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Carbon black and fumed alumina exhibiting high interface-derived mechanical energy dissipation

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ABSTRACT

High interface-derived dissipation has been discovered by instrumented indentation in carbon black and fumed alumina. Both materials comprise nanoparticle aggregates that interlock mechanically upon compaction without a binder. The high dissipation is attributed to the high deformability and the abundance of interfaces. Compared to carbon black, similarly 600-kPa compacted 100-mN maximum-load tested fumed alumina gives lower dissipation (2.1 vs. 4.1 μJ, both values being higher than the highest previously reported value for any material, 0.175 μJ for dental enamel), lower maximum displacement (72 vs. 134 μm), higher fraction of displacement that is permanent (0.74 vs. 0.59), higher modulus (41 vs. 7 MPa), higher fractional dissipation (0.80 vs. 0.70), and lower solid content (12 vs. 18 vol.%). These differences are attributed to the greater compressibility of carbon black. The relative movement of the particles of carbon black or the graphite layers of exfoliated graphite becomes less reversible as the degree of compaction increases. Microwave-exfoliated graphite (5.25-MPa compacted, 37 vol.% solid) gives lower dissipation (1.0 μJ) and higher modulus than carbon black or fumed alumina. Furnace-exfoliated graphite (5.25-MPa compacted, 43 vol.% solid) gives even less dissipation than microwave-exfoliated graphite, due to its greater compressibility and consequent greater deformation reversibility.

1. Introduction

The dissipation of mechanical energy occurs when the stress–strain curve during loading does not overlap with that during unloading. The area between these two curves gives the dissipated energy (i.e., the energy loss) per unit volume. The energy loss involves the conversion of mechanical energy to another form of energy, which is commonly heat. Energy dissipation is not the same as the toughness, which refers to the mechanical energy input (per unit volume) needed to deform a material up to fracture.

Mechanical energy dissipation is important for passive vibration damping and sound absorption. Vibration damping is needed for essentially all structures, including wind turbines, airframe, cars, buildings, helmets, ski boards, etc. Sound absorption is needed to alleviate the noise pollution that increasingly erodes the quality of life of most people.

Mechanical energy dissipation requires a degree of viscous character in the material. The viscous character is commonly provided by bulk viscous deformation, as in the case of rubber and other polymers. However, an unconventional mechanism for providing viscous behavior is dynamic low-amplitude interfacial sliding that involves friction [1,2]. This unconventional mechanism can be significant when the material has a large amount of interface area, as in the case of an appropriately nanostructured material. Conventional carbons (such as carbon fiber) and ceramics (such as alumina) that are not in the form of polymer-matrix composites are not viscoelastic. In contrast, polymers and polymer-matrix composites are viscoelastic. However, significant viscous behavior based on the interfacial mechanism has recently been reported for exfoliated graphite [1] (not a composite), with the interfacial mechanism supported by dynamic flexural testing results and analytical modeling [2].

The interfacial mechanism mentioned above is expected to be less dependent on the temperature than the conventional bulk viscous deformation mechanism. For example, in the case of

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polymers involving the bulk viscous deformation mechanism, the viscous character depends considerably on the temperature, particularly for temperatures around the glass transition temperature. Furthermore, polymers have limited elevated temperature resistance and limited chemical resistance compared to materials such as graphite. The concept of non-polymeric materials with strong viscous character is novel and transformative.

The plastic deformation of steel is commonly used to provide energy dissipation in steel traffic barriers, which encounter high loads during automobile impact. However, there are other applications that require energy dissipation under low loads; examples include microelectronic packages, medical devices, mechatronic devices, micromachines, robots and loudspeakers.

An effective method for evaluating the mechanical energy dissipation ability of a material is instrumented indentation (nanoindentation) during loading and subsequent unloading. This method allows tests to be conducted at different locations on the same specimen, thus allowing investigation of the spatial distribution (if any) of the energy dissipation. In addition, the specimen for nanoindentation can be small, in contrast to the relatively large specimens for conventional mechanical testing (such as tensile testing) under dynamic loading. In nanoindentation, the area between the loading and unloading curves of load vs. displacement gives the dissipated energy per loading cycle. However, comparison of this quantity for various materials should be conducted either at the same maximum load or the same maximum displacement. In the following comparison of various previously reported materials, comparison was conducted for the same maximum load. Since the maximum load values differed for different pieces of prior work, scaling of the energy dissipation was conducted in the following comparison so as to compare at the same maximum load. This scaling assumes linearity between the dissipation and the maximum load. This linearity occurs when both the loading and unloading curves of load vs. displacement are linear. However, these curves deviate from linearity, so the scaling gives only approximate dissipation values.

