

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/393265811>

Sintering Under High Heating Rates

Article in *Annual Review of Materials Research* · July 2025

DOI: 10.1146/annurev-matsci-080323-042441

CITATIONS

0

READS

573

5 authors, including:



Levent Karacasulu

University of Trento

19 PUBLICATIONS 288 CITATIONS

SEE PROFILE



Cekdar Vakif Ahmetoglu

82 PUBLICATIONS 2,300 CITATIONS

SEE PROFILE



Charles Manière

Laboratoire CRISMAT

121 PUBLICATIONS 1,813 CITATIONS

SEE PROFILE



Sylvain Marinel

University of Caen Normandy

227 PUBLICATIONS 3,478 CITATIONS

SEE PROFILE

Sintering Under High Heating Rates

Levent Karacasulu,^{1,2} Charles Manière,³
Cekdar Vakifahmetoglu,² Sylvain Marinel,³
and Mattia Biesuz¹

¹Department of Industrial Engineering, University of Trento, Trento, Italy;
email: levent.karacasulu@unitn.it, leventkaracasulu@gmail.com

²Department of Materials Science and Engineering, İzmir Institute of Technology, İzmir, Turkey; email: leventkaracasulu@iyte.edu.tr

³Normandie Univ, ENSICAEN, UNICAEN, CNRS, CRISMAT, Caen, France;
email: charles.maniere@ensicaen.fr

ANNUAL
REVIEWS **CONNECT**

www.annualreviews.org

- Download figures
- Navigate cited references
- Keyword search
- Explore related articles
- Share via email or social media

Annu. Rev. Mater. Res. 2025. 55:203–30

The *Annual Review of Materials Research* is online at
matsci.annualreviews.org

<https://doi.org/10.1146/annurev-matsci-080323-042441>

Copyright © 2025 by the author(s). This work is licensed under a Creative Commons Attribution 4.0 International License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See credit lines of images or other third-party material in this article for license information.



Keywords

fast firing, ultrafast high-temperature sintering, flash sintering, microwave sintering, spark plasma sintering, blacklight sintering

Abstract

Rapid sintering using a high heating rate is growing in technological and scientific interest. This is motivated by the promise of reducing the carbon footprint of sintering and developing materials with properties and microstructures different from those achievable by conventional heating. For instance, rapid heating can induce suppression of grain growth, the possibility of obtaining modified space charges and elemental segregations, and the development of out-of-equilibrium materials. Severe challenges still exist for the industrial exploitation of rapid sintering technologies, and, nowadays, only fast firing can be considered mature. Most of these limitations are related to the homogeneity of the sample and the possibility of obtaining complex shapes. This review investigates developments in rapid sintering by comparing different processes, suggested mechanisms, and future challenges.

1. INTRODUCTION

Sintering is the cornerstone of ceramics manufacturing; the word “ceramic” derives from an ancient Sanskrit root meaning “to burn.” The first sintered artifacts date back to the Paleolithic age when small pottery statuettes were manufactured, likely for ritual or religious purposes. Since then, different innovations have taken place in terms of materials composition and microstructures. Among them are the invention of faience in Egypt and Mesopotamia (~5000 BC), the development of dense vitrified ceramics in China (stoneware in ~1000 BC and porcelain in ~600 BC) (1), and the introduction of technical and advanced ceramics starting in the nineteenth century (2). Similarly, shaping technologies have also evolved. The first ceramics were hand-formed for thousands of years by squeezing, pinching, molding, or drawing plastic bodies. Coiling was also widely applied in the manufacturing of jars and ceramic wineskins. A significant innovation occurred in Asia around 4000 BC when wheel throwing was introduced (3). The first extruded bodies date back to the onset of the seventeenth century (4), whereas only around 1830 was pressing introduced for tile manufacturing. Slip casting is longstanding, with several reports from the ancient age, but its use remained limited till the eighteenth century.

On the other hand, for thousands of years, ceramics have been consolidated following more or less the same thermal cycles. Typically, a powder compact is heated to elevated temperatures at rates ranging from a fraction of a degree to a few degrees Celsius per minute (5). Indeed, some evolution has occurred regarding furnace design, refractory compositions, and fuels. However, the first steps toward establishing sintering theory were taken only in the middle of the twentieth century (6, 7). Additionally, nonconventional sintering methods that enhance densification by applying an electric field or current, electromagnetic radiation, external pressures, or specific liquid solvents are very recent. Today, more than ever, scientific research is trying to put forward approaches that can reduce the carbon footprint of sintering and develop novel microstructures (2, 8–16).

Two main guidelines are currently driving the field. The first is to reduce the sintering temperature; among different techniques, cold and hydrothermal sintering processes are the most promising (17). The other driver is the reduction of sintering times that can be accomplished by exploiting different rapid heating sources, from Joule heating [flash sintering (FS) and flash spark plasma sintering (FSPS)] to IR [fast firing (FF), ultrafast high-temperature sintering (UHS)] and dielectric heating [microwave sintering (MWS)].

This review rationalizes the latest developments in rapid sintering, highlighting the processes, mechanisms, and advantages and disadvantages of the presently available techniques.

2. MASS TRANSPORT PHENOMENA

2.1. Sintering Mechanisms

The driving force for sintering can be the surface free energy involved in the curvature of particle surfaces (capillarity forces), an applied pressure, or a chemical reaction (18). The capillarity forces are the main drivers of pressureless sintering of single-phase powders. For pressure-assisted sintering processes such as hot pressing or spark plasma sintering (SPS), the driving force includes both internal (capillarity forces) and external pressure. The capillarity force is inversely proportional to the pore curvature radii (proportional to $1/r$). It decreases during sintering due to changes in the pore geometry and can be analytically modeled on the basis of surface energy and effective pore curvature (19).

Different diffusional paths can be activated during the sintering of inorganic polycrystals (6). Matter transport occurs from the source (high chemical potential) to the sink (low chemical potential). The source of matter can be convex particle surfaces (nondensifying mechanism) or the

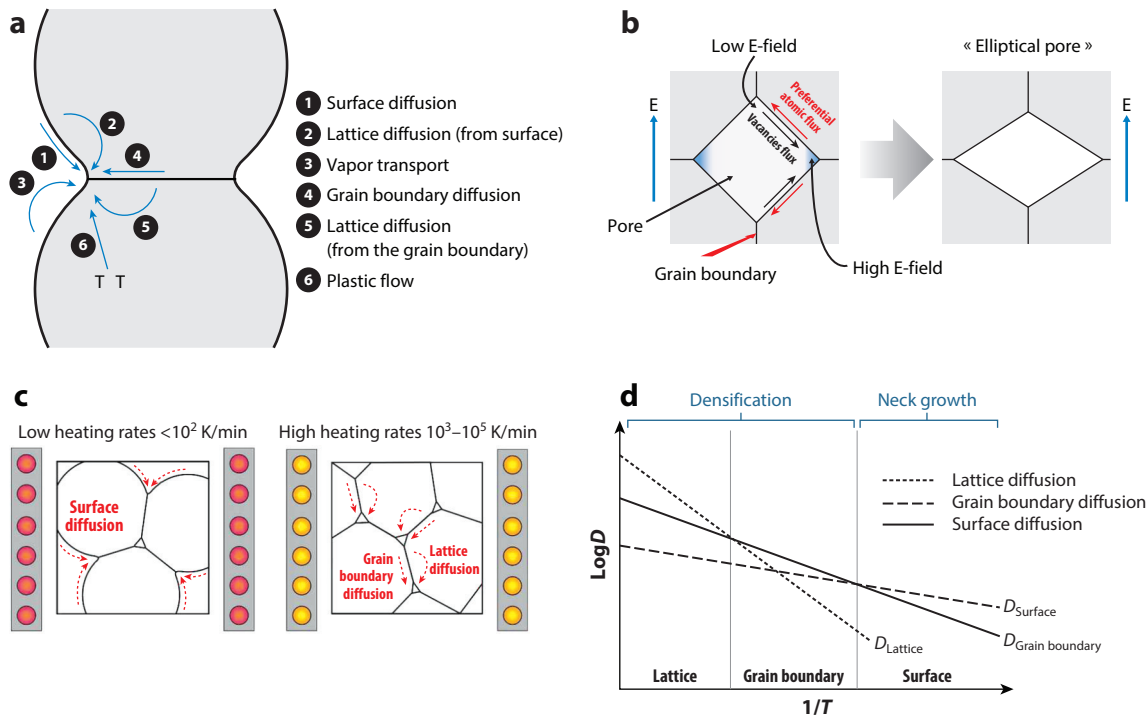


Figure 1

(a) Scheme of the six matter transport paths of solid-state sintering. (b) Scheme of the ponderomotive sintering effect for a four-grain structure. The coloration of the blue region mimics the electric field (E-field) gradient, which is maximized at the pore corner. It causes a preferential atomic flux toward the lower field zone; the final pore geometry tends to be elliptical after sintering. (c) Influence of heating rate on sintering with different diffusion mechanisms under low and high heating rates. (d) Diffusion coefficients plotted against inverse temperature. Panels c and d reproduced with permission from Reference 20; copyright 2023 The Authors (CC BY-NC-ND 4.0).

