Efficient Sintering Equipment for the Production of Engineering Ceramics

Based on an integrated definition of "efficiency", this article explains concepts and principles useful for the realization and improvement of high-efficiency sintering equipment. Real industrial applications and plants are cited for further clarification. In addition, a report is given on the most important ongoing developments that will lead to continuing progress in the efficiency of modern sintering technology.

Introduction

In ceramic technology, the process step "sintering" effects the consolidation of powdered material, generating a solid body with properties that are influenced significantly by this process step. Hence the product quality is affected by sintering to a large extent. But in most cases sintering is also the process step with the highest energy consumption in the value-added chain [1]. It contributes substantially to the fact that a major part (approx. 68 %!) of energy consumed in industry is used for processing heat [2]. Moreover the technology required for sintering is frequently complex and expensive, especially in the field of engineering ceramics. These brief considerations already indicate the huge relevance of the efficient design of the process step "sintering". But what is "efficient sintering"?

Efficient Sintering – Influencing Factors

According to the encyclopaedic definition "efficiency in general de-scribes the extent to which time or effort is well used for the intended task or purpose." Mathematically this is equivalent to the ratio of outcome and effort. "Outcome" in this context is the productivity of a sintering facility, which is influenced among other things mainly by the following factors:

- Batch size (useful capacity of the furnace)
- Cycle time
- Feed time
- Availability rate
- Shift operation
- Scrap rate.

With regard to the "effort", it is not sufficient to consider just the energy consumption ("energy efficiency"), although this is one of the most important aspects. Instead an integrated view of effort is becoming increasingly accepted (TCO = Total Cost of Ownership or LCC = Life Cycle Costing), which generally covers the following factors:

- Investment costs (equipment, kiln furniture, auxiliary units, infrastructure)
- Expected useful life
- Disposal of equipment
- Required space
- Costs for consumables (energy, auxiliary media e.g. protection gas, cooling water etc.)
- Disposal of potential waste or exhaust gas
- Personnel costs
- Service, repair und spare part costs (e. g. kiln furniture)
- Cost of regular and unscheduled downtime.

The above-mentioned influencing factors show that the efficiency of a sintering facility depends critically on how carefully the sintering technology is selected and how precisely its design is matched to the respective application. This selection and matching are forming the basis of the company strategy at FCT Systeme GmbH [3]. Here for nearly 30 years now sintering facilities for engineering ceramics and powder metallurgy are not only built, but very early during project planning, technological development is performed in close collaboration with the customers and with the use of the company's own well-equipped pilot plant lab. This customer service ranges from simple feasibility tests to pilot production under real industrial conditions, if required. The final result is a complete package of optimally matched sintering technology and equipment design, ensuring the user obtains high-efficiency sintering technology.

During this development work, several principles and trends have become apparent that are most important for the realization of efficient sintering technology. With the help of several examples, this is demonstrated and explained in the following.

Fig. 1
View into a production hall with a number of identical "quasi-continuously operating high-temperature sintering furnaces

Downsizing vs. Upscaling

A core consideration in the design of sintering facilities is the realization of the required productivity. Here it is often not advisable to try to reach the required productivity with the use of one single, big sintering furnace. It is often much better to split production between more than one, identical small-size furnaces operated parallel ("downsizing"). Small furnaces have lower electrical connection power as well as shorter cycle times, which increase productivity compared with a single big furnace and benefits product quality in many cases. Furthermore, the potential downtime of just one of several smaller furnaces is much less significant. If more than one furnace is operated, personnel, electricity, cooling water, service intervals etc. can be kept relatively uniform by offsetting the individual cycles appropriately, resulting in a "quasi-continuous operating mode". This option successfully implemented by several users. As an example, Fig. 1 shows a view into a production hall, where over 20 identi-

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Fig. 2
One of the largest monolithic parts made of SSiC, sintered to high contour and dimensional accuracy by means of precise sintering technology

Fig. 3
View of the FCT pilot plant stations with high-temperature furnaces, designed for the combi-process

