Ultrasonic Measurement of Mechanical Properties

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Abstract-The current status of one of the "holy grails" of nondestructive testing, the measurement of mechanical properties such as the strength, forming parameters or fracture toughness of metal polycrystals, is assessed. Starting from the perspective of materials science, the microstructural features which control various mechanical properties is reviewed, followed by a discussion, from the perspective of elastodynamics, of the degree to which these microstructural features can be sensed by ultrasonic measurements. Given this background, the possibility of achieving the "holy grail" is discussed. When the mechanical property is controlled by a single microstructural feature, the quest can be fruitful, as is illustrated by several examples. However, more generally, there will not be a one-to-one relationship between the microstructural features sensed by ultrasound and those controlling the mechanical properties, and empirical correlations which are restricted to particular situations must be utilized. It is suggested that this empiricism will be most effectively reduced if future effort is concentrated on understanding the relationships between the ultrasonic measurements and microstructural features and on developing new measurement modalities which provide complementary information.

INTRODUCTION

Nondestructive evaluation (NDE) encompasses a variety of measurement techniques that have been developed to ensure the integrity of structural and electronic components, including measurements performed during processing, after manufacture, and during service [1]. One major objective is the detection, characterization and sizing of discrete flaws, information that is needed to determine whether these flaws can be tolerated in future service. However, the accept-reject decision depends not only on the properties of the flaw but on the environment in which it resides. Residual stresses, superimposed on the stresses associated with applied loads, can increase or decrease the driving forces causing the extension of the flaw. Changes in material microstructure can modify the resistance of the material to crack growth and/or fracture. The phrase mechanical properties is often used to describe particular parameters quantifying this resistance to deformation and failure, a notable example being the fracture toughness. This is but one of a number of mechanical properties, others being yield stress, bond strength, forming parameters, hardness, and others. In many applications in which one wishes to characterize the material, rather than discrete flaws, it is the determination of one of these mechanical properties that is the user's end objective, thus defining a second major objective of NDE. However, satisfying this need can be quite difficult, and achieving this goal has become one of the "holy grails" of the field. In this paper, the problem and its challenges will be discussed, examples will be given where notable successes have been achieved, and areas which are believed to be fruitful topics for future work will be noted.

Before turning to these technical details, however, it should be noted that this is an area that is likely to become increasingly important in the coming decades. The aging of much of the world's structural infrastructure, including bridges, highways, railroads, power generating stations, and aircraft, all require periodic assessment of serviceability [2]. Determination of mechanical properties is a crucial step in this assessment.

GENERAL STATUS OF ULTRASONIC MEASUREMENT OF MECHANICAL PROPERTIES

In many cases, correlations have been noted between ultrasonic parameters, such as velocity, attenuation, and backscattering, and material properties. In general, the underlying cause of these correlations is that the same microstructural feature which controls the ultrasonic measurement plays an important role in controlling the property of interest. However, there are generally multiple microstructural features which control both the ultrasonic measurements and the properties of interest. Since the functional relationships are not the same, only empirical relationships, under controlled conditions, have generally been observed. As noted by Vary, "Ultrasonic measurements give indirect indications of mechanical property variations and morphological conditions. Empirical correlations and calibrations must be established for each material even where theoretical bases exist [3]."

As an example, Vary reported a correlation between fracture toughness and a parameter associated with the ultrasonic attenuation for a variety of materials, including certain low carbon steels [4], as shown in Fig. 1. Similar results were reported by Canella and Tadei [5]. However, in other material systems, such as those showing a ductile-brittle transition, no such correlation was observed [6-8]. It was concluded by the community that such techniques only work well when the fracture toughness is strictly controlled by such microstructural features as grain diameter and/or the size of various phases, which interact with the ultrasonic waves via scattering mechanisms. This is consistent with the absence of this correlation in materials exhibiting ductile-brittle transitions, since the above microstructural features typically do not change as one passes through the transition temperature.

The mechanisms of damage are considerably different during neutron embrittlement. However, again, correlations with ultrasonic measurements have been observed. Figure 2 shows the shifts in ultrasonic velocity and attenuation, as observed by an acoustic microscope operating at a frequency of 15 MHz,

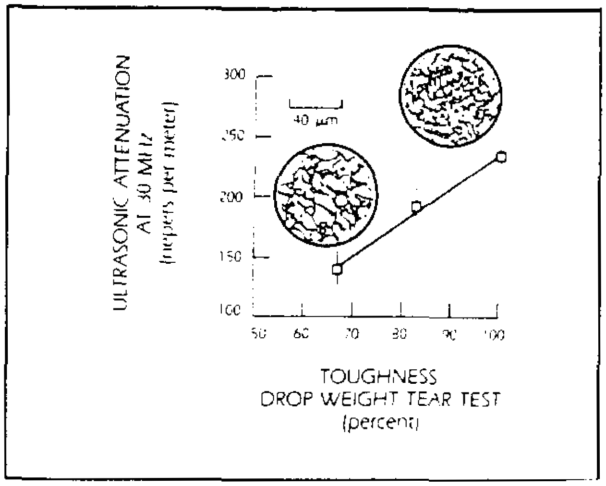

Figure 1. Correlation between ultrasonic attenuation factor and toughness for three heats of low carbon steel; photomicrographs show decreasing grain size associated with increased toughness and attenuation [3].

