Carbon in Biomedical Engineering

Carbons are easily recognizable in a wide variety of forms, such as graphite and diamond. Each type of carbon has a specific atomic structure and mechanical properties. Carbons were first examined for their potential as biomedical materials in the 1970s. Subsequent research has identified three forms of bulk carbons that have sufficient chemical and mechanical properties for biomedical applications. All three have a similar atomic structure, but are fabricated by different techniques. The medically relevant carbons do not elicit an adverse reaction in the host tissue, and conversely, the host environment does not have a harmful effect on the carbons.

1. *Medically Relevant Carbons*

Three forms of carbon have been used extensively in clinical applications. These include vitreous carbon, pyrolytic carbon (also called low temperature isotropic, or LTI carbon), and vapor-deposited carbon (also called ultra-low temperature isotropic, or ULTI carbon). Vitreous carbon is an amorphous, isotropic and monolithic bulk material. Pyrolytic carbon is a coating that is applied to a substrate, typically graphite. The coating is approximately 1–3 mm thick. Vapor-deposited carbon is a thin film, approximately 1 μm thick, which is applied to a substrate. The film is sufficiently thin for the mechanical properties of the substrate to be retained.

2. *Structure of Biomedical Carbons*

The medically relevant carbons have a crystal structure that is loosely similar to that of graphite. The structure of graphite consists of carbon atoms arranged in planar hexagonal arrays. Strong covalent bonds, with a bond energy of $114\,\mathrm{kcal\,mol^{-1}}$, exist between the atoms in the basal plane. The planar arrays are stacked in an ordered ABAB sequence to produce a hexagonal close-packed crystal lattice. The carbon atoms between adjacent planes are bound by weaker van der Waals bonds, which possess a bond energy of $4\,\mathrm{kcal\,mol^{-1}}$.

In contrast to graphite, the three medically relevant carbons have a turbostratic structure. The basal planes are warped and contain defects, such as missing carbon atoms. The crystallites in the turbostratic structure are relatively small, with a size less than 100 Å. The layers within the crystallites lie roughly parallel to one another, but the atoms in one layer may have no additional relationship to those in other layers of the same crystallite. The stacking of the planes is haphazard, and thus there is very little order in the direction perpendicular to the planes. This results in higher bonding strengths between the planes, and contributes to enhanced mechanical properties.

3. *Fabrication of Biomedical Carbons*

Vitreous carbon is formed by slowly heating a solid polymeric substrate, during which the volatile by-products diffuse away, leaving only a glassy carbon material. The polymer must be heated at a rate slow enough to allow for the by-products to diffuse to the surface, rather than form bubbles in the substrate. As a result of the diffusion requirement, the size of the nonporous carbon structures is limited to less than 7 mm, and the entire fabrication process takes a minimum of one week. During the processing, the volume of the substrate shrinks approximately 50%.

Pyrolytic carbon is often deposited as a coating, with a thickness of 1–3 mm. The substrate to be coated is floated in a fluidized bed, which is created by the flow of an inert gas, such as helium. The fluidized bed is typically heated to 1400 °C, but the temperature can range from 1200 to 1500 °C. A hydrocarbon gas, typically methane, is then passed through the fluidized bed. Owing to the high temperature within the bed, the hydrocarbon is thermally decomposed, or pyrolyzed. As a result, spheres of carbon develop and deposit onto the substrate, where they coalesce to form the coating. Improvements in processing techniques have resulted in enhanced mechanical properties of pure pyrolytic carbon.

Prior to the improvements in processing, alloying elements such as silicon were often added to pyrolytic carbon. Up to 20% of silicon can be added to pyrolytic carbon without compromising the biocompatibility of the material. To fabricate silicon-alloyed pyrolytic carbon, a carrier gas containing silicon, such as methyltrichlorosilane, is mixed with the hydrocarbon gas during processing. Silicon carbide crystals then deposit uniformly through the coating. The resulting material typically has increased strength and wear resistance.

Vapor-deposited carbon is a thin coating that is deposited onto a substrate. Carbon atoms are evaporated in a vacuum from a solid or gaseous precursor by a high-energy electron beam. The atoms are then deposited at a high rate onto a cool substrate that is held at a distance from the source. The resulting coating is typically less than 1 μm thick, and thus, the properties and topography of the bulk substrate are retained. Because the substrate is held at a low temperature during processing, polymers, metals and ceramics can all be coated by this technique.

4. *Mechanical Properties of Biomedical Carbons*

Mechanical properties of the medically relevant carbons are shown in Table 1. These properties depend largely on the density of the material, and increase as the density increases. Vitreous carbon has the lowest density of the three carbons, while that of pyrolytic carbon and vapor-deposited carbon are approxi-