ELECTROMAGNETIC ACOUSTIC RESONANCE OF SiC$_f$/Ti COMPOSITES AT ELEVATED TEMPERATURES

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INTRODUCTION

We studied electromagnetic acoustic resonance at elevated temperatures up to 1000 K. Using Lorentz-force transduction, we measured the temperature dependence of resonant frequencies and attenuation coefficients in SiC-fiber-reinforced Ti-alloy composites. Evolution of the resonance frequencies is consistent with the changes of elastic constants of the matrix, and attenuation evolution is explained by dislocation damping in the matrix.

Ultrasonic measurement provides a powerful tool for studying the temperature dependence of elastic constants and damping of solid materials developed for elevated temperatures. For the elastic constants, resonant ultrasonic spectroscopy (RUS) [1-4] provides a good measurement method. The usual RUS configuration uses a rectangular-parallelepiped specimen, whose sides are typically a few millimeters, and two sandwiching transducers that contact the specimen corners. One of them transmits a cw oscillation and the other detects ultrasonic oscillation to acquire a series of resonance frequencies. Inverse calculation [1,2] makes it possible to determine all independent elastic constants from the resonance spectrum. When it is used at elevated temperatures, one needs to insert waveguides between the specimen and transducers because of the low Curie point of conventional transducers, around 520 K for PZT. Using such devices, it is possible to determine the resonance frequencies and then the elastic constants. However, it is difficult to isolate the specimen's ultrasonic-energy loss, that is attenuation, because ultrasonic waves propagate not only in the specimen but also in the waveguides and transducers. Kuokkala and Schwarz [5] used magnetostriction for noncontact ultrasonic transduction and measured internal friction up to 520 K. The temperature limit depends on the Curie point of magnetostriction, typically below 1000 K. This technique requires coating a magnetostrictive material onto specimen surfaces, which requires further interpretation for a double-layered

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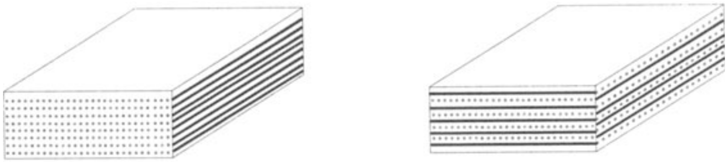


material U *material X*

Figure 1. Rectangular parallelepiped specimens of SiC-reinforced Ti-6Al-4V.

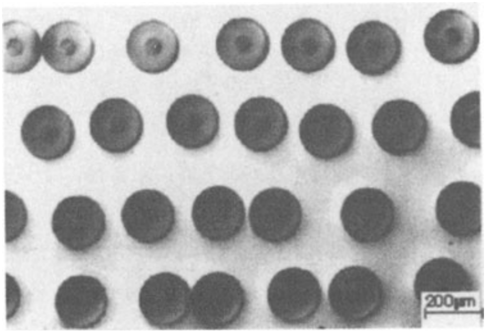


Figure 2. Micrograph of Ti-6Al-4V uniaxially reinforced by SiC fibers (*material U*).

resonant system. Johnson [6] developed an electromagnetic acoustic-resonance system to measure temperature dependence of attenuation in an aluminum sphere up to 800 K. He used the Lorentz-force mechanism for wave transduction. This technique can be used at higher temperatures.

The present study focuses on the electromagnetic-acoustic-resonance (EMAR) method to measure the velocity and attenuation at elevated temperatures. The sample material is SiC-fiber-reinforced Ti-alloy composite. This MMC is a candidate material for jet-engine components and expected to be used around 700 K. We used electromagnetic acoustic transduction, which requires no coupling agents. A rectangular-parallelepiped specimen was inserted in a solenoidal coil located within a stainless-steel cylinder, in which the temperature was raised up to 1300 K. A pair of permanent-magnet blocks was placed outside the cylinder to provide the bias field for the electromagnetic excitation and detection of ultrasound with the Lorentz-force mechanism.

