

Fully automated high-pressure injection molding of complete ceramic parts.

Credit: Ceramco

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Near net shaping of ceramic components— ‘Plant tour’ of a custom manufacturer

By Thomas O. Henriksen

Automated near net shaping of custom ceramic parts saves time, material, and energy.

Contract manufacturers of customized ceramic parts face tangible challenges. In the spirit of continuous improvement, those of us in mature markets always are looking for ways to reduce delivery lead times and cost. Machining post-fired, high-hardness materials is costly and chews away at already squeezed delivery lead times. The impact of energy cost always is a consideration. For example, pressing ceramic powder into a bulk shape and then machining it down to final form consumes energy. Machined-away material that ends up in the dust collector represents a loss of the material and the energy it took to make it—from raw material through firing. Thus, there are practical and economic drivers for shaping ceramic components as close to final form as possible and minimizing the postfired operations.

Capsule summary

ECONOMIC DRIVERS

Manufacturing ceramic components consumes material and energy and creates an economic driver for improving efficiency. Near net shaping forms parts as close to final dimensions as possible and minimizes post-firing processes.

APPROACH

Ceramic injection molding allows for near net shaping of almost any ceramic formulation across a wide range of complex geometries. Automation improves manufacturing efficiency.

KEY POINT

Successful near net shaping of ceramic components by ceramic injection molding starts with careful formulation of ceramic powders and binders, as well as design and crafting of customized tooling. Diamond grinding achieves final dimensions in the critical areas of parts with tight dimensional tolerance specifications.

Growing importance of technology

Near net shaping (NNS) is an established process. Early approaches to NNS date back to iron casting in the 1620s followed by steels after 1850 and light alloys in the 1940s. Plastic injection molding was developed in the 1920s, and the first plastic parts were produced in the 1930s after the invention of polyethylene in 1933. Besides metals and polymers, engineering materials such as Portland cement, refractories, cermets, and fused silica were being formed to near net shape during the 1930s. Combining injection molding with powder metallurgy led to powder injection molding (PIM). Delco first used injection molding to form ceramic spark plug insulators in the 1940s after securing a patent on the process in 1938.

The same manufacturing evolution experienced by the metals and plastics industries in the 20th century is now transforming ceramic component manufacture. Ceramic parts can be manufactured by many techniques. Pressing, casting and extruding likely always will have a place in the NNS of ceramic components, especially for simple geometries, such as plate and rod stock. These are considered to be the core, traditional ceramic manufacturing technologies. Pressing, from a NNS viewpoint, means the die or tooling allows for complete forming of the entire shape. Adding binders to starting powder gives green, pressed compacts enough structural integrity to be handled. However, press-forming NNS components that include holes, slots, interior diameters, and outside diameters—while not impossible—is extremely difficult. Therefore, as part geometry becomes more complex, molding and casting become process considerations.

Although variants of earlier pressing and extrusion NNS techniques (especially isostatic pressing) will continue, complex ceramic shapes will require efficiencies achievable with casting or ceramic injection molding (CIM) methods. Slower than pressing, NNS by casting lends itself to making complex shapes, especially components that are large or have thick walls. Casting involves pouring or injecting liquid slurry into a mold. After solidification, the shape is removed and fired. Variations of this process include gelcasting, freeze casting, 3D casting, and slip casting. Low-pressure injection molding can be considered casting too, making shapes in fictile materials with virtually no pressure forces. In higher quantities, cost effectiveness diminishes when economies of scale are factored into the equation, such as labor and time it takes to make product.

Similar to pressing, CIM begins with ceramic powder. The material is injected into a die or tool cavity with pressure and heat to melt the binder and fuse the material together. The starting shape has gross dimensions larger than specifications to compensate for shrinkage during firing and densification. After firing, the ceramic component is fully densified and at its final size (net dimensions). The result is a near-net-shaped component. Achieving “near-net” dimensions requires process control and precision. As the term implies, although there is a target dimension, the objective is to be as “near” to target as possible after firing and within acceptable tolerances. The intended application and design parameters of the component often dictate just how closely it is possible to achieve near net shape.

