

Biomorphic Materials: Silicon Carbide Derived from Natural Carbon Precursors

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The recent initiative to cater toward an environmentally efficient lifestyle has put pressure on many industries and practices. However, the success of these green initiatives has not been an easy achievement. During the past decade, scientists and engineers have worked tirelessly to discover a more natural way to process Silicon Carbide (SiC). A new category of materials, called biomorphic materials, has provided insight into how materials can be synthesized from bio-organic materials while retaining similar properties and performance.¹ In comparing SiC with its biomorphic cousin, BioSiC, there are notable similarities and differences in the properties, structure, processing, performance, and environmental concerns between each material discussed in this article.

Properties and Structure

SiC (also known as carborundum²), is a ceramic material with multitudes of industrial applications. The industrial applications range from use as an abrasive (SiC cutting blades) to use as a semiconducting material (SiC microchips). Properties of SiC include high hardness, high strength, thermal stability, oxidation resistance, and erosion resistance.³ The high thermal and electrical stability of SiC have allowed it to be accepted as a wide band gap (WBG) semiconductor.³ A WBG semiconductor allows for “smaller, faster, more reliable, and more efficient” electronic components.⁴ SiC also “has the highest [chemical] corrosion resistance of all advanced ceramics”.² Each of these properties support the performance of SiC in high temperature and abrasive technological applications. SiC has many different crystalline structures (polytypes). There are over two hundred polytypes of SiC, which contribute to slight alterations in the properties of SiC. The most common polytype is alpha SiC which has a hexagonal crystalline structure.³ Each polytype is varied by the stacking sequence of the tetrahedrally bonded SiC bilayer.³ This allows for differences in band gap energies and electronic properties of each polytype.

The differences in the properties of SiC and BioSiC are very minimal because the biomorphic properties of BioSiC mimic the properties of SiC. BioSiC behaves as a ceramic material, but its microstructure (Figure 1) and properties are determined by the material it is derived from.⁵ The similar structure of BioSiC to SiC allows BioSiC to retain important properties such as high conductivity and other WBG classifications. BioSiC is mainly hexagonal as well but its dependency on the natural material it is derived from (wood, bamboo, etc.) cause the Si to infiltrate the amorphous C scaffolding differently when processing BioSiC. However,

an advantage of the natural derivation is that BioSiC and other biomorphic materials tend to interact better with biological systems.⁶ The natural derivation of BioSiC imposes advancements in bioelectronics⁶ and medical implant technologies⁷ that synthetic SiC cannot achieve. BioSiC is more porous and this porosity affects the density of the material, which can lower the overall hardness and strength of BioSiC.⁸ However, porosity increases thermal resistivity and insulation which is useful for the electronic applications of BioSiC.

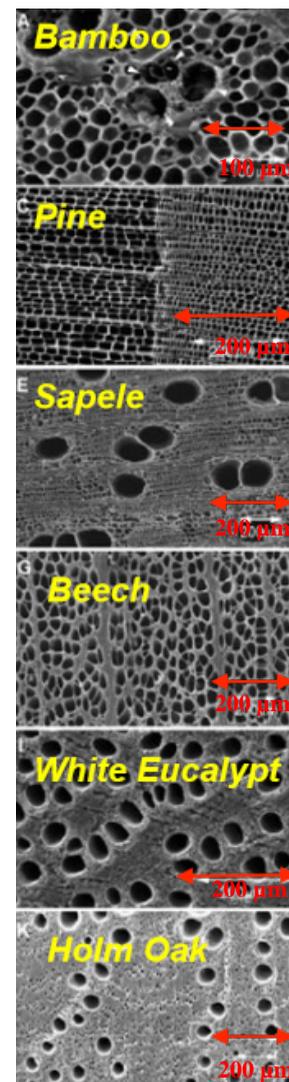


Figure 1: Represents a comparison of the various natural precursors and their final microstructures for BioSiC.⁹

Processing

SiC and BioSiC are processed in fairly different ways. SiC can actually be found in the environment naturally as a mineral known as moissanite.³ Moissanite is rare and only found in certain types of meteorites.³ SiC is generally synthetically grown. The many polytypes of SiC result from different processing methods, but the most common ones are known as the Acheson Process and the Lely Method. The Acheson Process is typically used when abrasive properties are desired for SiC. This process involves a solid-state reaction between silica sand and petroleum coke (a solid form of carbon).³ Processing SiC in this way requires a lot of energy (due to the large furnaces) and oxygen, nitrogen, and aluminum impurities are common in the final material.³

An alternative method to grow SiC is called physical vapor transport (PVT) and one of the first methods using this was called the Lely Method. The Lely Method grows synthetic SiC crystals in an inert gas environment and graphite container at high temperatures.³ This method consumes less energy (depending on the quantity of crystals to be grown) but is equally as time consuming as the Acheson method.