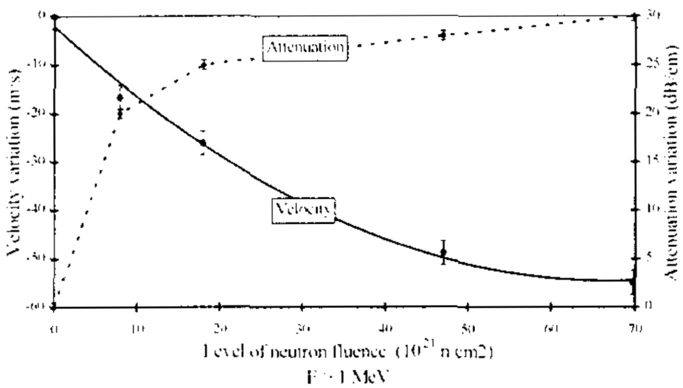

Figure 2. Rayleigh wave velocity and attenuation as a function of neutron irradiation, measured at four different levels in the same control rod [9].

in 304L stainless steel control rods [9].

The degree of remaining fatigue life is a performance parameter of considerable interest in the operation of critical structural components. Numerous studies have demonstrated its influence on ultrasonic velocity and attenuation. Figure 3, following the work of LeBrun and Billy [10], provides a typical example. Here the time of flight of 4 MHz ultrasonic waves propagating in mild steel between a pair of transducers, separated by a fixed distance, is shown as a function of the fraction of fatigue life. It can be seen that the wave speed decreases (time of flight increases) by 0.7% during the fatigue life, with the majority of the change occurring in the early stages. Although such measurement precisions are easy to obtain, it is clear that the technique faces significant difficulties since (a) other microstructural variations can produce comparable shifts, (b) most of the effect is in the early stages of life and (c) care must be taken to discriminate the fatigue effects from the effects of temperature changes.

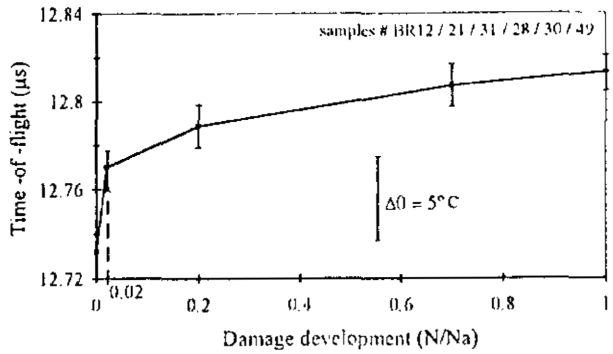

Figure 3. Influence of fatigue on the time-of-arrival of ultrasonic Rayleigh waves propagating on the surface of mild steel samples [10].

The measurement of residual stress is a crucial ingredient in the prediction of performance. There has been considerable effort devoted to the development of ultrasonic tests for this purpose [11]. The physical principles are well understood. Via anharmonic effects, stress causes a small shift in the ultrasonic velocity. Practical implementation is inhibited by a problem associated with inverting the data, since microstructural changes can produce competing shifts in velocity. This problem has been approached through the use of multiple measurements which allow the effects of stress and microstructure to be differentiated [12-14], or by obtaining a reference velocity from a region of the component in question which is believed to have no stress but the same microstructure as the region in question.

THE IDEAL SCENARIO

Developing satisfactory solutions, which minimize the need for such empiricism, is a highly interdisciplinary activity. Figure 4 illustrates that the development of techniques to measure mechanical properties involves a substantial overlap of the resulting expertise of materials science and NDE. In a recent self-assessment, the former community has identified itself as being concerned with the study of the interactions of synthesis/processing, structural/composition, properties, and performance [15]. By analogy, we could include in the elements of NDE the study of the interactions of nondestructive *measurements, microstructural parameters and material* properties. To the extent that we can quantify and utilize these interrelationships, we can reduce the degree to which the differences between the microstructural features sensed by NDE and those controlling failure/deformation lead to the need for empirical correlations and calibrations. In the next section, we will present examples in which it has been possible to accomplish this objective.