Living in an era of energy awareness, however, focuses bright new light on its promise for contract manufacturers of custom ceramic components. Ceramic powders require energy to mine and prepare for industrial processing, so why waste any during the forming step? NNS can provide an efficient means to produce shapes with the least amount of energy and material waste, in a shorter amount of time.

Most often, economics determine which NNS process is best for manufacturing a particular ceramic component. Factors to consider include time (manufacturing speed), materials, and tolerances. At present, pressed parts own the lion’s share of the market. A well-run press is fast and efficient, and it can press parts of high-quality ceramic powders (alumina, zirconia, silicon carbide, etc.). However, pressing is limited to manufacturing components with simpler geometries.

Powder metallurgy processes are finely tuned and can achieve very near net shapes. In particular, PIM parts made with powder blends, such as tungsten carbide with cobalt binder, are very near specified net shape. Similarly, CIM under tightly controlled process conditions, dialed-in tooling, perfected binder-powder system, etc., performs just as accurately.

Even with such dimensional accuracy now achievable via CIM and NNS, the ceramic component industry tends to offer a wider tolerance window, by a few standard deviations. Typically, as-fired tolerances for ceramic parts are quoted to be $\pm 1\%$. As technology and experience improves, tolerances likely will become tighter.

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Figure 1. Tooling for ceramic injection molding must be custom built for each part design and material combination.

Onto the factory floor

To demonstrate NNS of ceramics, join us on a tour of our NNS operation at Ceramco (Center Conway, N.H.; see sidebar, p. 31). Ceramco manufactures custom ceramic parts for aerospace, scientific instrumentation, energy, medical, and wire/cable industries. On this brief “plant tour,” we will focus on the plant’s CIM facilities and explain the many considerations that must be appraised in a custom manufacturing business.

Raw materials

Ceramic powders, such as alumina, zirconia, mullite, silica, magnesia, yttria, and special blends, generally are stored in a ready-to-mix state, although some minor powder processing such as sifting and jar milling, is done before batching. The customer, as original designer (OEM) or user of the part, typically

specifies material requirements, such as alumina purity level, for which there are standard formulations. Additionally, unique formulations and customer-supplied powders contribute to the product mix. All raw materials are mixed in batches and standard compositions, such as high-alumina formulations, to make a wide variety of parts.

Depending on the type of powder and binder (which carries the powders), we select one of four industrial mixer machines to make feedstocks. Coarse-grained powders incorporate into binder differently from fine-grained powders. Various binder types have a range of melting temperatures and shear sensitivities, and, therefore, the machine used depends on the feedstock formulation. The process is much like something done in a kitchen, with a recipe for combining critical amounts of ingredients. Powder selection and the ability to control additives provides versatility and enhances process control. Therefore, this is a major advantage over depending on outside sources to process powder and make feedstocks. Almost any ceramic powder can be made into a feedstock—oxides, carbides, nitrides, and borides.

Compounding of ceramic powders is integral to making ceramics. It requires an “industrial kitchen” of mixers and mills, a “recipe book” on powder technology, and years of experience to learn to do it correctly. Ceramco belongs to The Association of American Ceramic Component Manufacturers (AACCM, see sidebar, p.29), a trade association for powders-to-parts manufacturers. Processing from a powder is a requirement for membership in AACCM, which currently comprises

18 like-minded member companies, all experts in their own NNS methods and formulations. Processing parts from powders is more profitable for companies and demands disciplined adherence to ceramic science principles, which is an advantage to customers. Every successful ceramic NNS technology depends on it.

CIM tooling

During the quotation process for new parts, the ceramic material and the plan for tooling (which is made in-house) are determined (Figure 1). The product life, quantity needed, and quality details factor into the plan. Net-shaping molds are made of aluminum, tool steel, and/or carbide by our expert moldmaker. In rare and very special circumstances hard rubber also is a candidate material for the molds.

Customers provide, at the minimum, a 2-D drawing to design tooling for a part of simple geometry. As geometries become more complex, a 3-D model file is preferred. The 3-D files can be fed directly into computer numerical control (CNC) machine centers to make the most accurate mold shape.

