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Internal Friction and Elastic Constants of Sintered Titanium

H. Ledbetter, M. Dunn* and S. Kim

Materials Science and Engineering Laboratory, National Institute of Standards and Technology, Boulder, Colorado 80303, U.S.A.

** Center for Acoustics, Mechanics, and Materials, Mechanical Engineering Department, University of Colorado, Boulder, Colorado 80309, U.S.A.*

Abstract. Using a Marx-oscillator standing-wave resonance method, we measured the internal friction Q^{-1} of sintered titanium containing up to 26 volume-percent voids (c). The surprising Q^{-1} -versus- c curve shape, an exponential increase, lead us to remeasure Q^{-1} -versus- c by acoustic-resonance spectroscopy, which gave similar results. We hypothesized that both void shape and void size change with c . For the void shape, we confirmed this hypothesis by measuring longitudinal and transverse sound velocities v_l and v_t and comparing them with Mori-Tanaka model predictions. As c increases from 0 to 0.26, effective void shape changes from near spherical to oblate spheroidal with an aspect ratio near 0.05. Optical microscopy confirmed the void-size change. We outline a model based on wave-scattering theory that explains the observed Q^{-1} - c behavior. Increased particle size with increased c provides the dominant factor for the exponential Q^{-1} increase.

I. INTRODUCTION

Elastic-stiffness constants and their imaginary part, the internal friction Q^{-1} , provide much valuable information about a material's microstructure, about all defects representing departures from an ideal, pure, perfect monocrystal. The defect considered here is voids arising from sintering of spherical particles. At least at low void concentrations, we expect the voids to possess simple shapes, approaching in many cases the concave-face tetrahedron associated with the interstices of close-packed spheres.

2. MATERIAL

As a specimen material, we chose sintered titanium. Chemically pure titanium powder was prepared by a rotating-anode method, sieved through -35 mesh to give an average 180- μm particle size, sealed in titanium canisters, and hot isostatically pressed to various mass densities, which were determined by pressure and temperature.

3. MEASUREMENT METHODS

In this study, we used five measurement methods:

1. Marx-oscillator [1]. In the extensional mode, this gave the Young modulus E and the associated internal friction Q^{-1} .
2. Acoustic-resonance-spectroscopy [2]. For a near- C_{44} mode, this confirmed the Q^{-1} measurement made by method 1. In Table 1, we label this Q_G^{-1} .
3. Rod-resonance [3]. This confirmed the E and Q^{-1} measurements made by method 1.
4. Pulse-echo-superposition [4]. This gave the complete set of elastic constants. Because of large bond and transducer corrections, we ignored the accompanying attenuation measurements, which give Q^{-1} .

5. Impulse-excitation rod-resonance [5]. By exciting extensional, bending, and torsional modes of a rectangular bar, this gave the elastic constants of a $c=0.39$ specimen, which resisted accurate measurement by the above four methods. The accompanying Q^{-1} measurement was too inaccurate.

4. RESULTS

Figure 1 shows the change of Q^{-1} with c , the void volume fraction, obtained from Archimedes-method mass-density measurements. Table 1 gives numerical values for mass density, sound velocities, various polycrystalline (quasi-isotropic) elastic constants, and internal friction. In this table, ρ denotes mass density, v_l and v_t longitudinal and transverse sound velocities, C_l longitudinal modulus, G shear modulus, B bulk modulus, E Young modulus, ν Poisson ratio, and Q^{-1} internal friction, where subscript E denotes Young-modulus (extensional) mode and subscript G shear mode.

Figure 1: Dependence of internal friction Q^{-1} on void concentration. The upper curve corresponds to C_{44} transverse-modulus mode from acoustic-resonance spectroscopy. The lower curve corresponds to Young-modulus E mode from Marx-oscillator standing-wave resonance. For an isotropic material, C_{44} equals the shear modulus G .

Table 1. Measured elastic constants and internal friction

Void content (%)	ρ (g/cm ³)	v_l (cm/ μ s)	v_t (cm/ μ s)	C_l (GPa)	G (GPa)	B (GPa)	E (GPa)	ν	Q_E^{-1} (10^{-3})	Q_G^{-1} (10^{-3})
0*	4.421	0.6061	0.3157	162.4	44.06	103.7	115.77	0.3139	0.730 [†]	0.996 [§]
11.7*	3.968	0.4532	0.2609	81.49	27.01	45.47	67.639 67.516 [†] 67.563 [‡]	0.2521	0.816 [†]	1.395 [§]
21.3*	3.626	0.3529	0.2168	45.16	17.04	22.44	40.792 42.120 [†] 42.501 [‡]	0.1971	1.672 [†]	2.390 [§]
25.9*	3.417	0.2955	0.1954	29.84	13.05	12.44	29.007 29.827 [†] 28.583 [‡]	0.1113	2.664 [†]	3.675 [§]
38.6 ^x	2.763	0.1147	0.0755	3.634	1.577	1.531	3.522	0.117		

* pulse-echo-superposition
† Marx-oscillator

§ acoustic-resonance-spectroscopy
‡ resonating-rod

^x impulse-excitation resonance

5. MODELING OF ELASTIC CONSTANTS

Many models exist for predicting a composite's effective sound velocities and elastic constants from constituent properties and phase geometry [6].