center of the neck (densifying mechanism); the sink of matter is the neck surface of two grains. There are six matter transport paths represented in **Figure 1a**. Note that the matter redistribution through paths 1, 2, and 3 causes a substantial drop in the driving force for sintering without causing densification.

To investigate each possible mechanism using modeling, sintering is traditionally divided into three stages corresponding with different idealized geometries. A breakthrough in sintering theory was the development of a unified model by Hansen et al. (21). They demonstrated the similarities between the initial, intermediate, and final stages and unified the geometrical parameters in a porosity-dependent scaling parameter, also called the stress intensification factor [$\Gamma(\rho)$]. The traditional model of pressureless sintering is formulated as follows.

$$\frac{\dot{\rho}}{\rho} = \frac{C_0 \alpha \Gamma(\rho)}{G^m k T} \exp\left(-\frac{Q}{RT}\right), \quad 1.$$

with C_0 a material constant, ρ the relative density, α the surface energy, G the grain size, and T the temperature. The exponent term comes from the diffusion coefficient D (D_v for volume diffusion and $\delta_{gb} D_{gb}$ for grain boundary diffusion, with δ_{gb} the grain boundary thickness) with Q the activation energy. From Coble's (22) solid-state sintering models and in accordance with Herring's scaling law (23), the grain size exponent m has a value of 4 for grain boundary diffusion and 3 for volume diffusion (6). R is the perfect gas constant (8.31 J/mol·K). This model from

Hansen et al. (21) combined sintering stage theory is used in well-known modeling approaches, such as the master sintering curve (24), and in regression strategy, such as that in Wang and Raj (25), among others.

The grain size, G , is located in the denominator with an exponent of 3 or 4, depending on the diffusion mechanism. There is, therefore, a high grain-size sensitivity, which reflects the impact of grain size on diffusion distances and driving forces for sintering. The simultaneous modeling of the grain growth during densification is essential, particularly for the final stage. There are numerous grain growth models with and without the pinning effect of porosity, but the following grain growth rate ($\dot{G}$) model is valid in most cases (5, 6, 26):

$$\dot{G} = \frac{k_0}{G^p} \exp\left(\frac{-Q_G}{RT}\right), \quad 2.$$

where the p exponent is 3 for surface diffusion or 2 for bulk mass transport phenomena. The coarsening mechanisms are dependent on the sintering stage. In the early stages, coarsening is usually dominated by surface diffusion and evaporation condensation. In the final sintering stages, the surface area is reduced, and other mechanisms with higher activation energy become dominant; these can include diffusion through the grain boundary or, more likely, grain boundary disconnection nucleation and motion.

Many rapid sintering technologies involve the use of electric fields and currents (FS, SPS, MWS, etc.). Such technologies can affect current and field effects that accelerate the sintering kinetics. The proposed mechanisms involve ponderomotive forces, localized overheating of the grain boundaries, thermodiffusion, interaction between field and currents, point defects concentration and diffusivity, and electromigration. Electromigration is mainly related to the processing of metals and is, therefore, out of the scope of this review, though some reports of electromigration in ceramics exist (27).

The ponderomotive mechanism is a field effect that can occur if high field gradients develop at the triple points and can be activated in MWS (28). A charged particle in an oscillating inhomogeneous electromagnetic field experiences a force directed from the most intense toward the weakest field regions. As highlighted by Rybakov et al. (29), various effects may occur under the influence of the oscillating electromagnetic field. In ionic crystals, a vacancy can be considered a point defect with an effective charge, and the electric field may disturb the concentration of vacancies at the pore surfaces. As the diffusivity is often higher at the grain surface than in the bulk, the electric field normal to the grain surface tends to push the charged vacancies (positively or negatively charged) toward the grain surface. In addition, when the microwave electric field is polarized as in a single mode, the local electric field near a triple point arising from a grain boundary is different depending on whether it is perpendicular or parallel to the field (see **Figure 1b**). Thus, the applied external electric field generates a strong electric field gradient involving guided vacancies and atom flux (marked by the blue arrows in **Figure 1b**). This mass flux tends to remove the matter from the triple junction, decreasing the triple junction curvature radii, which increases the sintering driving force. The experimental demonstration of this phenomenon is not trivial, but an interesting experimental fact is the modification of pore shape, which may become elliptical rather than spherical under the action of a polarized microwave electric field (30, 31) (**Figure 1b**). This phenomenon is the most-often cited mechanism to account for the nonthermal effect of a polarized microwave field on atomic diffusion.

Localized grain boundary overheating might occur in sintering techniques, such as FS, where strong power dissipation occurs in the sample (32). The overheating might be related to the local current concentration and the space charge resistivity. However, the simulations conducted by Holland et al. (33) suggest that the temperature difference between the bulk and grain boundary

is limited, though strong thermal gradients might exist at the microscale. The presence of thermal gradients might activate other mass transport phenomena such as thermodiffusion, that is, diffusion driven by thermal gradients (34, 35).