Based on nanoindentation results, the highest energy dissipation values previously reported [3–7] are listed in Table 1. Not listed in Table 1 due to the unclear testing conditions are the following low values of the energy dissipation (listed in order of decreasing energy dissipation): (i) 22 nJ for dentin (which is the calcified tissue underneath the dental enamel and is a composite comprising hydroxyapatite and a minor proportion of an organic material, mainly collagen, such that the proportion of organic material is higher than that of enamel) [8], (ii) 5.5 nJ for nanocrystalline glass [9], (iii) 4.1 nJ for metallic glass [10], (iv) 0.2 nJ for indium tin oxide (ITO) [11] and (v) 0.1 nJ for cement [12,13]. The high value for TiN-coated steel or TiN-coated cemented carbide [3] suggests the importance of an interface such as the coating-substrate interface in contributing to the energy dissipation.

This work provides the first report of the high mechanical energy dissipation of carbon black (a nanostructured material [14]) and fumed alumina (a similarly nanostructured material [15]). The energy dissipation is up to 4.6 and 4.1 μJ for compacted carbon black and compacted fumed alumina respectively. These values are much higher than all of the abovementioned values at comparable values of the maximum load (Table 1).

Both compacted carbon black and compacted fumed alumina are in the form of aggregates of primary particles, such that the aggregates are compressible and interlock mechanically upon compaction, thereby forming a monolithic porous solid. Compacted carbon black in the absence of a binder is a viscoelastic material [14], as recently shown by dynamic mechanical testing, with its viscous character increasing and its elastic character decreasing with increasing aggregate size. The relative movement of the particles in an aggregate contributes to the viscous deformation, while the connectivity among the aggregates contributes to the stiffness [14]. However, the viscoelastic behavior of compacted fumed alumina has not been previously reported.

Because the particles in an aggregate can move relative to one another quite easily, carbon black is compressible. Because of the compressibility, carbon black spreads under compression and conforms to the topography of the sandwiching surfaces. The spreading promotes the formation of a carbon network, even though the carbon black aggregates do not form a network before the spreading. As a consequence, carbon black is highly effective as an additive for enhancing the electrical connectivity and hence the electrical conductivity of a composite comprising nonconductive particles [16]. An example involves manganese dioxide particles, which are nonconductive and are commonly used as a cathode material in batteries. Carbon black is commonly added to this electrode in order to render the electrode conductive [17,18].

The surface topographic conformability resulting from the compressibility allows carbon black to be valuable as a constituent in thermal interface materials, which are used to reduce the thermal resistance of thermal contacts [19–23]. The improvement of thermal contacts is much needed for alleviating the problem of overheating in microelectronics. In addition, the conformability makes carbon black effective as an interlaminar filler for improving the thermal conductivity of continuous carbon fiber polymer-matrix composites in the through-thickness direction [24].

Carbon black is widely used as a reinforcing filler in rubber tires [25–27]. The spreading of the carbon black during the composite material fabrication tends to cause the carbon black to develop a fibrous morphology, which promotes the reinforcing ability. The viscoelastic behavior and energy dissipation ability of carbon black is expected to contribute to these characteristics of composites containing carbon black. However, such characteristics of carbon

Table 1
Mechanical energy dissertation of various materials tested by nanoindentation at various maximum loads.

Material	Maximum load (mN)	Energy dissipation scaled to maximum load 100 mN[a] (nJ)	Ref.
TiN-coated steel or cemented carbide[b]	5000	94	[3]
Fe-18Cr-8Ni austenitic stainless steel	500	127	[4]
Nickel-tungsten alloy	400	60	[5]
Dental enamel[c]	100	175	[6]
Carbon fiber (axial)	70	34	[7]
Carbon black	100	4600	This work
Fumed alumina	100	4100	This work

[a] The scaling conducted in this work is based on the assumption of linearity between the energy dissipation and the maximum load.
[b] The TiN coating thickness of 10 μm and the maximum displacement of 4 μm indicate that the energy dissipation involves not just the coating but also the substrate and the coating-substrate interface.
[c] The dental enamel comprises crystalline hydroxyapatite and a low proportion of organic material. The organic component contributes substantially to the energy dissipation ability.