In addition to simplifying toolmaking, 3-D files often illustrate the part in its assembly. This visual communication of the part’s requirements is absolutely critical for production planning, especially the tooling design stage. Engineers review parting lines, gate locations, draft angles, and ejector pin locations that are necessary for the mold to work and compare against the design to avoid interference with fit or function.

The ability to produce tooling is advantageous. New tooling, despite our experience, sometimes requires

Circuit coverlid - Alumina



Bobbin for aerospace



Detector component for homeland security



Heater core



Octahedron high pressure synthesis chemistry



adjustments. (In ceramics manufacturing, Murphy's Law always applies!) Whether those adjustments are minor or major, the ability to make and maintain molds in-house is more economical and timely and enables tighter control of dimensions. Tooling wears and loses accuracy as it is cycled and, because customers pay for their custom-made molds, the in-house tooling capability is a valuable asset.

Molds made of aluminum last for 10,000 cycles and cost less. Therefore, new low-volume and new prototype parts often are made first from unit cavity aluminum tooling. Multiple cavities to NNS mean more parts in the same tooling set can be added later when usage volumes increase or to decrease cycle times. Value in tooling made with New Hampshire frugality of "don't make it any more than it needs to be" benefits the customer and defeats the prejudice that injection-molding tooling has to be expensive.

In general, CIM parts are small and should be designed with uniform wall thicknesses (although we can stretch the rules and make large parts or design combinations of thick and thin walls). In addition, process limitations exist. Part features, such as undercuts and negative draft, can be very challenging for toolmaking, because the net-shaped ceramic must be removable from the mold cavity. Special techniques, such as green or postfire machining, or employing collapsible cores in the mold, can get around these limitations, but these add expense. A mature product with such added complexities can tolerate the additional investment and the associated lead time, although adapting designs to be CIM friendly is the best policy.

When the order is complete what happens to the tooling? In most cases, the customer pays for it separately and, therefore, owns it. However, tooling is engineered for use with our technology and generally is not transferrable to other manufacturers.

NNS by molding

What happens after preparing feedstock and building tooling depends on the product. Each injection-molding pro-

cess uses equipment requiring feedstock and tooling specifically designed for it. In general, the feedstock is added to the injection-molding machine, which in turn injects it into the molding tooling where the part is near-net shaped.

The geometry of the finished component and the quantity ordered by the customer most often determine the manufacturing process to achieve the NNS. Short production runs of up to 10,000 pieces, for example, generally are made by low-pressure injection molding (LPIM). Longer production runs of 50,000 pieces or more generally employ high-pressure injection molding (HPIM). Orders of very small quantities may be manufactured using hand or stack molds.

Larger, complex HPIM orders often require automated tooling, having pins, slides and cores moving in an intricate sequence to produce one NNS component at a time. Less complex HPIM shapes often can be made in multiples by injecting feedstock in many cavities at once, reducing production time. Other factors that the manufacturer must consider when choosing the process to use include the material, dimensional precision and other quality specifications, including product life cycle and part design.

Secrecy

Manufacturers have an innate propensity to be secretive. In the case of ceramists, secrecy may trace back to the 1600s when Europeans formulated their own version of highly sought Ming Dynasty hard porcelain and processed their fine pottery under a cloak of secrecy.

Like Medieval ceramic manufacturers, much of the "trick of the trade" in ceramic manufacturing today remains undisclosed. CIM components are chemically and thermally processed to arrive at a fully fired ceramic component. In Ceramco's experience, the degree of progress made in ceramic manufacturing technology is a function of how quickly we embrace new world machinery and techniques (replacing the old) to meet the demands for 21st century ceramic materials. However, we still have our secrets!



Figure 2. Circle gates are used for cylindrical parts and break off when the parts eject from this six-cavity CIM tool. All runners and sprues are reclaimed and molded into parts.

