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Ultrasonics for Microcrystalline Structure Examination [and Discussion]

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Ultrasonics for microcrystalline structure examination

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Non-destructive testing (NDT) methods are used to determine the ability of materials and components to withstand applied loads of different kinds. Besides defects, materials' properties are the interesting features from the engineering point of view. But although defect parameters of materials can be determined quantitatively by NDT, the mechanical–technological parameters cannot be measured directly. They are related to the structure of the materials by different types of multi-parameter dependencies. Ultrasound interaction with the structure can be measured by adjusting the ultrasonic wavelength to the linear dimension of the interesting structural parameter. A second advantage of ultrasonics is the great amount of information about the microstructure obtained by the frequency-dependent measurable quantities: velocity, attenuation, absorption and scattering. The determination of different structural features in this way enables their correlation with the wanted technical materials' properties to be investigated. This contribution discusses, in particular, the following aspects:

velocity depending upon microcrystalline features as higher-order effects, leading to correlations with materials properties;

scattering as the information parameter about microstructures integrally while describing microcrystalline features locally;

independent absorption measurements for the description of microcrystalline structures;

interdependence of velocity and attenuation, via the Kramers–Kronig relation.

1. Introduction

Engineers are interested in properties of materials like strength, hardness and toughness for the design and construction of components and systems. If the system is already built they want to determine these properties non-destructively.

However, non-destructive testing and evaluation (NDT and NDE) are able only to describe and to determine defects, structure and stress. Their multiparameter correlation to the material properties is still unknown. This is especially true for the microstructure because of the influence of a set of features like macroscopic homogeneity and isotropy, grain size, size and distribution of inclusions and segregates as well as the different types of lattice defects; therefore the ability of a component to withstand applied loads can only be found out non-destructively by measuring defects, stresses and the relevant microstructural parameters with NDT techniques and by determining the correlation between these parameters and the properties.

The main advantage of ultrasonic testing is the possibility of adjusting the wavelength to the linear dimension of the interesting parameter. The second advantage is that there are (with reference to the microstructure) only two relevant parameters (velocity and attenuation) and their dependence upon frequency, stress, magnetic field strength, temperature, etc. contains the necessary information about the microstructure.

This contribution deals in particular with the higher-order effects on ultrasonic-wave propagation parameters due to the microcrystalline structure.

2. Velocity

The velocity v of ultrasonic waves is a well-known material constant related to density ρ and elasticity, e.g. for transversal waves

$$v_T = (G/\rho)^{\frac{1}{2}},$$

where G is the shear modulus, therefore the mapping of velocities or time-of-flights over components is accepted as a tool for qualitative homogeneity characterization of materials (for example in the cast iron or advanced ceramics industry). One of the problems with velocity measurements is their dependence upon elasticity *and* density. Variations of both parameters in the same direction will not influence v significantly.

In reality v is a function of a set of structural features:

$$v = v\,(\rho;\ E, G, \nu;\ \text{texture};\ \epsilon_{el}, \sigma_{el},\ \text{TOEC};\ \epsilon_{pl};\ d, f;\ T; \ldots),$$

where E, ν are Young's modulus and Poisson's ratio, respectively, ϵ_{el}, ϵ_{pl} and σ_{el} are the elastic strain, plastic strain and elastic (residual) stress, respectively, TOEC are third order elastic constants, d is grain size, f is frequency and T is temperature.

This means that the locally measured absolute value of v only gives a qualitative information about the material. Nothing can be said about the microstructure. This information comes from 'derivatives' like:

(*a*) v (position): homogeneity, fatigue, damage (Goebbels & Theiner 1985), radiation embrittlement (W. Arnold, unpublished results);

(*b*) v (direction and polarization): ϵ_{el}, σ_{el} (Hughes & Kelley 1953), texture (Schneider *et al.* 1984; Hirsekorn 1985) and plastic anisotropy (Goebbels & Salzburger 1983);

(*c*) v (frequency): grain size (Goebbels & Theiner 1985), see figure 1, for example;

(*d*) v (ϵ_{el}): TOEC (Hughes & Kelley 1953);

(*e*) v (direction, polarization and frequency): separation of σ_{el} and texture (Goebbels & Hirsekorn 1984);

(*f*) v (temperature): separation of σ_{el} and texture (Schneider *et al.* 1984).