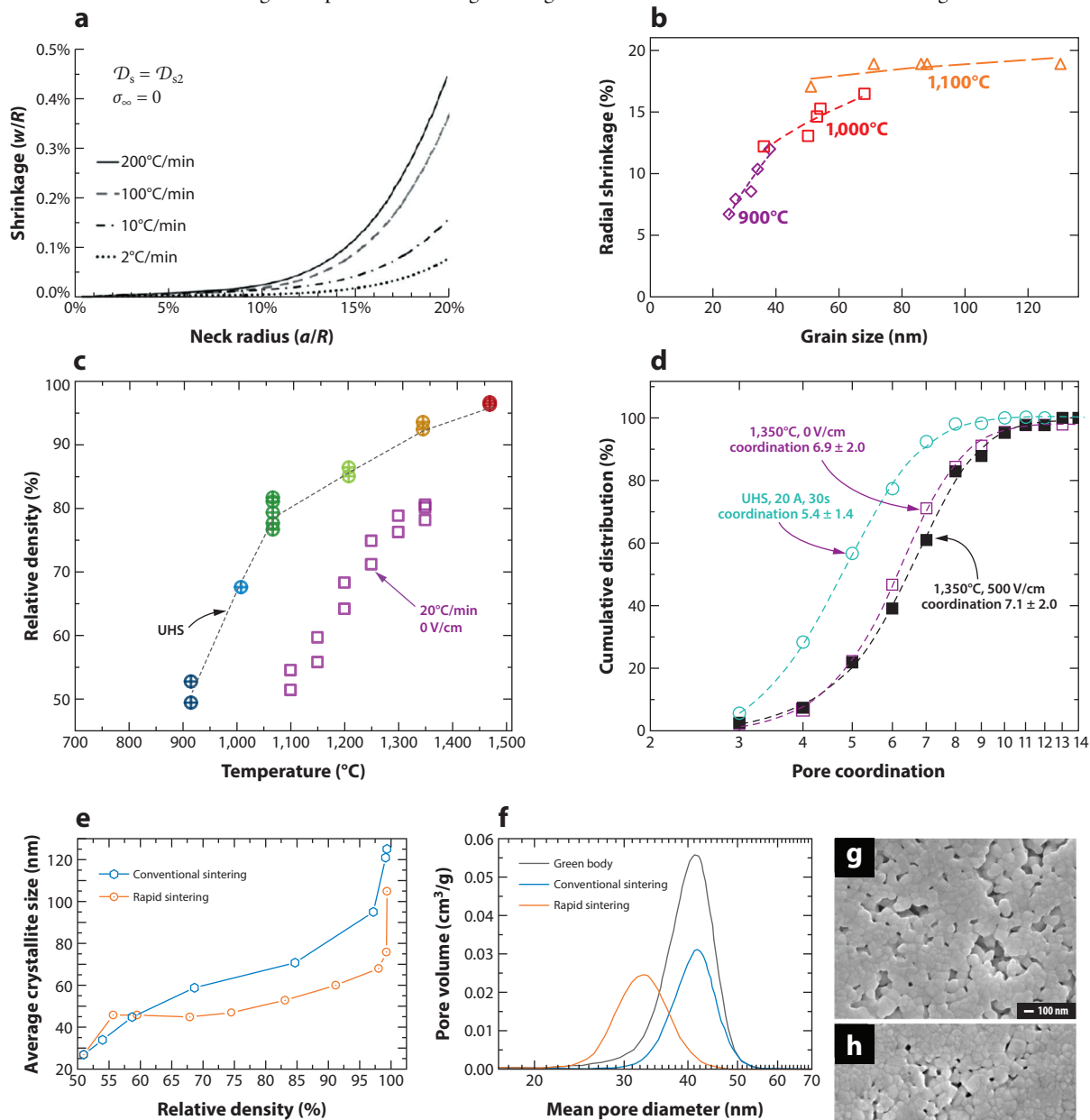
The field or field current can also interact with the point defect chemistry. This has been discussed explicitly for FS, where it has been argued that a point defect (Frenkel pairs) avalanche could occur at the flash onset. This would be induced by the excitation of phonons at the edge of the Brillouin zone (36). The increased point defect concentration would eventually lead to faster diffusion due to the proportionality between the defect concentration and the self-diffusion coefficient in diluted systems. This mechanism is highly controversial and still lacks clear experimental evidence. Comprehensive reviews on the topic are already available (8, 9, 20, 37, 38). On the other hand, the presence of current leads to strong redox phenomena (39–41) that might change the activation energy for diffusion (42), thus interacting with densification and coarsening kinetics (43, 44). The redistribution of point defects due to the presence of the electric field is also well known and experimentally substantiated (45).

2.2. Impact of Heating Rate on Sintering

Distinct mass transport mechanisms contribute to sintering and coarsening at different temperatures, including evaporation and condensation and lattice, grain boundary, and surface diffusion. Generally, the activation energy for grain boundary and lattice diffusion (densifying) is higher than that for evaporation, condensation, and surface diffusion (nondensifying mechanisms). Accordingly, nondensifying mechanisms govern mass transport at low temperatures, causing coarsening and a decrease in $\Gamma(\rho)$, while densifying mechanisms dominate at high temperatures (**Figure 1c,d**). High heating rates reduce the loss of driving force for sintering by passing quickly through the low-temperature region where nondensifying mechanisms dominate. These mechanisms reduce the surface area and capillarity stresses without increasing the density; examples include surface diffusion and evaporation condensation. The inhibition of the nondensifying mechanisms by fast heating has been detected in UHS, FS, pressureless SPS, and FF (20, 46–51). **Figure 2** summarizes some examples. UHS of yttria-stabilized zirconia (YSZ) nanopowder (20-nm particle size) provides a significantly smaller pore and grain size than conventionally sintered materials at the same density level (47), thus increasing the sintering kinetics. Interestingly, the effect seems fainter—though still present—when 40-nm powders are considered (52) and disappears for coarser (90 nm) powder compacts (53). This resulted in only a modest improvement of the sintering kinetics by fast heating or UHS, as described by the modest shift in the master sintering curves (**Figure 2c**). On the other hand, microstructural refinement (pore or crystallite size) has been reported both in samarium-doped ceria (SDC) nanopowders obtained by coprecipitation, where increasing the FF temperature causes a substantial reduction of the crystallite size at the same shrinkage level (51), and in mesoporous YSZ powders constituted by small crystallites (48) (**Figure 2e,f**). These results suggest that grain size is crucial and that rapid heating can achieve greater advantages for tiny nanopowder compacts.

Todd and coworkers (54) have proposed other mechanisms for rapid sintering. These include forming a thinner and less-coordinated pore structure in rapid sintering (probably related to the suppression of surface diffusion) detected after FS or SHS. Such a result has also been confirmed in UHS of 3YSZ (47) and seems, therefore, a universal feature of rapid sintering (**Figure 2g,h**). Additionally, the authors suggested that the grain boundaries formed by rapid sintering might possess an out-of-equilibrium structure and diffusion coefficients different from those obtained conventionally (49, 55) or the formation of a transient liquid through surface impurities melting.

Rheinheimer et al. (58) have recently proposed a new mechanism for explaining rapid sintering and the out-of-equilibrium dislocation density in flash-sintered SrTiO_3 (**Figure 3**). Starting from the concept described above, that rapid heating prevents the loss of driving force for sintering by suppressing surface diffusion, they argued that the sintering stresses that could be preserved at high temperatures are high enough to activate viscous flow and dislocation glide. These lead



(Caption appears on following page)

Figure 2 (Figure appears on preceding page)

(a) Numerical simulation of the sintering of micrometer-sized alumina powder, showing shrinkage versus neck size a , normalized on the particle size R , as temperature increases from 600°C to 1,400°C at different heating rates. (b) Radial shrinkage upon sintering versus grain size of the sintered samarium-doped ceria for different firing temperatures. (c) Density evolution for conventional sintering and ultrafast high-temperature sintering (UHS) of 3 mol% yttria-stabilized zirconia (3YSZ) as a function of temperature. (d) Cumulative distribution of the pore coordination of sintered 3YSZ ceramics after conventional sintering and UHS. (e) Crystallite size–density trajectories of conventionally and rapidly sintered 3YSZ green body derived from the Rietveld refinement. (f) Incremental pore size evolution during conventional sintering and rapid sintering determined by mercury porosimetry ($\rho = 67\text{--}70\%$). (g) Scanning electron microscopy (SEM) micrograph of conventionally sintered 3YSZ at 1,150°C for 60 min ($\rho = 82.6\%$). (h) SEM micrograph of ultrafast-fired 3YSZ at 1,193°C for 6.7 s ($\rho = 89.7\%$). Panel a adapted with permission from Reference 56; copyright 2015 American Ceramics Society. Panel b adapted with permission from Reference 51; copyright 2017 Elsevier. Panels c and d adapted from Reference 47 (CC BY 4.0). Panels e and f adapted from Reference 48 (CC BY 4.0). Panels g and h adapted with permission from Reference 57; copyright 2020 Elsevier.

to a proliferation of dislocations (detected by transmission electron microscopy after FS), which also impacts the properties of the sintered compound. Interestingly, this mechanism suggests that rapid heating not only enhances the driving force for sintering but also alters the densification mechanisms. The conclusion is justified by the fact that the plastic flow rate is proportional to the third (or higher) power of the sintering stresses, whereas the other densification mechanisms are linear. Therefore, fast heating preserves the high sintering stress that can make plastic flow dominant. A vital limitation of this mechanism is that, besides not including any field or current effects, it has not been observed in other rapid sintering technologies such as FF or UHS.

