ULTRASONIC ATTENUATION MEASUREMENT USING BACKSCATTERING TECHNIQUE

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INTRODUCTION

Ultrasonic backscattering measurements by means of spatial averaging technique were carried out in steel to determine the ultrasonic attenuation coefficient. The attenuation coefficients were evaluated from the exponential decay of the backscattering signal. The results were compared with those obtained by evaluating the amplitude decay of the main pulse. Good agreement is observed provided the condition $\alpha_S \cdot \lambda \ll 1$ is valid, i.e. Rayleigh scattering with $d/\lambda \leq 0.2$ and/or weak elastic anisotropy of the single crystal. Otherwise multiple scattering becomes dominant and the amplitude decay of the backscattering curve is no longer related to the attenuation coefficient.

Ultrasonic attenuation in polycrystalline materials is closely related to microstructural features. One example of practical interest is the nondestructive evaluation of grain size in metals [1-4]. Attenuation measurement itself can be performed using different techniques. Usually, the attenuation coefficient α is determined from the amplitude decay of a backwall-echo sequence. However, this technique has some inherent drawbacks preventing its wider use in practical application. Especially, well-defined specimen geometry such as parallel surfaces which is usually not available in practical cases is required for correct evaluation. Here, the use of backscattering technique is often advantageous. Backscattering in polycrystalline materials is caused by the impedance mismatch occurring at the grain boundaries. The ultrasonic attenuation coefficient is determined from the amplitude decay of the backscattered signals. The question arises whether backscattering technique yields the same attenuation coefficient as the conventional technique measuring the amplitude decay of the propagating ultrasonic pulse. In a recent work [5], it was reported that the attenuation coefficient α_{BS} (BS - backscattering) is often much less than α_{TM} (TM - transmission), at least less than 0.5 α_{TM}. According to our experience [1,6], however, this conclusion is not of general validity. We are presenting some experimental results showing a comparison of both techniques. Based on these results, we point out the limits and conditions, under which backscattering technique can be used for attenuation measurements.

PHYSICAL BACKGROUND

Generally, ultrasonic attenuation in polycrystalline materials is caused by both absorption and scattering processes. At room temperature, ultrasonic absorption in steel is mainly due to dislocation damping, thermoelastic losses and magneto-elastic losses. The overall frequency dependence of ultrasonic absorption in the lower frequency range (1-30 MHz) is often found to be linear [1,7]. Typical absorption coefficients α_A in steel are below 0.4 dB/cm at 5 MHz [7].

Scattering is caused by the jump in acoustic impedance occurring at the grain boundaries. Assuming a quasi-isotropic, monophase material and neglecting multiple scattering, the ultrasonic scattering coefficient α_S in the Rayleigh approximation, defined by the condition $d/\lambda \ll 1$, is given by [8]:

$$\alpha_S = S_\beta \cdot d^3 \cdot f^4. \tag{1}$$

Here, d is the grain diameter, λ is the ultrasonic wavelength and S_β depends on material characteristics (density, sound velocity, elastic anisotropy) and wave type β, respectively [1]. A theoretical result for shear wave in steel is shown in Fig. 1 where the upper curve is calculated in Rayleigh-approximation. The lower curve in Fig. 1 includes second order perturbation theory taking into account multiple scattering [9]. For $d/\lambda = 0.2$ the deviation between both curves is about 15 percent (see Fig. 1). Whether multiple scattering has to be taken into account or not depends not only on the ratio d/λ but also on the scattering parameter S_β (Eq. 1). S_β essentially includes the elastic anisotropy factor which is assumed to be small. In the case of large fluctuations in the elastic constants, i.e. high anisotropy factor, multiple scattering may become dominant even under the condition $d/\lambda \ll 1$. This is observed in materials with large scattering parameter S such as, for example, copper.