For this study, we used the Mori-Tanaka effective-field approach [7] to obtain explicit analytical expressions for the effective long-wavelength-limit longitudinal-wave and transverse-wave sound velocities of porous solids. This approach offers the advantages of yielding, for undilute concentrations, explicit analytical expressions, not simply bounds or estimates that require iterative calculations. The solid's effective elastic properties are estimated by assuming that a representative inclusion (void) feels the effect of the average matrix stress in the same way that an isolated inclusion feels an applied uniform stress. Thus, the inclusion feels an *effective field*.

From the Mori-Tanaka model, we obtained explicit longitudinal and transverse sound-velocity (v_l and v_t) expressions for several possible void shapes. For brevity, we give only the following results for randomly oriented spheroidal pores:

$$\frac{v_l}{v_{l0}} = \left[\frac{3(1-c)(1-\nu_0) + 2cf(\nu_0, \alpha)(1-2\nu_0) + c h(\nu_0, \alpha)(1+\nu_0)}{3(1-\nu_0)[1-c\{1-f(\nu_0, \alpha)\}][1-c\{1-h(\nu_0, \alpha)\}]} \right]^{1/2}; \quad (1)$$

$$\frac{v_t}{v_{t0}} = \left[\frac{1}{1 - c\{1-h(\nu_0, \alpha)\}} \right]^{1/2}. \quad (2)$$

Here, v_l = longitudinal velocity of the porous solid; v_t = transverse velocity of the porous solid; v_{l0} = longitudinal velocity of the bulk solid; v_{t0} = transverse velocity of the bulk solid; ν_0 = Poisson ratio of the bulk solid; α = pore aspect ratio; c = pore concentration;

$$f(\nu_0, \alpha) = \frac{1-\nu_0}{6(1-2\nu_0)} \frac{4(1+\nu_0) + 2\alpha^2(7-2\nu_0) + [3(1-4\nu_0) - 12\alpha^2(2-\nu_0)]g(\alpha)}{2\alpha^2 + (1-4\alpha^2)g(\alpha) + (\alpha^2-1)(1+\nu_0)g(\alpha)^2}; \quad (3)$$

$$h(\nu_0, \alpha) = \frac{4(1-\nu_0)(\alpha^2-1)}{15} \left\{ \frac{6}{\alpha^2 - 4(1-\nu_0)(\alpha^2-1) + [2(1-2\nu_0)(\alpha^2-1) - 3/2]g(\alpha)} \right. \\ \left. - \frac{6}{4\alpha^2 + [(1-2\nu_0)(\alpha^2-1) - 3(\alpha^2+1)]g(\alpha)} \right. \\ \left. - \frac{1}{2\alpha^2 + [(1-4\alpha^2)]g(\alpha) + [(1+\nu_0)(\alpha^2-1)]g(\alpha)^2} \right\}; \quad (4)$$

and

$$g(\alpha) = \frac{\alpha}{(\alpha^2-1)^{3/2}} \{ \alpha(\alpha^2-1)^{1/2} - \cosh^{-1}\alpha \} \quad \text{for } \alpha > 1 \\ = \frac{\alpha}{(1-\alpha^2)^{3/2}} \{ \cos^{-1}\alpha - \alpha(1-\alpha^2)^{1/2} \} \quad \text{for } \alpha < 1 \\ = 2/3 \quad \text{for } \alpha = 1. \quad (5)$$

6. DISCUSSION

Previously, we described the expected dependence of Q^{-1} on c , derived from a scattered-plane-wave ensemble-average model and applied to SiC particles in an Al matrix [8]. For fixed particle size and shape, Q^{-1} increases linearly, decreases in slope, and passes through a broad maximum. For a fixed shape and concentration, Q^{-1} strongly increases nonlinearly with increasing particle size. Thus, as void size increases with increasing c , Q^{-1} can increase exponentially. Our previous study [8] showed that decreasing particle-shape aspect ratio (spherical to oblate spheroidal) decreases Q^{-1} ; thus, a Q^{-1} - c curve dominated by the shape factor would be convex rather than concave. Our measurement results show that the size change more than compensates for the shape change.

7. CONCLUSIONS

In studying the internal friction and elastic constants of sintered titanium, we reached five principal conclusions:

1. Against expectation, internal friction Q^{-1} increases exponentially with increasing void content.
2. Elastic-constant measurements combined with the Mori-Tanaka theory show that the effective void aspect ratio decreases with increasing c , that is, from spherical to strongly oblate spheroidal ($\alpha \approx 0.05$).
3. The unexpected Q^{-1} - c curve can be explained by invoking increased void size, supported by optical microscopy and using a model developed previously for particle-reinforced composites. The model considers plane waves scattered from a particle ensemble.
4. Change in void shape causes an opposite and smaller effect on Q^{-1} than does void size.
5. Internal friction provides a valuable probe of these materials because it depends strongly on void size, which produces no effect on the elastic stiffnesses.

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