIZED*	~15	7,300	12.6
2D C-C composite (across planes)	*GRAPHITIZED*	~15	2,200	3.7

TABLE V. Materials suitable acoustics explained by "suitability" and "unsuitability" of selected ultrasonic characteristics as functions of two compositionally and microstructurally varying materials.

EXAMPLE MATERIAL	PARTICLE SIZE	THICKNESS (mm)	VELOCITY (m/s)	SAMPLE TOF[1]	INCIDENT ULTRASONIC CHARACTERISTICS			
					1MHz (PW - 1μs) 2		20MHz (PW - 50ns) 2	
					λ[3]	SUITABILITY	λ[3]	SUITABILITY
Fused Silica (direct-bonded)	50μm - >1mm	19	4,100	9.3μs	4.1mm	OK[4]	0.205mm	NO[6]
SiC (dense)	sub-micron	1	12,000	170ns	12.0mm	NO[5]	0.6mm	OK[7]

[1] TOF - Round Trip Time-Of-Flight when DIRECT REFLECTION technique is applied.
[2] PW - Pulse Width, assumed one period at the specified frequency.
[3] λ - Wavelength in example material at the specified frequency. v/f.
[4] At 1MHz PW is small enough for resolution and accurate TOF measurement, besides at this frequency there is no significant attenuation by this material.
[5] At 1MHz PW (1μs) is too large to interrogate this material, the TOF of which is only 170ns.
[6] The coarse-grained texture of this material will almost completely attenuate 20MHz frequency.
[7] At 20MHz PW (50ns) is small enough for resolution and accurate TOF measurement of this material.

transducer coupling methodology as a function of test material composition and microstructure, and the processing stage at which NDC is desired. While dry coupling is highly desirable for the analysis of liquid-sensitive and green materials, it must be noted that complex shapes and rough surfaces are likely to limit the application of this technique. This is particularly true when only one side or one surface of a component is available for testing.

TRANSDUCER SELECTION MECHANISM

In the foregoing sections we have demonstrated apparent compositional and microstructural diversity of conventional and modern industrial materials in generic terms. We have also shown that if a given set of incident acoustic characteristics are applicable to one type of material, they may not be applicable to another type, Table V. Reliability of ultrasonic data and thus the conclusions about test material quality are directly dependent upon the selection of suitable transducer acoustics. Prior to the applications of ultrasound for non-metallic materials, the majority of metals and their common alloys could be investigated within the 2 to 10MHz frequency range. However, this range is too narrow to analyze the diverse body of materials at various stages of their manufacture, Table IV and V. Also, if a given high frequency can be propagated in an otherwise attenuative media, then it may yield inaccurate measurements and conclusions, as shown in the section "Material-dependency of Ultrasonic Attenuation," Table III.

In strict terms transducer acoustics are defined by the composition and microstructure, while the transducer type (mode of coupling and shape and size of active transducer container) and its field parameters are defined by the shape of test materials. The condition of the test material and the environment of its testing also determine the applicability of the transducer type. Since transducer acoustics are of paramount importance for the execution of the NDC of a given material, a transducer selection guide for a variety of materials has been prepared, Table VII. This table provides general ideas about applicable frequency and pulse widths of interrogating ultrasound as functions of materials compositions and microstructures. Importance of transducer characteristics such as its active dimensions and sensitivity have been omitted for the sake of brevity, and have been described elsewhere.[35]

TABLE VI. Suitability of transducer coupling methodology as a function of test materials characteristics and their compositions.

TEST MATERIALS & THEIR CHARACTERISTICS	TRANSDUCER COUPLING SUITABILITY
All impervious, closed-porosity, and liquid-insensitive materials (dense ceramics, metals, most single crystals, most clear and porous glasses, etc.)	*WET or DRY*
All open-porosity, green, and liquid-sensitive materials (porous ceramics, ceramic electrolytes, ceramic superconductors, alkali-based materials, C-C composites, etc.)	*DRY*

TABLE VII. Transducer selection guide.

MATERIALS CATEGORY	APPLICABLE TRANSDUCER CHARACTERISTICS	
	FREQUENCY RANGE	PULSE WIDTH[1] (Wavelengths)
Super-hard & super-dense oxides, nitrides, carbides, & borides of metals & non-metals, and their composites; high silica glasses, most single crystals, and low viscosicty liquids.	<5 to >50MHz	0.5 to 3 λ
Non-porous fibrous & particulate composites, dense ceramics, medium grained materials, metals, powder metals,glasses, liquids, and colloidal suspensions.	<2 to >20MHz	0.5 to 3 λ
Refractories (granular & porous), concretes, porous fiber & particulate composites, lumber & wood products,visco-elastic materials, and viscous liquids, slurries, etc.	<100KHz to 5MHz	2 to 6 λ
Gases	<10MHz	3 to several λ

[1] ***Pulse width is described as the number of wavelengths (λ) or cycles contained in the time domain envelope of ultrasound. Shorter pulse widths are desirable for thinner materials sections, while longer for thicker and attenuative materials.***