The total ultrasonic attenuation coefficient α is given by

$$\alpha = \alpha_A + \alpha_S. \tag{2}$$

The amplitude A of a propagating plane wave decays exponentially with soundpath x:

$$A \propto \exp[-\alpha \cdot x]. \tag{3}$$

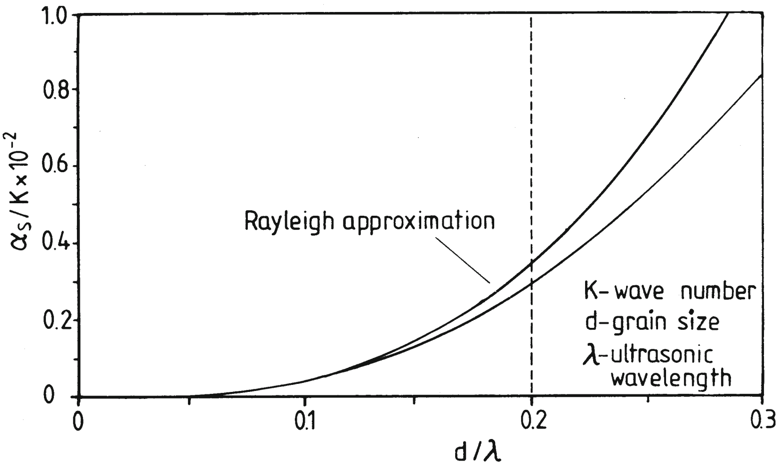

Fig. 1. Normalized ultrasonic scattering coefficient for shear wave in steel as a function of d/λ (upper curve: Rayleigh approximation)

The backscattered amplitude A_S takes the form

$$A_S \propto \sqrt{\alpha_S \cdot \Delta} \cdot \exp[-\alpha \cdot x] \qquad (4)$$

provided $\alpha \cdot \Delta \ll 1$($\Delta$ - pulse length) [1].

Measurement of ultrasonic attenuation coefficient is based on Eq. (3) using transmission techniques and on Eq. (4) using backscattering techniques. Obviously, either technique should yield the same result. However, if multiple scattering is not negligible, the backscattered amplitude is larger than expected from Eq. (4) and the amplitude decay can no longer be described by an exponential relation. In fact, the difference in amplitude increases with time-of-flight due to the increasing number of possibilities for the scattered waves to reach the ultrasonic probe by multiple scattering. The problem of sound field diffusion in case of multiple scattering has been treated in [10] by diffusion theory. As a result, it is found that for large time-of-flight the amplitude decay of the backscattered signal can be associated with the absorption coefficient [10].

BACKSCATTERING MEASUREMENT BY SPATIAL AVERAGING TECHNIQUE

The principle of ultrasonic backscattering measurement by spatial averaging technique is demonstrated in Fig. 2, Fig. 2a shows backscattered signals measured at a ferritic steel specimen ($d = 60\ \mu$ m) in pulse-echo technique. The backscattered ultrasonic waves are recorded as a function of time yielding a A-scan. Due to the phase-sensitive measurement by piezoelectric transducers, the signal exhibits a strong interference pattern which prevents an accurate evaluation of the decay constant, i.e. the ultrasonic attenuation coefficient, according to Eq. 4. In order to smoothen the curve, spatial averaging is performed. Changing the position of insonification, the interference pattern changes as well. A position variation of about 1 mm at a probe diameter of 8 mm is sufficient to get uncorrelated signals (Fig. 2b). Adding up several hundreds of rectified single A-scans while moving the probe within a range of ± 10 mm leads to a very smoothed backscattering curve (Fig. 2c). In case of homogeneous material and negligible multiple scattering, the backscattering curve decays exponentially (Fig. 2c) and the attenuation coefficient α_{BS} can be determined with a repeatability of ± 10 percent by using Eq. (4).

Figure 3 shows an ultrasonic device for backscattering measurement which was developed at IzfP [11]. Narrow-band tone-bursts with adjustable frequency and pulse-length are used for probe excitation. Frequency range is from 2.5 MHz to 30 MHz and variable in steps of 0.1 MHz. The backscattered signals are received in pulse-echo technique and amplified by means of a heterodyne amplifier. The rectified signal is digitized and stored. Maximum sampling frequency is 20 MHz, storage depth is 4 kilobyte. Up to 1024 A-scans can be summed for signal averaging. The evaluation of the backscattering curve is performed by an internal micro-computer using linear regression analysis.

