FUNDAMENTALS OF ULTRASONIC NDE FOR
MICROSTRUCTURE/MATERIAL PROPERTY INTERRELATIONS

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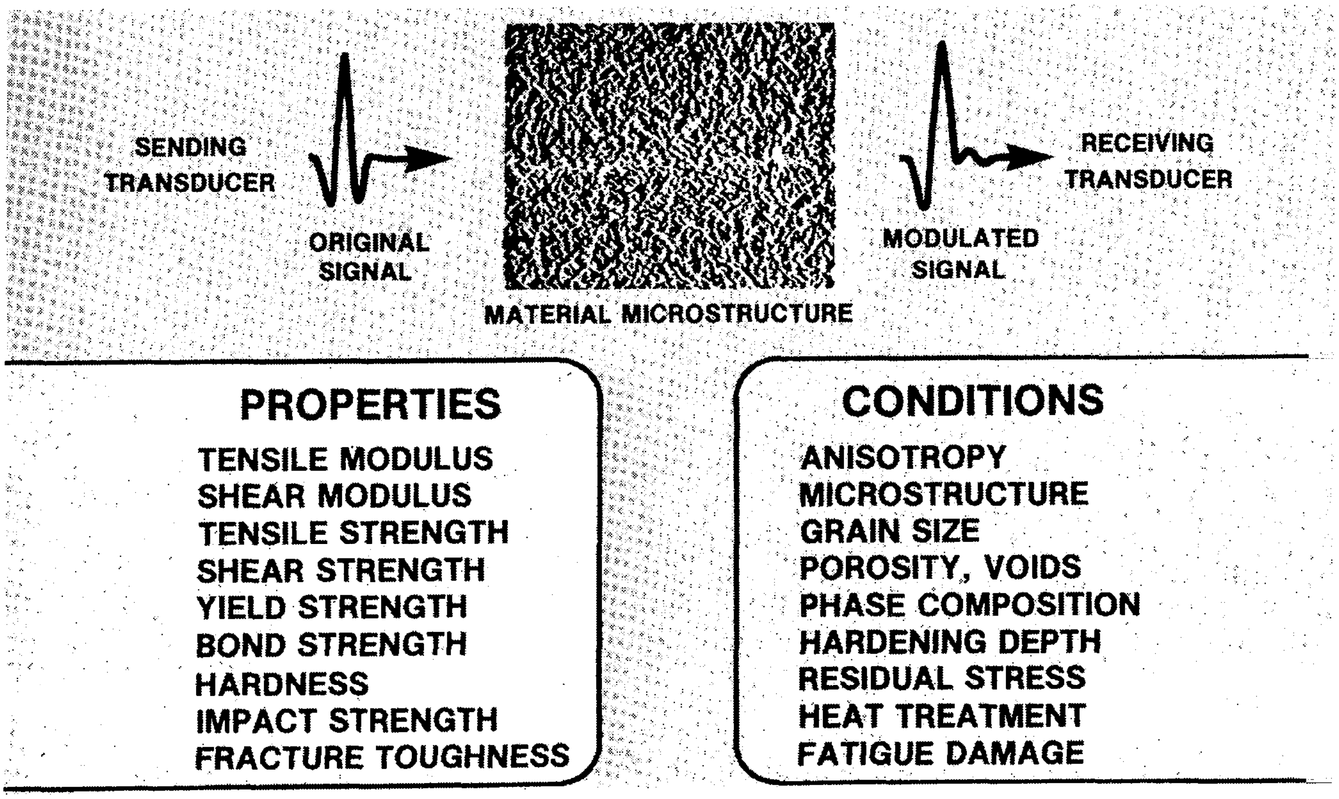
INTRODUCTION - PRELIMINARY CONSIDERATIONS

In its most general context, nondestructive evaluation (NDE) is a branch of materials science that is concerned with all aspects of the uniformity, quality, and serviceability of materials and structures. Therefore, NDE should not be defined solely by the current emphasis on the detection of overt flaws. On the broadest scale, NDE addresses the integrated effect of defects and the material environment in which the defects reside. This calls for NDE technology that can characterize inherent material properties as well as individual defects. In this case the emphasis is on the evaluation of microstructural and morphological factors that govern mechanical strength/toughness, dynamic performance, and residual life (ref. 1).