Before doing so, however, it must be emphasized that the foundations of the NDE component of this paradigm must be an understanding of how elastic waves interact with microstructure. Considerable progress along these lines has been made in the last decade, but much remains to be done. The quantities which are observed in a classical ultrasonic measurement are velocity, as inferred from an arrival time, attenuation, as inferred from a rate of decay of multiple echoes, and backscattered noise, which produces a general background of signals between the discrete signals associated with reflections from major discontinuities or the surfaces of a component. Discussions of the relationships of these quantities to the microstructure [16] and of the underlying theory necessary to quantitatively interpret these measurements [17] may be found in the literature. Speaking somewhat generally, it can be noted that the velocity is often independent of frequency in the cases of interest and hence can be interpreted in terms of the ratio of a modulus to density. Hence, the relationship of velocity to microstructure can often be interpreted in terms of static theories for the influence of the microstructure on these quantities. Attenuation and backscattering, on the other hand, are consequences of the scattering of energy out of the beam by inhomogeneities in the material and must be interpreted in terms of elastodynamic theories. For a number of simple cases, these relationships have been worked out in some detail, as will be illustrated by the following examples.

Consider the case of a polycrystal with randomly oriented, equiaxed grains. A variety of authors have considered the relationship of attenuation to grain size, with perhaps the most sophisticated calculation being the work of Stanke and Kino [18]. These theories show that the ultrasound-microstructure interaction can be described by a universal plot of αd versus d/λ, where α is the attenuation, d is a measure of the grain size, and λ is the ultrasonic wavelength, as shown in Fig. 5. These theories have been confirmed by careful experiments on copper [19].

A difficulty which limits the use of attenuation measurements is the necessity that the components have parallel faces, sufficiency far apart that a train of echoes can be observed whose rate of decay defines the attenuation. On thin sheet, an alternate approach involves resonance techniques [20]. When only one surface is available, one can infer the attenuation from the rate of decay of the backscattered noise [21].

In the materials used for structural applications, the microstructures are generally considerably more complex. Of particular interest in the degradation of energy-producing structures is the effect of porosity, e.g. as develops during creep. Thompson, Spitzig, et al. [22-23] studied the effects of porosity in the related problem of monitoring the decrease of porosity during sintering. It was found that the observable ultrasonic properties were influenced by the scattering from both the grains and pores. It was concluded that, for these sintered iron samples, the porosity controlled the velocity through its influence on the static modulus and density, whereas the grains controlled the attenuation through scattering effects, essentially as described by Stanke and Kino [18]. In these samples, the contributions of the pores to the attenuation were insignificant, a conclusion that is not general since it is sensitive to the relative sizes of the grains and pores as well as the elastic anisotropy of the crystallites [24].

There are, of course, a variety of more complex situations which have not yet been analyzed in such detail. These include many of the complex microstructures which have been developed by metallurgists to achieve particularly desirable mechanical properties. Results such as those described above provide a general strategy and may give considerable insight into the influence of the microstructural features of interest. The specifics of a particular case determine whether further quantitative efforts are warranted.

RECENT ADVANCES IN MECHANICAL PROPERTY MEASUREMENTS

In this section, we will discuss examples of mechanical property measurements in which the strategy presented in Fig. 4 has been followed. These will be arranged in order of the degree to which heterogeneity present in the microstructure must be taken into account. The first two deal with metal polycrystals while the last one deals with composites.

The first example given will be the prediction of sheet metal forming properties from measurements of the

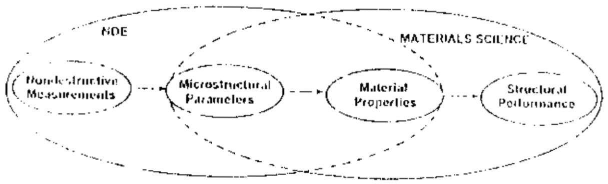

Figure 4. Overlap of the Interdisciplinary Couplings in NDE and Materials Science.

anisotropy of the ultrasonic wave speed. Forming properties are controlled by the plastic anisotropy of the sheet, which is in turn strongly influenced by its texture (preferred grain orientation). As shown in the top portion of Fig. 6 [25] this texture also produces an anisotropy in elastic parameters which can be determined either destructively through measurement of Young's modulus or nondestructively through measurements of ultrasonic velocity. As both the plastic and elastic anisotropy are controlled by the texture, there is reason to hope that sheet metal formability parameters can be inferred from measurements of the anisotropy of the ultrasonic velocity. Should this be true, it opens the way for on-line measurements, using non-contact sensors such as electromagnetic-acoustic transducers (EMATs) or lasers, for process control or 100% characterization purposes, as shown at the bottom of Fig. 6.

