Novel Composite Structures for Microwave Heating and Cooking

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A novel composite structure for microwave heating has been developed. This composite structure is ceramic in nature, and is designed and engineered for use as a heating element in microwave ovens. Previous attempts to develop ceramic or cermet microwave heating elements have faced the following challenges: (1) slow heat rates that negate the benefits of microwave heating and cooking, (2) conductivity problems that result in arcing, (3) poor thermal shock resistance that results in cracking if foods or fluids are splashed onto the element, or (4) overall lack of mechanical strength resulting in breakage and inadequate life. A unique form of silicon carbide has been synthesized to overcome these deficiencies. This silicon carbide is grown as a large single crystal, and consequently, exhibits unique properties. In addition, ceramic composites utilizing this silicon carbide are developed to deliver microwave-heating elements that overcome past deficiencies. This paper will describe the chemistry and structure-property relationships, and well as the practice of using this composite technology in microwave heating and food processing.

INTRODUCTION

The microwave food processing industry has long desired microwave ovens with that have built-in, microwave heatable grilling or cooking capability. The purpose of these elements is to enable speed cooking, where foods can be cooked extremely fast yet still maintain ideal texture. Attempts to develop microwave-heating elements capable of grilling or browning foods have been less than successful. A review of patents and development activity has shown the following drawbacks. Many composites: (1) heat too slowly in a microwave field, negating the ability to speed cook, (2) tend to be too conductive, and therefore arc, (3) exhibit poor thermal shock resistance, resulting in cracking when splashed with foods, or (4) have an overall lack of strength, and crack or break until the rigors of food preparations.

We have developed a novel composite structure that overcomes these deficiencies and enables very rapid speed cooking. This composite consists of a ceramic matrix doped with a unique single crystal silicon carbide.

FUNDAMENTALS OF MICROWAVE HEATING

The microwave power equation governs all materials that act as absorbers of microwaves and subsequently heat in a microwave field:

$$P = 2\pi f E^2 \varepsilon \tan \delta \qquad (1)$$

Key words:

where: P = power (watts/m^3)
f = frequency (Hz)
E = voltage gradient (V/m)
ε = dielectric permittivity
$\tan \delta$ = dielectric loss tangent

And the temperature rise of this material is governed by the following equation:

$$\frac{\Delta T}{\Delta t} = \frac{P}{\rho \cdot Cp} \qquad (2)$$

Where:

ΔT = temperature rise (°C)
Δt = time (s)
P = power generation, (w/m^3)
ρ = density (Kg/m^3)
C_p = specific heat (J/Kg/°C)

So the temperature rise is directly proportional to the $\varepsilon \tan \delta$ of the material, and to effect a rapid temperature rise, we desire lossy materials with as high an $\varepsilon \tan \delta$ as possible. The challenge in finding a material suitable as a microwave-heating element is one that exhibits the desired electrical properties, as well as the toughness and mechanical properties required for the harsh food preparation environment.