Some of theses relations are verified by experiments only, some by theory alone and in some cases already proved by theory *and* experiment.

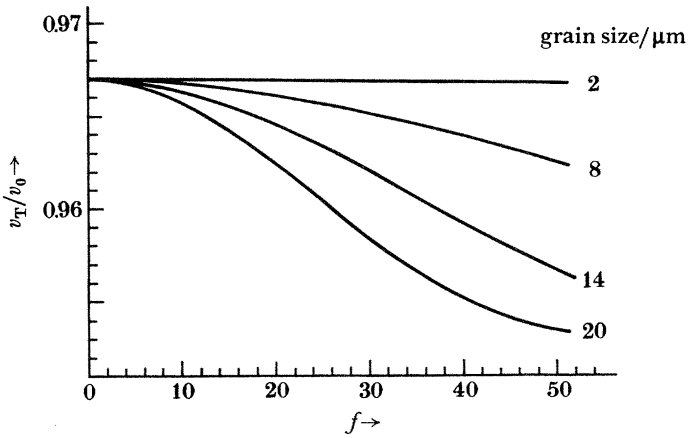

Figure 1. Frequency dependence of shear-wave velocity, v_T, due to scattering for different grain sizes in polycrystalline iron ($v_0 = v_T$ (homogeneous, isotropic material)).

The evaluation of the above parameter correlations shows that changes in technical material properties are related to changes of second order effects (e.g. TOEC) while not affecting basic physical constants (e.g. E, G) as much. Figure 2 gives an example referring to plastic deformation of steel (Pitsch 1985).

The first results recommending research in this direction (Salama & Alers 1967, 1977) were not followed by detailed studies. Now such types of higher order effects will be further analysed.

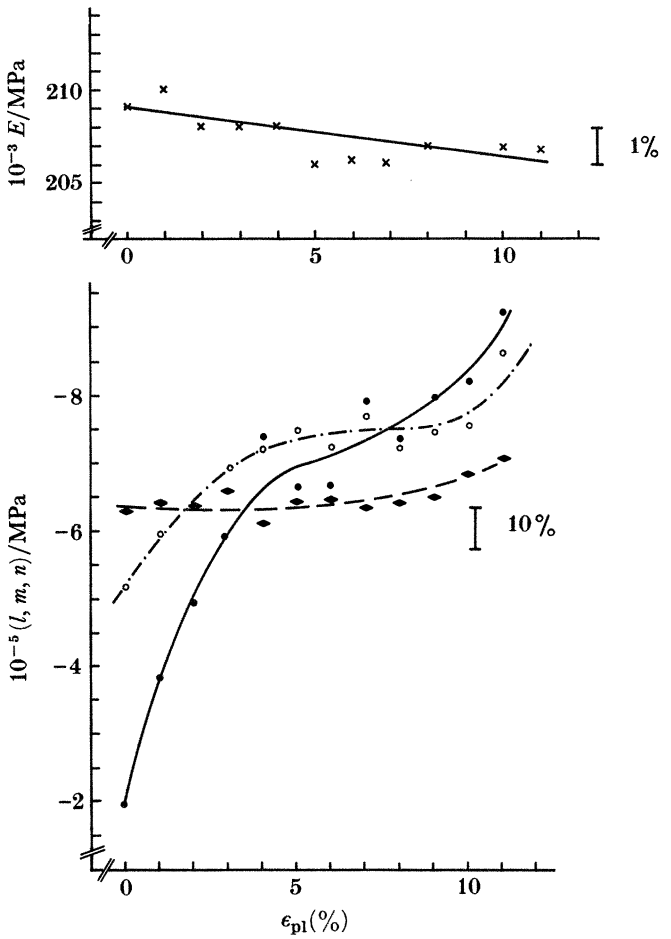

FIGURE 2. Influence of plastic deformation ϵ_{pl} of steel onto the elastic modulus E and the third order elastic constants l, m and n. ●, l; ○, m; ◆, n.