Recent research has shown that a technique based on measurement of the anisotropy of velocity of Lamb waves [26-27] propagating in the plane of the sheet is quite successful [28]. Two modes are commonly used. The fundamental symmetric

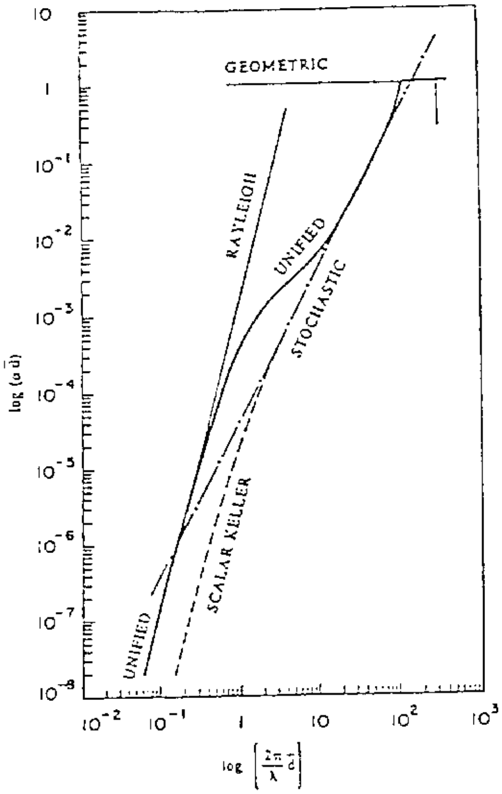

Figure 5. Normalized plot of attenuation versus grain size in iron [19].

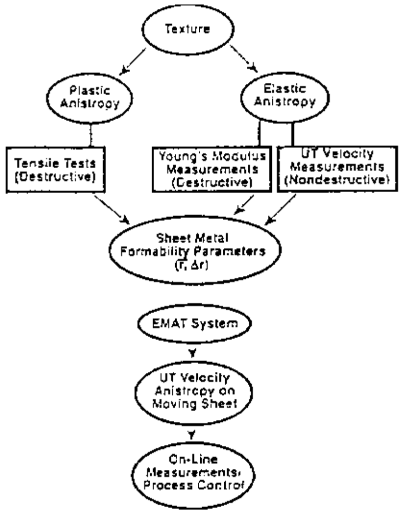

Figure 6. Strategy of Ultrasonic Determination of Sheet Metal Forming Parameters [25].
(a) Common Role of Texture in Determining Elastic and Plastic Anisotropy
(b) Opportunity for On-Line Measurements

Lamb (S_0) mode travels at a velocity which is slightly less than that of a plane longitudinal mode due to the vanishing of stress at the surface. The velocity asymptotically approaches a constant value, V_{LIM}, as frequency goes to zero. Correction for this slight dispersion plays an important role in relating practical measurements, always made at finite frequencies, to the theoretical results which are simplest to interpret in the long wavelength limit [29]. Another commonly used mode is the fundamental horizontally polarized shear mode (SH_0), in which the polarization lies in the plane of the plate. To lowest order in the anisotropy, the velocity of this mode is uninfluenced by the surfaces of the plate since the wave fields do not contain stress components on those surfaces.

By expressing the wave velocities in terms of the anisotropic elastic constants (assumed to have macroscopic orthotropic symmetry), relating these to certain parameters describing the texture, and inverting, one can find expressions for the texture parameters. From these, the plastic properties can be predicted based on either experimentally defined correlations or direct theory of the plasticity of polycrystalline aggregates.

Perhaps the most noteworthy application of these techniques has been in predicting the drawability of steel samples, as developed in a variety of countries [30-37]. In this section, we will review results which were recently reported in the Ph.D. dissertation of Forouraghi [36-37]. Here, a set of 270 samples from 26 lifts of steel, provided by LTV Steel Company and National Steel Corporations, were analyzed to test the reproducibility of the ultrasonic predictions and to numerically compare these predictions to those of tensile tests. Predictions of plastic strain ratios to be defined below were made in two ways from the ultrasonically determined texture parameters. In the first, one calculates the anisotropic values of Young's modulus and uses these as input to the previously established correlations of Mould and Johnson [38]. In the second, the texture parameters are direct inputs to polycrystalline plasticity theory utilizing relaxed constraints [39].

Figures 7a and 7b present comparisons of the ultrasonic and tensile predictions of $\bar{r}$ and Δr, respectively. Here, the plastic strain ratio, a mechanical property, is defined as the ratio of width to thickness strains in a tensile coupon pulled in tension to about 15% strain. Because of anisotropy, the plastic strain ratio will generally depend on the angle of the coupon with respect to the rolling direction of the sheet. It is useful to define other engineering parameters which summarize important aspects of this anisotropy. The average normal anisotropy, $\bar{r}$, is defined as

$$\bar{r} = \left[r(0^\circ) + r(90^\circ) + 2r(45^\circ) \right] / 4. \qquad (1)$$

This quantity is a measure of the ability of the material to successfully undergo deep drawing [40].

