The Heat Is On

➤ **Many options are available for improving the performance of high-temperature kiln furniture systems.** *by Doug Thurman, President, Sunrock Ceramics Co., Broadview, Ill.*

Manufacturers of advanced ceramics are undoubtedly aware of the important role that kiln furniture plays in the quality and economics of the finished product. As we sit here today, with an economic downturn staring us in the face, it is an opportune time to revisit the key issues and trade-offs inherent in optimizing kiln furniture design for the very demanding temperature and/or chemical applications of the advanced ceramics industry.

Many important considerations should be taken into account with respect to high-temperature kiln furniture. (By "kiln furniture," we are of course referring to the support structures used to hold ware through the firing cycle.) For the demanding cycles of the advanced ceramics industry, the two most fundamental requirements are that: a) the kiln furniture arrangement physically survives the firing cycle, preferably more than just once; and b) after surviving the cycle, the kiln furniture does not ruin the finished product being fired, whether from cross-contamination, loss of flatness, or, in some cases, surface finish issues.

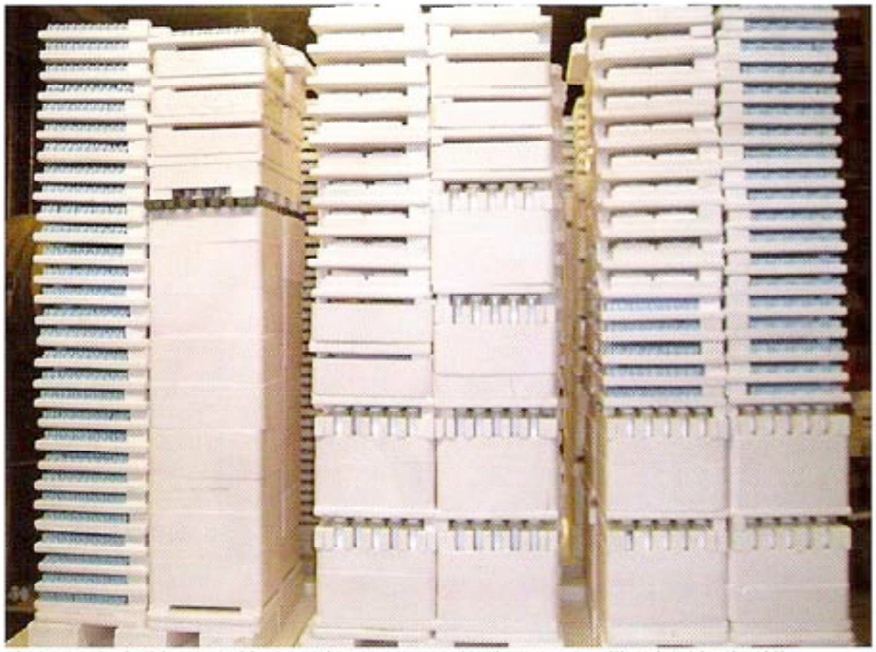
Alumina kiln furniture can be made in a wide assortment of shapes tailored to specific applications.

After these fundamentals are achieved, we can begin thinking about ways to maximize life, minimize energy usage and lower operating costs through a better understanding of the trade-offs inherent in the design of high-temperature kiln furniture systems.

Material Development Background

We are fortunate to have an abundant, relatively low-cost material that is a great starting point for a very functional high-temperature kiln furniture material—alumina, or aluminum oxide (Al_2O_3). This very prevalent and versatile oxide ceramic, so well known to the advanced ceramics industry as a ware material, also has nearly all of the attributes needed for an outstanding high-temperature kiln furniture material. Alumina has many properties that make it valuable in a host of applications, but for kiln furniture its most important properties include its high thermal refractoriness, very strong compression strength and good resistance to chemical attack by a wide range of chemicals, even at elevated temperatures.

In its pure form, however, alumina does not have the thermal shock resistance



Plates stacked with spacer blocks and open rectangular rings can provide a long-lasting kiln loading system.

necessary for use as a long-lasting kiln furniture material. In other words, rapid changes in temperature tend to produce breakage of kiln furniture made with pure alumina. This weakness (literally and figuratively) is even more of a problem today as kiln cycles have gotten faster, hotter and more chemically severe with the onward march toward better, faster and cheaper advanced ceramics.

The thermal shock problem was overcome in the 1950s when an economical means of increasing the performance of alumina kiln furniture was developed by the spark plug operations of the Detroit automotive industry. As it turns out, the introduction of bonded silica in the form of mullite ($Al_2O_3SiO_2$), added via the inclusion of fused grains of mullite and the creation of a mullite ceramic matrix, provides a very good "shock absorber" system. The lower thermal expansion of the mullite in relation to the alumina provides this thermal shock improvement without meaningful deterioration of the desired properties of the alumina. The propagation of cracks that may develop during thermal cycling is then minimized by existing micro-cracks at the interface of the dissimilar materials, which create a "firewall" where minute stress cracks are interrupted and the stress relieved.