MATERIALS

Two types of SiC-fiber-reinforced Ti-6Al-4V alloy were used. One is reinforced with unidirectional fibers and the other with alternately orthogonal-aligned (cross-ply) fibers. We call the former *material U* and the latter *material X* (see Fig.1). They were fabricated by foil-fiber-foil techniques at 1173 K under a compressive stress of 69 MPa. In both cases, the volume fraction is 0.35. A rectangular-parallelepiped specimen 1.903 mm thick, 4.568 mm long, and 4.013 mm wide was cut from 8-ply composite panels by electrical-discharge machining. Figure 2 shows the microstructure.

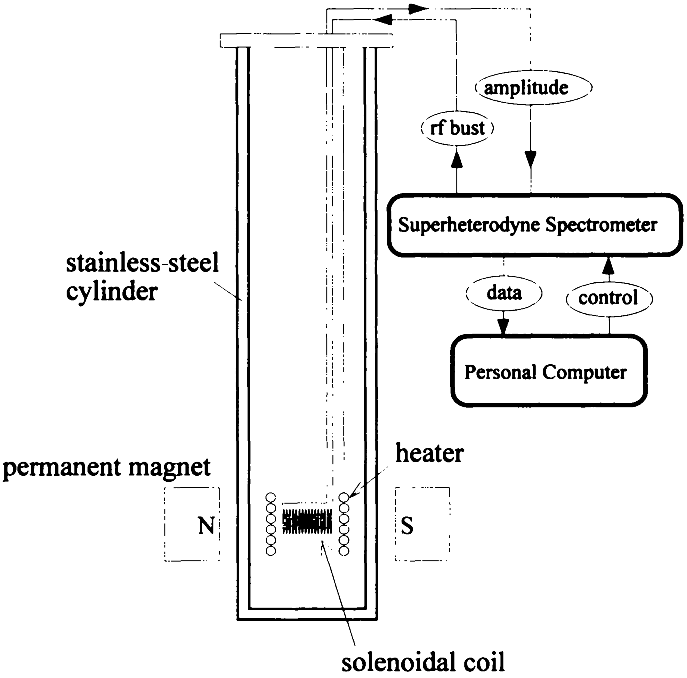
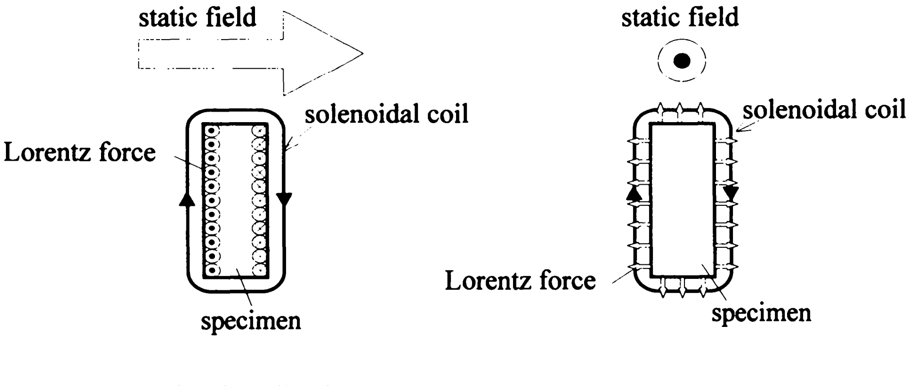


Figure 3 Measurement setup for electromagnetic acoustic resonance.



(a) shearing vibration

(b) dilating vibration

Figure 4 Lorentz forces generated by the static magnetic field and eddy currents caused by the solenoidal coil.

MEASUREMENT SETUP

Figure 3 shows the setup for electromagnetic acoustic transduction. The specimen is inserted in a solenoidal coil located within the stainless-steel cylinder, in which the temperature is raised by the heater surrounding the coil. A pair of permanent-magnet blocks are placed outside the cylinder to provide the static field needed for the electromagnetic excitation and detection of ultrasound. The direction of the static magnetic field is variable about the cylinder-vessel axis by rotating the permanent magnets.