There are many NDE techniques that can to varying degrees characterize material properties (ref. 2). Herein, the focus is on ultrasonic techniques because of their wide potential for materials characterization. All the material properties and conditions listed in figure 1, for example, are amenable to ultrasonic evaluation (ref. 3). In this paper some fundamental aspects of ultrasonic NDE for material properties and microstructure assessment are given. Ultrasonic wave interaction concepts, some recent findings, and practical ramifications are illustrated. The concepts are discussed in nonmathematical, narrative form. Additional information can be found in the references cited herein.



PROPERTIES

TENSILE MODULUS
SHEAR MODULUS
TENSILE STRENGTH
SHEAR STRENGTH
YIELD STRENGTH
BOND STRENGTH
HARDNESS
IMPACT STRENGTH
FRACTURE TOUGHNESS

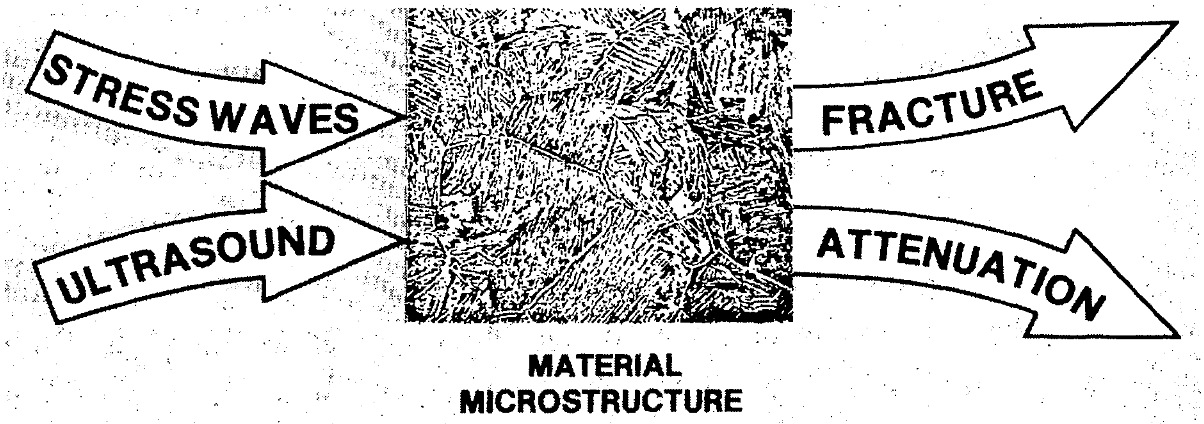
CONDITIONS

ANISOTROPY
MICROSTRUCTURE
GRAIN SIZE
POROSITY, VOIDS
PHASE COMPOSITION
HARDENING DEPTH
RESIDUAL STRESS
HEAT TREATMENT
FATIGUE DAMAGE

Figure 1

ULTRASONIC INTERACTIONS WITH MICROSTRUCTURE

The basis for ultrasonic materials characterization lies in the analysis of wave interactions with microstructure. Material microstructure and grain morphology affect ultrasonic wave velocity and attenuation. These same factors also affect material properties and dynamic performance. For example, velocity measurements correlate with elastic moduli and residual stresses. Attenuation measurements correlate with mechanical properties such as strength, hardness, and toughness. Both velocity and attenuation measurements correlate with microstructural factors that influence or govern material properties and performance. A basis for these correlations is suggested in figure 2. Spontaneous stress waves that arise during dislocation movements, deformation, cracking, and fracture failure are ultrasonic in nature. It is reasonable, therefore, to expect that by introducing benign ultrasonic probe waves one can interrogate the microstructure and infer its effect on the stress waves that interact with it during deformation, failure, etc. An approach to ultrasonic materials characterization consists of treating the microstructure as having a mathematically definable modulation transfer function that governs stress wave propagation. The analysis then proceeds by comparing output versus input signals as indicated in figure 1. An especially useful method involves frequency domain signal deconvolution procedures to determine the ultrasonic attenuation characteristics of a sample of material (ref. 4).

