Increase in Q factor of Poly Phenylene Sulfide at high-amplitude ultrasonic vibration by thermal annealing

アニーリング処理による PPS 樹脂の超音波大振幅領域における Q 値の向上

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1. Introduction

Ultrasonic transducers are core components for high-power ultrasonic applications. In general, they comprise piezoelectric ceramics and vibrating bodies. In conventional ultrasonic transducers, metals are commonly used as vibrating bodies. To achieve lightweight transducers for mass production, polymers are potentially applicable as the vibrating bodies owing to its low densities and high production efficiency. We have reported that poly phenylene sulfide (PPS) exhibits low mechanical loss in high-amplitude flexural vibration [1], and tried some functional ultrasonic devices with PPS. The PPS-based airborne ultrasonic transducer provides better performance than the metal-based transducers [2]. To gain a deeper understanding of vibrational properties of PPS, it would be meaningful to evaluate the mechanical losses in high-amplitude longitudinal and torsional vibrations.

Mechanical quality factors (Q factors), inversely proportional to mechanical loss, indicates the suitability of a material as a vibrating body. To overcome the shortcoming of the existing methods, we proposed a new method on the basis of the original definition of the Q factor. The strain and frequency dependences of Q factors of several commonly-used polymers in flexural vibration and some metals in torsional vibration have been measured from the distributions of the vibration velocities on the side surface [1,3]. A method for measuring Q factors in longitudinal vibration is required, and the effect of thermal annealing on the Q factors of PPS should be evaluated.

PPS belongs to semicrystalline polymers, of which the degree of crystallinity can be enhanced through thermal annealing [3,4]. In general, a material with a regular arrangement of molecules (or atoms), e.g., metals and ceramics, tends to exhibit low mechanical loss. It implies that, by performing thermal annealing on the commercial PPS products in laboratory, the mechanical loss

may be lowered. The relationship between the mechanical loss of PPS and the annealing conditions, such as temperature and heating time, should be clarified for practical applications.

In this study, first, we introduce a new method for measuring the Q factors under longitudinal vibration. Subsequently, we measure the Q factors of several PPS samples annealed with different temperatures and periods.

2. Principle of Q-factor measurement method

On the cylindrical specimen shown in Fig. 1, a longitudinal wave is excited by a vibration source located on one end. An axis (z) is set along the cylindrical specimen. The amplitudes and the phases of the vibration velocities at sampling points 0, 1, and 2 are v_0, θ_0; v_1, θ_1; and v_2, θ_2; respectively. The Q factor is defined as the ratio of the reactive energy E_k to the dissipated energy E_d in a period between the cross-sections L_L and L_R:

$$Q = 2\pi \cdot \frac{E_k}{E_d}. \qquad (1)$$

The reactive energy E_k stored in the sample between L_1 and L_2 is expressed as

$$E_k = \frac{1}{2}\Delta m v_1^2 = \frac{1}{2}\rho A \cdot \Delta z \cdot v_1^2 \qquad (2)$$

where Δm denotes the mass of the specimen
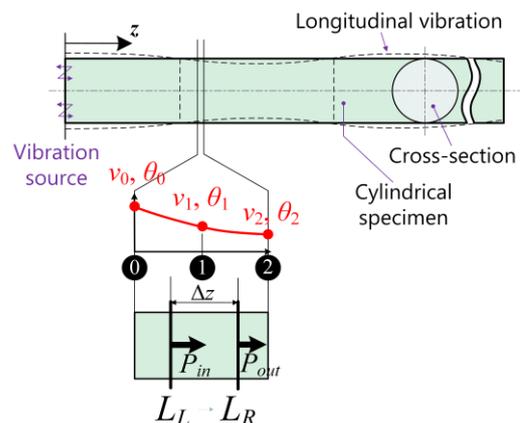
Fig. 1 Schematic of the developed method.