The planar anisotropy, Δr, defined by

$$\Delta r = \left[r(0^\circ) + r(90^\circ) - 2r(45^\circ) \right] / 2. \qquad (2)$$

is a measure of the in-plane anisotropy and correlates with the earing, ε. The latter is defined in terms the profile of the scallops, or ears, that develop during a deep drawn test.

Two ultrasonic predictions are shown in Fig. 7, based on the Mould-Johnson correlation [38] and the relaxed constraints (RC) model [39], respectively. In each figure, the solid line indicates perfect agreement while the dashed lines represent the expected variability in the tensile data. For the case of $\bar{r}$, the RC model appears to give the better results, particularly for the higher values of $\bar{r}$ characteristic of IF steels. The two approaches give about equivalent results for Δr.

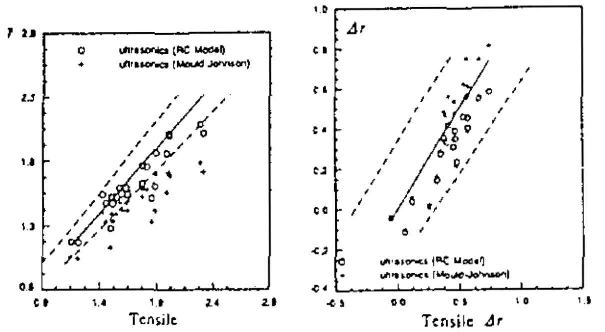

Figure 7. Experimental Predictions of $\bar{r}$ and Δr by Ultrasonics, Diffraction and Tensile Measurements [36]
(a) Ultrasonics and Tensile Predictions of $\bar{r}$ on all Samples
(b) Ultrasonics and Tensile Predictions of Δr on all Samples

Aluminum is another widely used metal with a cubic crystal structure. Texture control is important in a variety of applications, including the fabrication of beverage cans. Hence it is reasonable to consider the utility of using ultrasonics to monitor texture in a fashion analogous to the steel applications discussed above.

There are, however, a number of differences. Because of the difference in crystal structure (FCC versus BCC), there are differences in (a) the deformation modes (i.e. active slip planes and directions, (b) processing sequence and controlling parameters, and (c) formability parameters of interest. For example, in the formation of beverage cans, the degree of earing is an engineering parameter of particular interest. From the perspective of ultrasonic measurements, the fact that the elastic anisotropy of Al is much less than that of Fe means that more precise measurements are required to achieve the same level of accuracy in the prediction of texture and formability parameters.

Correlations of ultrasonic anisotropy with degree of earing on cold rolled sheet have been reported. Figure 9 presents data, based on a combination of the work of Lu et al. [41], Thompson et al. [42]. It can be seen that a significant correlation exists between the % earing and the texture parameter W_{440}.

In the above example, the material was viewed as a homogeneous medium and the mechanical property of interest was inferred from the wave speed anisotropy. At the next level of complexity, one must consider heterogeneities in the medium, e.g. the grain structure of a metal. Because of the anisotropy of the elastic constants of the crystallites, waves will scatter at grain boundaries, leading to attenuation and backscattered noise. From the analysis of the strength and spectral characteristics of these phenomena, e.g. as illustrated in Fig. 5, one can obtain a

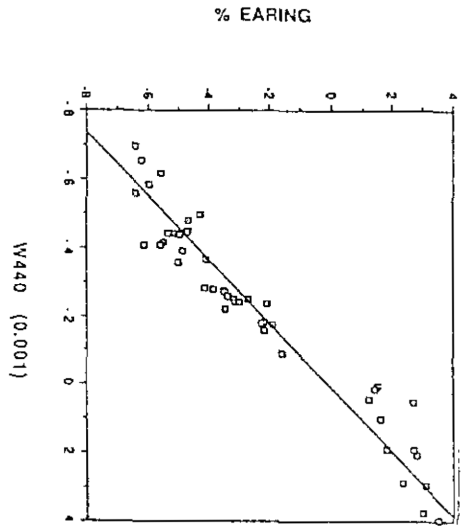

Figure 8. Correlation of the Texture Parameter W_{440} with the Degree of Earing in Cold Rolled Aluminum [42].

measure of the grain size, which controls a number of mechanical properties in metal alloys with simple microstructures. One example is described by the Hall-Petch relationship, which states that the yield stress, σ_0 is given by

$$\sigma_0 = \sigma_1 + KD^{-1/2} \tag{3}$$

where D is the grain size and σ_1 and K are constants.

