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Flexible Graphite for Gasketing, Adsorption, Electromagnetic Interference Shielding, Vibration Damping, Electrochemical Applications, and Stress Sensing

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The applications of flexible graphite are reviewed. They include gasketing, adsorption, electromagnetic interference shielding, vibration damping, electrochemical applications, and stress sensing.

Keywords EMI shielding, graphite, vibration damping

1. Introduction

Flexible graphite is a flexible sheet made by compressing a collection of exfoliated graphite flakes (called worms) without a binder.[1–5] During exfoliation, an intercalated graphite (graphite compound with foreign species called the intercalate between some of the graphite layers) flake expands typically by over 100 times along the *c*-axis. Compression of the resulting worms (like accordions) causes the worms to be mechanically interlocked to one another, so that a sheet is formed without a binder.

Due to the exfoliation, flexible graphite has a large specific surface area (*e.g.*, 15 m^2/g[6]). As a result, flexible graphite is used as an adsorption substrate. Due to the absence of a binder, flexible graphite is essentially pure 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.

Gasketing (*i.e.*, packaging and sealing) is by far the main application of flexible graphite, which can replace asbestos. Other than gasketing, a number of applications have emerged recently, including adsorption, electromagnetic interference (EMI) shielding, vibration damping, electrochemical applications, and stress sensing.

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This paper is a review of the applications of flexible graphite. Not included in this review are the applications of exfoliated graphite that has not been compressed into a sheet; such is the subject of a previous review.[7] Exfoliated graphite composites (*e.g.*, exfoliated graphite bound by using a polymer)[8–14] are also outside the scope of this paper, as the presence of a binder tends to degrade the thermal and chemical resistance and to greatly affect the types of applications that are suitable. The process of making flexible graphite and the structure and properties of flexible graphite are not emphasized in this review, although the applications are presented in light of the structure and properties.

2. Gasketing, Packing, and Sealing

Due to the health hazard associated with asbestos, there is a need to replace asbestos gaskets. Flexible graphite in planar or wound forms, regardless of whether it is corrugated, and in various shapes is used for gasketing, packing, and sealing.[15–34] Its attractive properties are resilience, impermeability to fluids, chemical inertness, and high-temperature stability.

Flexible graphite is made by compressing exfoliated graphite, which is in turn made by exfoliating intercalated graphite by heating or by electrochemical methods. The residual amount of intercalate in flexible graphite is small, but nonzero. The presence of the intercalate is of concern to some applications. Thus, proper choice of the intercalate species and minimization of the residual intercalate concentration are recommended.

3. Adsorption

Flexible graphite has a large specific surface area compared to conventional graphite, but the specific surface area is much lower than that of activated carbon. This is because exfoliation, as attained by heating (common method), involves the ballooning of an intercalate island in intercalated graphite[35] due to vapor generated by the vaporization[36] and/or decomposition of the intercalate. The ballooning is made possible by the shear of the graphite layers lining the surface of the balloon. The balloons may or may not burst during exfoliation, depending on the intercalate species. For bromine as the intercalate, bursting does not occur much. For nitric acid as the intercalate, bursting occurs much more.

The high specific surface area, chemical inertness, and chemical resistance make flexible graphite attractive as an adsorption substrate. Flexible graphite has been widely used as an adsorption substrate for fundamental study of the physics of the adsorbed layer (usually a monolayer). However, of more practical interest are industrial adsorption applications, such as the adsorption and recovery of heavy oil,[37] the adsorption of methanol,[38] and the adsorption involved with gas chromatography for separating isomers.[38] However, the industrial applications make use of exfoliated graphite rather than flexible graphite.

4. EMI Shielding

Electromagnetic interference shielding is increasingly needed due to the increasing abundance and sensitivity of electronics, particularly radio frequency devices, which tend to interfere with digital devices. A shielding material needs to be an electrical conductor, although the electrical conductivity does not have to be very high. Due to the skin effect (*i.e.*, the phenomenon that high frequency electromagnetic radiation only interacts with the surface region of a conductor), a high surface area of the conductor is desirable. As the electrical conductivity (especially that in the plane of the sheet) and specific surface area are both quite high in flexible graphite, the effectiveness of this material for shielding is exceptionally high (up to 130 dB).

In addition to conventional shielding applications, flexible graphite can serve as a shielding gasket material, due to its resilience. As the resilience of a polymer-matrix composite decreases rapidly with increasing filler content, the attainment of a shielding gasket using a polymer-matrix composite has been a challenge.[39,40]

The high thermal conductivity, low CTE, high-temperature resistance, and excellent chemical resistance of flexible graphite add to the attraction of this material for use in EMI shielding.