2.3. Rapid Heating Mechanisms

Heat transfer by IR radiation plays a crucial role in rapid sintering techniques (59, 60) such as UHS and FF. This causes limitations on the sample thickness since the sample is heated from the surface. Blacklight sintering (BS) relies only on heat transfer by radiation, though shorter wavelengths are used (mainly in the UV range) that can excite electrons through the band gap (61). Such a technique may increase the absorption ability of the material, raise the heating rate, and enhance

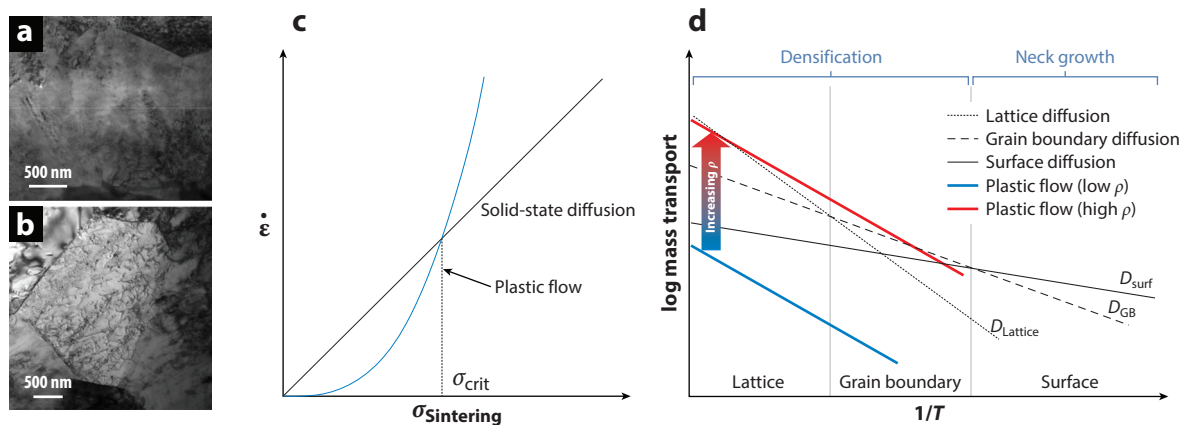


Figure 3

(a) Transmission electron microscopy (TEM) micrograph of conventionally sintered SrTiO_3 at 1,425°C for 1 h with low dislocation density. (b) TEM micrograph of flash-sintered SrTiO_3 with high dislocation density. (c) Influence of plastic flow on densification of SrTiO_3 by flash sintering. (d) Inverse temperature dependence of different mass transport processes on flash sintering of SrTiO_3 . Panels a, b, and d adapted with permission from Reference 58; copyright 2023 Elsevier.

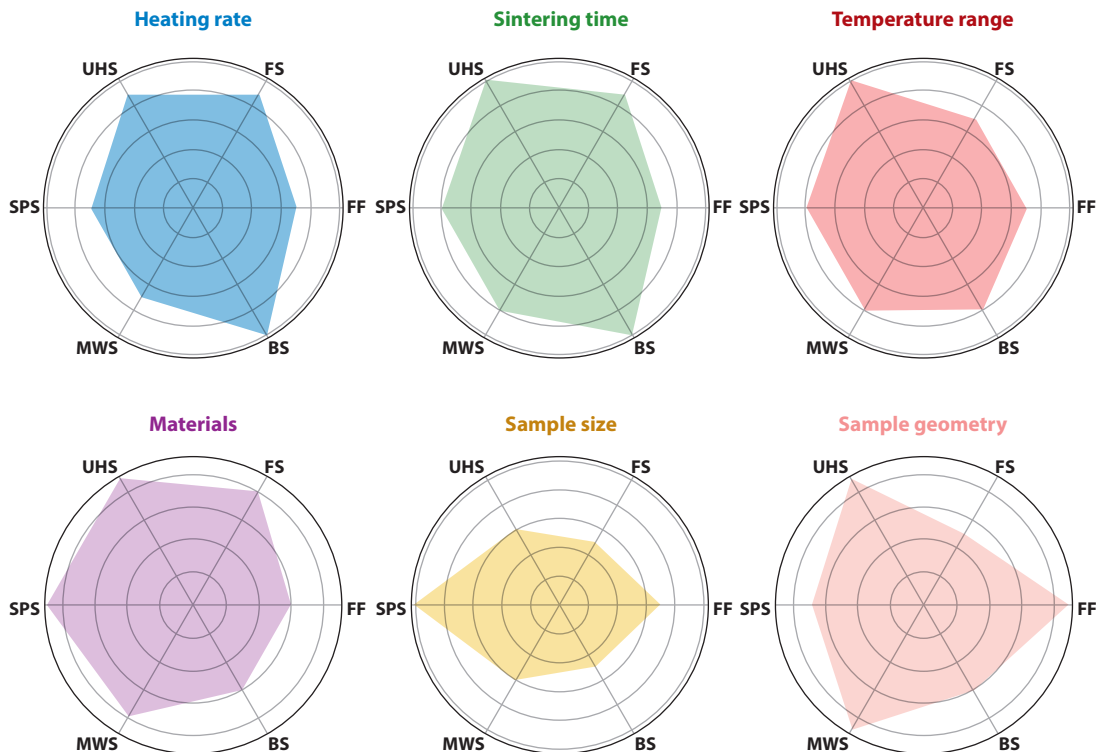


Figure 4

Key processing features including applicability to materials systems, maximum achieved temperature, reduced sintering time, heating rate, and suitability of a greater sample size and complex geometries, which are related to rapid sintering technologies. Abbreviations: BS, blacklight sintering; FF, fast firing; FS, flash sintering; MWS, microwave sintering; SPS, spark plasma sintering; UHS, ultrafast high-temperature sintering.

the overheating of the surface with respect to the bulk. Other rapid sintering techniques such as FS make use of internal heat generation by the Joule effect, resulting in a thermal gradient within the sample that is opposite to what is typically observed in FF and UHS; in FS, the sample surface is colder due to heat losses by radiation (62). MWS presents an intermediate behavior depending on the dielectric loss factor of the ceramic.

3. SINTERING TECHNIQUES WITH A HIGH HEATING RATE

This section discusses the leading rapid sintering technologies, including FF, UHS, FS, SPS, BS, and MWS. These technologies present specific features, advantages, and disadvantages, summarized in **Figure 4**. A detailed discussion can be found in the following subsections.

3.1. Fast Firing

FF is the most straightforward rapid sintering approach, exploiting IR heating of the green body by introducing it quickly within a preheated furnace (**Figure 5**). Reports of using pressureless SPS as a kind of FF furnace also exist (48, 63–67). The typical heating rates are on the order of 100–1,000 K/min.

FF was proposed at the beginning of the 1970s to increase the productivity of the traditional ceramic industry; in fact, traditional ceramics were (and are) fired in continuous tunnel kilns, which