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between L_L and L_R, A represents the cross-sectional area, and ρ is the density of the specimen. The dissipated energy E_d is the decrease in the active vibration energy along the z axis, and is given as

$$E_d = \frac{2\pi}{\omega}\left(P_{in} - P_{out}\right), \qquad (3)$$

where ω denotes the angular frequency; P_{in} and P_{out} represent the active vibration powers across the cross-sections L_L and L_R, respectively. In longitudinal vibration, the active vibration power $P(z)$ across a certain cross-section is calculated from the normal force along the z axis $F(z)$ and the vibration velocity of the outer surface of the cylindrical specimen $v(z)$:

$$P(z) = \frac{1}{2}\mathrm{Re}\left[F(z)\cdot v^*(z)\right]. \qquad (4)$$

where Re represents the real part. The P_{in} and P_{out} can be respectively expressed as

$$P_{in} = \frac{EA}{2\omega}\cdot\frac{v_0 v_1 \sin(\theta_1 - \theta_0)}{\Delta z}, \qquad (5)$$

and

$$P_{out} = \frac{EA}{2\omega}\cdot\frac{v_1 v_2 \sin(\theta_2 - \theta_1)}{\Delta z}, \qquad (6)$$

where E denotes the elastic modulus. In theory, the Q factor of a small portion of the bar can be estimated from the vibration velocities of three points. The strain at a certain point $\varepsilon(z)$ is expressed as

$$\varepsilon(z) = \frac{1}{j\omega}\frac{d\left[v(z)\right]}{dz}. \qquad (7)$$

Thus, the strain dependence of Q factor can be obtained.

3. Q factors under different annealing conditions

Using the developed method, we experimentally evaluate the influence of thermal annealing on the Q factor. The 10-mm-diameter PPS samples were heated in a thermostatic chamber. The annealing was performed at 100°C for 6, 12, and 24 hours. After annealing, the samples were quenched in air at 24°C for 1 hour. Note that the piezoelectric transducers, which were employed to excite vibration on the sample during measurement, were not heated. Fig. 2 demonstrates the strain dependences of Q factor of the PPS samples annealed under different temperatures and periods.

Fig. 2(a) shows the results measured at 17 kHz. After heating for 6 hours, the Q factors had almost no variation comparing to the results without annealing. However, the Q factors of the PPS bar at 0.01% increased to 380 and 520, after it was heated for 12 and 24 hours, respectively. Fig. 2(b) shows the results measured at 48 kHz. Observably, the Q-factor increase was lower at 48 kHz than that at 17 kHz.

4. Conclusions

(1) A method for measuring the Q factors of materials in longitudinal vibrations is proposed.
(2) The Q factors of PPS can be enhanced through thermal annealing.

References
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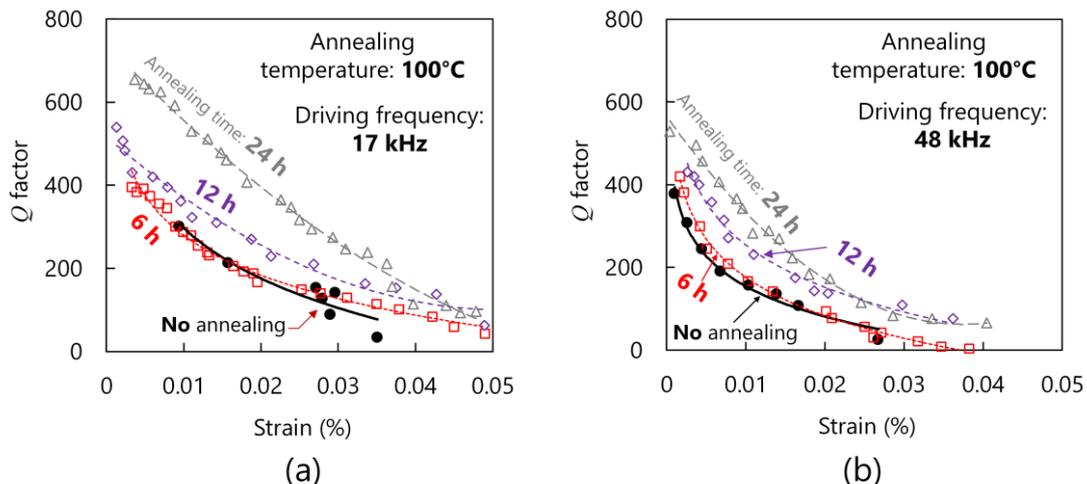
Fig. 2 Q factor as a function of strain under different annealing temperatures and periods.