5. Vibration Damping

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. Both passive and active methods of damping are useful, although active methods are usually more expensive due to the devices involved. Passive damping most commonly involves the use of viscoelastic materials such as rubber, which suffers from its poor stiffness. High stiffness is useful for vibration reduction. Moreover, rubber and other polymeric viscoelastic materials suffer from their limited resistance to heat and chemicals, in addition to high thermal expansion and poor thermal conductivity, which aggravate thermal stresses.

Due to its resilience, in addition to its thermal resistance, chemical resistance, low thermal expansion, and high thermal conductivity, flexible graphite was investigated for use in vibration damping.[41] 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 (0.4 to 2.0 Hz). 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.

Flexible graphite exhibits a lower value of the loss tangent than rubber, but much higher values of both storage and loss modulus. Although the loss tangent of flexible graphite (0.2) is lower than that of rubber (0.6), it is much higher than those of metals (*e.g.*, 0.02 for zinc-aluminum high-damping alloy). That the loss modulus of flexible graphite exceeds that of rubber means that flexible graphite is better than rubber for vibration reduction.

6. Electrochemical Applications

The flexibility, ease of shaping, and unusual microstructure (compared to other forms of carbon) suggest possible attraction for the use of flexible graphite as an electrode material in batteries, for electrolysis, or in chemical sensors. In the case of batteries, flow cell developers concentrate efforts on developing low-cost, solid carbon, and graphite electrodes. The current technology utilizes carbon polymer composite structures, glassy carbon, or dense graphite. These materials limit electrode design in that they are not very flexible and (especially in the case of glassy carbon) are difficult to shape. Regarding electrolysis, platinum is commonly the electrode material of choice. Platinum, however, is very expensive. Therefore, practical electrodes, which are corrosion resistant, low in cost, and electrocatalytically active, are desired. Carbon and graphite satisfy these requirements. Flexible graphite offers the advantage of shapeability. Finally, carbon and graphite electrodes are characteristically used as sensors for detecting organic and inorganic species in solution. Typically selected are glassy carbon (which is hard, brittle, and poses some problem when it comes to forming or shaping) and polymer coated or polymer bound graphites (which are often limited to use in aqueous media given the incompatibility of the coating or binding media with organic or inorganic electrolytes). Like the previous cases cited, flexible graphite offers easy forming and shaping and, because flexible graphite is uncoated and absent of binders, provides excellent chemical compatibility in all electrolytes as well as thermal stability.

Compared to carbon paste, flexible graphite is capable of offering a better electron transfer rate, higher electrochemical area, and lower capacitance, without the need of a binder for flexibility. Flexible graphite is also easily cut into flat sheets. Flexible graphite, on the other hand, offers a lower electron transfer rate compared to glassy carbon, which is an electrode material that is very difficult to machine. The electron transfer rate, however, increases with increasing number of edge sites. Flexible graphite can display lower or higher capacitance compared to glassy carbon, depending on the ratio of basal to edge sites. Its electrochemical area is, in general, much higher than glassy carbon or carbon paste.[42]

Flexible graphite bonded to aluminum can serve as current collectors for sodium-sulfur cells.[43]

7. Stress Sensing

Piezoresistivity is the change of electrical resistivity with stress. A common piezoresistive material is a composite containing electrically conducting particles or fibers. Upon tension, the distance between adjacent filler units increases, so the resistivity increases; upon compression, this distance decreases, so the resistivity decreases.

Due to its resilience, flexible graphite sandwiched by copper, after stabilization by two cycles of compressive stress, is a piezoresistive compressive stress/displacement sensor for stresses (perpendicular to the sandwich plane) up to 4 MPa and displacements up to 25% of the flexible graphite thickness.[44] The stress sensitivity (fractional change in resistance per unit stress) is up to 5.4 MPa^{-1} and displacement sensitivity (fractional change in resistance per unit strain in graphite) is up to 6.2. The sensitivities decrease with increasing stress/displacement. The electrical resistance decreases reversibly upon compression, due mainly to the reversible decrease in the contact resistivity between graphite and copper. The reversibility stems from the resilience of flexible graphite. Stabilization removes most irreversibility. Compared to other piezoresistive sensors, flexible graphite is attractive in high stress sensitivity, high-temperature resistance, and chemical resistance.

8. Conclusions

Due to its unique combination of properties, flexible graphite is finding applications in numerous areas, including gasketing, adsorption, EMI shielding, vibration damping, electrochemical applications, and stress sensing, although gasketing remains the dominant application.

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