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Dynamic Elastic Modulus and Vibration Damping Behavior of Porous Silicon Carbide Ceramics at Elevated Temperatures

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The piezoelectric ultrasonic composite oscillator technique (PUCOT) has been used to measure the Young's modulus, *E*, the mechanical damping, Q^{-1}, and the strain amplitude, ε, of a sintered silicon carbide containing pores (Hexoloy-SP). The silicon carbide material used in this study had at least 14 vol% porosity. Young's modulus was found to have a linear temperature dependence from room temperature to 740 °C. The damping was near 10^{-4} and was independent of strain amplitude above room temperature.

Keywords ceramics, damping, high temperature, silicon carbide, Young's modulus

1. Introduction

In recent years, there has been a surge of interest in the research, development, and applications of silicon carbide-based advanced ceramics for a number of high temperature applications. These ceramic materials have very good strength, high thermal conductivity, and good creep and environmental resistance at high temperatures (Ref 1). These attractive thermomechanical properties have made them one of the most widely used ceramic materials for a number of applications in aeronautics, energy, electronics, nuclear, and transportation industries. In the aeronautical arena, these materials are being considered for applications in jet engine components. Applications in the energy industries include radiant heater tubes, heat exchangers, heat recuperators, and components for land-based turbines for power generation. These materials are also being considered for use in the first wall and blanket components of fusion reactors, in furnace linings and bricks, and in components for diffusion furniture (boats, tubes) in the microelectronics industry.

There are a number of critical issues related to the use of these materials. For a number of engineering applications, high temperature elastic modulus and damping behavior become very important. In earlier publications, dynamic Young's modulus and damping behavior of a wide variety of reaction bonded and reaction formed silicon carbide ceramics have been reported (Ref 2-6). The goal of this study was to characterize the elastic modulus and vibrational damping behavior of a sintered silicon carbide with controlled porosity (Hexoloy-SP, Carborundum Co., Niagara Falls, NY). Typically, these materials were fabricated by the pressureless sintering of α-SiC powders with boron carbide or aluminum carbide as sintering aids and a pore forming material.

The goal of this study was to determine the dynamic Young's modulus, *E*, and vibration damping, Q^{-1}, of a sintered silicon carbide ceramic (Hexoloy-SP) with controlled porosity at room and elevated temperatures.

2. Experimental Procedure

The silicon carbide material (Hexoloy-SP) used in this study had about 14 vol% porosity. Specimens were machined from the as-supplied plates. The size of the specimens was relatively small (50 by 4 by 3 mm).

The density of the material was determined using the Archimedes technique. Four samples of Hexoloy-SP were used to determine the average density. The influence of porosity on the density of the specimens was checked by leaving the specimens immersed in water for a prolonged period of time. It was determined that porosity did not affect the value of the density of the

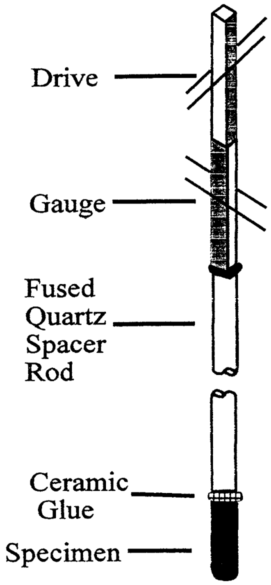

Fig. 1 Schematic drawing of the piezoelectric ultrasonic composite oscillator technique

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specimens. The density of the material was found to be 3.019 ± 0.003 g/cm^3. Microstructural examination and microhardness measurements were carried out on as-received specimens.

The piezoelectric ultrasonic composite oscillator technique (PUCOT) (Ref 3-6) was used for the measurements of E, Q^{-1}, and strain amplitude, ε. Alpha-quartz piezoelectric crystals with a frequency of 120 kHz were employed. Figure 1 shows a schematic drawing of the PUCOT. The mechanical damping versus strain amplitude was measured and plotted. From the analysis of Q^{-1} versus ε plots in terms of the Granato-Lücke theory of dislocation damping (Ref 7), the minor pinning length and the dislocation density were estimated.