During the process of initially sintering the kiln furniture, it is important that the mullite matrix be created such that the occurrence of silica not captured in the strong mullite bonds is minimized. Otherwise, this "free" silica will create a glassy phase that greatly weakens the high-temperature strength of the material. The free silica can also impair some beneficial chemical inertness properties, particularly when used in hydrogen atmospheres at elevated temperatures where the free silica can reduce and subsequently re-oxidize.

The composition of this alumina/mullite formulation was patented for use in the production of high-alumina spark plug insulators and subsequently licensed to certain producers of alumina ceramics for the production of a broader range of high-temperature kiln furniture. After the patent expired, nearly all domestic manufacturers used a variation of this composition to produce high-alumina kiln furniture where thermal shock performance is a necessary feature.

Forming Techniques

For many years after the development of the alumina/mullite formulation, kiln furniture was formed exclusively by a casting process. To produce shapes with this technique, the primary raw materials are combined with clays, plus a deflocculent and water that cause the mixture to be thixotropic (to flow under vibration). This allows the water content to be relatively low (in comparison to slurry casting) and consequently minimizes the separation of the material during forming.

The material then resides in a plaster mold for a period of time, allowing a portion of the water to be absorbed by the plaster. After removal from the molds, the remaining water in the green part is removed in a dryer and the part is then fired to a minimum of 2850°F to sinter the material and create the new mullite in the ceramic matrix.

Since clay is a source of impurity and variability, work has been done in recent years to substitute binders and reduce or eliminate the clay content in cast production, with limited success. Nonetheless, most producers of cast alumina kiln furniture still continue to use clay because it provides good drying uniformity and increases densification during sintering, properties that are difficult to replicate with other additives.

Another problem with cast products is the occurrence of one rough surface that arises where the mold is open for the pour. In certain applications, such as saggers (open-top ceramic boxes) in roller-hearth kilns or pusher plates in pusher furnaces, a rough surface can prove very problematic and lead to pileups inside the kiln—a real productivity killer. Finally, bubbles often occur in cast parts, which can then be exposed during lapping or grinding of the parts. Exposed voids are a problem for many firing applications.

To address these issues, and also improve the economics of larger production runs, variations of the formulation were developed that allow pressing certain shapes as opposed to casting them. To meet the needs of the demanding advanced ceramics industry, improvements in pressing techniques and equipment were introduced that greatly reduce air entrapment in the ceramic body, improve the surface qualities of the parts and provide for the removal of clay.

In addition, recent press and tooling developments have allowed for the pressing of more complicated shapes that previously would have required casting. With all of this press development, however, a number of more complicated kiln furniture shapes still cannot be effectively pressed and must be cast.

Maximizing Life

When designing high-temperature kiln furniture systems, a natural tension exists between the ongoing effort to minimize the mass of the kiln furniture for energy efficiency and the ensuing impact on the life of the kiln furniture. It's a bit of an oversimplification, but in general, the "beefier" the kiln furniture, the longer it will last. However, given the high—and continuously rising—energy prices we all face, finding ways to further reduce mass while preserving, or even enhancing, the life of kiln furniture is of utmost importance in the advanced ceramics industry.

The eventual failure of alumina kiln furniture in high-temperature applications is typically due either to thermal shock cracks (from the fatigue of thermal cycling under mechanical load) or excessive loss of shape of the kiln furniture. Also, in some firing applications in atmosphere, such as hydrogen, failure can also occur due to chemistry changes over time. Since the latter chemistry issue is very application-dependent, we will focus this discussion on minimizing cracking or warping of the alumina kiln furniture that results from thermal and mechanical stresses.

Thermal shock susceptibility is primarily a function of 1) the geometry of the part (the simpler the shape and smaller the size, the better the thermal shock resistance), 2) thermal conductivity (the better the heat conduction, the better the thermal shock resistance), 3) thermal expansion (the lower the thermal expansion, the better the thermal shock resistance) and 4) fracture toughness (the higher the fracture toughness, the better the thermal shock resistance). The last three issues are material-dependent and are therefore affected by the ceramic's density, composition and grain structure.

Geometry

Geometry is a primary issue in kiln furniture system design because of both the functional impact on firing economics (i.e., ideal geometries should reduce kiln mass but also maximize kiln loading) and the major role of geometry on thermal shock and warpage. In our discussion of geometry, a "simpler" shape relates to a minimum of sharp edges and directional changes, such as corners and bends, which create stress risers that hasten the occurrence of thermal shock cracks. Sharp corners and bends also increase the likelihood of density variances within the ceramic created during the forming process, further exacerbating the adverse impact of shape complexity. With respect to warpage, creep at high temperature increases exponentially as the thickness of the span is reduced.