Fig. 4
Twin-furnace for pyrolyzing and siliconizing C/SiC parts

cal furnaces are working in a parallel, time-offset mode. This type of furnace has a useful volume of up to 1,2 m^3 and is able to realize a working temperature of 2200 °C in protection gas atmosphere (Ar, N_2, He, etc.) between $5 \cdot 10^{-2}$ and 1000 mbar. Thanks to a special heat exchanger system, very short cooling cycles are possible, although the thermal insulation layout was designed amply in order to ensure excellent energy efficiency of the furnaces. A typical application of this type of furnace is the sintering of SSiC mass products, e.g. sealing rings in the automotive sector (water pump) with a capacity of >20 000 per 23 h sintering cycle as well as various parts for wear protection or ballistic protection. As an example, Fig. 2 shows one of the biggest monolithic SSiC parts ever made, which weighs approx. 100 kg (diameter = 600 mm and length = 1200 mm). Owing to the very good, for SSiC specially optimized thermal homogeneity inside the furnace, an extraordinary contour accuracy of the part – e. g. ±0,5 mm for the inner diameter – is achieved, minimizing mechanical post-processing with costly diamond tools.

Fig. 5
Ceramic brake discs made of C/SiC

Batch vs. Conti

In oxidizing firing as well as powder metallurgy, continuously operating furnaces like roller and push cup kilns have been state-of-the-art for a long time. But in engineering ceramics, the requirements not only include very high working temperatures (e. g. 1600–2500 °C), but similarly protection gas atmosphere or even vacuum, i. e. very low, variably adjustable and exactly controllable oxygen partial pressure. In continuously working furnaces these requirements can only be realized with high technical effort, making the equipment expensive, complex, difficult to operate and service as well as susceptible to failure and malfunction. Because even small conti-furnaces have high productivity, any downtime results in a significant loss of productivity, similar to the failure of a large batch furnace, as described in the last section. All these facts are, in our view, arguments against real conti-furnace technology in engineering ceramics. In contrast – as explained in the last section – a larger number of small furnaces working in parallel with a smart time offset can facilitate “quasi-continuous” sintering technology, which – as a whole – works much more robustly, reliably and uniformly.

Combi-Process

One more important instrument for improving efficiency can be the merging of process steps in the value-added chain, e. g. in our case the combination of debinding and sintering in one single sintering system.

Fig. 6 Twin-furnace for series production of RSiC diesel particulate filters

Fig. 7 Diesel particulate filters made of RSiC for commercial vehicles

With such a “combi-process” not only are all the costs of a separate debinding step avoided, product quality is also improved because the risky step of transferring debinded, mechanically sensitive parts from the debinding to the sintering furnace is eliminated. In the FCT pilot plant lab two large-volume, induction-heated furnaces are available for customer tests, which are both designed for the “combi-process” (Fig. 3) The disposal of the organic vapours and gases is performed by a thermal reburning device (TRD, see centre of Fig. 3). These furnaces boast a sintering performance similar to the furnaces described in the last section. They are also equipped with fast cooling technology, in order to realize high efficiency with shortened cooling cycles.

Twin-Concept

With the development of the idea of the above-mentioned “quasi-continuous” operation mode, the “twin-concept" was born. This concept is based on the pair-wise aggregation of furnaces using a common process control system, power supply, gas and vacuum supply, TRD (if required) etc. Now every single furnace is no longer independent, but significant costs can be saved. With a respective time offset of the sintering cycles, a twin system shows practically the same productivity as two single furnaces, but at a much lower price. This concept has proven itself in many industrial applications. Fig. 4 shows by way of example a pilot-scale twin furnace used for pyrolyzing and siliconizing C/SiC brake discs (Fig. 5) with 400 dm^3 useful volume each, using a common process control system, power supply, gas & vacuum supply and TRD. For the industrial series production of such brake discs (400 mm diameter) combi-process facilities are in use, realizing batch mode pyrolyzing and siliconizing of 80 discs with a cycle time of 23 h. Promising tests are currently underway aimed at shortening the cycle time to 11 h, which will be an important step to an efficient siliconizing technique with broad applicability. Of course a large number of twin furnaces can be combined in order to form a "quasi-continuous" sintering technology, as de-scribed above, in order to harness the advantages of both concepts. In this way DPF (diesel particulate filters, Fig. 7) made of RSiC for utility vehicles are industrially produced, with the use of a large number of the twin furnace shown in Fig. 6. These furnaces operate at maximum temperatures of 2500 °C, have a useful volume of 1,6 m^3 each (corresponding to 1000 kg of DPF) and realize a cycle time of 23 h.