Important foundations for understanding and measuring attenuation include the works of Bhatia [45] Papadakis [46], Evan et al. [47] and Stanke and Kino [18]. A variety of techniques have been considered to measure the attenuation. Basic measurement procedures are discussed by Papadakis [48]. However, the interpretation of the data can be somewhat problematic, since the single crystal elastic constants, needed as inputs for any of the theories, may not be known for alloys or the current theories may not be applicable to more complex microstructures where scattering at grain boundaries is not the only significant mechanism of attenuation. Figure 10 presents one alternative approach, the use of experimentally determined calibration curves [49]. Fitting these to the frequency dependence of the attenuation provides a measure of grain size.

A second approach, particularly appropriate to thin sheets, involves the measurement of the rate of decay of resonances, from which attenuation can be inferred. Based on a correlation of this resulting attenuation with grain size, ultrasonic prediction of grain size is realized. Figure 11 presents a comparison of the ultrasonic and metallographically determined grain size for low carbon steel [20]. As was noted previously, the attenuation

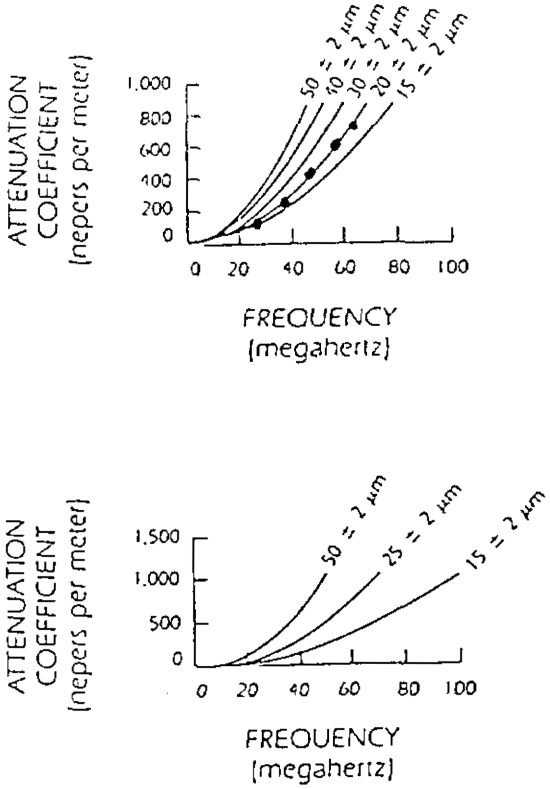

Figure 9. Use of Calibration Curves to Infer Grain Size from Attenuation [49]
Top: 99.99% Pure Copper
Left: 99.5% Pure Nickel

can also be inferred from the rate of decay of backscattered noise, again providing a measure of grain size [21].

It is well known that the tensile strength, yield strength, and hardness are interrelated in polycrystalline metals. Based on the Hall-Petch relationship, one would then expect a correlation between attenuation and hardness. Figure 12 presents such a result for the aluminum copper alloy 2024-T351A in which the hardness varied as a result of age hardening. As expected, we see that the samples with high attenuation (large grains) had the lowest hardness [50]. However, in developing such applications, care must be taken to ensure that it is the grain size, rather than some other microstructural factor, which controls the mechanical property.

Many modern structural materials have a much greater level of heterogeneity than the single-phase polycrystals discussed above, and here the challenges in mechanical property predictions are considerably greater. A very important example is the case of fiber-reinforced composites, the mechanical properties of which are often controlled by those of the interface between the fibers and matrix. For example, in metal and intermetallic matrix composites, special interphasial reaction barrier coatings and compliant coatings are introduced to improve chemical and thermal compatibility. In ceramic-matrix composites, the interphase is designed to provide frictional sliding contact between fiber and matrix to prevent fiber fracture

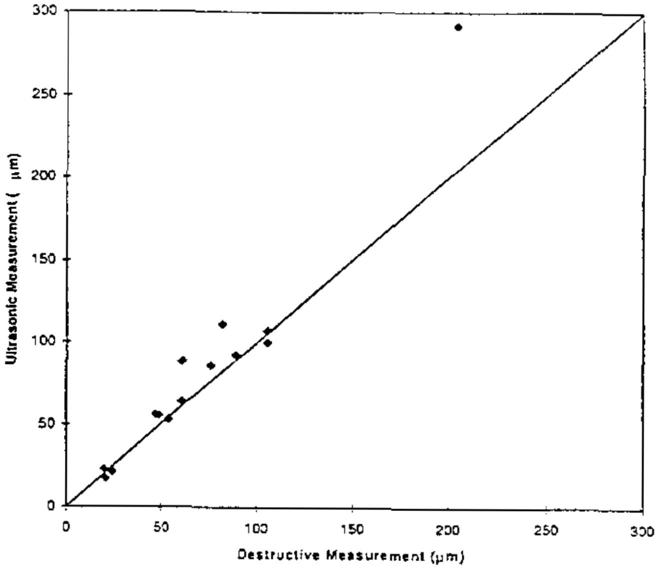

Figure 10. Comparison of the Destructive and Ultrasonic Measurements of Average Grain Size of Steel Samples [20].

due to matrix cracking. A major challenge to the NDE community has been the development of techniques to measure and interpret the mechanical properties of the interphasial region [51].

