Current Problems in the MIM Sintering Process

Throughout the last two to three decades, the use of increasingly complex MIM parts has expanded into a wide range of diverse applications and industries. The growing demand for high-quality components with tighter geometrical tolerances, as well as more powerful material properties, has continuously triggered the integration of the MIM process into the production lines of various industries, including Automotive, Medical and Consumer Goods manufacturing. Higher power densities in modern car engines, power trains or mechanical machineries require the miniaturization of mechanical systems that offer large potential for innovative and cost-efficient production technologies. Furthermore, the enhanced functionality of intricate MIM parts can also lead to reduced assembly costs when mass-producing products such as premium-designed notebook computers or mobile phones. However, to meet the increasing number of technical specifications and requirements of the industry, the potential for further improvements to the accuracy and efficiency of the MIM process equipment must be explored. Current limitations – in terms of mechanical and chemical properties, as well as optical appearance – of the parts are determined, amongst others, by:

1. Inhomogeneous shrinkage (i.e., geometrical distortion) caused by:
   a. Non-uniform powder and feedstock mixing
   b. Density fluctuations introduced during molding and/or the first debinding step
   c. Inaccurate temperature uniformity in the sintering furnace

2. Chemical decomposition and discoloration caused by:
   a. Inaccurate process gas management
   b. Binder redeposition during the second debinding step
   c. Residual sintering furnace contamination

In addition to the above technical limitations, highly competitive market conditions put intense cost pressure on part manufacturers. Hence, in order to push the MIM industry forward, the need for more cost-efficient, technically improved production equipment and material is crucial.

Beside high purchasing prices for raw materials (e.g., fine-grained metal powders, polymer binder systems and ready-to-mold feedstock), high-temperature sintering is among the top cost drivers of the overall MIM process. Low investment and operating costs of debinding and sintering furnaces, therefore, play a key role in gaining a competitive edge for MIM part producers. Consequently, depending on the specific production situation of the individual
manufacturer, the choice of the most suitable furnace technology is precursory to becoming a successful player in the MIM industry.

**Suitability of Different MIM Sintering Furnace Types**

Without regard to tailor-made, highly specialized systems, most of the sintering MIM furnaces on the market can be subdivided into batch vacuum or continuous atmosphere furnaces. Both technologies offer the possibility of integrating the thermal removal of residual polymer still contained in the brown parts after molding and catalytic or solvent debinding.

On the one hand, for MIM mass producers that have correspondingly large lot sizes of identical or geometrically similar parts, the operation of a continuous atmosphere furnace may be appropriate if fully utilized. In this case, comparably low cycle times with high sintering capacities can result in a favorable cost-benefit ratio. However, with minimum annual production volumes in the range of 150 to 200 metric tons, high investment costs and large footprints, continuous atmosphere furnaces are not economical in small or medium lot production lines. Moreover, they are still prone to longer downtimes for maintenance, causing reduced manufacturing agility.

On the other hand, vacuum batch sintering furnaces, as offered by a number of commercial suppliers, allow for excellent control of the debinding and sintering process. The aforementioned limitations, in terms of geometrical distortion and chemical composition of the finished MIM parts, can be contained. One such method of containment is through sophisticated gas management systems providing continuous flow of unloaded gas to flush away outgassing binder material. Additionally, by means of the smaller hot zone volume, temperature uniformity in vacuum furnaces can be extremely accurate and reach values as low as ±5 °F (±3 °C). In general, the superior cleanliness of the gas atmosphere, the enhanced adjustability of the process parameters, as well as the reduced concussion on the parts place vacuum batch furnaces as the technology of choice when producing high-quality components for various applications (e.g., medical applications). The lower investment and higher cycle flexibility offer further advantages when companies are facing volatile order situations and need to run parts with different geometries and materials. Operating an array of vacuum furnaces not only provides a redundant and robust production line, but also offers the possibility to run multiple operating programs (recipes) at the same time.

However, some of the specialized MIM vacuum furnaces combining the previously mentioned technical advantages are limited to rather small useable volumes. Due to their disadvantageous investment-to-capacity ratio and lower energy efficiency, sintering costs per part might consume potential savings realized in other MIM process steps.

**Vacuum Furnace Requirements for MIM Industry**

An important factor for a cost-efficient operation of vacuum MIM furnaces is the economical consumption of process gas and electrical power. Depending on the gas type, those two elements of the sintering process can account for more than 50 percent of the total costs. The
adjustability of a partial pressure mode with the lowest possible gas flow must be implemented while still enabling a contamination-free debinding and sintering operation. Low heat losses in a well-designed hot zone with an efficient setup of optimized heating elements helps reduce electrical power consumption. To achieve this efficient setup, and to keep design and development costs reasonable, powerful computational fluid dynamics simulation tools are used to find optimized gas and heat flow patterns in modern, resource-saving vacuum MIM furnaces.

Depending on the load size and residual polymer content of the brown parts to be sintered, the formation of binder buildup in peripheral components (e.g., gas outlet lines, pumps and hot zone area) can lead to considerable downtimes for manual cleaning and maintenance. With MIM load net weights as high as 882 lbs. (400 kg) (furnace volume > 1,000 liters) and binder contents in the range of three to four percent, up to 33 lbs. (15 kg) of polymer material needs to be carried away during the outgassing period. Even though most of this exhaust material (> 95 percent) should be collected in defined condensation points, such as binder traps or wax separators, door-to-door cycle times can be increased by more than two hours through decontamination and manual cleaning work. As a result, the operational availability of less efficient and ill-conceived MIM furnace units is reduced by up to 15 percent. Consequently, MIM manufacturers are looking for more robust systems with optimized filtration systems that aid in reducing maintenance efforts and keeping unscheduled breakdowns to a minimum.