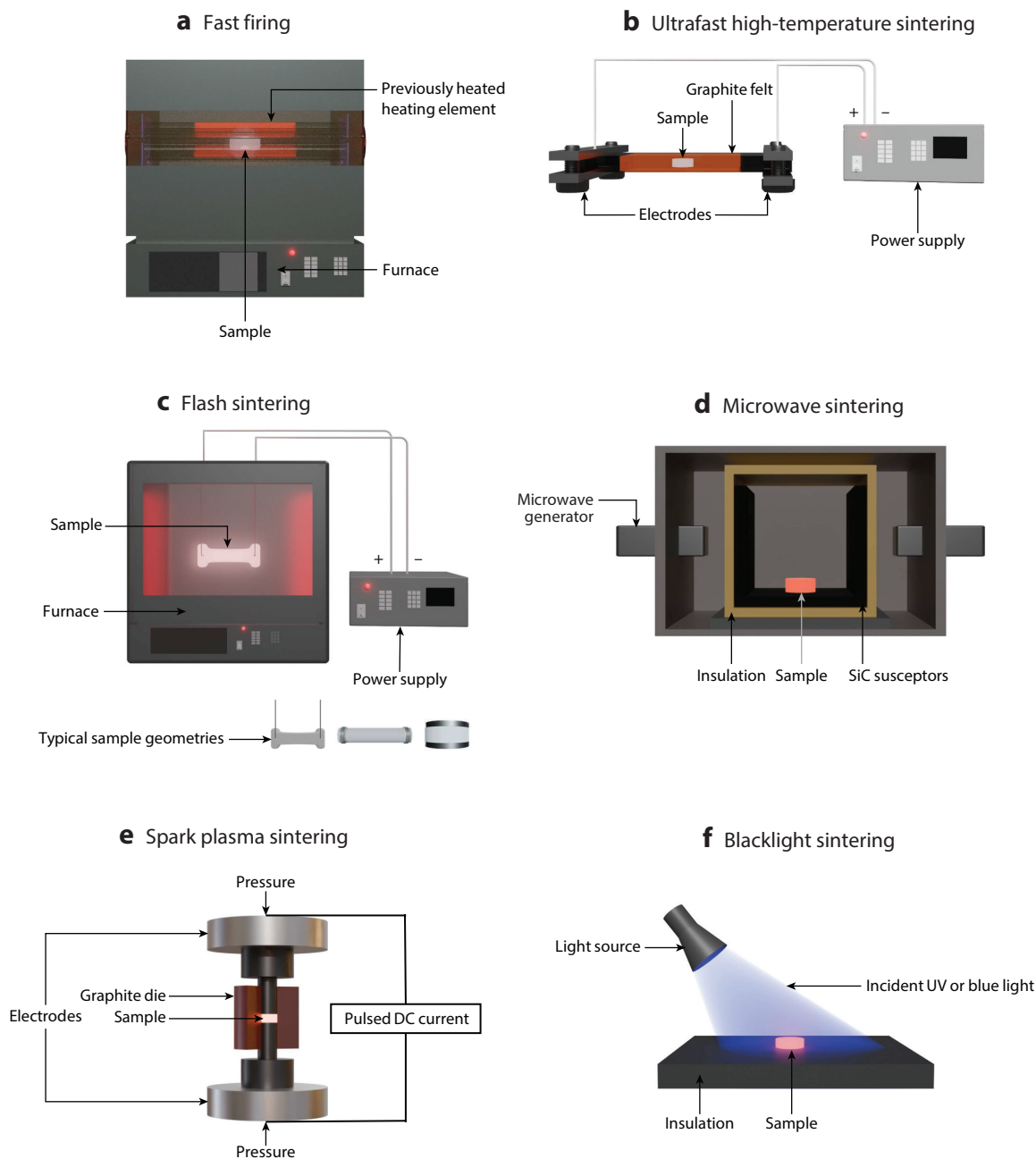


Figure 5

Schematic representations of the working principles of various rapid sintering technologies, including fast firing, ultrafast high-temperature sintering, flash sintering, microwave sintering, spark plasma sintering, and blacklight sintering. Abbreviation: DC, direct current; UV, ultraviolet.

makes it possible and easy for the rapid introduction of the green body in the furnace hot zone (68). During the 1970s, just a few papers on FF could be found in the scientific literature (17 manuscripts over the entire decade, according to Scopus); these are all focused on traditional ceramics (69, 70) and refractories (71–73). During the 1980s, FF started to be applied to technical and advanced ceramics (74–82), and still today, it is studied for the densification of electroceramics (51, 83, 84), including additively manufactured complex lattices (85).

Given the recent development of different rapid sintering techniques, a renewed interest in FF has emerged. In fact, it represents a kind of benchmark for rapid sintering (49, 57), and its comparison with more advanced techniques allows us to differentiate effects associated with rapid heating from those associated with the presence of currents, fields, and electromagnetic radiations.

Fast-fired samples typically possess a refined microstructure (5, 50). For instance, it has been shown that fast-fired SDC nanopowders possess a smaller crystallite size compared with their conventionally sintered counterpart (51) and that reduced pore coarsening occurs in fast-fired 3YSZ (50). FF is also of interest for systems characterized by viscous flow sintering, which might be competitive with crystallization phenomena, as rapid heating favors densification by delaying the crystallization. Some examples include glasses (86) or glass-containing systems, such as Mars regolith simulants (87).

FF is the more mature rapid sintering technology used by the tile production industry. The critical limitation of FF is the development of temperature gradients, which originates as the IR radiation is absorbed at the sample surface (88). Hence, even though complex shapes are possible and the integration between FF and additive manufacturing (AM) has already been proven (67, 85), the thickness of the sample is limited and strongly dependent on the applied heating schedule and thermal properties of the green body.

Moreover, the microstructural advantages of FF hold on until the activation energy for coarsening is lower than that for densification, which is not always true [e.g., MgO possesses a similar activation energy for coarsening and densification (89)]. While there are various studies on FF of oxide materials, research involving nonoxide materials is limited due to specific furnace requirements (e.g., atmosphere-controlled furnaces) (90). The performance of this technique on covalently bonded ceramic materials remains a subject of curiosity.

3.2. Ultrafast High-Temperature Sintering

Wang et al. (46) introduced UHS in 2020. It can be considered the heir of FF as it relies on the IR heating of the specimen, but the setup and typical heating schedules are different. The scale-up studies of UHS carried out since its introduction in 2020 truly demonstrate the potential industrial applicability of this process (46, 91).

UHS enables the rapid densification of monolithic ceramics (10^3 – 10^4 K/min), usually in an inert atmosphere such as argon (46), though rare reports in the air can be found (92). Rapid heating is attained by wrapping the green body within graphite felts, which are quickly Joule-heated by an electric current flow (**Figure 5**); other heating elements, such as tungsten (93) or conductive powder beds (91), have also been considered. Some authors also reported modified setups where thermal insulation is employed to increase the efficiency of the process and concentrate the heat at the sample location (53). The main advantages of UHS are its simple and inexpensive setup, scalability, ability to process multiple samples in a single batch, and possibility of achieving super rapid heating with modest power, as the graphite felt is characterized by a small thermal conductivity and heat capacity. Due to the low thermal conductivity of the felt, the heat concentrates in the

central part of the heating element, thus enabling ultrahigh temperatures that exceed 2,500°C. This allows for the pressureless consolidation of SiC and Si₃N₄ (94–96) as well as ultrahigh temperature ceramics such as ZrB₂–B₄C composites (97), ZrB₂ (98, 99), ZrC (100), Cr₃C₂–TiC (101), high-entropy carbonitrides (102), diborides (103), and carbides (104). Furthermore, the reactivity of the material with the atmosphere can be enhanced at ultrahigh temperatures; it is, therefore, possible to tailor the defect chemistry of the ceramics. For instance, it has been shown that YSZ can react with N_{2(g)} in a few seconds by incorporating N^{3–} in the anionic sublattice (105).

As extreme temperatures can be achieved very quickly, UHS can tailor microstructures, elemental segregations, and the sublimation of volatile elements. It has been shown that 3YSZ nanopowders (20 nm) processed by UHS possess a reduced grain size and pore coordination compared with the samples obtained by conventional sintering at the same density level (the grain size is reduced by more than 60% in the intermediate sintering stages) (47), similar to previous reports on FS (57). Other researchers reported that the rapid heating suppresses the Y³⁺ segregations at the grain boundary of 3YSZ, leading to a more homogeneous phase distribution (57). Recently, it has been shown that UHS prevents undesired Li loss during the sintering of Li_{1.3}Al_{0.3}Ti_{1.7}(PO₄)₃ (106) and Li₇La₃Zr₂O₁₂ (107). Similar conclusions were also reached for cermet, for which UHS reduced metal evaporation (108). The possibility of changing the point defect chemistry, tailoring the grain size, and the segregation and volatilization control makes UHS very attractive for the development of functional electroceramics. As a matter of fact, it has been widely studied for the manufacturing of piezo-, ferro-, and thermoelectrics, as well as ionic conductors (107, 109–114).

An additional driver of the research in UHS is the manufacturing of high-entropy ceramics. In this regard, UHS represents a simple avenue to achieve the temperatures needed for solid-state diffusion and stabilizing the high-entropy compound. Moreover, a quenching of the obtained phases by suddenly removing the electric power can be achieved. Different high-entropy oxide systems have been investigated, including zirconate and hafnates (115–118), fluorites (119), and rock salts (47, 120, 121).

The last driver of the research into UHS is the integration between rapid sintering and complex shapes that can be attained by AM. The first report on UHS by Wang et al. (46) in 2020 already contained the proof of concept of UHS of AM components employing polymer-derived ceramics shaped by stereolithography. Then, Zuo et al. (91) showed that digital light processing could be used to shape alumina samples that, after thermal debinding, are consolidated by UHS. More recently, we have applied UHS to 3YSZ gyroids obtained by fused filament deposition. Before UHS, the lattices were chemically debinded in acetone at near room temperature. This treatment allowed the removal of ~50% of the organic binder; subsequently, the debinding and sintering can be completed in UHS in 30–120 s without needing a prior long thermal debinding (122). Eventually, other AM techniques employing small amounts of binder, such as direct ink writing, showed promising results and could likely be integrated with UHS (85).