Pressure-Assisted Sintering

Some engineering ceramic materials cannot be consolidated to sufficient density by purely using thermal energy. In these cases, by means of all-over acting gas pressure, densification can be assisted, as soon as all open porosity is closed in the first (pressure-less) sintering phase. This method is known as GPS (gas pressure sintering) or Sinter-HIP (hot isostatic pressing). For this technology, obviously the furnace must have a vessel designed for the required gas pressure. An example of such equipment is the GPS furnace shown in Fig. 8, which is able to assist densification with a maximum gas pressure of 100 bar up to 2200 °C (useful volume 90 dm^3). Such furnaces are available with useful volume up to 1000 dm^3. Typical applications are LP-SiC and Si_3N_4 parts, e. g. wear parts or cutting tools. Special layouts,

Fig. 8 Gas pressure sintering furnace for up to 100 bar at 2200 °C

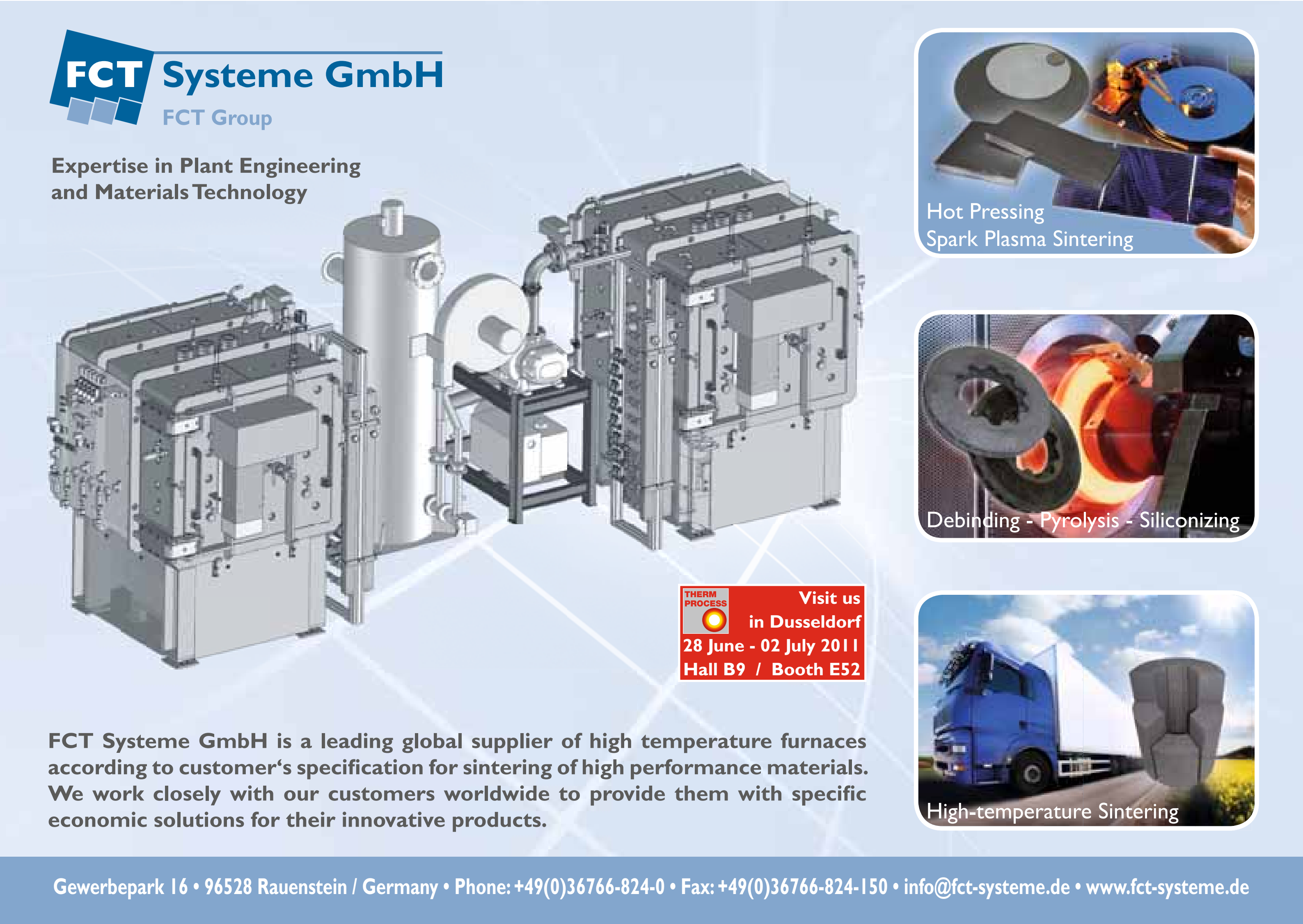

Fig. 9
Hot press for the production of cutting tools and sputter targets

which are designed for the combi-process as well, are successfully applied for the debinding, sintering (in H_2-atmosphere) and gas pressure sintering of MIM (metal injection moulding) automotive mass products.

Hot press technology (HP) is used if 100 bar gas pressure is not sufficient or if the open porosity does not close at all or not early enough – e. g. owing to lack of liquid phase. Here the required pressure on the powder is applied in a pressing tool uniaxially by pressing punches, limiting this method to relatively simple shapes on one hand, but making a preliminary forming step (e.g. powder pressing) unnecessary on the other hand.

The HP technology has been con-tinuously developed and optimized at FCT since the beginning of the company's history, already reaching a technical level enabling reliable and efficient industrial application many years ago. The hot press shown in Fig. 9 provides a maximum pressing force of 6000 kN up to 2200 °C and is capable of densifying six discs measuring in 500 mm in diameter and 10 mm in thickness made of silicon nitride simultaneously in just 8 h for instance. Again the system is equipped with a special fast cooling device in order to realize the short cycle times. Similar systems with 9000 kN pressing force are currently under development.

