Traditionally, microwaves and metals have not been thought to be compatible. However, microwaves have significant possibilities for use in a variety of metal processing applications including binder removal, powder metallurgy sintering, metal melting, brazing, and a range of surface treatments.

Shawn Allan*,
Holly Shulman, and
Morgana Fall
Ceralink Inc., Troy, N.Y.

Rick Sisson*
and Diran Apelian*

*Member of ASM International and member, ASM Heat Treating Society

Worcester Polytechnic Institute’s (WPI) Metal Processing Institute (MPI), Worcester, Mass., has teamed up with Ceralink Inc., Troy, N.Y., to pursue microwave heating technology for use in a variety of materials processing applications. Ceralink develops advanced materials, processes, and green technologies for industry in its Microwave Technology Center, working with R&D laboratories, equipment manufacturers, and end users to accelerate commercialization. For example, Ceralink and BASF Corp. (headquarters in Florham Park, N.J.; www.basf.com), with $5 million in DOE funding, developed a process to reclaim precious metals from fuel cells using microwave leaching. In that project, Ceralink assembled and managed a three-company team to design and build a scale-up microwave autoclave. Development and implementation of new processes in the microwave autoclave are currently underway.

Microwaves produce internal friction and heat via dielectric or magnetic losses, known as “suscepting,” or “coupling,” in the microwave field. In the case of bulk metals, microwaves can induce eddy currents and skin heating, but are otherwise reflected. However, powder metals heat up well in a microwave field due to their high surface area and low electrical connectivity. High surface area metal powders contain oxides, water, and other species absorbed at the surface. These complex surface chemistries facilitate the heating of metal powders.

There are many strategies that allow the use of microwaves in metal processing even when the materials reflect or do not suscept well. The combination of radiant heat and microwaves is one effective method. Radiant heat can be added with conventional electric or gas, or through microwave susceptors, such as silicon carbide. A microwave susceptor is a material that is used to convert microwave energy into heat, functioning as a wireless heating element. Bulk metals can be efficiently melted using such a combination approach.

Microwave Metal Melting
Ceralink developed a method to melt scrap aluminum using microwave energy in a furnace (Fig. 1) constructed with a layer of embedded silicon carbide-susceptor blocks (Research Microwave Systems, Troy, N.Y.). The silicon carbide is heated at 100 to 150°C/min (180 to 270°F/min), producing a fast, clean metal melt (Fig. 2). There are significant energy savings (0.7 kWh/kg consumed) compared with that con-

Ceralink has the resources, equipment, and know-how to successfully develop microwave processes for a variety of materials.
sumed using traditional reverberatory furnace melting. The yield increased from 94% to 99% by eliminating the natural-gas environment. The process is green, and is 10 times faster than conventional melting. A 36 kg (80 lb) charge of aluminum was melted and cast in only 40 min. (Fig. 3). The furnace is available for further scale up with one of Ceralink’s industrial partners. Numerous metals and alloys can be quickly melted using microwave hybrid heating, including copper, bronze, brass, gold, silver, tin, iron, and titanium.

**Microwave Powder Metallurgy (PM) Sintering**

Dielectric testing is used as a tool to predict a material’s ability to heat in a microwave field. Dielectric data have been obtained at microwave frequencies and elevated temperatures for many PM compositions, and continues to be gathered and evaluated. Microwave heating experiments correlate well with dielectric data. In certain temperature regimes, sufficient dielectric losses occur to promote microwave heating. During sintering, the powder compact more closely resembles a bulk metal. The metal becomes conductive as the protective surface layers decompose, and connectivity between particles increases. This causes the metal to lose its dielectric behavior, which prevents full sintering using pure microwaves. The use of a combination heating technique, such as susceptor assist, can supplement the later stages of sintering. Another approach is to engineer the grain boundaries and preserve dielectric heating behavior. There may be advantages in the resultant properties of the workpiece by increasing the heating rate, even in the early stage of sintering.

**Microwave Binder Removal**

Powder compaction is a standard method to produce part shapes. Compaction requires the use of a binder to provide green-part strength and handleability. The binder must be removed before parts begin to densify during sintering. This is generally accomplished through thermal processing. For most ceramic materials, the part is heated slowly in a furnace and the binder is burned out of the part. For powder metallurgy parts, the parts are heated in an atmosphere-controlled furnace, and the binders are volatilized and evacuated.

In both cases, binder removal is a time and energy consuming process, especially for parts with significant cross section. Heat must be transferred from the surface of the part into the center of the part. If the part is heated too quickly, binder can volatilize rapidly forming pockets of gas, which expand and can potentially crack the part. In addition, if high heat is applied to the surface, the part surface can begin to densify before the binder is removed from the center of the part, trapping the binder and also leading to defects or failure.

