Vibration damping using flexible graphite

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Vibration damping is valuable for structures, as it mitigates hazards (whether due to accidental loading, wind, ocean waves or earthquakes), increases the comfort of people who use the structures, and enhances the reliability and performance of structures. The basic concept about damping involves the absorption of external energy through internal motion or friction [1,2]. A layered structure is attractive for damping due to the large internal surface area involved [3,4]. The relative motion between layers produces extra shear, which means more energy dissipation [5]. For instance, a viscoelastic material or a fluid layer is sandwiched within a beam for both passive and active damping [6–8]. However, fluid and viscoelastic materials suffer from their poor stiffness, limited resistance to heat and chemicals, in addition to high thermal expansion and poor thermal conductivity, which aggravate thermal stresses.

Flexible graphite is a flexible sheet made by compressing a collection of exfoliated graphite flakes without a binder [9–18]. Due to the exfoliation, flexible graphite has a large specific surface area (e.g. 15 $m^2 g^{-1}$ [19]). As a result, flexible graphite is used as an adsorption substrate. Due to the absence of a binder, flexible graphite is essentially entirely graphite (other than the residual amount of intercalate in the exfoliated graphite). As a result, flexible graphite is chemically and thermally resistant, and low in coefficient of thermal expansion (CTE). Due to its microstructure involving graphite layers that are preferentially parallel to the surface of the sheet, flexible graphite is high in electrical and thermal conductivities in the plane of the sheet. Due to the graphite layers being somewhat connected perpendicular to the sheet (i.e. the honeycomb microstructure of exfoliated graphite), flexible graphite is electrically and thermally conductive in the direction perpendicular to the sheet (although not as conductive as the plane of the sheet). These in-plane and out-of-plane microstructures result in resilience and impermeability to fluids perpendicular to the sheet. The combination of resilience, impermeability and chemical and thermal resistance makes flexible graphite attractive for use as a gasket material for high temperature or chemically harsh environments.

Due to its resilience, in addition to its thermal resistance, chemical resistance, low thermal expansion and high thermal conductivity, flexible graphite was investigated in this work for use in vibration damping. The investigation involved simultaneous measurement of the loss tangent (tan δ, i.e. damping capacity) and storage modulus (stiffness) under dynamic flexure (three-point bending at a very small deflection amplitude) at fixed frequencies. The product of loss tangent and storage modulus is the loss modulus. As high values of both loss tangent and storage modulus are desired for vibration reduction, a high value of the loss modulus is desired. Rather low frequencies are used in this study due to their relevance to the vibration of large structures and due to the fact that the loss tangent decreases with increasing frequency and hence becomes hard to measure at a high frequency. For the sake of comparison, the loss tangent and storage modulus of rubber were also measured.

Flexible graphite sheet (Grade GTB) was provided by EGC Enterprises, Inc. (Mentor, Ohio). The specific surface area was 15 $m^2 g^{-1}$, as determined by nitrogen adsorption and measurement of the pressure of the gas during adsorption using the Micromeritics (Norcross, GA) ASAP 2010 instrument. This specific surface area corresponds to a crystallite layer height of 0.18 μm within a sheet. According to the manufacturer, the ash content of flexible graphite is $<5.0\%$; the density is 1.1 $g\,cm^{-3}$; the tensile strength in the plane of the sheet is 5.2 MPa; the compressive strength (10% reduction) perpendicular to the sheet is 3.9 MPa; the thermal conductivity at 1093°C is 43 $W\,m^{-1}\,K$ in the plane of the sheet and 3 $W\,m^{-1}\,K$ perpendicular to the sheet; the coefficient of thermal expansion (CTE) (21–1093°C) is -0.4×10^{-6}/°C in the plane of the sheet.

Dynamic mechanical testing (ASTM D4065-94) at controlled frequencies (0.2, 1.0 and 5.0 Hz) and room temperature (20°C) was conducted under flexure using a Perkin-Elmer Corp. (Norwalk, CT) Model DMA 7E dynamic mechanical analyzer. Measurements of tan δ and storage modulus were made simultaneously at various frequencies. The specimens were in the form of beams of length at least 25 mm under three-point bending, with the span being 20 mm. The width of the flexible graphite

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Table 1
Loss tangent, storage modulus and loss modulus of flexible graphite, neoprene rubber, and metals