The transduction mechanism is schematically expressed in Fig.4. The Lorentz force arises from the interaction between the static magnetic field and the eddy currents induced near the specimen surface by the solenoidal coil. When the static field is perpendicular to the axial direction of the solenoidal coil, shearing Lorentz forces occur (Fig4.(a)); with a parallel static field, dilating Lorentz forces generate on the sample surfaces. Thus, the vibration modes can be selected by changing the field direction. This reduces the complexity of identifying the resonant modes in the RUS method.

We measured the resonance frequencies and attenuation using a superheterodyne spectrometer. Driving the solenoidal coil with high-power tone bursts causes interferences of ultrasonic vibration within the specimen. The same coil detects the mechanical vibration on surfaces by means of the reversed Lorentz-force mechanism. The superheterodyne circuit extracts only the operating frequency component from the received electric signals, and its amplitude is stored in the personal computer. Sweeping the frequency of the bursts and getting the amplitude as a function of the frequency, we obtain a serious of resonance peaks, at which all overlapping waves coherently intensify each other and build up a large amplitude. A resonance frequency is determined from the central axis of the Lorentzian function fitted to the spectrum measurements around a particular peak. Then, we drive the solenoidal coil with the measured resonance frequency to obtain the attenuation coefficient. Just after the excitation, we observe the reverberation decay with time. Fitting an exponential function to the relaxation curve, we determine the attenuation coefficient. Details can be can be found in Ref.7.

RESULTS AND DISCUSSION

Figure 5 shows typical measured resonance spectra. The different spectrum pattern between the shearing and dilating vibrations indicates that we can select the resonant modes. With

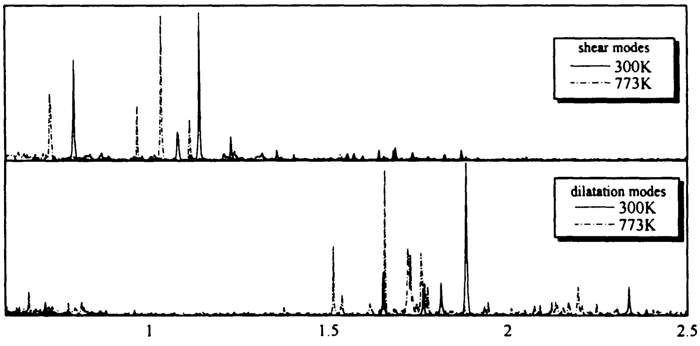


Figure 5. Examples of resonance spectra at 300 K and 773 K for shear modes and dilation modes.

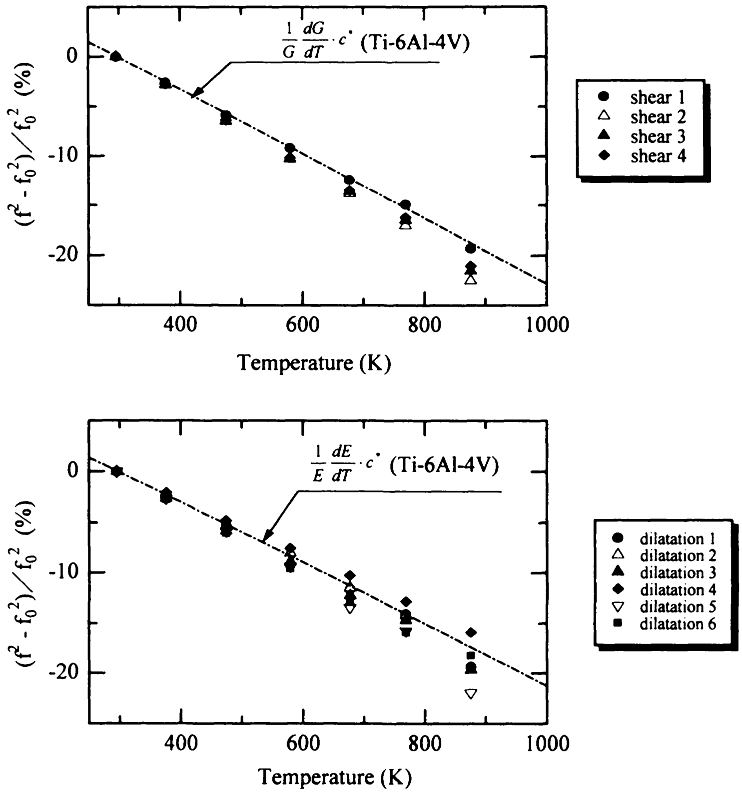


Figure 6. Temperature dependence of normalized square of resonant frequencies and those of Young's modulus *E* and shear modulus *G* of a Ti-6Al-4V polycrystal multiplied by the matrix volume fraction.