The drawbacks of UHS are similar to those of FF, such as the limitations to the sample thickness. On the other hand, UHS presents some peculiar issues such as:

1. The sample can be contaminated with carbon unless tungsten is used as a heating element; however, in this case, contamination from the refractory metal should also be considered.
2. There could be strong reduction phenomena. In some cases, this is welcome, such as when sintering ultrahigh-temperature diborides. It could sometimes represent a serious issue,

though, as it might trigger electronic conductivity (not always desired), darken the sample (122), or cause mechanical failures. It is, for example, not easy to process ceria-based ceramics that might break because of the volume change associated with the variations in the oxidation state of cerium (123, 124).

3. The heating element can be worn quickly and must be replaced to guarantee reproducibility.
4. The temperature measurement is not trivial as the sample location might not be easily accessible (125). Also, the experimental data from shielded thermocouples must be treated with care as the metal shielding can greatly participate in the heat removal from the specimen. Accurate calibration of the sample temperature is therefore needed and can be obtained by checking the melting point of high-purity metals. Temperature calibrations coupled with finite element modeling can provide a picture of the thermal history of the sample.

3.3. Flash Sintering

FS is an electric field-assisted sintering technique developed in 2010 at the University of Colorado (126). An electric field is applied to the ceramic body, and current is forced to flow through it (**Figure 5**). At a specific onset combination of electric field and furnace temperature, densification is triggered by a flash; the flash event occurs for an extremely short time (usually a few seconds). The phenomenon is coupled with sudden sample heating through the Joule effect. After the flash, an equilibrium condition is reached where the power input in the sample is balanced by the radiative losses from its surface; therefore, the surface is generally colder than the bulk. This feature is uncommon (partially shared with MWS) since in most sintering processes, the surface is hotter, absorbing heat from the furnace.

Although flash sintering necessitates a furnace, the temperature typically remains significantly under 1,000°C in most cases. However, specific scenarios, such as with $\alpha\text{-Al}_2\text{O}_3$, may demand elevated temperatures above 1,000°C (2, 127, 128). Nevertheless, these temperatures are several hundred degrees lower than those employed in conventional sintering. A significant advantage of FS lies in its limited processing duration and thermal concentration within the ceramic; this enables the processing of materials with a consolidation temperature even higher than the maximum temperature allowed by the furnace used (129). Although the melting temperature of the platinum electrode is specified as the maximum operating temperature of the system, this value can often be exceeded during the process because platinum is well-conductive and removes heat much faster than the sample (125). The utilization of thermal insulators to prevent thermal distribution (thermally insulated FS) further enhances the efficiency of the process (2, 62).

FS can operate on samples with specific dimensions (usually a few millimeters or centimeters) and simple geometries to guarantee a homogeneous current distribution. Limitations also exist in terms of the electric properties of the material. As power dissipation is needed, a minimum level of conductivity is required (a minimum power of approximately 50 mW/mm³ is required to activate the flash). Generally, FS operates in batches, though some reports on continuous FS also exist (130–132). Moreover, conductive pastes (e.g., silver paste) are usually needed to increase electrical conductivity at the metal–ceramic interface.⁽⁹⁾ To overcome such problems, contactless or touch-free FS systems were introduced, which allow the use of electric arcs, cold plasma, conductive flame, and magnetic field (132–137). Although there have been initial attempts at industrial applications of flash sintering, it seems this technique might remain at the laboratory scale unless relevant developments occur (20).

Much literature has discussed the mechanisms leading to the activation of the flash and the ultrarapid densification throughout the last decade. These have been extensively reviewed, and the

details of opportunities and disadvantages have been provided (8, 9, 137–141). For such reason, we merely underline the latest research trends in the field:

1. Reactive FS is getting growing attention. It provides a quick reaction and simultaneous sintering of different ceramic systems, including high-entropy ceramics (135, 138–141). It can also be employed to crystallize amorphous phases with improved properties (142).
2. Different classes of materials can be integrated with FS, including conductive ceramics with positive temperature coefficients for electrical resistivity such as WC, ZrN, and various metals (143–147).
3. Tailoring the properties of the material is possible by obtaining out-of-equilibrium defects in terms of point (39, 45, 148, 149), line (58), and surface (150, 151) defects and modified solubility (152). For instance, flash-sintered ceramics possess dislocation densities and grain boundaries different from their conventionally sintered counterparts, impacting mechanical (58, 150, 153–159) and functional (153) properties.
4. When reducing the activation temperature of the flash event by forming a plasma between the electrodes, such plasma provides heat to the specimen until it becomes conductive enough to be heated by the Joule effect (160–162).
5. Integrating FS with complex shapes (163) and AM (164–166) increases its productivity and possible geometries with multiphase flash processes (167).

3.4. Microwave Sintering

Microwave heating results from the interactions between matter and electromagnetic radiation, with a frequency ranging from 0.3 to 300 GHz (168, 169). The heating comes from the polarization of electrically charged species within solids (electrons, ions, dipoles, space charges), leading to dielectric loss (170). The complex dielectric constant ($\epsilon^* = \epsilon' - j\epsilon''$) includes two parts: (a) ϵ' is the real permittivity, which characterizes the material's ability to polarize, and (b) ϵ'' is the imaginary part, which quantifies the dielectric losses under microwave radiation. The loss factor $\tan(\delta)$ is the ratio of ϵ'' to ϵ' :

$$\tan(\delta) = \frac{\epsilon''}{\epsilon'}.$$

The power dissipated per unit of volume (P) in a dielectric material is:

$$P = 2\pi f \epsilon_0 \epsilon' \tan(\delta) E_{\text{rms}}^2,$$

where f is the frequency and E is the root mean square value of the microwave electric field.

Dielectric ceramics with low dielectric losses [$\tan(\delta) < 10^{-4}$] behave like transparent materials, making them difficult to heat (171). In contrast, semiconducting ceramics or those with a higher loss factor [$\tan(\delta) > 10^{-2}$], such as SiC and many transition metal oxides (CuO, MnO, Fe₂O₃, etc.), easily convert microwave energy into heat (172).

The penetration depth of microwaves is inversely proportional to the frequency and the loss factor (170). For example, at room temperature and at 2.45 GHz, it is a few tens of centimeters in alumina (173) but only a few millimeters in SiC (174). The material's ability to absorb microwaves usually increases with temperature, meaning that a transparent material at room temperature can become an absorber at higher temperatures. As SiC is stable and couples very easily with microwaves from room temperature to very high temperatures ($> 1,500^\circ\text{C}$), it is often used as a susceptor for microwave sintering of dielectric materials (175). The susceptors absorb microwaves at room temperature and transmit heat to the material, which, eventually, could start to

absorb the MW due to the rise in $\tan(\delta)$. In semiconducting and dielectric materials, energy is typically transferred within the volume of the part, with a penetration depth of a few centimeters, leading to what is often referred to as volumetric heating. This process can achieve high heating rates ($>200^{\circ}\text{C}/\text{min}$) and reduces energy consumption by heating only the piece and its immediate surroundings.

The general setup of a microwave heating system consists of a microwave source, usually a magnetron, delivering variable power at a fixed frequency (176, 177). The most commonly used frequencies are 915 MHz and 2,450 MHz, but other frequencies permitted by current regulations are also possible. From the source, the microwave radiation is transferred to an applicator, or microwave cavity, via a waveguide. Multimode or oversized applicators, whose volume is large compared with the guided wavelength, can be used as applicators. However, at the laboratory scale, resonant cavities are often preferred. Single-mode cavities have dimensions that are multiples of the guided wavelength ($\lambda_g = 17.3$ cm at 2.45 GHz), creating constructive interferences that lead to resonance phenomena. This resonance increases electromagnetic field values as standing wave patterns form within the cavity. With magnetron technology and a single-mode applicator, temperature regulation can be implemented using two feedback loops (176). The first is a conventional proportional–integral–derivative loop, which calculates the incident microwave power to follow up the programmed thermal cycle. The second loop is needed to tune a motorized short-circuit piston, ensuring the reflected power remains minimal.