3. Results and Discussion

The elastic modulus found for the material was 385 GPa at room temperature with a standard deviation of 1.86 GPa. The literature on Hexoloy SA (Carborundum Co., Niagara Falls, NY), a similar form of SiC, stated that the elastic modulus was around 410 GPa (Ref 8-9). This suggests that, with Hexoloy SA having a slightly different composition compared to Hexoloy SP, the value obtained for Hexoloy SP is reasonable. The elastic modulus showed an inverse relationship with temperature, varying from 385 GPa at room temperature to 358 GPa at 568 °C (Fig. 2). For temperatures, T, in the range of 21 to 740 °C, the modulus (in GPa) fitted the equation, $E = 382.35 - 0.0323T$ with an R^2 value of 0.84. The normalized modulus, defined as $(1/E_0)\,(dE/dT)$, where E_0 is the value of E at 0 °C, is -0.84×10^{-4}K^{-1} and is close to the values found by Wachtman (Ref 10) for several oxides. This low rate of decrease in modulus with an increase in temperature is a consequence of the strong ionic/covalent interatomic bonding in ceramics.

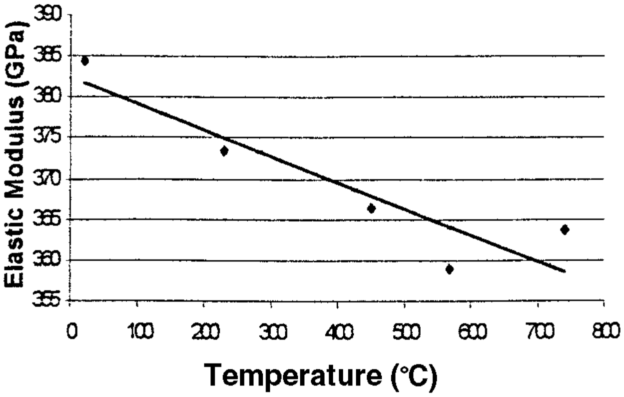

Fig. 2 Temperature dependence of Young's modulus

The strain amplitude dependence of the mechanical damping at room temperature yielded the behavior expected in some ceramic materials. The mechanical damping was relatively constant near 10^{-4} for small strain amplitudes. However, the shape of the plot for room temperature indicated breakaway damping at the higher values of strain amplitude (Fig. 3). This is a favorable characteristic for the applications of this ceramic in situations where vibrations may be unwelcome.

A Granato-Lücke analysis (Ref 7) of Fig. 3 allowed estimation of the minor pinning length as 5×10^{-9} m and the dislocation density as 10^{10}m^{-2}. The minor pinning length determined for impurities is reasonable, and the mobile dislocation density is within the expected range for ceramics ($\leq 10^{12}$m^{-2}). The network length of the dislocations was determined by calculating the average distance between large pores seen in Fig. 4 and 5.

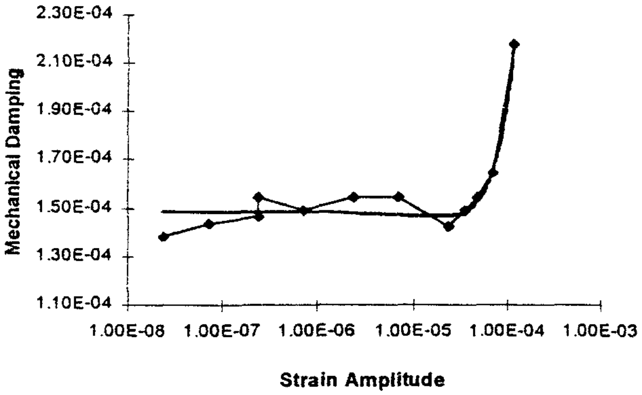

Fig. 3 Breakaway characteristic at higher strain amplitude for damping measurements at room temperature