3. SCATTERING

Scattering of ultrasound in polycrystalline materials has been under investigation since the early work of Bhatia (1959). But only recent theoretical works allow the wave propagation (velocity v and scattering coefficient α_s) outside the Rayleigh-region $d \ll \lambda$ (where λ is the wavelength) (Hirsekorn 1982, 1983; Stanke 1983) and even for textured material (Hirsekorn 1985) to be understood. Background for this work is the non-destructive grain size determination and homogeneity characterization by backscattered ultrasound (Goebbels 1980). Figure 3 shows how much v (polarization or direction) is influenced in textured material whereas α_s remains practically constant.

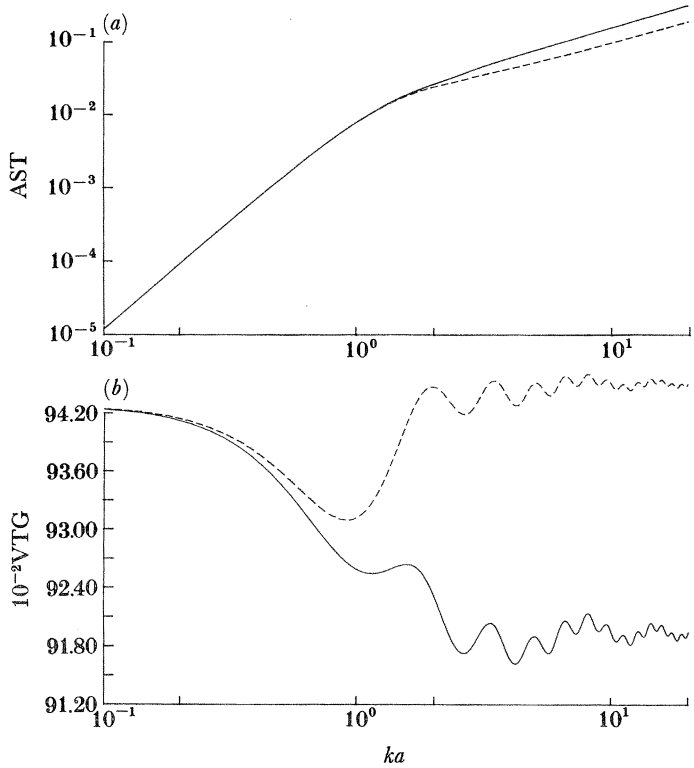

FIGURE 3. Shear waves in 70% cold rolled steel propagating in rolling direction with polarization in normal direction; (——) and polarization in transverse direction (– – –) (after Hirsekorn 1985). (*a*) Normalized scattering coefficients; (*b*) normalized group velocities; $ka = \pi d/\lambda$, whereas d is the grain size and λ is the wavelength.

One goal for the grain size determination based on α_S-measurements is the correlation to yield strength σ_y following the Hall–Petch equation

$$\sigma_y = k_0 + k_1 \cdot d^{-0.5}.$$

The problem is obviously the determination of the constants k_0 and k_1, which until now have had no correlation to NDT parameters.

One step down in the microcrystalline structure of polycrystalline material is the understanding of the formation of backscattering signals. Figure 4 shows that a measured backscattering signal has to be interpreted as the superposition of the single backscattering signals, coming back to the transducer from all the grains, in a sound beam for a given time of flight; amplitude and phase are the significant parameters (Goebbels 1982). Usually this is a superposition of several thousand individual scattering signals; the use of focused beams and $\lambda < d$ should allow the microstructure of a single grain inside the specimen to be identified. Experiments in this direction have not yet been done.