Additionally, an impedance tuning system is compulsory to ensure the efficient transfer of microwave power to the applicator (176). Manual or automatic three-stub tuners are often used for this purpose in rectangular cavities. Recently, a new generation of microwave sources based on solid-state semiconductor junctions has become available, with microwave power up to a few tens of kilowatts (178). The advantages of solid-state sources over conventional microwave sources are significant: They operate at low voltage instead of the high voltage required by magnetrons and their frequency is monochromatic and stable. It can be automatically tuned (within a small frequency range) for impedance matching. As these microwave sources have just arrived on the market, they are not yet widely used in materials laboratories, especially for high-temperature applications. However, there is no doubt that this new type of microwave source will increase the use of microwave energy for sintering applications.

Microwave furnaces are suitable for FS-like technologies, as they can provide electrodeless rapid heating (**Figure 5**). In 2009, Marinel et al. (179) reported the MWS of CuO and ZnO in less than 2 min by heating the material in a single-mode microwave cavity without any susceptors (heating rate of ~ 400 K/min). Another group also reported the MWS of various oxides, including yttria-doped (LaY) $_2\text{O}_3$ (180), MgAl_2O_4 , and Y_2O_3 (181). They demonstrated the possibility of achieving high relative densities of roughly 98% for all materials in less than 10 min (total heating cycle duration with heating rates from 100 to 200 K/min). Manière et al. (182) showed that direct microwave flash-heating leads to several heterogeneities (183). A first attempt was made using a high heating rate and a SiC susceptor on centimetric zirconia, but the maximum heating rate was limited to 400 K/min (184).

Riquet et al. (185) have recently reported the design of an original multiple-susceptors cascade strategy, allowing heating rates up to 1,000 K/min, with reasonable control from room temperature to high temperature, to sinter YSZ. The principle of these multiple susceptors is to use a SiC susceptor, which heats efficiently from room temperature. Inside the SiC susceptor, another susceptor made of YSZ is heated by its proximity to the SiC. Once its temperature reaches around $700\text{--}800^{\circ}\text{C}$, the YSZ starts to directly absorb the microwave radiation and heats up very rapidly. A phenomenon similar to a thermal runaway occurs, and the zirconia sample placed inside the

two susceptors is subjected to very high heating rates (up to 1,000 K/min). In summary, the susceptor flashes with the sample, providing homogeneous heating. Using this strategy, the authors succeeded in sintering YSZ with a homogeneous microstructure and fine grains in less than 45 s, including 3D-printed YSZ gear structures.

3.5. Spark Plasma Sintering

SPS is a particular type of hot pressing process where the heating is provided directly to the pressing tools by a pulsed current (**Figure 5**) (10). It operates up to high temperatures (2,000°C) and high pressures (100 MPa) in a vacuum, thus enabling the densification of nearly all materials, from metals to ultrarefractory ceramics. Compared with traditional hot pressing, it allows high heating rates (up to 400 K/min). This provides high potential to control the microstructure and minimize the grain growth with improved mechanical properties (186).

After the advent of FS (8, 126), SPS technology appeared quickly as a very promising alternative to traditional FS for the production of numerous materials in a few seconds. The first configuration consists of a sinter-forging pressing of presintered ceramics pellets surrounded by a graphite felt (or foil) that initiates the sample heating; once the sample is conductive enough, it is then internally Joule-heated (187). This allowed the consolidation of ultrarefractory ceramics (188–192) that could not be processed by traditional FS. An alternative FSPS configuration emerged using an electrically isolated die (193, 194) or a thinner die (153) to better control the shape of the flashed sample (166). In general, the hybrid heating of the FSPS configuration is an advantage as it provides a homogeneous microstructure, with the heating coming from both inside and outside the sample. FSPS is flexible and can be applied to materials with different electric properties, from conductors (188) to dielectrics (195).

3.6. Blacklight Sintering

Initial efforts in the late 1960s on intense pulsed light sintering (i.e., photonic sintering) were focused on metals (196), and an increasing interest in the field of ceramics is currently developing (20). Specifically, intense pulsed light sintering has been applied to ceramic coatings (197) using heating sources such as selective laser sintering (198) and rapid thermal annealing with IR heating (199).

BS was developed in 2022 as a novel photonic sintering concept (61). It enables contactless densification of ceramics under high heating rates ($\sim 10^4$ °C/s) (61). In this process, a blue or UV wavelength is employed to enhance the optical absorption in the ceramic powder. One of the important issues for BS is that in order to heat up, the photon energy of the used light source should match or exceed the material's bandgap. Accordingly, xenon flash lamps or blue lasers can be used as light sources to get such wavelengths. Sintering temperatures may exceed 2,000°C depending on the optical absorption ability of the sample, its thermal properties, and the light source used, with irradiation densities typically in the range of 100–200 W/cm² (20). So far, BS has been studied to densify various ceramic materials (61, 200–202). Although there are not many studies yet, possible drawbacks of BS may be the high cost of the light source, geometric constraints, the sample thickness and penetration depth, and certain materials systems for optical absorption characteristics.

4. CHALLENGES IN RAPID SINTERING

4.1. Heating Homogeneity

In the ultrarapid sintering approaches, the homogeneity of the specimen being heated is one of the most important aspects that directly impact the success of the process. In SPS, UHS, BS, and

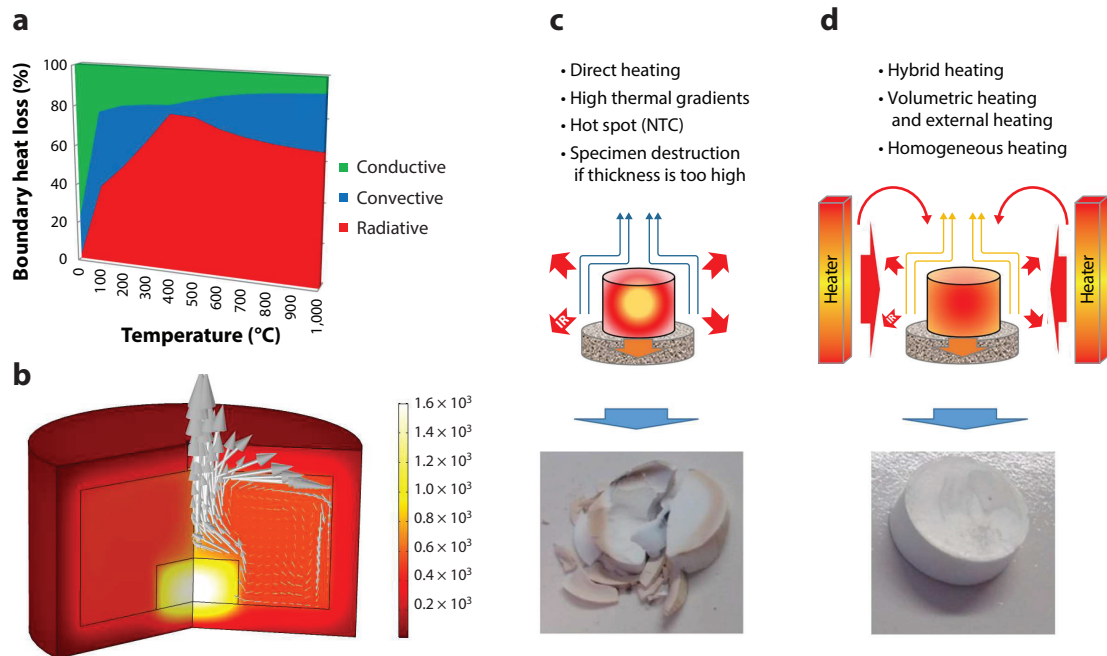


Figure 6

(a) Quantitative proportion of convective, radiative, and conductive cooling fluxes at the specimen surface of (b) a sample directly heating in an insulation box. (c) Direct-heated sample resulting in highly heterogeneous heating. (d) Hybrid-heated specimen with specimen cooling flux compensation by external susceptors (heater). The images below panels c and d are equivalent experiments in microwave sintering. Abbreviation: NTC, negative temperature coefficient for resistivity.