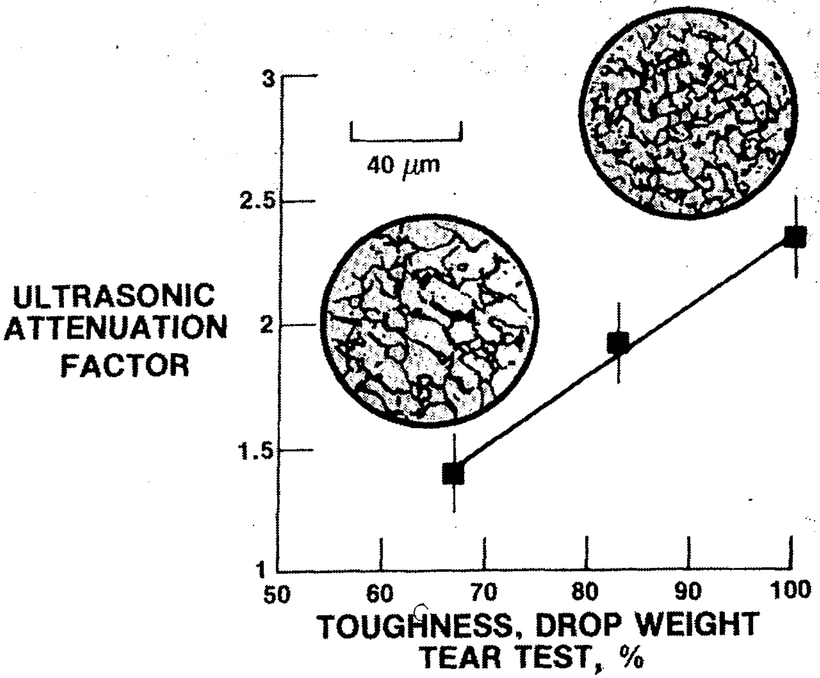


ULTRASONIC WAVES CAN EVALUATE MICROSTRUCTURAL FACTORS THAT GOVERN DISLOCATION MOVEMENTS, DEFORMATION, CRACKING, ETC.

Figure 2

ULTRASONIC VERIFICATION OF MATERIAL PROPERTIES

Tensile strength, yield strength, and fracture toughness are examples of extrinsic material properties that depend on microstructure and grain morphology in polycrystalline aggregates that constitute typical structural materials. Herein, we will concentrate on illustrative examples of ultrasonic measurement of fracture toughness in metals. Increased toughness in structural materials means increased resistance to catastrophic fracture failure due to sudden crack growth. Tougher materials tolerate larger naturally occurring or fatigue-induced cracks. One goal of NDE is to detect and characterize cracks that are greater than a critical size and likely to cause catastrophic fracture failure. The criterion for what constitutes a critical crack size presupposes that a material's fracture toughness is known. The usual way to determine fracture toughness is to conduct destructive tests on samples of material. Representative toughness indexes, such as the plane strain fracture toughness or drop weight tear test values, are used to calculate critical crack size (ref. 5). But this does not satisfy the need for verification of the actual toughness of the material in which the cracks reside. This need can only be met by NDE techniques that characterize material properties. As indicated in figure 3, ultrasonic attenuation measurements can be used to verify fracture toughness once calibration curves are established for a given material.



A CORRELATION BETWEEN AN ULTRASONIC FACTOR AND TOUGHNESS IS SHOWN.

EACH DATA POINT REPRESENTS A DIFFERENT HEAT OF STEEL.