Among the important contributions in this area is the work of Rokhlin et al., [51-53] who have studied the effects of fatigue on interphasial properties of metal-matrix composites and of oxidation on the interphasial properties of ceramic matrix composites. As an example, Fig. 13 shows measurements of the reduction of the interphasial moduli of a ceramic matrix composite after oxidation at various times and temperatures [54].

OUTSTANDING ISSUES IN MICROSTRUCTURAL CHARACTERIZATION

In the above examples, we have discussed in detail techniques to infer formability from grain orientation measurements, hardness from grain size measurements, and oxidation induced degradation of interfacial stiffness in composites. Although significant progress has been made, there is much more to do. Material scientists are constantly working to improve the mechanical properties of materials through the manipulation of their microstructure. Included in alloys are the creation of

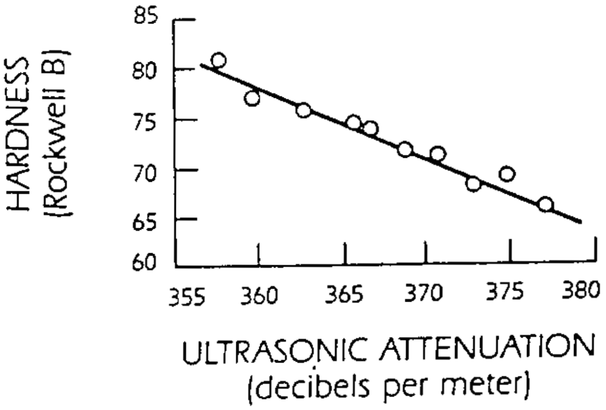

Figure 11. Correlation of Ultrasonic Attenuation with Hardness in 2024-T351A After Different Amounts of Age Hardening [50].

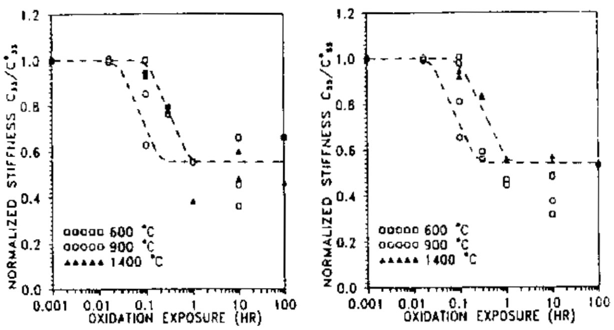

Figure 12. Composite Moduli C_{33} and C_{55} Versus Oxidation Exposure Time in Ceramic Matrix Composite [54].

second phase particles, segregation of atomic species or precipitation of second phases at grain boundaries, controlled interstitial concentrations, and microstructures with multiple dimensional scales such as those produced by Martensitic transformations. In composites, a wide variety of tailored interphases are of interest. Some encouraging preliminary results have been obtained in each of these areas. As an example, Mittleman et al have shown the ability to use backscattering to detect second-phase shells in parts fabricated by powder metallurgy routes [55] and Han and Thompson have demonstrated the relationship between the frequency dependence of backscattering and the features of a duplex microstructure [56]. However, there is clearly much to be done if we are to develop a comprehensive set of tools for mechanical property measurements.

EMERGING MEASUREMENT TECHNIQUES

To develop a full set of information needed to measure mechanical properties, it is clear that new measurement modalities are required. All of the above examples are based on linear, elastic wave propagation and can be interpreted in terms of such events as scattering processes. Although such measurements can be extremely powerful, there is a limit to the amount of information that can be recovered.

Nonlinear measurements are emerging tools which have shown considerable promise in feasibility studies but for which a detailed understanding has not yet been developed. As an example, Fig. 14 presents the dependence of ultrasonic harmonic generation on fatigue for a metallic and composite system [57]. The large increase in the nonlinear parameter seen towards the end of the fatigue life is much greater than the corresponding changes in the linear parameters, attenuation and velocity. A candidate interpretation of this result involves the opening and closing of the partially contacting microcracks, which are much stiffer in compression [58]. Other studies have suggested that harmonic generation can be used to measure the quality of interfaces [59] and adhesive bonds [60]. In a preliminary interpretation, it is argued that a simple summation of the amplitudes of the harmonics is a measure of the binding force at an interface [59].