MEANS OF MICROWAVE HEATING

Based on the above equations, there are three potential

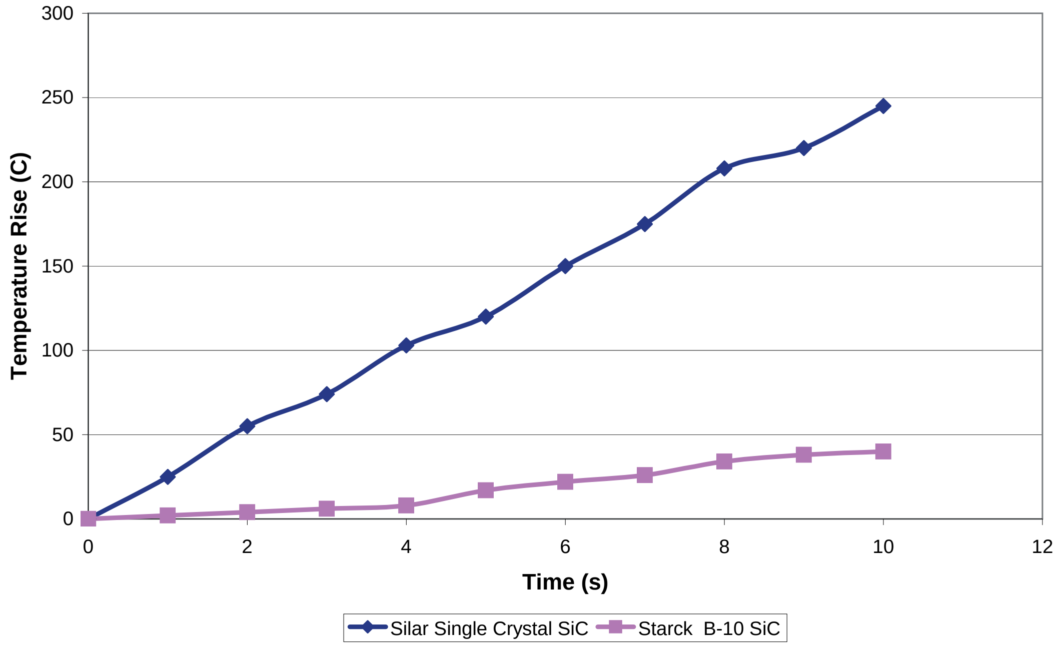

Figure 1. *Time vs. Temperature Rise.*

means go generate heat via high ε tan δ: polar molecular rotation, induction, or capacitance. The polar molecular rotation effect is seen most commonly in water, but there are other polar molecules that can heat in a microwave field as well. We rejected the polar approach, since there materials must exhibit high molecular mobility, and with that, some lower strength and temperature resistance. The induction approach is also less desirable, since that method is not compatible with existing microwave oven designs. The material we designed uses a capacitance approach, which provide rapid heating in a microwave field, in addition to the other essential properties of toughness and durability.

SILAR® MICROWAVE ABSORBENT CERAMICS: KEY PERFORMANCE PARAMTERICS

Heating Rates of Silar® Microwave Absorbent Materials

Many commercial microwave-convection ovens operate in a low heat state at temperatures of 100 ^{o}C to 150 ^{o}C.

A target speed cook temperature for the microwave elements is usually 220 ^{o}C to 250 ^{o}C. Therefore, the microwave rods need to experience at least a 120 ^{o}C temperature rise as quickly as possible to effect speed cooking.

Figure 1 shows the time versus temperature rise of the product. In 6 seconds the product exhibits a 150 ^{o}C rise. The product clearly demonstrates a very rapid rise to cooking temperature in a short time frame. Conversely, other form of silicon carbide, such as Starck grade B10 heat too slowly and never reach operating temperature. This rapid temperature rise is novel and enables microwave-conduction speed cooking on a level that has not been seen before.

Heating Rates Based on Silar® Loading Levels

The Silar® single crystal silicon carbide acts as a microwave receptor in what otherwise would be a blank ceramic that transmits microwave radiation. Therefore the heating rate can be engineered into the materials based on loading levels.
Figure 2 demonstrates two different heating rates based on Silar® loading levels. Note that both of these rates are still exceptionally fast, as these were done in a low wattage field (900 watt). The 15% Silar product went from room temperature to 800 ^{o}C in approximately two minutes. The 7.5% Silar product was at 500 ^{o}C in the same amount of time.

Clearly one benefit of this technology is to be able to tune your heating rate based on the Silar ® loading level, as well as the power for the field itself.

Thermal Shock Resistance and Fatigue

Another problem that has plagued previous technologies is low resistance to thermal shock. Material with low thermal shock resistance also typically exhibit excessively high thermal fatigue caused by cyclic heating and cooling

