The Evolution
OF SiC KILN FURNITURE

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Low-mass kiln car superstructures based on recrystallized silicon carbide were first introduced in the mid-1970s. Since then, a number of other silicon carbide manufacturing processes have been developed and are now used to produce a variety of new and innovative kiln furniture components. An understanding of the material options currently available and their respective advantages and applications can allow the kiln furniture user to select intelligently from among them.

Types of Advanced Silicon Carbide Materials

For the purpose of this review, advanced silicon carbide materials will be arbitrarily defined as those that have hot modulus of rupture (MOR) values greater than 100 Mpa (about 15,000 psi). Four major types exist that meet this criterion, and their important characteristics are shown in Table 1 (p. 8). The types are listed in order of increasing MOR. Each type is offered by two or more suppliers, and the property data shown indicate the range of values published by all suppliers. Differences in individual manufacturer formulations and manufacturing processes (as well as differences in measurement techniques) account for the property variations.

Recrystallized silicon carbide (ReSiC) was the first advanced silicon carbide material to be used extensively for kiln furniture. ReSiC components are produced by firing a slip-cast green body formed from a mixture of various sizes of SiC particles at a temperature sufficiently high to cause vaporization of the finest particles. Upon cooling, the SiC vapor condenses and causes the large grains to be joined together (recrystallization). ReSiC is inherently porous and therefore more subject to oxidation. However, recent advances in re-firing, coating and doping processes have improved the performance of ReSiC so that it is still a viable choice in many applications, especially in the temperature range from 1350°C up to its maximum use temperature of 1600°C.

Advanced nitride-bonded silicon carbide (NSiC) is distinguished from conventional nitride-bonded silicon carbide in that the silicon nitride bond structure is formed in-situ in the slip-cast green body by the reactions that occur during the controlled-atmosphere firing process. This results in a MOR for NSiC that is about 50% higher than that of ReSiC. NSiC is also porous, but oxidation can be inhibited by re-firing in air, which forms a silica layer and closes the surface pores. NSiC has the lowest thermal conductivity of the advanced SiC materials, and is therefore more sensitive to thermal shock in fast-firing applications. Its maximum use temperature is 1450°C.

Reaction-sintered, silicon-infiltrated silicon carbide (SiSiC) components are produced by slip-casting or extruding a mixture of silicon carbide, carbonaceous material and other ingredients into the desired shape. The resulting green body

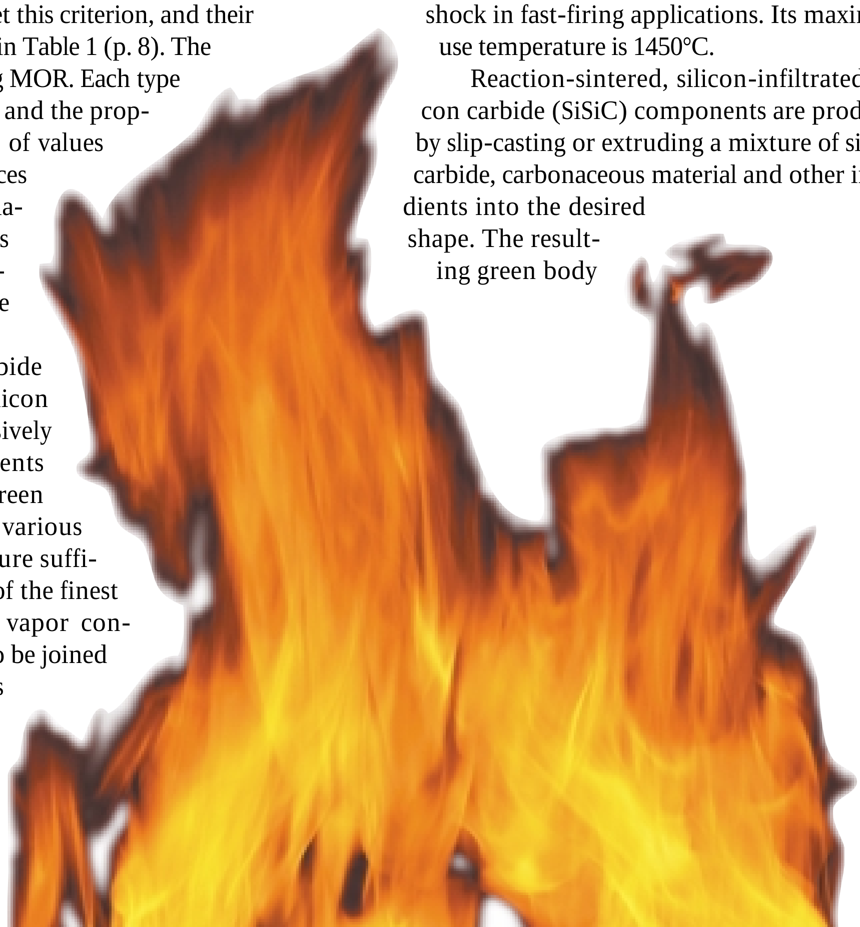

Table 1. Characteristics of advanced silicon carbide kiln furniture materials.