EXPERIMENTAL RESULTS

Attenuation measurements were performed on ferritic steel specimen having grain sizes in the range from 30 μ m to 175 μ m. Shear waves, longitudinal waves and Rayleigh waves were used in contact technique. The center frequencies of the probes used were 5 MHz and 10 MHz. Figure 4 shows a typical backscattering curve as obtained by spatial averaging over 1024 A-scans. In the logarithmic representation, the curve shape is linear over an amplitude range of nearly 40 dB indicating exponential decay. According to Eq. 4 the slope is taken as attenuation coefficient. However, exponentially decaying backscattering curves are only obtained under the condition $d/\lambda \ll 1$. This can be seen from Fig. 5 where backscattering curves are shown for different d/λ-values. For

$d/\lambda \sim = 0.20$, only the first part of the backscattering curve has a constant slope. At larger times, the slope changes and becomes smaller due to the increasing condition of multiple scattering to the backscattered amplitude. For $d/\lambda = 0.59$ (Fig. 5), multiple scattering is already dominant from the beginning of the signal and the slope of the curve is no longer related to the attenuation coefficient. From Fig. 5, it can be seen that attenuation measurement in case of multiple scattering is possible for $d/\lambda \lesssim 0.2$ by evaluating the linearly decaying part at the beginning of the backscattering curve. The same specimens

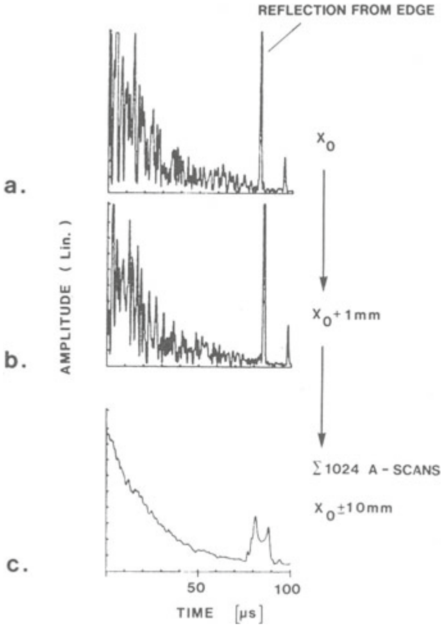

Fig. 2. Backscattering measurement by spatial averaging (ferritic steel, 5 MHz Rayleigh wave).

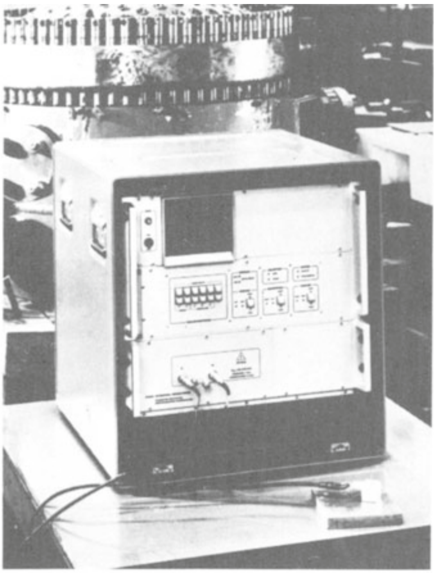

Fig. 3. Device for ultrasonic backscattering measurement.

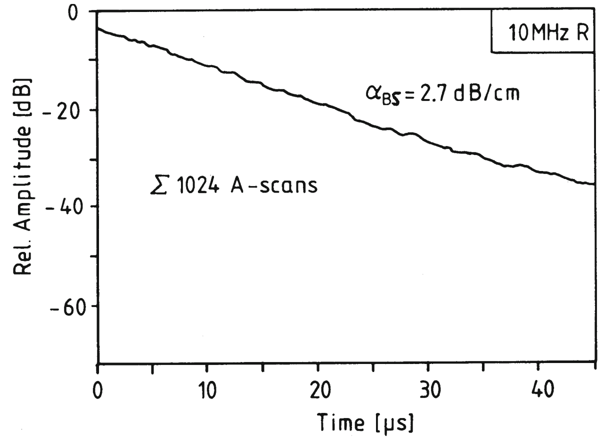

Fig. 4. Backscattering curve in ferritic steel (10 MHz Rayleigh wave, grain size: 43 μ m).

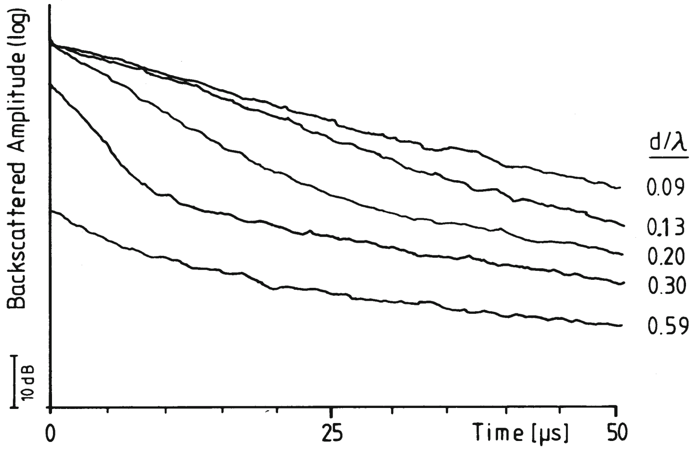

Fig. 5. Averaged backscattering curves for different ratios of d/λ.