the help of recent advances of inverse calculation, it is possible to determine the independent elastic constants from the measured resonant frequencies. This will be reported elsewhere. Here, we focused on the temperature dependence of the resonant frequencies and the attenuation coefficients.

To estimate the temperature dependence of elastic constants, we studied the change of the squares of the resonant frequencies, which correspond approximately to the change of the elastic constants. Figure 6 shows the results for *material X*. We compared them with the previous study by Naimon et al. [8]. They measured the temperature dependence of shear and longitudinal moduli of polycrystalline Ti-6Al-4V between 4 K and 300 K, and presented an equation of the temperature dependence of Young's modulus *E* and shear modulus *G*. We used this equation up to 1000 K multiplied by the volume fraction of the matrix c^* (=0.65) using a linear rule-of-mixtures. The broken lines in Fig.6 are thus calculated. Good agreement exists between the measurements and the calculations, indicating that the temperature dependence of the matrix dominates, and the elastic constants of the fiber change little with temperature. The averaged decremental rates of square of the normalized resonance frequency were -3.7×10^{-4} K^{-1} for the shearing modes and -3.0×10^{-4} K^{-1} for the dilating modes in the case of *material X*. Those for *material U* were -4.0×10^{-4} K^{-1} and -3.1×10^{-4} K^{-1} for the shear and dilating modes, respectively. Thus, the two specimens behaved similarly.

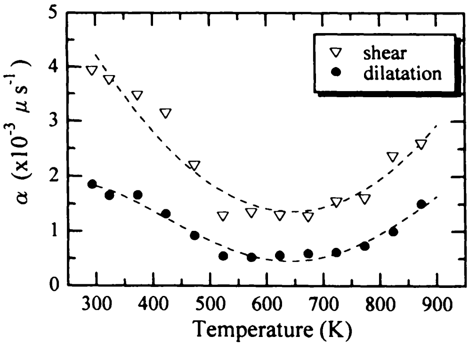


Figure 7. Temperature dependence of attenuation coefficients for *material X*.

The attenuation coefficient α changed nonmonotonically as shown in Fig.7. Decreases with temperature occurred up to 650 K and increases above it. Similar evolutions were found independent of mode and material. The attenuation decrease at lower temperature we attribute to the release of residual stress and decrease of the dislocation density in the matrix. Because the material was fabricated at elevated temperature and cooled to room temperature, residual stress occurs because of the different thermal-expansion coefficients between the fiber and the matrix. Residual stress causes dislocation multiplication in the matrix. Upon increasing the temperature, the dislocations can be activated thermally, leading to rearrangement and annihilation. The classical string model of dislocation vibrations [9] shows a proportional relationship between dislocation density and attenuation. On the other hand, the viscosity of metals generally increases with temperature. This is caused by thermally activated dislocations and point defects, phonon scattering and so on. All of these operates to raise the damping coefficient *B* in the motion equation of the dislocation vibration. Therefore, two mechanisms contribute to the present evolution of α; changes in the dislocation density and dislocation viscosity.

CONCLUSION

The electromagnetic-acoustic-transduction system developed here made it possible to perform RUS measurement at elevated temperatures. This method has no temperature limit as long as material remains conductive. The resonance frequency decreased with temperature. The decremental rate showed good correspondence with that of Ti-6Al-4V after considering the volume fraction of the matrix. Evolution of the attenuation coefficient with increasing temperature was interpreted as the decrease of dislocation density followed by increase of the matrix viscosity.

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