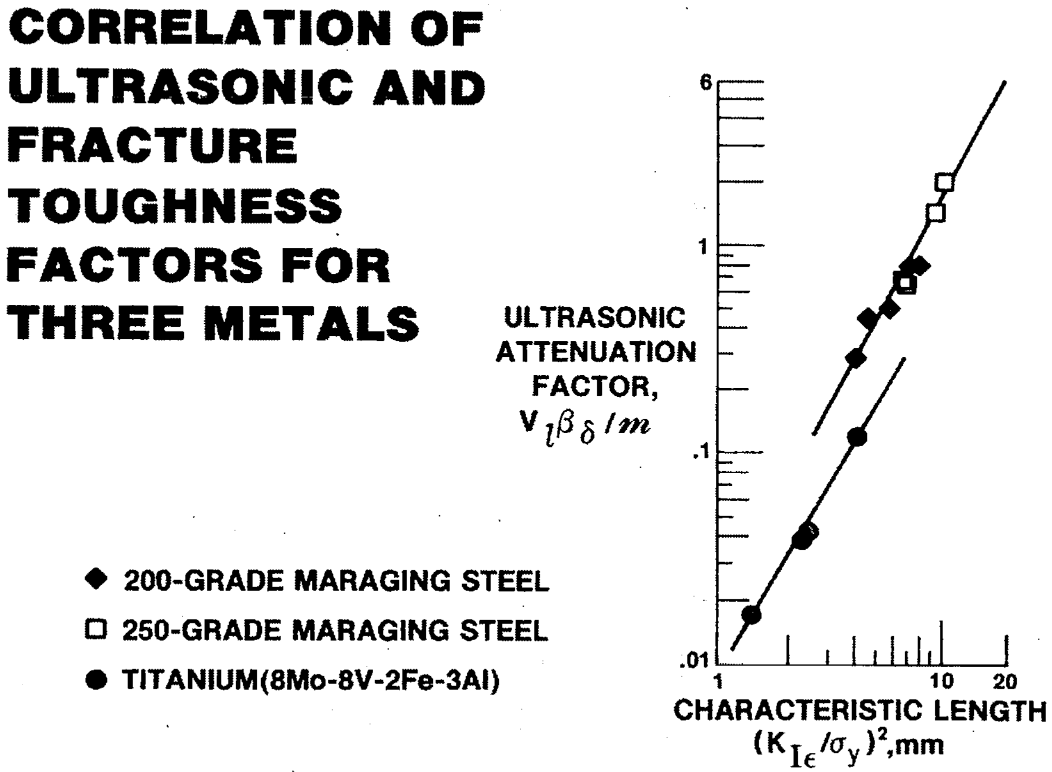
THE BARS INDICATE THE SCATTER ASSOCIATED WITH THE ULTRASONIC MEASUREMENT.

PHOTOMICROGRAPHS SHOW THAT GRAIN SIZE DECREASES WITH INCREASED TOUGHNESS AND ATTENUATION.

Figure 3

ANALYTICAL BASIS FOR ULTRASONIC PREDICTION OF TOUGHNESS

Although significant empirical correlations of ultrasonic attenuation and velocity with material mechanical properties exist, the theoretical bases for predicting extrinsic properties such as toughness are only now being investigated. A recent development initiated at the NASA Lewis Research Center invokes a stress wave interaction (SWI) model and the interrelation of ultrasonic attenuation and microstructure. The SWI model postulates that spontaneous stress waves generated during crack nucleation and onset of rapid unstable crack growth strongly interact with specific microstructural features. The SWI model has been successfully used to derive equations that predict experimentally observed correlations (e.g., fig. 4). For polycrystalline aggregates the predicted relation consists of a power function between the "characteristic length" factor and ultrasonic attenuation factor. The characteristic length factor consists of the ratio of plane strain fracture toughness and yield strength. The square of this ratio is proportional to the plastic or "process" zone size at the tip of a crack verging toward instability. Tougher materials exhibit larger process zones and, hence, a greater degree of crack blunting. SWI theory and empirical data (as in fig. 4) agree in identifying the ultrasonic attenuation properties of material microstructure as significant in determining the process zone size and, concomitantly, the material toughness (ref. 6).