One important potential application of nonlinear measurements is in the characterization of dislocations, microstructural elements which control many mechanical properties. The understanding of the interaction of ultrasound with the dislocation structures found in structural metals is not well developed. However, progress is being made. Figure 15 presents ideas discussed by Buck [58], building on the work of Gremaud and Bujard [61]. The central idea is that, while dislocation loop lengths in many commercial metals are sufficiently short that the interaction of ultrasound with the dislocations is small, this situation can be changed by the application of a stress which causes the dislocations to break away from their pinning points, thereby increasing their loop length. An example of a possible test based on this idea would be high frequency ultrasonic attenuation measurements made while the material is being insonified by a relatively low frequency acoustic signal of sufficient power to unpin the dislocations [62]. Recent progress in the understanding of dislocation/ultrasound interactions includes the work of Cantrell [63].

CONCLUSIONS

In general, ultrasonic techniques to measure mechanical properties have been based on empirical correlations, and the range of samples on which successful results can be obtained is limited. However, as our understanding of wave-material interactions matures, improved techniques are emerging. Specific examples discussed included measurements of sheet metal formability parameters based on a determination of preferred orientation, metal hardness based on a determination of grain size, and composite interphasial moduli which control mechanical properties.

It is believed that future efforts should follow several lines. The continued development of techniques such as those described here is required. Increased emphasis should be placed on establishing mechanistic understanding of the observations through the application of appropriate theories of energy-material interactions. A number of the fundamental analysis tools are in place, and the range of microstructural complexities to which they can be applied is increasing as the power of

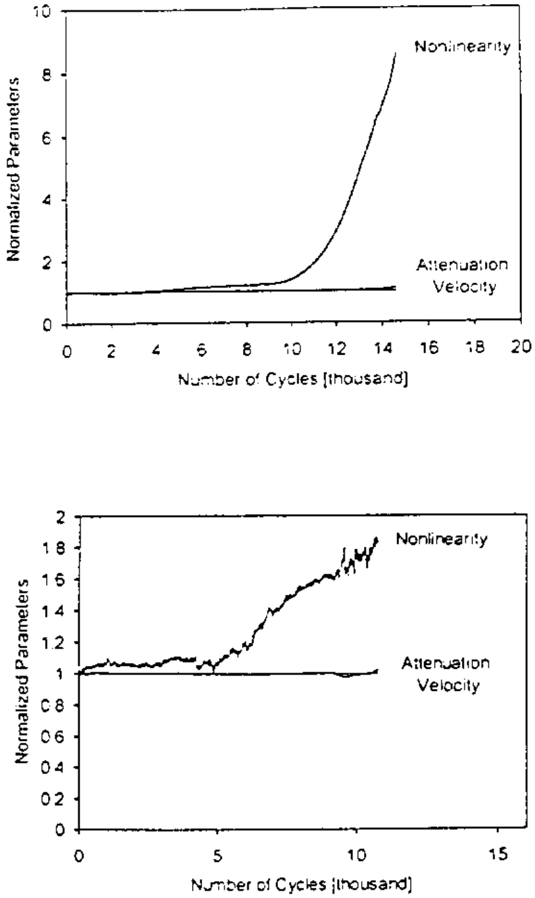

Figure 13. Ultrasonic Nonlinearity as a function of fatigue [57].

(a) 2090 Aluminum

(b) Titanium Matrix Composite

modern computers grows. Increased attention needs to be given to improved strategies for interpreting, through data inversion strategies, the measurement results. A first step is the improved mechanistic understanding that is discussed above. Such understanding would provide a basis for combining multiple measurements, either based on different parameters sensed with the same modality or the use of information gained from multiple modalities (i.e. data fusion), to suppress the interference of competing microstructural effects with the prediction of the quantities of interest. Finally, new measurement techniques, such as those based on nonlinear effects, should receive increasing attention.

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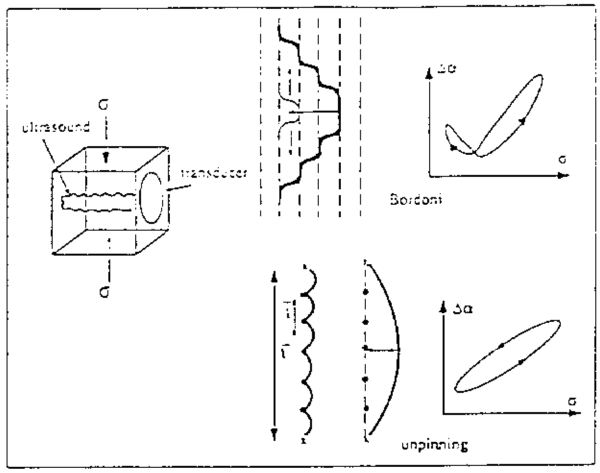

Figure 14. A conceptual view of an experiment to sense dislocations with ultrasound. Superimposed bias stress, as might be produced by high amplitude, low frequency insonification, leads to the dislocation structures and attenuation as shown at the right [58].

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