Material	Property	0.2 Hz	1.0 Hz	5.0 Hz
Flexible graphite	Loss tangent	0.187±0.047	0.146±0.020	0.150±0.030
	Storage modulus (GPa)	1.03±0.21	1.25±0.36	1.40±0.42
	Loss modulus (GPa)	0.205±0.074	0.221±0.077	0.202±0.031
All State neoprene	Loss tangent	0.67±0.14	1.12±0.08	4.52±1.22
	Storage modulus (MPa)	7.45±0.28	7.83 ±0.11	6.52±0.83
	Loss modulus (MPa)	6.72±1.50	8.23±0.76	24.9±8.7
Badger neoprene	Loss tangent	0.59±0.16	0.71±0.29	1.78±0.73
	Storage modulus (MPa)	14.9±0.2	18.9±0.3	17.5±2.5
	Loss modulus (MPa)	8.86±2.53	13.2±5.0	30.8±11.7
Pure aluminum	Loss tangent	0.019	0.014	–
[20]	Storage modulus (GPa)	51	58	–
	Loss modulus (GPa)	1.0	0.8	–
Zn–Al	Loss tangent	0.021	0.009	–
[20]	Storage modulus (GPa)	74	76	78
	Loss modulus (GPa)	1.5	0.5	–

specimens ranged from 2.4 to 2.6 mm; the width of the rubber specimens ranged from 2.0 to 2.5 mm. The thickness of flexible graphite was 1.5 mm; the thickness of the rubber specimens ranged from 2.0 to 2.5 mm. The loads used were all large enough so that the amplitudes of the specimen deflection was from 5 to 10 μm (over the minimum value of 5 μm required by the equipment for accurate results). The loads were set so that each type of specimen was always tested at its appropriate stress level. Three specimens of each type were tested.

The rubber tested was neoprene from two sources, i.e. All State Rubber & Tool Corp., Palos Heights, IL, and Badger Rubber Company, Chicago, IL.

Table 1 gives the loss tangent, storage modulus and loss modulus of flexible graphite and neoprene. The loss tangent of flexible graphite is lower than that of neoprene (whether All State or Badger neoprene), but the storage modulus is higher by about two orders of magnitude. Covalent bonding makes flexible graphite stiffer (higher storage modulus) than rubber, in which molecules are bonded by secondary bonding. As a result, the loss modulus of flexible graphite is much higher than that of neoprene, whether the frequency is 0.2, 1.0 or 5.0 Hz. The loss tangent of neoprene increases with increasing frequency, especially between 1.0 and 5.0 Hz. However, the loss tangent of flexible graphite does not vary much with the frequency.

Although the loss tangent of flexible graphite is lower than that of neoprene, it is much higher than those of pure aluminum and Zn–Al alloy (ZA-27, an alloy which is known for its high damping capacity), as shown in Table 1. Compared to these metals, the layered structure and the large specific surface area of flexible graphite are possible reasons for the loss tangent of flexible graphite to be higher than the metals by about an order of magnitude. Although the storage modulus of flexible graphite is higher than that of neoprene, it is lower than those of aluminum and Zn–Al alloy.

Flexible graphite provides a well-balanced set of dynamic flexural properties, i.e. quite high values of both loss tangent and storage modulus. In addition, flexible graphite is chemically and thermally resistant, low in thermal expansion and high in thermal conductivity, in sharp contrast to rubber. The combination of these properties makes flexible graphite attractive for use in vibration damping.

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Formation of carbon nanotubes from jet fuel on superalloys at moderate temperature and high pressure

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Carbon nanostructures, particularly carbon nanotubes, have created much interest among many researchers because of the unusual structure and properties of these carbon materials. Carbon nanotubes are nanometer wide needle-like cylindrical tubes of concentric graphitic carbon with diameters as small as 1 nm and a length up to many micrometers. They consists of either a single layer of graphite that has been rolled into a cylinder (single-walled nanotubes) or multi layers of concentric graphite sheets (multi-walled nanotubes). After their discovery by Iijima [1], carbon nanotubes have been prepared by various techniques, including carbon arc-discharge [1], catalytic pyrolysis of hydrocarbons [2,3], condensed-phase electrolysis [4], template carbonization [5,6], and laser-ablation [7]. All these processes take place at relatively high temperatures (>950 K) and low pressures (10^{-6}–760 Torr).

There are some reports in the literature on the formation of carbon tubes and shells in the filamentuous carbon deposits. Smith et al. [8] reported the formation of graphitic tube structures upon steam reforming of *n*-butane on Ni/MgO catalysts at 923 K. Audier et al. [9] observed truncated multi-shell carbon tubes in the deposit obtained from heating a mixture of CO_2 and CO to 873 K at atmospheric pressure in the presence of iron–cobalt and iron–nickel alloys. Oberlin et al. [10] observed the formation of hollow carbon fibers upon pyrolysis of a mixture of benzene and hydrogen at 1373 K. In all these cases, metal particles were found in the carbon tubes. There has been no report of carbon nanotube, or nanoparticle formation at pressures much above the atmospheric pressure and at

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