Besides the consideration of test material composition and microstructure, it is important to consider their thickness/distance traveled by ultrasound. It is reasonable to assume that as the ultrasound propagation distance increases, so does the linear absorption/attenuation of the interrogating wave. For example, while 2MHz ultrasound may be successfully applied to the examination of a 10mm alumino-silicate material, a 500mm component of the same material would dramatically attenuate this frequency, producing a poor transmitted signal. In such events, either the frequency of the transducer is reduced, or conversely, the sensitivity of the higher 2MHz transducer is increased. Such problems can also be circumvented by increased transducer excitation voltage as well as by higher amplification of transmitted signals. To this effect, ultrasonic systems - varying in excitation and amplification levels, and in frequencies from <20KHz to ~100MHz - are commercially available.

Experience shows that while "ideal" characteristics of ultrasound are desirable with respect to a particular materials study, in reality there is a degree of "compromise" with applicable and producible transducer parameters.

ULTRASONIC CLASSIFICATION OF MATERIALS

When dealing with ceramics, metal matrix composites, and like materials, we are actually addressing materials characterized by extremes in chemical composition, microstructure and ultrasonic characteristics. While base metals and non-metals (iron, aluminum, silicon, zirconium, etc.) exhibit relatively slower ultrasonic velocities; their oxides, nitrides, carbides and borides are characterized by much higher velocties. For example, the longitudinal wave velocity of zirconium is 4,800m/s, and for dense ZrO_2 it is 7,600m/s. Similarly, the velocity of aluminum is 6,320m/s, whereas that of its dense oxide in green stage is ~2,000m/s, and after sintering it is 11,000m/s. Not only does the chemical composition affect velocity, but it is also greatly influenced by the material microstructure, grain or fiber shape & size, porosity, etc. Ultrasonic parameters are also affected by the materials processing stage at which they are examined, Table III. Just as the

TABLE VIII. Ultrasonic Classification of Materials.

MATERIAL CATEGORY	VELOCITY RANGE	EXAMPLE MATERIAL		ULTRASONIC CLASSIFICATION
		Velocity	Wavelength*	
Highly porous, large grain, and high attenuation ceramics, refractories, GFRP, concretes, lumber, green materials, liquids, etc.	<400 to 4,000m/s	*Rigid Ceramic Foam* 400m/s	0.40mm	SHORT-WAVELENGTH MATERIALS
Relatively non-porous fibrous & particulate composites, relatively dense & medium grained ceramics and powder metals, glasses, etc.	4,000 to 7,000m/s	*Float Glass* 5,820m/s	5.8mm	MEDIUM-WAVELENGTH MATERIALS
Non-porous super-hard & super-dense oxides, carbides, nitrides, & borides of metals and non-metals and their composites.	7,000 to >12,000m/s	*SiC* 12,000m/s	12.0mm	LONG-WAVELENGTH MATERIALS

****All wavelengths (V/f) are functions of 1.0MHz.***

behavior of materials varies at different stages of manufacture, so do their acoustic characteristics. Since velocity of ultrasound determines the wavelength (as a function of a given frequency), development of velocity-wavelength relationships are extremely significant for proper NDC, facilitating accurate and reliable measurements of ultrasonic velocities, resolution and detectability limits, and frequency-dependence of ultrasonic attenuation of materials. In order to ultrasonically enhance our understanding of materials, we propose classification based upon velocity-wavelength relationships, Table VIII.

This approach facilitates several practical and important generalizations:

1. ***Definition of wavelength (at a given frequency) establishes optimum resolution in a given material.***

2. ***Shorter wavelength materials are characterized by relatively lower ultrasonic velocities, and vice versa.***

3. ***Higher ultrasonic frequencies or shorter pulse widths are required to analyze longer wavelength materials.***

4. ***Although Table VIII does not describe the frequency-dependence of ultrasonic attenuation, most shorter wavelength materials are more sensitive to frequency attenuation than their longer wavelength counterparts. Exceptions to this rule may be observed when examining polymer based particulate and fiber reinforced composites. For example, whereas the velocities of rubber impregnated aluminum and tungsten are 450m/s and 1,800m/s, respectively, the latter exhibits strong frequency-dependence of ultrasonic attenuation.***

CONCLUSIONS

In this paper we have described the diversity of conventional and modern materials in terms of their ultrasonic parameters for reliable nondestructive characterization. Underscoring the fact that NDC constitutes a new discipline in materials science and technology, a materials-suitable approach has been presented, differing from *metals-NDT* practice in magnitude and *modus operandi*. Not only does modern ultrasound offer exciting possibilities for establishing materials quality, economical methods of manufacturing, and safer uses, but it also offers challenges to researchers for the creation of new standards of materials characterization. To this effect, practical ideas and observations have been given by this author, based upon his experience in the development and uses of ultrasound for NDC.

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