were used for attenuation measurement by means of conventional technique in order to see whether backscattering technique yields comparable attenuation coefficients. In case of both shear wave and longitudinal wave, attenuation coefficient was determined from the amplitude decay of the backwall-echo sequence. Measurement with Rayleigh waves were performed using a pitch-and-catch arrangement and measuring the amplitude of the transmitted pulse as a function of distance between transmitting probe and receiving probe.

Figure 6 shows an averaged backscattering curve obtained from a ferritic steel specimen by using a 5 MHz shear-wave probe with 45°-insonification. The grain size of the specimen was 42 μ m. The first two backwall-echoes measured on the same specimen using a 5 MHz shear wave probe at normal incidence are also shown in Fig. 6. Here, the backwall-echoes whose absolute amplitude is about 40 dB higher than the backscatter amplitude are plotted below the backscattering curve in order to compare the amplitude decay. As can be seen, the backscattering curve as well as the amplitude decay of the backwall-echoes indicate the same attenuation behavior. A comparison of the results of attenuation measurement with both techniques is shown in Fig. 7. A fairly good agreement is observed taking into account the experimental scatter of about ± 10 percent.

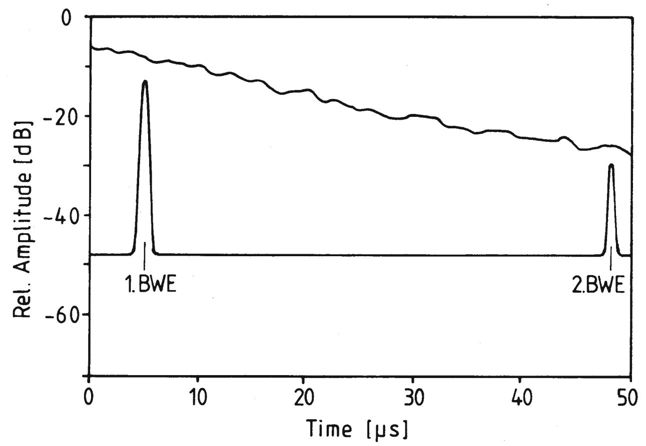

Fig. 6. Backscattering curve (5 MHz shear wave, 45°) and backwall-echo sequence (5 MHz shear wave, 0°) in ferritic steel (grain size 42 µ m).

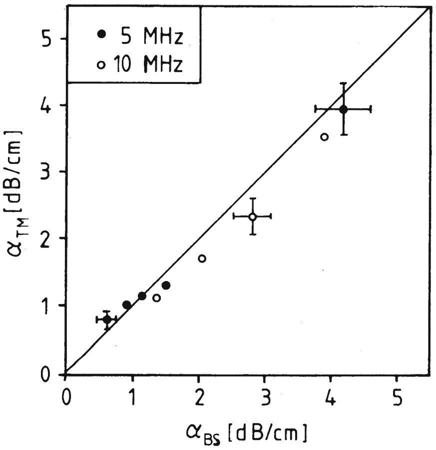

Fig. 7. Comparison between ultrasonic attenuation coefficient measured by backscattering technique (α_{BS}) and by transmission (α_{TM}).

CONCLUSIONS

Based on these results presented as well as on the wide experience with backscattering measurement gained at IzfP over the last decade, we arrive at the following conclusions for backscattering measurement as far as ferritic steel is concerned:

1. Under the condition $d/\lambda \lesssim 0.2$, ultrasonic backscattering measurement by means of spatial averaging technique yields backscattering curves which exhibit exponential decay within a dynamic range of up to 40 dB.
2. The attenuation coefficient determined from the exponential part of the backscattering signal is in reasonable agreement with attenuation coefficient determined from the amplitude decay of the transmitted pulse.
3. For $d/\lambda \gtrsim 0.2$, multiple scattering can no longer be disregarded. The amplitude decay of the backscattering curve deviates more and more from an exponential shape. In that case, the slope of the curve varies with time-of-flight and cannot be directly related to the attenuation coefficient.

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