4. ABSORPTION

The absorption coefficient, α_A, (total attenuation $\alpha = \alpha_A + \alpha_S$) is a function of several influencing microstructural parameters. In polycrystalline metals mainly dislocation damping and magnetoelastic losses as well as thermoelastic losses are responsible for an overall linear

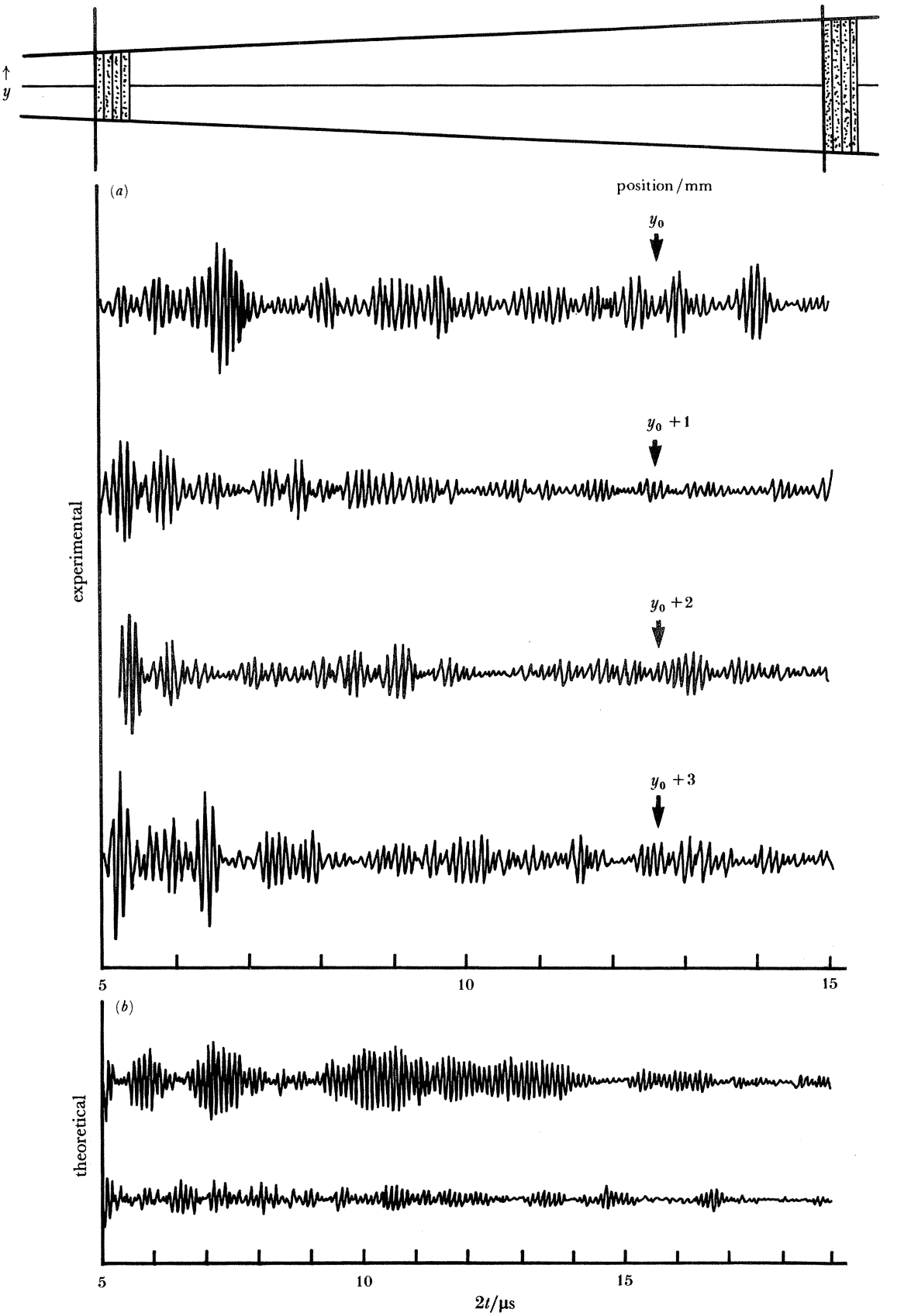

FIGURE 4.(*a*) Experimentally observed backscattering signals; (*b*) simulated backscattering signals obtained by superposition of backscattered amplitudes and phases from single scatterer signals.