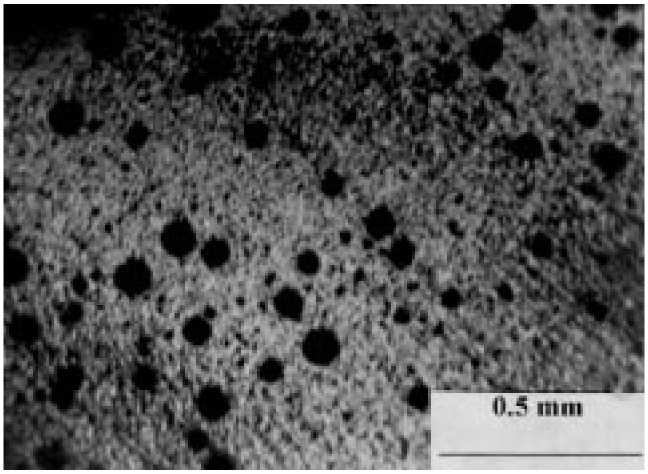

Fig. 4 Specimen as-received

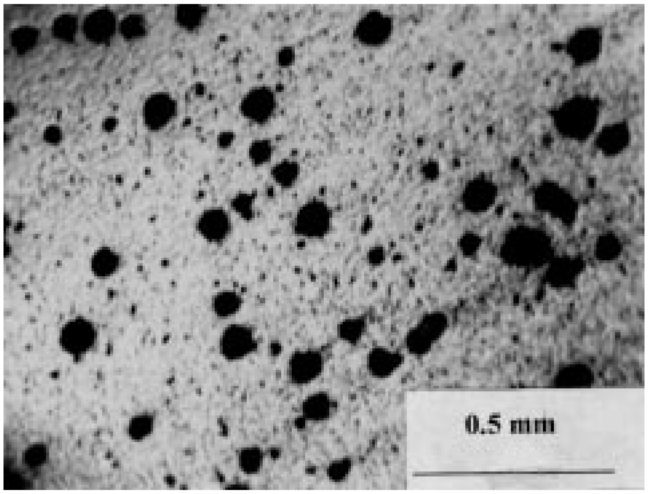

Fig. 5 Specimen after heating to 1000 °C

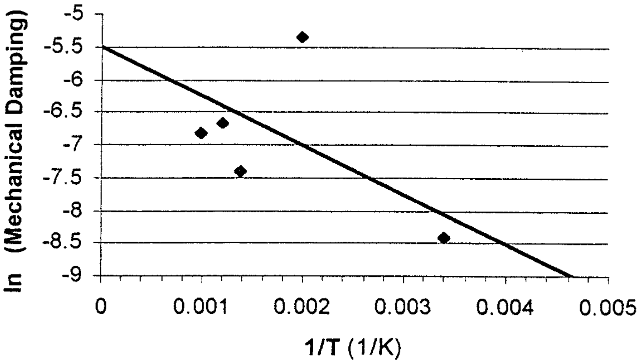

Fig. 6 Arrhenius plot of damping versus reciprocal temperature

The lattice parameter and the Burgers vector for SiC were taken from Nixon and Davis (Ref 11).

From the micrographs, it was noticed that the pores of the material are approximately spherical in nature, and the edges of the pores are not smooth. There was no noticeable change in the porosity or pore size due to the heating of the specimen to 1000 °C for 20 min. From microhardness testing, it was determined that the Vickers hardness number for the specimen maintained at room temperature was 2103 HV with a standard deviation of 140 HV. The Vickers hardness number for the specimen heated to 1000 °C was determined to be 1697 HV with a standard deviation of 60 HV. These large Vickers hardness numbers denote the extreme hardness of this specific ceramic.

Analysis of the Arrhenius plot (Fig. 6), in terms of the equation $Q^{-1} = Q_0^{-1} \exp(-\Delta H/kT)$, where Q_0^{-1} is a reference value of Q^{-1}, ΔH is the effective activation energy, and k is Boltzmann's constant, yields an activation energy of 0.065 eV/atom. This is close to kT, the background thermal energy. The effective activation energy of 0.065 eV/atom is much less than the value of 8 eV/atom for the activation energy of the diffusion of carbon in SiC (Ref 12).

4. Conclusions

The dynamic elastic modulus was measured over the temperature range 21 to 740 °C and has shown an inverse relationship with temperature. The plots of mechanical damping versus strain amplitude for room temperature showed breakaway characteristics. The minor pinning length and mobile dislocation density were determined for the specimen maintained at room temperature and were within expected ranges. The temperature dependence of the damping yielded an effective activation energy of 0.065 eV/atom, which is close to kT.

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