CORRELATION OF ULTRASONIC AND FRACTURE TOUGHNESS FACTORS FOR THREE METALS

Figure 4

ELEMENTS IN ULTRASONIC PREDICTION OF MATERIAL TOUGHNESS

A holistic approach to predicting toughness, ultimate strength, and similar properties involves three basic elements: a stress wave interaction (SWI) model, a microcrack nucleation mechanics (MNM) model, and a microstructure transfer function (MTF) model (see fig. 5). The SWI model invokes the concept that energy absorption sites are activated by spontaneous stress waves emitted at the onset of catastrophic crack growth. These sites are associated with distributed microstructural features that resonantly absorb stress wave energy. The model assumes that there is a threshold wavelength commensurate with the mean dimension of critically interacting microstructural features, e.g., second phase particles, precipitates, etc. The mode of stress wave interaction with critical microfracture sites is described by an appropriate microcrack nucleation mechanics (MNM) model. The MNM model delineates the specific ultrasonic energy absorption mechanism peculiar to a given material's microstructure, grain morphology, boundary spacing, etc. The SWI and MNM models are supplemented by the microstructure transfer function (MTF) model which is required for characterizing the material microstructure. The MTF model is the basis for nondestructive characterization of ultrasonic propagation properties of the material. Appropriate combinations of the three models can be used to derive analytical expressions that predict correlations between ultrasonic and material property factors, as indicated in figure 5.

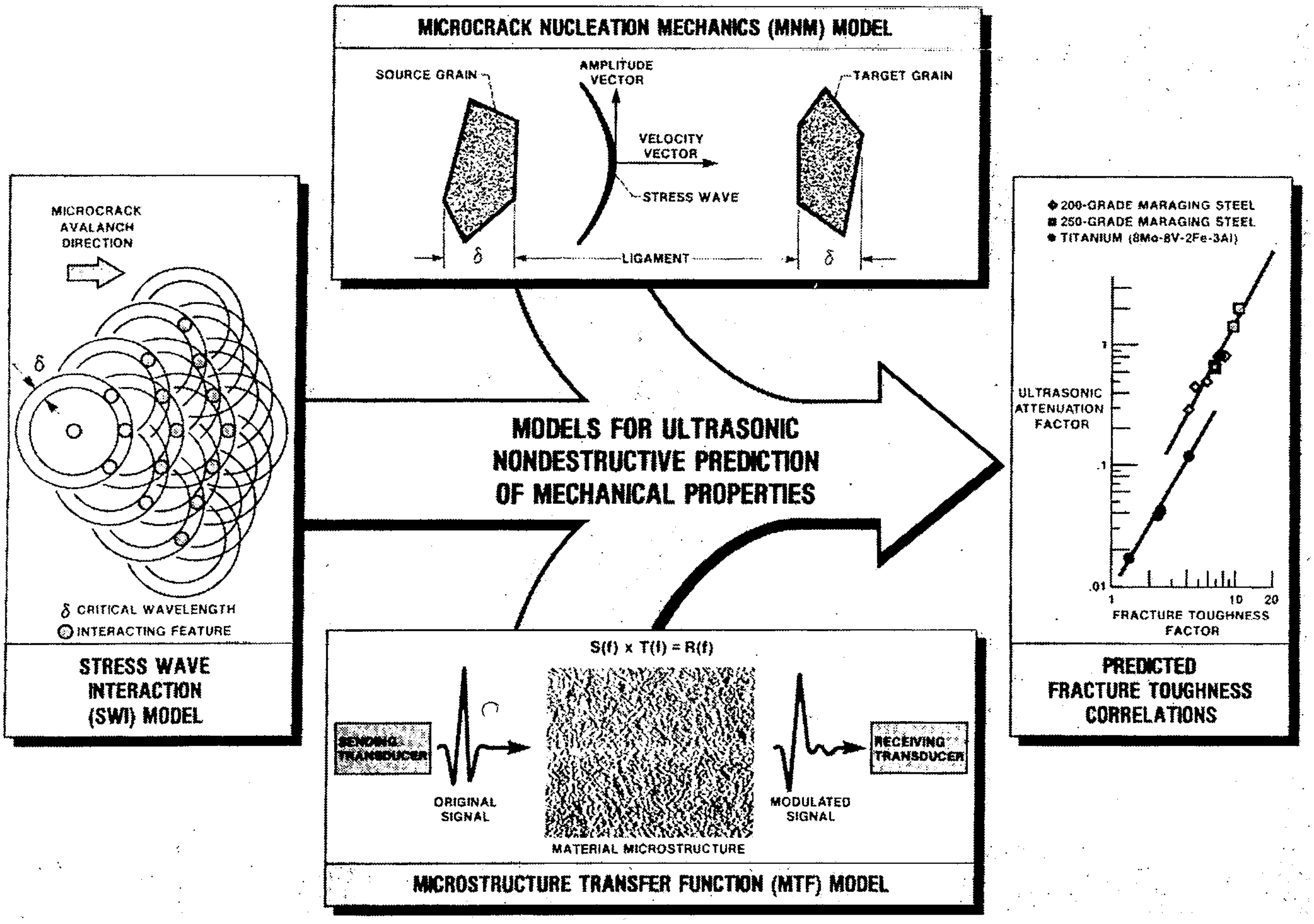
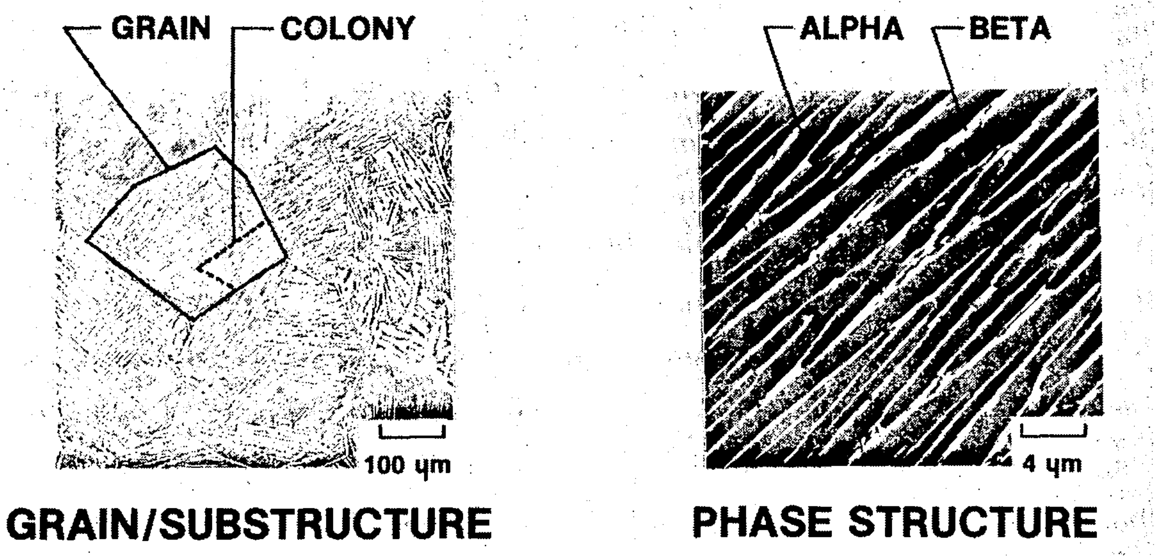