Firing

Production staff load green parts into high-temperature kilns and fire in batches. Our facility has electric kilns, with open-air and nitrogen-purged chambers, routinely heated to 1,700°C. Some parts are pre-fired or bisque-fired



The Association of American Ceramic Component Manufacturers (AACCM) is a trade organization for manufacturers of technical or advanced ceramic products for heat, corrosion, wear, electrical, and electronic applications. Membership is open to U.S.-based companies that form finished or semifinished ceramic parts from raw powders. Its mission is "to advance the capabilities of the members and the quality of their products, so that they may satisfy the emerging needs of American industry. This will be accomplished by addressing concerns relative to market requirement, raw material supply, and fabrication."

The Association of American Ceramic Component Manufacturers currently comprises 18 member companies. For more about AACCM, visit aaccm.org.

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Figure 3. Cooled-down kiln car loaded with fired fuse insulators formed by CIM.



Figure 4. Magnified visual inspection of final parts to detect flaws inside holes and other hidden areas.

by ramping slowly and not reaching the sintering temperature, getting them to a “brown” stage, where they remain soft for easy removal of tooling marks, mold flash, and parting lines. Figure 3 shows a kiln car loaded with fired fuse insulators. These parts are large, about 8 inches long by 1.5 inches tall.

Every material has its own firing schedule, and every part has specific firing requirements. Special setters support odd-shaped parts during firing. To keep net shapes shrinking uniformly, the kiln needs to heat uniformly from all the heating elements and dissipate heat evenly. Also, the particle size of the starting powders needs to be right. Materials with special additives need to be separated from other materials to avoid cross-contamination or unwanted chemical reactions. Thus, the firing team carefully selects appropriate furnace plates and even heating element types. Ceramco has 25 independent kilns, which enables us to process all orders at any time, regardless of product mix.

Parts with complex geometries formed by NNS methods have their highest value if the as-formed dimensions are “accurate enough.” However, sometimes tolerance specifications are tighter than “near-net” dimensions. Hard-fired ceramics with tight tolerances must be diamond ground for the last step. But not too much! These machine tools are retrofitted with diamond-impregnated

grinding wheels, which makes it an expensive process. Also, aggressive removal of material can inflict surface stresses and introduce microcracks that weaken the part. Therefore, only the areas of the component that are critical to function are ground. Doing so also minimizes labor investment and tool replacement costs.

Quality assurance

Fully fired parts are measured for dimensional accuracy and visually inspected for defects. Liquid dye penetration tests reveal hairline cracks and open porosity, making them visible to the inspector's eye. We use practical and ergonomic vision scopes (Figure 4) to inspect parts under magnification, especially inside holes and other hidden areas of parts. Most orders are processed

in batches using qualified tooling, allowing us to rely on process control and sample checking to ensure product consistency and acceptance.

Parts for use under vacuum and high-pressure environments are inspected using special test jigs and gauges, depending on the critical features. Applying air pressure or vacuum and submerging the parts in fluid will expose any leaks when inspecting high-voltage, deep-water, or semiconductor chamber parts. Customers provide mating components to check fit and compatibility with the ceramic parts, as shown in Figure 5. Sometimes customers require some assembly or mating work to be done. Other quality considerations include:

- Surface finish, although ultimately a function of the particle size of the start-