To highlight issues related to shape trade-offs, consider the simplest kiln furniture shape: the circular disc. Because of its minimal stress risers and resultant long life, many advanced ceramics manufacturers have historically used circular discs as a common firing surface for ware, with discs stacked many levels high separated by corresponding rings. However, with today's very high energy costs, many manufacturers have moved away from circular discs because of the inefficient kiln loading that results from all the "dead space" on the kiln car. Converting to rectangular loading systems has thus increased the loading of ware but shortened the life of the kiln furniture, though this is a trade-off that makes economic sense to many nowadays.

As stated, simpler shapes provide better resistance to thermal shock cracking. For instance, plates stacked with spacers run longer without thermal shock cracks than stacked saggers. Besides fewer stress risers, plates also heat up more uniformly than saggers. Stacks of plates also run longer without warpage because plates can be flipped between firings, whereas saggers are always exposed to creep in the same direction. The possible downsides of a plate-based system can include slightly longer kiln car loading times and less stable stacks if there is not good dimensional uniformity of the kiln furniture or the car deck is uneven.

Smaller sizes of a given shape survive kiln cycles better than larger sizes, all else being equal, because the heat transfer gradient across the smaller piece is lower. An additional benefit of going smaller when possible is that shorter spans allow for an exponentially thinner cross-sectional area to achieve the same creep resistance. As previously mentioned, a slight change in thickness can often provide a meaningful change in creep resistance. This creates another benefit of pressed kiln furniture in comparison to casting because, with pressing, it is easy to adjust thickness during the forming process, while casting requires a new mold. With pressed parts, it is therefore easier and more economical to collaborate with a supplier on experimentation.

Density

For the majority of advanced ceramics firing cycles, a high-alumina formulation of between 80 to 90% alumina (with the balance being mullite as discussed, as well as trace impurities that are minimized as much as possible) provides the best blend of thermal shock performance with the desirable alumina properties of thermal refractoriness, mechanical strength and chemical inertness. For optimal performance, the kiln furniture material should be produced with a density of between 170 to 180 lb/ft^3, which translates to a porosity level of 15 to 20%.

Lowering the density, while attractive for reducing the mass of the load, greatly reduces the hot strength and room temperature strength of the material. A substantial drop-off in strength occurs when densities get below about 165 lb/ft^3. Increasing the density above this range needlessly adds weight while adversely impacting the thermal shock resistance.

Composition

Most manufacturers of high-alumina kiln furniture offer various alumina contents, generally in the range of 85 to 92% of the total chemistry. The main trade-off is that as the alumina content is increased, thermal shock performance (and therefore kiln furniture life) is sacrificed, but hot strength and creep resistance might be improved. Instead of increasing alumina content, manufacturers should evaluate whether it could be better to slightly increase the thickness, add a center support or shorten an unsupported span. Shortening spans could also provide other longevity benefits related to thermal shock. Experimentation is necessary to achieve the most beneficial balance for a given application.

Grain Structure

Alumina kiln furniture made with a coarser grain structure tends to have better thermal shock performance because of its higher fracture toughness, but it will generally have a rougher surface finish and may exhibit more creep. In addition, with pressed kiln furniture, thinner shapes require finer grain structures because of the particle packing dynamics involved. With that said, pressing allows for the production of thinner shapes than does thixotropic casting because of the difficulty of holding flatness when casting thin shapes.

Experiment for Best Results

Every application is different and requires a unique solution. In the advanced ceramics industry, where firing curves are very hot and manufacturers face constant pressure to maximize kiln loads while simultaneously reducing energy consumption, kiln furniture design is a key part of the equation. Yet many operators continue to load with the same systems that have been used for years, letting inertia reign. Changes are made only at the margin.

In today's business environment, it is worth the time and effort to experiment to see if there might be a better approach. High-alumina kiln furniture products often look similar on a data sheet, but with the many variables in the selection of raw materials, grain sizing and processing methods, wide variances exist in performance for specific applications. Beyond the material, the geometry and layout are critical.

The key is finding a supplier that will work to tailor its kiln furniture to the process instead of asking the manufacturer to tailor the process to the kiln furniture. Experimentation specific to the firing cycle and loading goals, on all of these fronts, will surely pay off in the long run.

For additional information regarding high-alumina kiln furniture design considerations, contact Sunrock Ceramics Co., 2625 S. 21st Ave., Broadview, IL 60155; (708) 344-7600; fax (708) 344-7636; e-mail dthurman@sunrockceramics.com; or visit www.sunrockceramics.com.