Figure 5

IDENTIFICATION OF CRITICAL MICROSTRUCTURAL FEATURES

A case study helps illustrate the role of critical microstructural features in governing material properties such as fracture toughness. Moreover, it will be seen that ultrasonic measurements based on stress wave interaction (SWI) and associated models can help identify the critical features. When assessment of microstructure is based solely on photomicrographs, it is not always apparent what feature governs material performance. Judging from figure 3, one might infer that increasing fracture toughness can be associated with decreasing average grain size. This basis for ranking toughness may be correct for low carbon steels and other materials with similar microstructures. However, for materials with a more complex microstructure, such as that shown in figure 6, we do not have a priori criteria for ranking fracture toughness simply by examination of photomicrographs. In this latter case, and in general, the ranking can be accomplished with the aid of ultrasonic measurements and the previously mentioned models.

By using the SWI and associated models, one can derive equations relating ultrasonic and toughness factors. There is a particular equation that is valid only if one of the factors is the critical dimension associated with the microstructural feature that influences or governs fracture toughness. It is found that the best correlation of ultrasonic and toughness data occurs when the equation is evaluated using the correct (i.e., critical microstructural) dimension (see fig. 7).

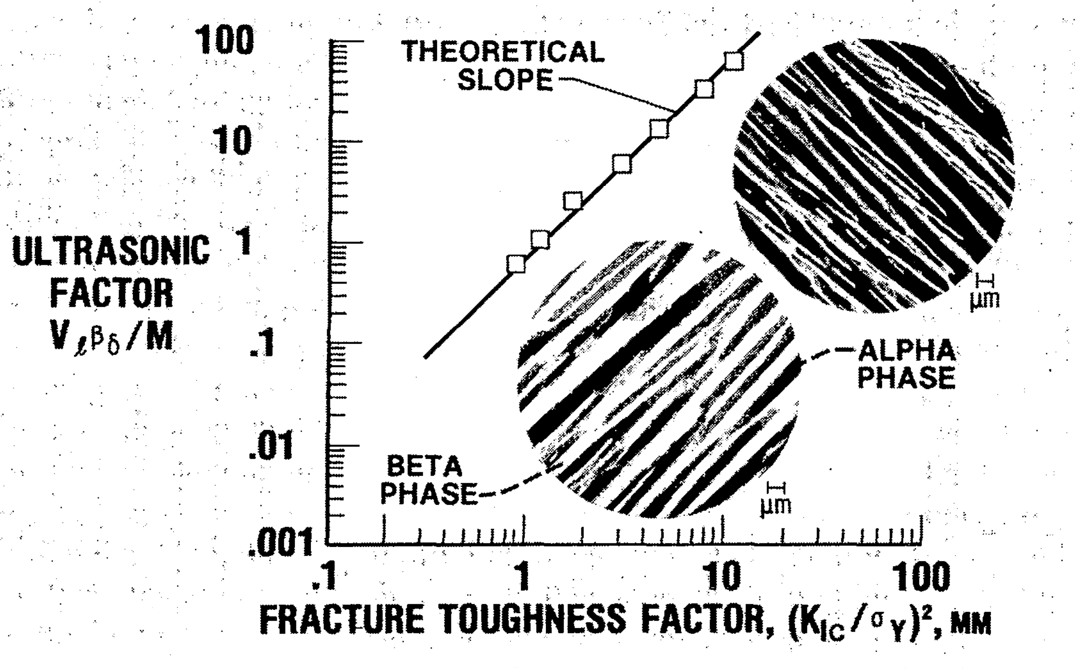


WHICH MICROSTRUCTURAL FACTOR GOVERNS FRACTURE TOUGHNESS?

Figure 6

In the case of the titanium alloy depicted in figures 6 and 7, there are three levels of microstructure: grains, colonies, and alternating alpha/beta phases, each with its own characteristic dimension. The question is which of these features exerts the greatest influence on toughness. The question has been answered experimentally and in conformance with the previously discussed analytical models (ref. 7). The results shown in figure 7 indicate that the best empirical correlation and also best agreement with theoretical expectations occur with data based on the beta-phase thickness. The alpha-phase thickness was found to be significant but less critical from the ultrasonic viewpoint. Colony size was weakly influential while the grain size was indeterminate in affecting toughness in the titanium alloy. Further analysis confirmed that the beta phase comprised the critical microstructural feature because of its high dislocation density and high attenuation (i.e., high energy absorption) for ultrasonic waves.

In all the cases studied thus far the experimental results agree with predictions based on the SWI and associated models mentioned previously. These models appear to be at least valid starting points for predicting and explaining correlations between ultrasonic and fracture toughness measurements. However, it should be admitted that we are only at a preliminary stage in establishing fundamental precepts for ultrasonic NDE of extrinsic properties.