Ceralink is addressing this problem using its exclusively licensed Microwave Assist Technology (MAT) for binder removal (Fig 4). MAT combines electric (or gas) and microwave heating in air and atmosphere-controlled environments (Fig. 5). MAT is a readily scalable microwave heating option, as systems are based on conventional electric- or gas-heated furnaces.

Applying microwave energy in conjunction with conventional radiant energy enhances binder removal. Most binders will suscect in the microwave field; they heat from inside of the part, and are driven to the surface (Fig. 6). This is the reverse
of conventional heating, where the surface of the part is heated first. As the binder is removed, the part loses its green strength and is susceptible to cracking due to thermal and mechanical stresses. Microwave binder removal allows faster heating while mitigating nonuniformities (stresses).

Ceralink is developing binder removal processes and equipment for powder metallurgy compacts through a NYSERDA (New York State Energy Research and Development Association) contract, and is collaborating with MPI.

**Metal Surface Treatments**

Aluminizing, chromizing, boronizing, carburizing, and nitriding all have been demonstrated at lab scale either through packed-bed cementation or chemical vapor deposition via microwave heating. Further work is needed to explore direct property comparisons, scale up strategies, and cost benefit. Collaboration between Ceralink and MPI is underway to demonstrate a process of microwave aluminizing tool steel pins. In die casting of aluminum components, die soldering is a common problem wherein the aluminum melt interacts with the H-13 tool steel die, which leads to downtime because the soldered parts of the die need to be removed and inserts replaced. Work at MPI’s casting research center shows that aluminizing die inserts mitigate soldering during die casting. Microwave aluminizing of pins for die casting is underway at Ceralink. This technology has significant potential for the metal casting industry.

**Commercialization of Microwave Technologies**

Many universities and national laboratories have been carrying out research in microwave heating over the past 25 years, however commercialization has been slow. Two companies have licensed technology from Pennsylvania State University (www.psu.edu). Dennis Tool Co. (Houston, Tex.; www.dennistoolcompany.com) uses microwaves to sinter carbide wear parts, which are said to have superior properties. The company also sells a turnkey, vertically continuous microwave sintering system for certain material types. Spheric Technologies Inc. (Phoenix, Ariz.; www.spherictechnologies.com) teamed up with Longtech Syno-Therm Co. Ltd. (Changsha, China) forming Spheric/Syno-Therm to supply microwave equipment. Among Spheric’s systems are horizontal continuous furnaces, which operate by moving the parts through the microwave-heating zone on ceramic belts or with ceramic pusher trays (Fig. 7).

An easy-to-use laboratory bench-top system, available through Research Microwave Systems, or RMS, (Troy, N.Y.; www.thermwave.com), uses pure or susceptor-assisted microwaves. Ceralink established RMS with a joint venture partner specifically to make inexpensive microwave systems and accessories available. CPI Industries Inc. (Beverly, Maine; www.cpii.com), manufacturer of Autowave and Heatwave microwave systems, produces large lab and small production units for processing using controlled atmosphere (Fig. 8). An Autowave at Ceralink’s Microwave Testing Center has been used for numerous metals related studies in argon, nitrogen, and hydrogen atmospheres, as well as vacuum, as shown in Figs. 9-11.
Technology uptake is expected as engineers, researchers, and managers gain experience using microwave processing. Ceralink is positioned to assist industry with manufacturability analyses for scale up. The shift to implement microwave heating requires new ways of thinking about traditional processing methods. The speed of microwave processing is difficult to fully grasp until experience is gained with real systems. A common error in microwave processing is to over-process the material, leading to a false conclusion that microwave heating does not have benefit, or that it produces nonuniform results. With the right equipment and experience, real processes can be proven, developed, and implemented using microwave heating technologies throughout the materials industry.

Ceralink’s Microwave Technology Center has systems and accessories for feasibility and scale-up studies. In addition, Ceralink works with furnace manufacturers and microwave-equipment suppliers to design standard and custom systems for processes ranging from traditional heat treating and sintering, to high pressure, low temperature chemical reactors. Exciting new microwave processes and materials are being explored in collaboration with MPI.


**Fig. 10** — Microwave heating profile for Robocast alumina/Mo cermet.

**Fig. 11** — Microwave sintered Fe-2Cu powder metallurgy part in CPI Autowave with RMS Thermcept susceptors in 4% H₂/N₂ atmosphere (inset) and heating profile.

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