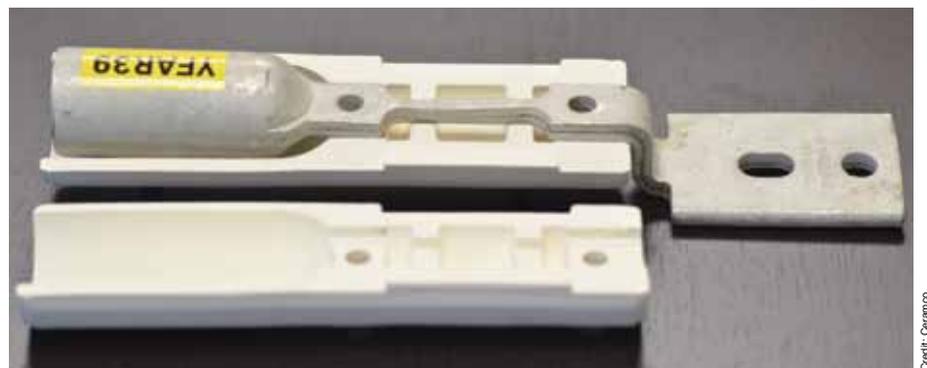


Figure 5. Finished ceramic fuse insulator formed by CIM. The foreground piece shows complex geometry achievable by NNS with slots, holes and walls of varying thickness. The background piece shows the ceramic piece with the metal fuse fitted inside. The part dimensions are 8 inches long x 2 inches wide x 1.5 inches high.

ing powder, also is a function of tooling surface character.

- Precision of as-fired net-shaped dimensions (i.e., how near are to the net) in general is $\pm 1\%$, although it can be as good as $\pm 0.3\%$, depending on tooling, equipment, feature size, and geometry.

- Quantities range from hundreds to hundreds of thousands. The production tooling is scaled to match the order quantity. Prototypes and short orders use low-cost molds, and high-volume orders use hard, multicavity tooling with appropriate degrees of automation in part handling.

New, competing technologies

Challenges for the future include competing technologies that are capable of fabricating complex geometries, such as 3-D printing, robocasting, and selective laser sintering. These tech-

nologies are exciting because of their ability to make geometries that cannot be injection molded, for example, undercut features.

All shaping processes influence the properties of ceramic parts, and, therefore, their usefulness for applications. These new technologies are no exception. Currently, they cannot demonstrate adequate bulk density or consistent surface quality. Strength also is an issue. CIM parts have no relic structures in the ceramic body. As a result, high bulk densities are achieved.

Practicality also must be considered. Thick parts would take a long time to manufacture, producing one layer at a time using 3-D printing, regardless of the technology's advancement. It remains to be seen whether high-volume 3-D manufacturing will be more economical than traditional forming techniques.

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Selected references

M.F. Ashby, *Materials Selection in Mechanical Design*, 2nd ed. Butterworth, Boston, 1999.

N.P. Bansal and A.R. Boccaccini, *Ceramics and Composites Processing Methods*. Wiley, New York, 2012.

G.Y. Onoda Jr. and L.L. Hench, *Ceramic Processing before Firing*. Wiley, New York, 1978.

R.M. German, *Powder Injection Molding—Design and Applications*. Innovative Material Solutions, 2003.

R. Cass and T.O. Henriksen, "A Gateway into Ceramics," *Ceram. Ind.*, June 2011.

"Tungsten Carbide—An Overview," International Tungsten Industry Association, 2 Baron's Gate, 33 Rothschild Road, London, W45HT, U.K. ■

Ceramco—A history of serving demanding niche markets

In 1982, Danish scientist and Massachusetts Institute of Technology Ph.D. Anders F. Henriksen settled in Chatham, N.H., and founded a consulting firm, Chatham Technology. Less than a year later, he adapted powder metallurgy methods to ceramic part fabrication and founded Ceramco Inc. to manufacture custom ceramic components using low-pressure injection molding. The business carved a niche for making unique, complex parts of high-purity alumina, zirconia, and other refractory ceramics.

Ceramco's niche business grew for the next 15 years, serving an increasing number of industries, to produce custom parts of increasing complexity for extreme environment applications. The ability to make functional internal and external threads for custom orders created a captive business manufacturing stock-sized ceramic nuts and bolts.

To produce parts with tighter tolerances, Ceramco partnered with, and eventually acquired, a diamond-grinding shop. In 1997, Ceramco built a new 10,000 square foot facility to house the newly acquired grinding capability and the growing manufacturing enterprise. The expansion provided an opportunity to improve overall operational efficiency.

Over time, Ceramco saw growing demand for high-volume, yet geometrically complex,



ceramic parts. In 2008, the company acquired high-pressure injection molding (HPIM) technology to meet the challenge. This decision opened opportunities for Ceramco to pursue new industries and markets.

Today, Ceramco's full-service manufacturing capabilities focus exclusively on near-net-shape ceramic component fabrication. ■