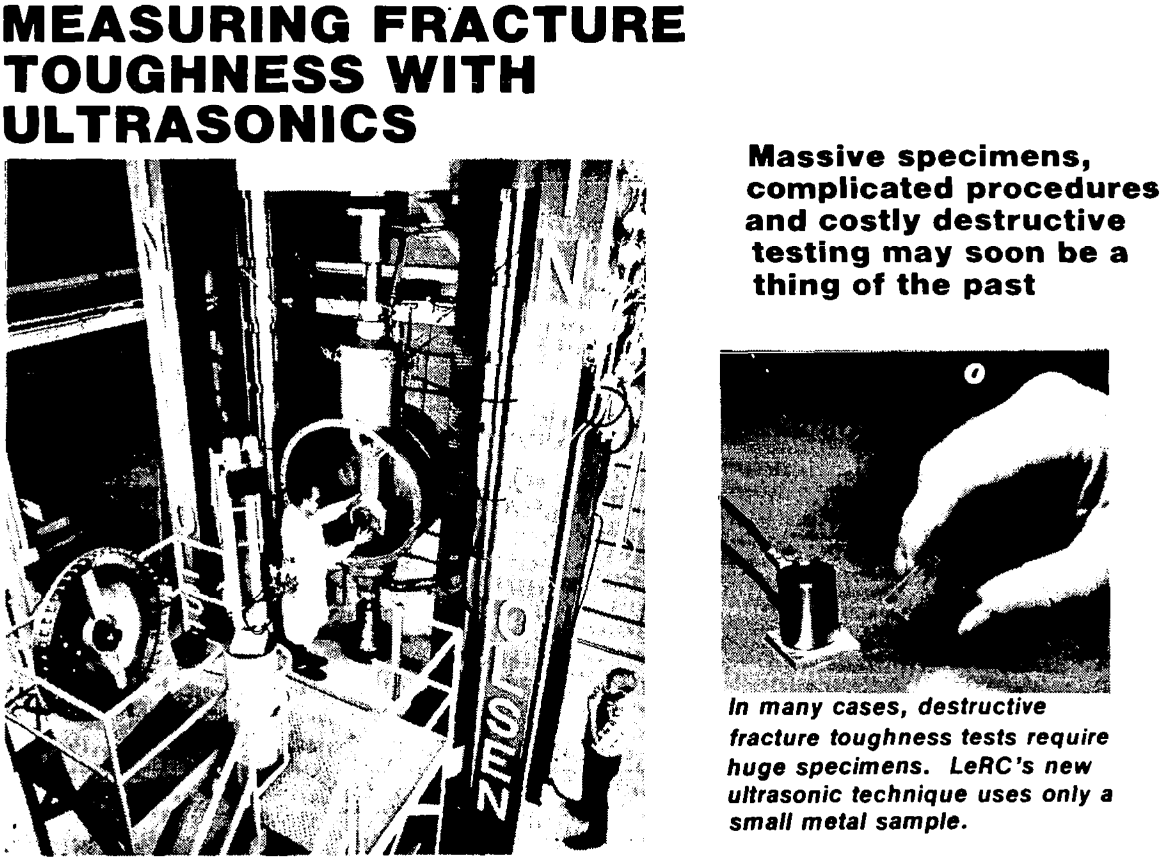
★ **DATA BASED ON MEAN BETA PHASE THICKNESS, THE CRITICAL MICRO-DIMENSION**
★ **SLOPE OF LINE THROUGH DATA CONFORMS WITH STRESS WAVE INTERACTION MODEL**
★ **MODEL PREDICTS RELATION FOUND BETWEEN ULTRASONIC & TOUGHNESS FACTORS**

Figure 7

PRACTICAL IMPLICATIONS - CONCLUSIONS

Among the obvious practical applications of the ultrasonic technology mentioned herein are those of material property assessment and verification. As indicated in figure 8, immediate benefits can be realized by ultrasonic measurement of fracture toughness and related properties. This would satisfy a widely recognized need for rapid, inexpensive alternatives to conventional destructive methods for fracture toughness testing (ref. 5).

The preceding text summarized concepts and experimental findings concerning nondestructive materials characterization. For illustrative purposes, there was some focus on ultrasonic assessment of fracture toughness. There are, however, ramifications that extend beyond toughness or any other extrinsic property. Therefore, the emphasis was on interrelations of ultrasound, microstructure, and extrinsic properties to indicate the potential scope of NDE. It should be apparent that NDE technology can span a rather large area of interest ranging from parts inspection to materials research. From the research viewpoint, the ultrasonic technology cited herein can contribute to better understanding of factors that govern material performance and also contribute guidance to microstructure tailoring to achieve better performance. This is in addition to the more standard role of ultrasonics for defect and materials characterization.



MEASURING FRACTURE TOUGHNESS WITH ULTRASONICS

Massive specimens, complicated procedures and costly destructive testing may soon be a thing of the past

In many cases, destructive fracture toughness tests require huge specimens. LeRC's new ultrasonic technique uses only a small metal sample.

Figure 8

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