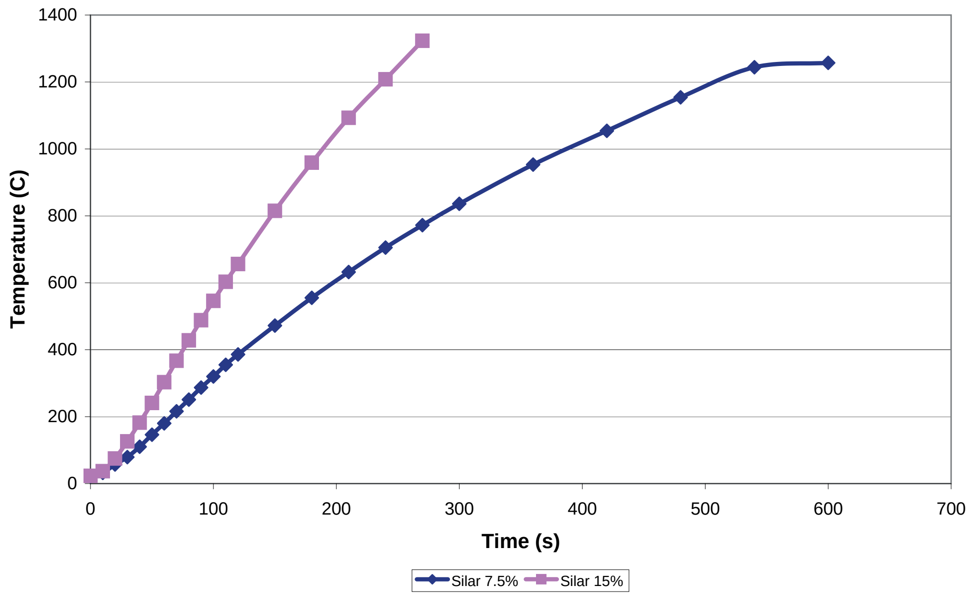

Figure 2. *Heating Rate vs. Silar Loading Level.*

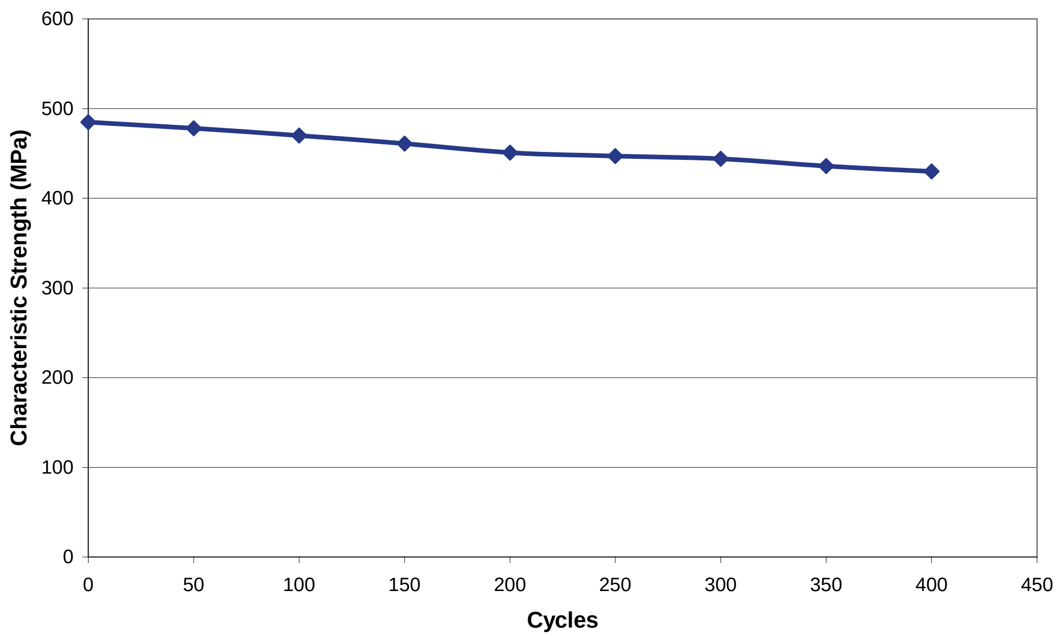

Figure 3. *Cyclic Thermal Shock and Fatigue.*

of the element. The composites developed for microwave heating can withstand a ΔT of close to 500 ^oC.

In addition, we tested for thermal fatigue. The composites developed for microwave heating elements were thermally shocked from 250 ^oC to room temperature. They were then subjected to a four-point bending test to determine the characteristic strength. As can be seen in Figure 3, the characteristic strength does indeed decrease with increasing shock frequencies. However, after 400 thermal shock cycles, the product never cracked and exhibited only a 12% strength loss. After 400 shock cycles, the material exhibited remarkable properties and strength well above that required for performance in the field.

