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Experimental Study of Relationships between Ultrasonic Attenuation and Dispersion for Ceramic Matrix Composite

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Abstract

In this paper an experimental study of different ceramic matrix composites with high elastic losses and dispersion (porous piezoceramics, composites ceramics/crystals) were carried out. Complex sets of elastic, dielectric, and piezoelectric parameters of the porous piezoceramics and ceramic matrix piezocomposites were determined by the impedance spectroscopy method using Piezoelectric Resonance Analysis software. Microstructure of polished and chipped surfaces of composite samples was observed with the optical and scanning electron microcopies. Experimental frequency dependencies of attenuation coefficients and ultrasonic velocities for different ceramic matrix composites were compared with the theoretical results obtained using general Kramers-Kronig relations between the ultrasonic attenuation and dispersion.

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Keywords: elastic losses; scattering; dispersion; ceramic matrix piezocomposites; complex impedance.

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1. Introduction

The multiphase ceramic matrix composites are very complex objects for theoretical modelling, NDT (non-destructive testing), and ultrasonic measurements (Rybyanets *et al.*, 2011). The accurate description of piezocomposites must include the evaluation of the dielectric, piezoelectric and mechanical losses, accounting for the out-of-phase material response to the input signal (Rybyanets *et al.*, 2007a). It was shown (Nasedkin *et al.*, 2005) that pulse-echo measurements of frequency dependencies of elastic properties for dispersive and lossy ceramic composites are inaccurate and ambiguous. In its turn, piezoelectric resonance measurements (PRAP) can give accurate and reproducible results that well agree with the results of 3D finite-difference simulations.

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Different methods were proposed for theoretical modelling and evaluation of ceramic composites properties (Nasedkin *et al.*, 2005). However, physical mechanisms and interrelations of elastic losses and dispersion in complex objects, such as, porous ceramics and ceramic matrix piezocomposites remain difficult to deeply understand and they would require a dedicated study.

In this paper the frequency dependencies of complex elastic moduli for different ceramic matrix composites with strong spatial dispersion and high elastic losses were measured and compared with the theoretical predictions.

2. General Relationships between Ultrasonic Attenuation and Dispersion

Relationships between attenuation and dispersion, sometimes called Kramers-Kronig or generalized dispersion relationships, have proved useful in several areas of physics (Mangulis, 1964).

Expressed in a form appropriate to ultrasonic studies, these relationships take the form (the derivations of the general relations are readily available elsewhere (O'Donnell *et al.*, 1981) :

$$K_1(\omega) - K_1(\infty) = \frac{2}{\pi}\int_0^\infty \frac{\omega' K_2(\omega')}{\omega'^2-\omega^2}\,d\omega', \tag{1}$$

$$K_2(\omega) = -\frac{2\omega}{\pi}\int_0^\infty \frac{K_1(\omega')-K_1(\infty)}{\omega'^2-\omega^2}\,d\omega', \tag{2}$$

where K_1 (ω) and K_2 (ω) are the real and imaginary parts, respectively, of the dynamic compressibility (inverse of the bulk modulus). If the ultrasonic wave vector is written as $k = \frac{\omega}{C(\omega)} + i\alpha(\omega),$ then C(ω) is the phase velocity and α(ω) is the attenuation coefficient for the incident wave, as observed in transmission (i.e., direct "straight-line" propagation) measurements.

In the form given by Eqs. (1) and (2) the Kramers-Kronig relationships are limited in usefulness because of their nonlocal character; i.e., a knowledge of either the attenuation or the dispersion for all frequencies is required. More useful, approximate nearly local forms of the attenuation-dispersion relationships can be obtained from the exact nonlocal forms given in Eqs. (1) and (2) under the assumptions that the attenuation and dispersion are sufficiently small and do not change rapidly over the frequency range of interest. These nearly local relationships are:

$$\alpha(\omega) \simeq (\pi\omega^2/2C_0^2)\frac{dC(\omega)}{d\omega} \tag{3}$$

$$\Delta C(\omega) = C(\omega) - C_0 \simeq \frac{2C_0^2}{\pi}\int_{\omega_0}^{\omega} \frac{\alpha(\omega')}{\omega'^2}\,d\omega', \tag{4}$$

where ω_0 is some convenient reference frequency and $C_0 = C(\omega_0)$ is the phase velocity at this reference frequency. The validity of these approximate relationships was demonstrated in several acoustic systems exhibiting substantially different attenuation and dispersion mechanisms (Mangulis, 1964; O'Donnell *et al.*, 1981).

3. Experimental Procedures

3.1. Experimental samples

The following two types of ceramic composites (Rybyanets *et al.*, 2011; Rybyanets *et al.*, 2007b) with high losses were chosen as model samples for simulation of ultrasonic wave propagation and comparison with piezoelectric resonance analysis (PRAP) and ultrasonic measurements (Figure 1):

- ceramic matrix composites A850L (Figure 1a) consisting of soft PZT matrix with randomly distributed α-Al2O3 crystals with a mean particle diameter ~ 200 μm and volume fraction from 9 up to 26 vol.%;
- porous PZT piezoceramics PCR-1 (porosity 18 %, average pore size ~ 20 μm) shown in Figure 1b.