To enable fast-growing MIM companies the flexibility to plan their production capacity and quickly react to changing market demands, long delivery times for production equipment can slow down a company’s growth rate. Usually, furnace manufacturers start producing equipment only after receiving an order, not keeping key components and long lead-time materials on stock. The resulting delivery times of nine to 12 months for new furnaces regularly leads to bottlenecks in MIM production lines when additional part orders have to be scheduled on short notice. Only recently have lean manufacturing and standardized production concepts been introduced by leading vacuum furnace manufacturers. For example, through a modular platform and standardized components design, Ipsen managed to reduce the delivery time for their newly introduced TITAN® DS vacuum MIM furnace to less than three months.

**MIM Furnace’s Key Components**

About 60 percent of commercial MIM activity is in stainless steels. The most popular alloys include 17-4 PH and austenitic stainless steels, 304L and 316L. Prices for commercially available, ready-to-mold feedstock are in the range of US$30-50 per kg. After molding and debinding, the monetary value of the raw parts loaded into the furnace can exceed thousands of U.S. dollars. Thus, the reliability and performance of the MIM furnace’s key components is essential.
As mentioned above, during temperature ramp up and intermediate soaking steps up to 1,112 °F (600 °C), outgassing of the residual polymeric binder takes place. To efficiently transport the gaseous material out of the hot zone area, a continuous and homogenous purge gas flow at all positions of the batch rack is required. For smaller vacuum MIM furnaces, this is often realized by a gas tight retort (or muffle) design, which is externally heated. The main advantage here is that the retort provides a high-purity gas atmosphere and ensures that heated gas flows evenly across the part load. However, it is not easy to have a cooling fan in the retort (this results in longer cycle times), and there are extra capital, maintenance and energy costs associated with the retort.

A less cost-intensive, and equally controllable, concept was realized in Ipsen’s TITAN DS MIM furnace. With a work zone volume of 1,000 liters, an annual throughput of 100 tons can be achieved with a single unit. The hot zone design is shown in Figure 1.

The basic structure is a round, carbon steel frame (plenum) that provides uniform strength for support of the hot zone, elements and shields. Flat-bar graphite heating elements completely surround the cylindrical section of the hot zone and are evenly distributed to provide optimum energy transfer into the workload. Additional element packs on the front and rear ends further improve the temperature uniformity up to ±5 °F (±3 °C). The thermal insulation system consists of a CFC hot face, which is backed by several layers of high-performance graphite felt. Independently adjustable and flow-controllable process gas inlets help to maintain a differential pressure between the inner region of the hot zone and the cavity between the plenum and cold vessel wall. The uniform process gas flow from outside the hot zone to inside ensures even binder evaporation, as well as prevents contamination of the hot zone and redeposition of the binder on parts.
Binder Removal Systems

After meticulous removal of the polymeric binder residuals from the hot zone, continuing to efficiently handle and filter the charged process gas is critical for avoiding unwanted binder buildup in pipes, valves or pumps, as seen in Figure 2.

Figure 2: Unwanted binder contamination in vacuum lobe pumps

Figure 3: Process gas flow and management in a modern MIM furnace.
For an uninterrupted and low-maintenance operation, it is essential to utilize an effective binder trap system for component protection. The schematics for the gas flow and binder separation, as realized in a modern MIM vacuum furnace, is shown in Figure 3. Efficient pumping out of the hot zone area is realized by means of a powerful pumping unit which, in this case, consists of a vacuum booster (lobe pump) supported by a mechanical screw pump. High-temperature and high-velocity process gas saturated with evaporated polymer material is pumped out through the pumping port located directly inside the hot zone.

To further protect the most critical components from extensive maintenance, a specialized filtration system is connected upstream (before the pumps). Figure 4 shows an easy-to-clean cartridge filter system that is well-proven in vacuum MIM furnaces. It features a four-stage effluent trapping system. The first stage knocks down heavy particles and condenses volatile solids and liquids on large surface areas. Stages two and three contain wire mesh screen elements that are strategically located to gradually filter the binder. The fourth, and final, stage is designed to trap any vapor molecules that might have made it past the previous stages. This modular system is designed with heaters to dissolve trapped binder, which is then gathered in a collection bucket that can be easily removed and changed for cleaning.

![Figure 4: Versatile binder traps equipped with heating elements and a quickly interchangeable collection bucket](image_url)

Even though the risk of contaminating the vacuum pumps is now reduced to a minimum, long-term buildup of binder deposits on the lobes or casings, for example, can still occur when continuously running the furnace in a 24/7 operation. In order to maintain maximum pumping performance, fast rotating parts with minimal clearance, such as lobes, must be kept clean. An innovative cleaning concept based on software-controlled pump flushing procedures was tested recently in a new vacuum MIM furnace from Ipsen. Liquid solvent capable of dissolving hardened polymeric binder is injected in the suction line of the vacuum
booster and the connected screw pump. Rotational speed of the lobes or screws can then be adjusted by means of a variable-frequency drive to control liquid flow velocity and to ensure efficient washing out of the polymeric precipitations. For enhanced efficiency of the cleaning process, the solvent is heated to temperatures close to its evaporating temperature.

Summary

Modern vacuum furnaces with innovative solutions for binder removal and process management systems help further improve the efficiency and competitiveness of the industrial MIM process. For its economic success, the capital and operational costs of specialized MIM furnaces must be kept within reasonable limits. The latest developments in furnace technology – which were presented in this paper – will help to fulfill the technical and commercial requirements of MIM manufacturers who directly compete with other part production methods, such as investment casting and machining. Additionally, manufacturing cost per part in larger vacuum MIM furnaces can be significantly reduced and are now comparable to those realized in continuous atmosphere MIM furnaces.

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