CERAMIC COMPOSITES OF ALUMINA AND SILICON CARBIDE

Understanding Silicon Carbide

Silicon carbide has over 70 known crystalline structures, and over 400 known polytypes. Depending on crystalline structure and dopant, the most common colors of the product can be black, brown, and green. However, forms

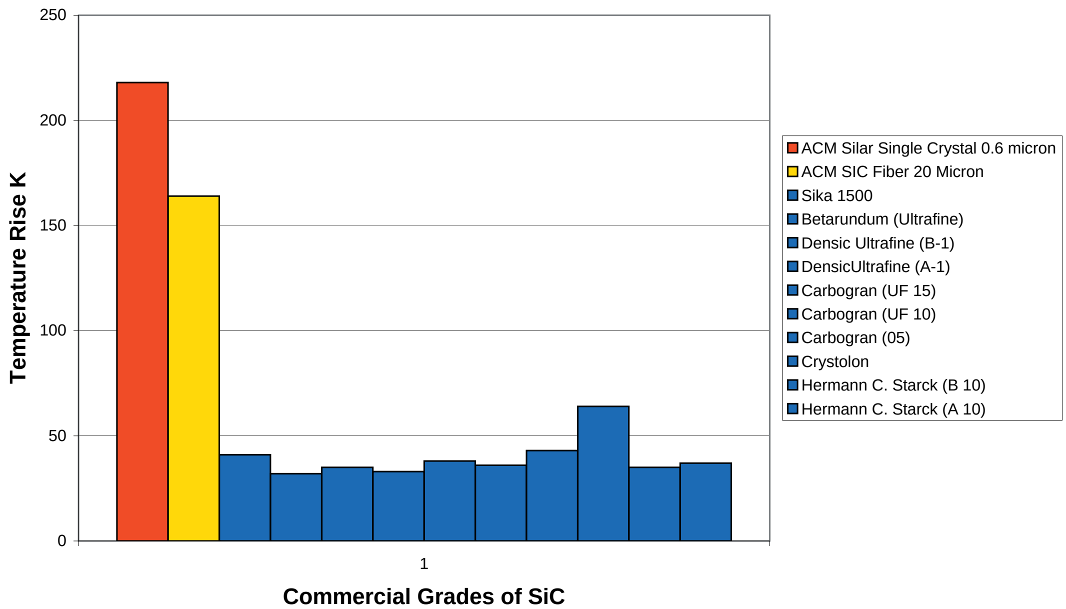

Figure 4. *Temperature Change of SiC in Microwave Field.*

also exist that are yellow, red, and blue.

Pure SiC does exit in nature. But it is only found in trace quantities and is not pure enough to be used commercially. Therefore, virtually all SiC today is made synthetically in high temperature furnaces.

SiC is commonly divided into two major categories: alpha and beta. Alpha is the so-called high temperature SiC and is produced at temperature above 2000 ^{o}C. Beta is typically made at temperatures from 1600 to 1900 ^{o}C. SiC has no real melting point and decomposes at 2860 ^{o}C. Beta SiC is typically found as a face-centered cubic lattice. The alpha version is either hexagonal or rhombohedral. Commercially, the vast majority of SiC produced today is alpha.

All versions of SiC are tough materials with high strength and high modulus. The different types of SiC can have wide ranges of electrical properties. In particular the permittivity, ε, and the dielectric loss tangent, tan δ can have very wide variations depending on crystalline structure and the presence of impurities. However, these properties have not been heavily investigated.

Marshall *et. al.* (1973) lists the following properties for alpha 6H silicon carbide at 300K:

$$\varepsilon = 9.72$$
$$\tan \delta = 0.003$$

And at 1200K, the tan δ is estimated to rise to 0.07 Unfortunately, these properties demonstrate a problem affecting the use of SiC today: at normal cooking temperatures, the loss tangent is still too low to effect rapid heating of an SiC containing ceramic. Typically temperatures about 1200 K are required. Obviously, this temperature is outside of the normal cooking range for foods.

Because there are so many types of SiC with varying dielectric properties, ACM did a review of various type of SiC available today in the marketplace to determine their microwave response. The result is shown in Figure 4. In this example, we mixed various SiC materials at 10% by weight in with alumina, which is a low loss transmitter of MW radiation. As can be seen in this Figure, the ACM derived SiC version exhibit exceptional heating properties. What is confusing here is many of these grades are supposedly the same type of SiC with the same dielectric properties, yet different responses are seen.