hysteresis $\alpha_A \lambda = \text{const}$. Because of too many single damping processes with too many characteristics (e.g. length, density, stress and orientation of dislocations) and the problems in separation α_A and α_S if α was measured, in the past there was not much interest in obtaining the absolute value of α_A. However, the dependence of α_A upon the cited microstructural features and because their correlation to technical material properties, the interest in α_A has increased. At the moment the starting point is several independently working methods to determine α_A which should be compared with each other and should be related to the microstructure. They are:

(*a*) two-frequencies method (Goebbels 1980) based on $\alpha = a_1 f + a_4 f^4$;

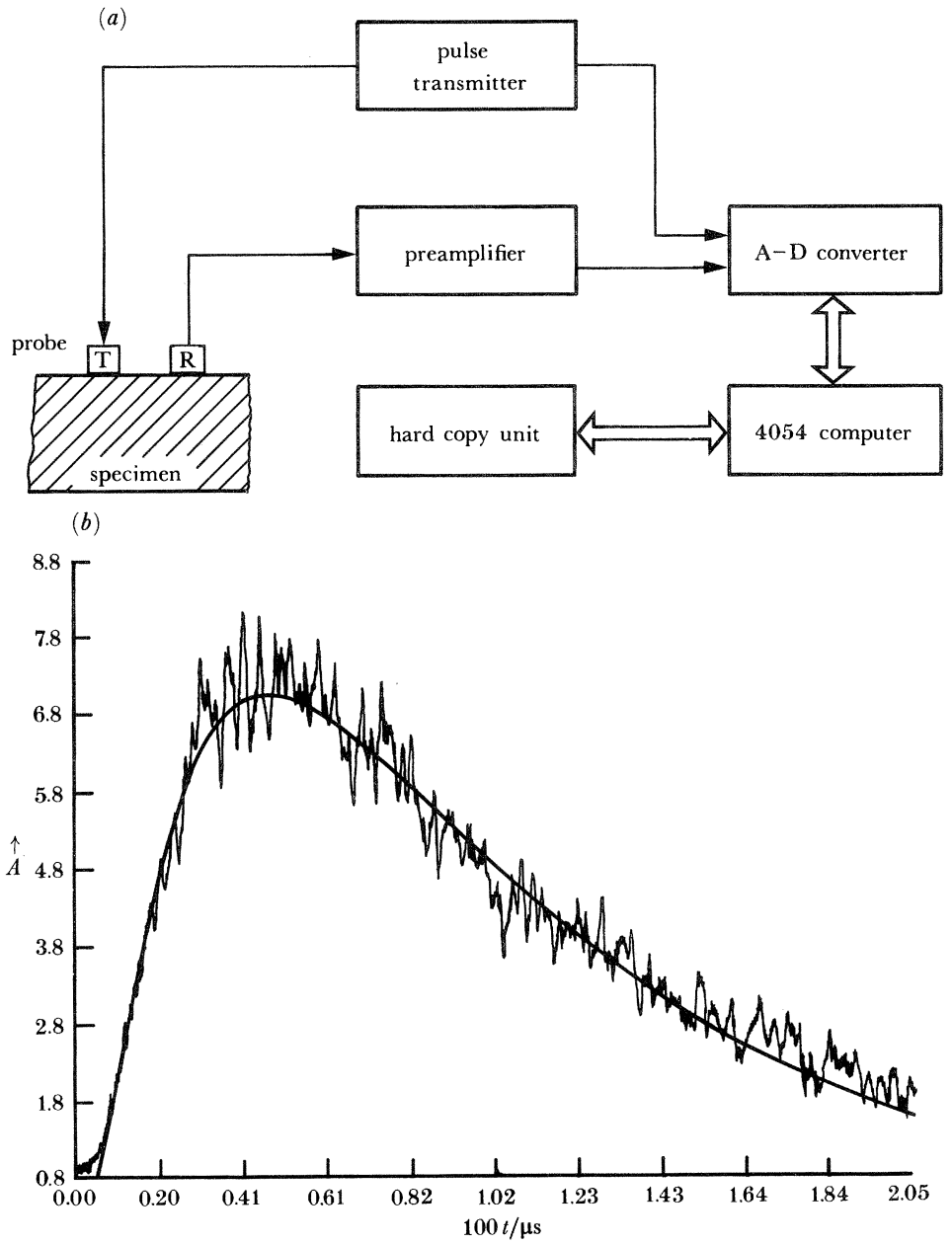

FIGURE 5. (*a*) Sideways scattering measurement arrangement, (*b*) sideways measured scattering amplitude, A, against time (frequency, 5 MHz; material, iron; grain size, 100 μm; transmitter–receiver distance, 60 mm).

(*b*) multiple scattering $A_{SM}(x) = A_{SE}(x)\,(1+\text{const. exp}\,(2\alpha_S x))^{\frac{1}{2}}$ with $A_{SE}(x)$ = scattering amplitude as function of sound path, x, without multiple scattering (Goebbels 1980);

(*c*) internal friction measurement (Deka & Eberhardt 1984) at high frequencies based on $\alpha_A \lambda = \pi Q^{-1}$ (Q^{-1} is a damping constant);

(*d*) thermo-emissivity measurement (Monchalin & Bussière 1984) with infrared detectors based on IR detector output proportional to α_A;

(*e*) diffusion model for scattering processes (Guo *et al.* 1985) based on scattering amplitude $\approx \exp(-\alpha_A x)$ (see, for example, figure 5).

If these directions are followed, consequently it can be foreseen that important new information about the microstructure can be taken from the absorption coefficient (e.g. the measurement of α_A with or without saturation magnetization will determine the contribution of magneto-elastic losses).

5. Kramers–Kronig relation