An advancement of the HP technology is the FAST/SPS technology (field-assisted sintering technology/ spark plasma sintering), brought to the market by FCT about seven years ago. In the meantime this technology is also successful in industrial application fields. FAST/SPS uses a pulsed DC current that runs directly through the pressing tool and/or the sintering part. This in-situ heating minimizes thermal gradients, allowing higher heating rates compared with HP. Dwell time is shortened or eliminated too. Moreover more or less higher sintering activity can be observed in many cases. All these factors reduce the required cycle time, increasing the energy and cost efficiency of the FAST/SPS technology compared to conventional HP technology.

For instance rectangular sputtering targets (150 mm × 170 mm, Fig. 10) made of pure tungsten carbide can be fully densified in just 35 min effective cycle time on an industrial scale. Fig. 11 presents a "semi-continuous" FAST/SPS production system with 2500 kN pressing force, which is also used by the industry for the production of sputtering targets and composite material parts. Here the above-mentioned twin-concept is further developed to a two-chamber system, by adding a second chamber (cooling chamber) via a gas/vacuum gate. With fully automatic transfer of the hot pressing tool (after completed densification) to the cooling chamber, the cycle time can be halved, doubling theefficiency of the system. Using suchsystems, which are available with 4000 kN pressing force as well, the mass production of sputtering targets made of high-purity noble metals is realized, with only 20 min effective cycle time for parts measuring 200 mm in diameter.

Outlook

The examples of high-efficient sintering technology presented above show a trend that will intensify in the future, namely increased concentration on targeted development of high-efficiency sintering facilities, precisely matching the respective application field as well as customer requirements. In this process all relevant influencing factors are considered from the very beginning, in an integral view of productivity and costs (Life Cycle Costing). This integral view increasingly provides the motivation for ongoing and new joint research projects [5], in which FCT is also participating (e. g. [6]).

The relatively new FAST/SPS method also offers innovation capabilities, which are investigated and developed to industrial applicability by FCT in the scope of several European and national research projects. Examples are the "hybrid-FAST" method for the fast sintering of large-area parts with minimized thermal gradients, the "hot ejection" method for zero expansion materials or very fast cooling as well as the "FAST^2" method for sintering small mass products with cycle times of just minutes.

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Fig. 10 Examples of high-quality sputtering targets made of various materials sintered by means of FAST/SPS

Fig. 11 Two-chamber FAST/SPS machine for highly efficient production of sputtering targets