Property	Unit	ReSiC[1]	NSiC[2]	SiSiC[3]	SSiC[4]
Chemical Analysis:	%				
SiC		>99	65-70	81-92	>99
Si (free)				8-19	
Si_3N_4/other			35-30		
Max. Use Temperature	°C	1600	1450	1350	1750
Density	g/cc	2.4-2.8	2.8-2.9	3.0-3.1	3.1
Open Porosity	%	15-18	<1[6]	<0.1	<0.1
Modulus of Rupture (Hot)	MPa	100-130	180-200	260-280	370-420
Modulus of Elasticity (RT)	GPa	210-230	220-235	330-370	350-420
Thermal Conductivity[5]	W/m°K	21-26	12-18	24-40	30-33
Coeff. of Thermal Expansion	$°C^{-1}$	$4.5\text{-}4.9 \times 10^{-6}$	$4.3\text{-}4.6 \times 10^{-6}$	$4.3\text{-}4.9 \times 10^{-6}$	$4.0\text{-}5.0 \times 10^{-6}$

1 Recrystallized silicon carbide
2 Advanced nitride-bonded silicon carbide
3 Reaction-sintered, silicon-infiltrated silicon carbide
4 Pressureless-sintered alpha silicon carbide
5 At 1000-1200°C
6 When re-fired

is then fired in the presence of a high concentration of silicon metal. As the silicon diffuses through the body, it reacts with the carbonaceous material to form additional silicon carbide, sintering the silicon carbide structure and increasing the density. The remaining open porosity is then filled with the excess silicon. SiSiC has a MOR approximately 40% higher than NSiC and twice that of ReSiC. Its high strength and oxidation resistance make SiSiC the material of choice for most applications where the maximum temperature is below its 1350°C use limit.

Sintered-alpha silicon carbide (SSiC) components are manufactured by pressureless-sintering a shape produced by slip casting, extruding, or pressing submicron alpha-silicon carbide powder. SSiC has the highest MOR, best oxidation resistance and highest use temperature (1750°C) of the four materials under discussion. SSiC is also the most expensive of the four materials and is generally economically viable only as an alternative to ReSiC at temperatures above the 1450°C use limit of NSiC.

Producers of Advanced Silicon Carbide Kiln Furniture

ReSiC was the predominant type of advanced silicon carbide for many years, so "recrystallized silicon carbide" has become something of a generic term for all types of advanced silicon carbide. As discussed above, there are major differences in the characteristics of the four types of materials, and it is very important to be aware of these differences when specifying kiln furniture and evaluating kiln furniture alternatives. This situation has been made more confusing by the proliferation of manufacturers' trade names for the various materials, and further complicated by changes in some of those trade names and elimination of others as a result of mergers and acquisitions.

To facilitate direct comparisons, the major suppliers of kiln furniture from advanced silicon carbide materials are listed alphabetically in Table 2 (p. 10), along with their trade names for the various types of advanced SiC materials. Absence of a trade name indicates a supplier does not produce a particular quality. When more than one trade name is listed for a specific supplier in a given category, this usually indicates the supplier distinguishes between slip cast and extruded grades or has slightly different formulations for different applications. In these cases, the kiln furniture user should contact the supplier for a specific recommendation.

KILN FURNITURE COATINGS

Advanced silicon carbide isn't the only type of kiln furniture that has changed over the past decade. In many ceramic firing applications, traditional heavy zirconia kiln furniture has been replaced with lightweight alumina bodies with zirconia coatings.

"Zirconia coatings can be applied to really thin alumina cards—anywhere between 25 and 60 thousandths of an inch thick—to achieve a durable, high-performance, low cross-section setter. These pieces are less than a fourth of the cross-section of traditional kiln furniture," said Tucker Herbold, director of engineering for Aerospace Coating Systems, Inc., in Berlin, Conn. "The increased kiln space provided by this low cross-section allows more layers of ware to be fired per kiln. Additionally, an interlocking rail on the side of the setter allows ware to be stacked with one hand—the setter won't tip over or fall apart like some of the old setters."

Lighter weight, faster ramp-ups and a cleaner surface are other benefits afforded by the zirconia-clad furniture.

Table 2. Major supplier trade names for advanced silicon carbide kiln furniture materials.