In linear and causal systems real and imaginary parts of propagation parameters are functions of each other. This interrelation is known as the Kramers–Kronig relation. The problem in finding out this relation between v and α is the limited frequency range which can be covered by experiments. The development of so-called local solutions (O'Donnell *et al.* 1978, 1981) has shown promising results at least for tissue characterization in medical diagnostics although the general formulation of a v–α equation (Ginzberg 1955) has not yet been verified successfully. Experimental difficulties as described above and basic questions (v–α, v–α_A, v–α_S) make the analysis of the Kramers–Kronig relation in ultrasonics an interesting challenge for future work.

6. Conclusion

Material properties determine the ability of components to withstand loads they are designed for and constructed for. These properties depend upon structure, stress and defects where the microstructure plays the key role if large defects are not present. Ultrasound can be used to determine the microstructure, measuring the properties of elastic and anelastic wave propagation. They are characterized by velocity, v, attenuation, α, absorption, α_A, scattering, α_S, and especially by their derivatives referring to frequency, thermal and mechanical load.

The knowledge to date shows that material properties like fatigue or strength are less related to the basic wave propagation parameters although influencing significantly higher-order elastic constants and dispersion behaviour.

Understanding, theoretical and experimental experience are still at the early stages of non-destructive material property determination but relevant ideas and methods of measurement are known and will be applied in the future.

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Discussion

R.B. Thompson (*Ames Laboratory, Iowa State University, Ames, Iowa, U.S.A.*). In the early part of the talk, Dr Goebbels presented the Kramer–Kronig relations. Could he comment further on their use?

