Supplementary

June 10, 2023

1 Ultrasonic phase velocity

The ultrasonic phase velocity was calculated using the Pulse-echo contact based setup. The transducer and sample were placed in a mass loaded setup to get consistent pressure between measurements. The first and second backwall echoes were captured. The phase velocity is given by:

$$v(\omega) = \frac{\omega \times \Delta d}{(\phi_{BW2}(\omega) - \phi_{BW1}(\omega) \pm 2\pi m)} \tag{1}$$

where, ω is the angular frequency, Δd is the difference in propagation distance between the two echoes, and ϕ is the phase of the signal as a function of the frequency. This processing was carried out in MATLAB. The factor m is used to correct phase uncertainty to within 2π, which arises due to spectral contents of the signals do no extend to zero frequencies [1].

2 Ultrasonic group velocity

The group velocity was using pulse echo method and a through transmission UT method. For the PE method, a delay-line transducer, which has a built in perspex delay was used. Two signals were captured: (a) reflection from the reference with no sample, and (b) reflection from the backside of the sample with the reference on top. To measure the group velocity, the envelopes of the waveforms were calculated using the Hilbert transform. The time of fight difference between the two waveforms (reference echo and reference + sample echo) was calculated by the capturing the time of arrival based on the peak amplitude of the Hilbert transform. Since we know the thickness of the sample, we can calculate the velocity using: $v_g = t/\Delta T$, where t is the total propagation distance in the sample.

For the shear measurements, a through transmission setup was used. Instead of capture the reflection, a pari fo transducers are positioned on either side of the sample. First, a fused silica delay was positioned between the transducers and the sample, and the wave that propagates through the sample + fused silica delay was captured. Next, the sample was removed and the propagation through just the reference delay was captured. Similar to the PE measurement, the

Hilbert transform was used to get the time of arrivals and eventually calculate the velocity.

3 Attenuation coefficient:

The method to measure the attenuation coefficient is very well known and the procedure described in Ref. [2]. The sample was immersed in water and the transducer was normalized to the sample surface. The front-wall echo, i.e. the first reflection from the top surface of the sample, and the first reflection from the back of the sample; backwall echo were used to calculate the attenuation coefficient of the solid:

$$\alpha_S(\omega) = \frac{1}{2x_b} ln \left[\frac{V(\omega)_{1a}}{V(\omega)_{1b}} T^2 \frac{D_{1b}}{D_{1a}} \right] \tag{2}$$

where x_b is the thickness of the sample, V is the receiver output voltage and subscripts $1a$ refers to the first frontwall and $1b$ refers to the first backwall. T refers to the transmission coefficient between sample and water, and the D terms refers to the diffraction correction of the frontwall and backwall echoes given by the Lommel diffraction correction[3]:

$$D(\omega) = 1 - e^{-2\pi i/s} \left[J_0 \left(\frac{2\pi}{s} \right) + i J_1 \left(\frac{2\pi}{s} \right) \right] \tag{3}$$

where the argument of the Bessel's functions are given by: $s = (2\pi \sum z_i v_i)/(\omega a^2)$, and z_i is the propagation distance of medium i, a is the transducer radius, v_i is the velocity of medium i, and ω is the angular frequency. This ensures that the received amplitude is corrected for diffraction, which will give us the absolute attenuation coefficient. A Tukey window was first applied to the signal before using the Fast Fourier Transform to convert the time domain data to frequency domain. All the postprocessing was carried out in the frequency domain including the corrections for the diffraction.

4 Backscatter coefficient:

The procedure for backscatter coefficient measurement is once again well described in Ref. [2, 4]. The measure of the noise generating capacity of the microstructure is given by the Figure of Merit (FOM):

$$FOM = \frac{|\Gamma_{sample}(\omega)| \ |R_{w-ref}| \ a^2 \rho_w v_w \ |D_{ref}| k_s}{|\Gamma_{ref}(\omega)| \ 2T_{ws}^2 \rho_s v_s e^{2\alpha_w x_w}} \frac{1}{\sqrt{\iiint_{-\infty}^{\infty} |C(\omega, x_1, y_1, z_1)|^4 \ P(z_1) e^{-4\alpha_s z_s} \ dx_1 dy_1 dz_1}} \tag{4}$$

Where:

- $FOM = \sqrt{\eta}$, where η is the backscatter coefficient
- $|\Gamma_{sample}(\omega)|$ is the backscatter spatial RMS magnitude
- $|\Gamma_{ref}(\omega)|$ is the reference echo magnitude
- D_{ref} is the diffraction correction for the reference echo
- R_{w-ref} is the reflection coefficient between water and the reference sample.
- T_{ws} is the transmission coefficient between water and the sample
- k_s is the wavenumber of the sample
- a is the transducer radius
- ρ_w, ρ_s are the densities of the water and the sample
- v_w, v_s are the longitudinal group velocities of the water and the sample
- α_w, α_s are the attenuation coefficients of the water and the sample
- $C(\omega, x_1, y_1, z_1)$ beam focal properties
- $P(z_1)$ corrects for time-domain window interval (equal to 1 within the interval and 0 outside of the interval).

References

[1] David K Hsu and Hyunjo Jeong. Ultrasonic velocity change and dispersion due to porosity in composite laminates. In *Review of Progress in Quantitative Nondestructive Evaluation*, pages 1567–1573. Springer, 1989.

[2] Frank J Margetan, R Bruce Thompson, Issac Yalda-Mooshabad, and Y Kim Han. Detectability of small flaws in advanced engine alloys. 1993.

[3] Peter H Rogers and Al L Van Buren. An exact expression for the lommel-diffraction correction integral. *the Journal of the Acoustical Society of America*, 55(4):724–728, 1974.

[4] Paul D Panetta, Leslie G Bland, Maureen Tracy, and Waled Hassan. Ultrasonic backscattering measurements of grain size in metal alloys. In *TMS 2014: 143rd Annual Meeting & Exhibition*, pages 723–730. Springer, 2014.