Supplier (country of origin)	ReSiC[1]	NSiC[2]	SiSiC[3]	SSiC[4]
Ferro Corporation (USA)	RX21®			
W. Haldenwanger (Germany)	Halsic-R®, RX®		Halsic-I®	Halsic-S®
Saint-Gobain Ceramics and Plastics (USA, Germany)	Crystar®	Advancer®	SILIT SK®,SKD®	Hexoloy®
Schunk Ingenieurkeramik (Germany)		CarSIK-NG®	CarSIK-Z®,G®	
Shenango Refractories (USA)	RSC®			

1 Recrystallized silicon carbide
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Editor's note: This is not a complete list. Some advanced SiC suppliers were unavailable for comment at the time this article was written. For a more complete listing of SiC kiln furniture suppliers, consult *Ceramic Industry's Data Book & Buyers' Guide* in print or online at www.ceramicindustry.com.

Table 3. Suggested applications of advanced silicon carbide kiln furniture materials.

Application	ReSiC[1]	NSiC[2]	SiSiC[3] (extruded)	SiSiC[3] (cast)	SSiC[4]
Support Beams	Y	Y	Y	Y	Y
Posts	Y	Y	Y	Y	
Rollers and Tubes	Y		Y		Y
Batts and Setting Disks/Rings	Y	Y			

1 Recrystallized silicon carbide
2 Nitride-bonded silicon carbide
3 Reaction-sintered, silicon-infiltrated silicon carbide
4 Pressureless-sintered alpha silicon carbide

Applications

Each of the four types of material has a rather broad theoretical range of application. However, based on experience, it is possible to suggest which materials provide the best performance and most favorable life-cycle cost for specific applications. Preferred materials for a number of kiln components are listed in Table 3 (p. 10). Where more than one quality is listed, it is understood that the final selection is made based on the specifics of the application—for example, the maximum temperature and the aggressiveness of the firing cycle. Some of these considerations are illustrated in the following examples:

Fast Firing of Dinnerware in a Tunnel Kiln at 1400°C

A car structure for the fast firing of dinnerware in a tunnel kiln is shown in Figure 1 (p. 11). A framework of NSiC posts and beams supports large ReSiC batts upon which hollowware pieces are set. Stacked dual flatware setters from ReSiC and NSiC maximize use of kiln volume while minimizing mass. All setting surfaces are coated to minimize sticking of the ware.

Fast Firing of Dinnerware in a Roller Hearth Kiln at 1400°C

The entrance area of a fast fire roller hearth kiln for dinnerware is shown in Figure 2 (p. 11). The rollers are SiSiC except for the hottest zone of the kiln, where ReSiC rollers are required. The ware is transported through the kiln on ReSiC batts, and ReSiC batts are also used for the second deck when needed. Again, all batt surfaces in contact with the ware are coated.

First Firing and Re-firing of Sanitaryware in a Shuttle Kiln at 1220-1250°C

In a triple-deck car for sanitaryware, SiSiC beams support coated NSiC batts upon which the ware is set. The overall result is a very lightweight car with the flexibility to efficiently fire a wide range of product mixes.

Automated Ware Handling Systems

An important consideration in the design of kilns today is the need for the kiln furniture to be compatible with automated ware loading/unloading (robotic) equipment. This leads to several specific kiln furniture design requirements, since the motion of the robot is based on the ware being in a certain location:

- The structure must be fundamentally stable and not shift with respect to the car base due to car motion.
- Structural components must be positively located with respect to one another.

Figure 1. Fast firing tunnel kiln with SiC plate setters and batts. Photo courtesy of Saint-Gobain Ceramics and Plastics.

Figure 2. Roller hearth kiln with SiC beams and batts. Photo courtesy of Saint-Gobain Ceramics and Plastics.

- The structure must not deflect significantly under load.
- The structure must remain dimensionally-stable over many firing cycles, with minimal deflection/distortion due to creep/oxidation.
- Components, such as setters or stacks of setters, which are placed and removed by the robot must not stick to their supporting static members.

The stability requirements are being met using sophisticated multi-level structures comprising SiSiC posts and beams or NSiC posts and beams, depending on the temperatures involved. The individual components are located by machined or cast interlocking features. Coated setters made from NSiC and ReSiC/doped ReSiC are being used successfully in some applications, but sticking remains a challenge.

Intelligent Evaluation

Kiln furniture producers have responded to the requirements of the marketplace with a number of new and innovative advanced silicon carbide materials and systems. The challenge to the kiln furniture user is to have sufficient understanding of the choices to be able to compare proposed kiln furniture solutions and intelligently evaluate their suitability for the application.

About the Author

Mac McGinnis is a registered professional engineer with a Ph.D. in mechanical engineering and more than 35 years of experience with kilns, industrial furnaces and thermal processes. He formed Supratec in 1983 and serves as a technical consultant to kiln and industrial furnace builders and end users. In addition, he assists manufacturers of kiln and furnace components in the application of their products. McGinnis can be reached at (214) 890-1341, fax (214) 890-1391, or e-mail supratec@sbcglobal.net.