K. Goebbels. Unfortunately not as much as I would like to. W. Saclise and J. G. Miller, for example, used it in materials characterization and in tissue characterization, respectively. I feel that it is worthwhile to do more in this direction for materials where we are not able to determine the exact attenuation coefficient by backscattering measurements (e.g. in plastics and other non-crystalline materials).

R. E. Green (*Center for Nondestructive Evaluation, The John S. Hopkins University, Baltimore, Maryland* 21218, *U.S.A.*). Why does Dr Goebbels prefer the use of the acoustical birefringence technique to measure residual stress, because it is well known that the energy-flux vector is different for the two differently polarized shear (quasi-transverse) waves propagating in a given non-symmetry direction in an anisotropic material? These two waves will therefore not propagate through the same volume of material, thus invalidating the acoustical birefringence technique. Although this may not be a major problem with very thin sheets, it will be an extremely large problem with all *real* bulk materials used for structural applications.

K. Goebbels. In my experience the wave propagation is nearly always in a symmetry direction, especially for real bulk materials like pressure vessels, pipings, big forgings, etc. If not, I assume that any ultrasonic method will fail, for example in dendritic structures of cast stainless steel.

R. B. Thompson. In response to the previous discussion, first I comment that measurements of differences in the acoustoelastic constants of certain steel alloys under tensile and compressive stresses have recently been reported by Allison *et al.* (1986). They interpreted these observations in terms of dislocation effects. Secondly, I ask a question regarding the measurement of stresses in front of a crack tip by using birefringence data. This would appear to depend on the assumption that the birefringence varies linearly with stress in the plastic region as well as

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the elastic region and that the two responses have the same slope. Can Dr Goebbels comment on the justification for this assumption?

K. Goebbels. I agree with the first comment but the magnetoelastic interactions also could slightly influence the measurement.

The advantage of the birefringence method is that only one third-order elastic constant (n) is used. Fortunately n varies by only a few percent even for high plastic deformation. Therefore a linear superposition of stress and texture due to plastic deformation can be expected for the measurement.

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G. A. D. Briggs (*Department of Metallurgy and Science of Materials, University of Oxford, U.K.*). To what mechanisms does Dr Goebbels attribute the observed absorption? Dislocation damping is often involved as a contributing mechanism; what direct evidence is there that dislocation damping operates in the materials and at the strain amplitudes of his experiments?

K. Goebbels. There is no 'direct evidence' because absorption is due to several microstructural interactions. But it is reasonable to assume that the dislocation contribution is the dominant one.

C. M. Sayers (*Materials Physics and Metallurgy Division, AERE Harwell, Oxfordshire, U.K.*). (*a*) Dr Goebbels mentioned that in an inhomogeneous medium the scattered wave can be approximated by a solution of the diffusion equation. If this were true the distance travelled in a time t would vary as $t^{\frac{1}{2}}$. Do you have any experimental evidence to support this? (*b*) As I understand it, the Kramers–Kronig relations relate the real and imaginary parts of the propagation vector describing the coherent wave. This implies that both the absorption and scattering enter into the imaginary part, as may be seen using the forward scattering theorem.

K. Goebbels. (*a*) We found, like others, (Kuttruff 1967) a $1/f^4$ law, experimentally as well as theoretically. (*b*) Scattering is responsible for dispersion, see, for example, the work of Hirsekorn (1982, 1983, 1985). However, this must not be a Kramer–Kronig relation, because scattering is not a pure energy dissipation process as absorption is. Therefore one should analyse it by calculation and by experiments.

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C. B. Scruby (*AERE Harwell, Oxfordshire, U.K.*). How does Dr Goebbels plan to measure residual stress in a weldment, where there may be a combination of compressive and tensile stresses, and bearing in mind that an ultrasonic velocity measurement is necessarily averaged over the propagation path?

K. Goebbels. We have no plans, so far, to measure residual stress in weldments.

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