BioSiC proves some advantages in its processing. One important aspect in processing of BioSiC is that the renewable or natural material it is made from alters the microstructure and properties of the material. Being derived from renewable materials is also key in considering any environmental concerns of BioSiC. The density of the precursor also has an effect on the final density of the BioSiC and anisotropic properties.⁵ To begin processing BioSiC the cellulose from which the biomorphic material will begin from must be chosen. Cellulose is a natural polymer and the main component of plant cell walls. For purposes of BioSiC, cellulose refers to the type of carbon precursor (examples shown in Figure 1). The next step is pyrolysis, which is a method of separating out C by heating up the carbon precursor in a low-oxygen environment.⁵ The carbon precursor is dehydrated of any excess water then higher temperatures are reached to separate C from the cellulose. At these high temperatures, the cellulose is essentially vaporized from the carbon precursor, leaving a C scaffolding to be infiltrated. The leftover amorphous C may then be precisely machined (this step is optional) to achieve complex shapes prior Si infiltration. Once the machining process is complete, the Si is infiltrated into the C scaffolding using the Si-melt method. This method involves pouring molten silicon over the pyrolyzed carbon so that Si may infiltrate the porous microstructure. This reaction is both spontaneous and exothermic.⁵ The result of this process is a ceramic matrix composite termed BioSiC which is cooled and can be used in the applications previously described. One advantage in the processing of BioSiC is that this method of pyrolysis and Si-melt infiltration is fairly rapid. The characteristics of BioSiC can be altered easily using this processing method too because the liquid Si is restricted

by the precursor's microstructure. This process does not only affect the properties of BioSiC but the performance of BioSiC as well.

Performance

When it comes to the performance of SiC, there are several different applications that are enhanced by this material. SiC performs well under high temperature and conductivity conditions which is why it is generally used for semiconducting wafers.¹⁰ SiC wafers can improve the energy efficiency of solar panels and in some semiconducting three-phase inverters, SiC can withstand temperatures of up to 200°C.¹⁰ Prior to its acceptance in the semiconductor and electronic field, SiC was more traditionally recognized for its abrasive uses. The high strength and thermal resistance of SiC allow it to maintain its properties in high stress applications. The abrasive technologies are mainly utilized for cutting and sanding in industrial workplaces.

One of the main advantages of BioSiC is its "tailorability".^{5,7} By being able to change the carbon template of the SiC, there becomes a wide range of performance options for BioSiC. BioSiC exhibits high thermal resistivity and mechanical properties, similar to that of SiC.⁵ These properties make BioSiC a competitive replacement for SiC since its processing methods are less expensive and faster. BioSiC can also withstand strengths in a range of 1100-1400 MPa.⁵ However, depending on the porosity of the natural precursor the mechanical strength can diminish due to the density of the final product. Increasing porosity also decreases the thermal conductivity of BioSiC.¹¹ On the other hand, porosity has been advantageous in a study of bone implants. The porosity of BioSiC may mimic that of the porosity of bone making it susceptible to tissue growth.⁷ Since BioSiC is a bio-organic material, it has shown improvements toward bioelectronic and biomaterial applications as well.⁶

Environmental Concerns

BioSiC is a more environmentally conscious material than SiC. SiC must be processed at temperatures over 2000°C³ while BioSiC can be processed at around 1000°C.⁵ The low processing temperatures of BioSiC make it a more environmentally conscious material that produces less contamination and uses less energy. Another advantage of BioSiC is that it does not require high-purity starting powder and additional additives (such as high quality seed-crystals and graphite for growing traditional SiC crystals).⁹ The porosity of BioSiC allows it to be manufactured into a recyclable absorbers which can be used for solar power plants.⁵ BioSiC absorbers are both more efficient at absorbing heat produced by solar radiation and more cost effective than current ceramic absorbers.⁵ Both BioSiC and SiC are generally processed in gas/vapor environments, which can contaminate the air, but BioSiC is processed more rapidly which allows less time for contamination.⁵ BioSiC and SiC

are also recyclable. They can be taken to a ceramic recycling facility where froth floatation, filtration, and centrifugation technologies are used.¹² Most SiC and BioSiC is recycled into grit for abrasive applications.

Conclusion

In comparing SiC and BioSiC there are notable similarities and differences. SiC is processed at higher temperatures and requires more time to generate higher quality and larger crystals. BioSiC is processed at lower temperatures and uses a natural C template that is infiltrated with Si. The mechanical, thermal, and electronic properties of SiC and BioSiC are very similar, resulting in high strength and high thermal resistivity. BioSiC has more diverse applications due to the wide range of natural precursors from which it can be derived. Lastly, BioSiC is more environmentally efficient than SiC due to the lower amount of energy and lack of additives required for its processing. BioSiC is relatively new and future advances are leading the material toward medical implant and recycleable solar panel applications.

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