ACM Alumina and Silar® Single Crystal Silicon Carbide Composites

ACM custom synthesizes a unique and proprietary version of silicon carbide. One grade we produce is a silicon carbide that consists of single crystal rigid rods that are 0.6-micron diameter by lengths of up to 120 micron. Figure 5 is a Scanning Electron Microscope photo of a grouping of the ACM silicon carbide single crystals. This material and the composites made from them go by the trade name Silar®.

As mentioned, ACM also produces ceramic composites based on the Silar ® single crystal technology. These ceramic composites possess all the critical performance criteria required for a microwave grilling rack, including rapid heating, thermal shock resistance, and durability. Figure 6 is a photograph of

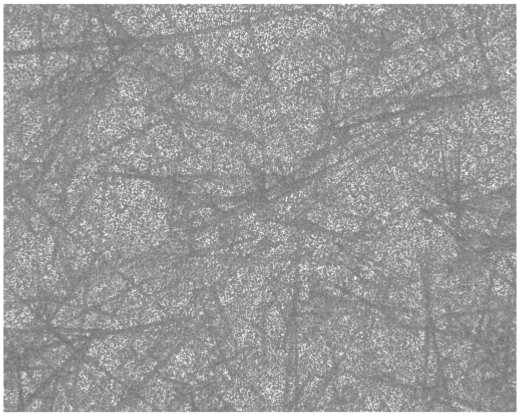

Figure 5. *Scanning Electron Microscope photo of a grouping of the ACM silicon carbide single crystals.*

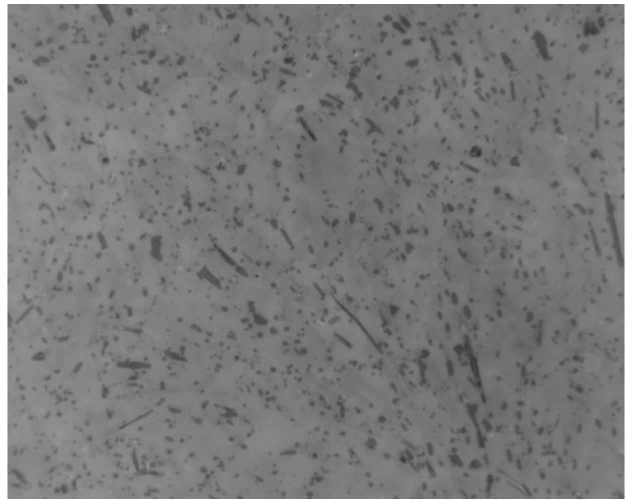

Figure 6*. Morphology of composites.*

Table 1. Properties of Silar® Microwave Ceramics.			
Property	Units	Silar® Ceramic	316 Stainless Steel
Flexural Properties			
Four Point Bend Strength	MPa	485	700
Failure Mode		Brittle Fracture	Yield
Young's Modulus	GPa	385	200 -300
Vickers Hardness	GPa	18.3	1.5 to 2.0
Fracture Toughness	$MPa \cdot m^{1/2}$	4.5	n/a

the morphology of these composites.

As can be seen through the morphology, these products have the morphology of, and behave like, fiber-reinforced composites. Of course, there are well known glass-phenolic resins composites, carbon fiber composites, etc. What is interesting about this product is it is a ceramic-ceramic fiber reinforced composite. Consequently, it is a very tough material.

Properties of this product vis-à-vis 316 stainless steel are shown in Table 1. As you can see the composite are ceramic, so as expected, they do exhibit brittle fracture. Most ceramics have relative low tensile modulus compared to compressive modulus. However, as seen in Table 1, theses composites have an impressive tensile modulus. In addition, they are very hard, and will not dent, but they can chip.

CONCLUSIONS

ACM is able to synthesize so unique versions of SiC that have remarkably high loss tangents. ACM is also able make composite ceramics that are highly microwave absorbent and heatable, and also have all of the mechanical properties required for use in high speed cooking. The materials are physically tough, fracture resistant, and withstand thermal shock. They exhibit rapid temperature rise and will come up to cooking temperatures in a microwave oven in 5-10 seconds.

Our belief is these Silar® based composites will indeed open up a new technology and new methodology for heating and cooking in combination ovens.

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