FF, one of the main limitations is related to the sample size, at least in one dimension. However, when direct heating is employed, the problem could become more severe.

Flash sintering uses the Joule effect to achieve a volumetric heating of the material. The heating heterogeneities have two main origins: the cooling fluxes from the surface and electrode region and the heterogeneities of the current or conductivity within the sample. The sample exchanges heat with the environment from its surface by convection and, mainly, radiation; hence, the surface is generally colder than the bulk. Another necessary exchange can develop between the sample and the electrodes by conduction. This could be more relevant when considering bulky metal electrodes used for flashing of cylindrical pellets (whereas such heat loss is nearly negligible in dog-bone specimens).

As reported in **Figure 6**, radiative exchanges are generally dominant at high temperatures. They increase with the fourth power of the absolute temperature. If the specimen is directly heated, the external surfaces are cooled, and a gradient is developed that depends on the specimen thickness, heating rate, thermal properties, and ambient temperature. These could be mitigated through the use of thermal insulation (62) or the use of a susceptor with dielectric (MWS) properties similar to those of the sample. This is probably the most promising solution: The susceptor heats the external specimen surface and counters (compensates for) the cooling fluxes at the origin of the heterogeneities (203). Susceptor cascade with designed dielectric properties has been successfully used for flash MWS (204). For FSPS, the configuration already uses graphite tooling or felt that acts as an electric susceptor, leading to hybrid and homogeneous heating.

The other source of heating heterogeneity is differences in the power dissipation in the sample, which originate from the positive feedback loop between temperature–conductivity–power dissipation in most ceramics (9, 205). Current concentrations can occur for different reasons: The shapes can generate heterogeneities of the current density (or electromagnetic field for MWS), and specimen composition heterogeneities can result in resistivity differences (203) or any random fluctuation in the green density or particle contact geometries. The formation of such hot spots in FS is favored by high power dissipation at the flash transition when the resistivity substantially drops with sintering or when the activation energy for conductivity is high. The main mitigation actions are to use current ramps instead of the standard voltage-to-current control FS mode or to add secondary phases (such as carbon nanomaterials with low activation energy for electrical conductivity) (137).

4.2. Rapid Sintering of Complex Shapes

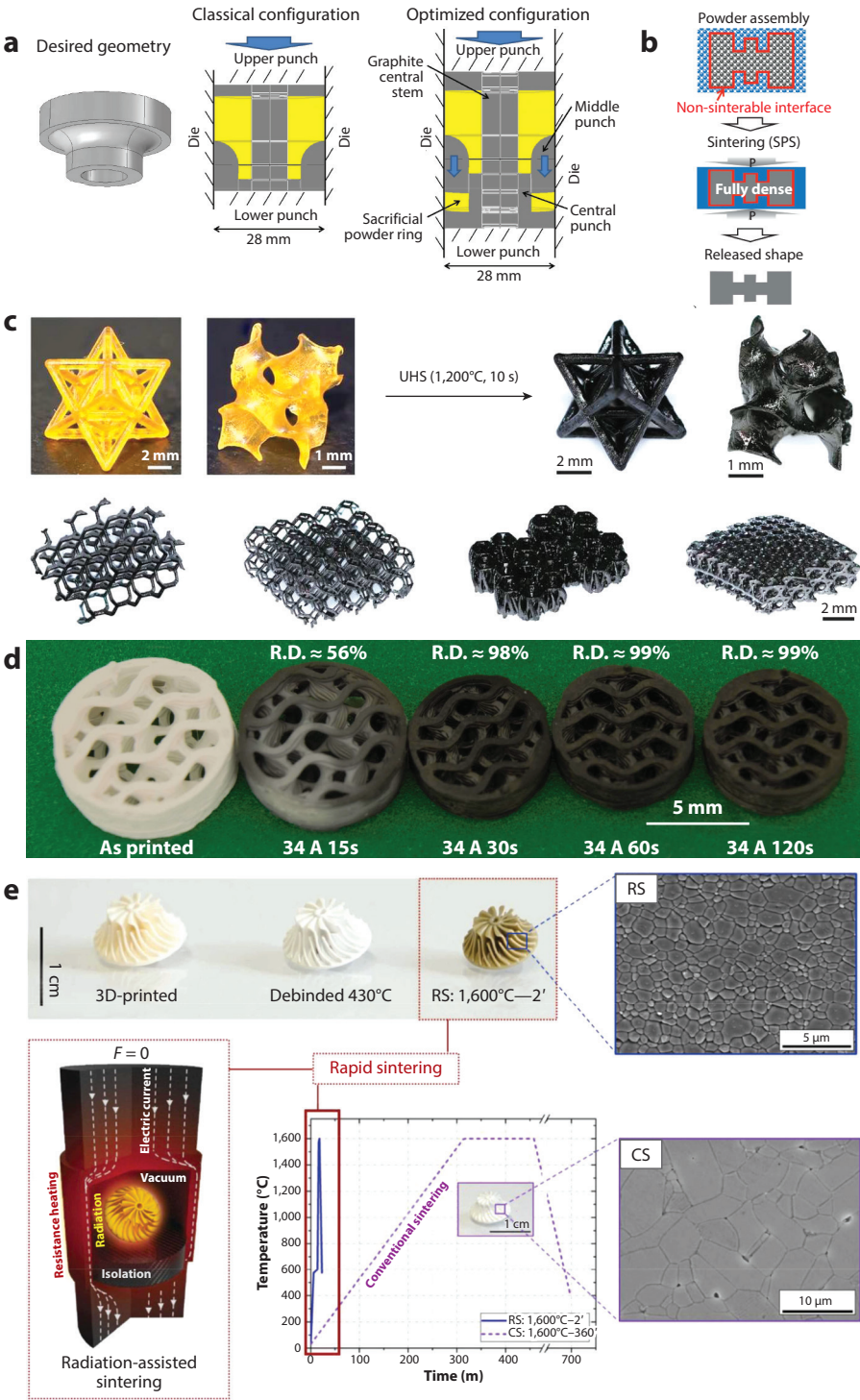
Pressureless sintering approaches are naturally favorable configurations for complex shape production. The only limitation is the use of electrodes in FS, which severely limits the shape to 2D or objects with a constant cross section (204). For flash MWS, the limitation is to ensure a homogeneous heating of the sample, which is difficult in a monomode configuration due to the inherent limitation of the wavelength and its irregular distribution (204). For FSPS, it is possible to use a multiple-punches approach (206) or a deformable-interface (166) approach to obtain complex shapes. For UHS, pressureless SPS, or FF processes, which mainly involve external heating, the configuration is naturally suited to fabricating thin-walled complex shapes (46, 85, 122) (**Figure 7**).

4.3. Processing Maps

The development of tools capable of determining the correct sintering conditions in FS or MWS holds significant technological relevance (9). In the case of FS, a processing map can, for instance, identify the “safe” and “fail” regions on the basis of the applied current and field (**Figure 8a**) (207). The first FS processing map was reported by Trombin & Raj (208) for whiteware, identifying the treatment conditions (in an electric field versus current density plane) that lead to the formation of hot spots. The same approach was recently developed for touch-free FS (136). Similar processing map strategies were also employed for UHS of potassium sodium niobate (KNN) (114). Such maps could be beneficial for future UHS studies, especially for materials with sintering temperatures close to the melting point (such as KNN). Additionally, they may play an active role in controlling microstructural evolution by influencing the stages of densification and grain growth (**Figure 8b**).

An important issue that should be considered with respect to rapid sintering techniques is the determination of the ratio of the sintering temperature and the melting temperature of the material (T_s/T_m). For instance, the sintering temperature of KNN is around 1,120°C, while its melting temperature is 1,140°C (209, 210). Therefore, KNN has a T_s/T_m ratio of 0.98, and based on this value, it can be deduced that the temperature control and homogeneity during sintering must be controlled at the highest level. Also, the reproducibility of the results might be poor, as a few degrees of difference can substantially impact the microstructure or even the sample integrity.

The development of processing maps combining optimal sintering conditions with respect to the material's properties is a key challenge for the next few years. This issue could also be addressed by using artificial intelligence algorithms that can identify the best sintering parameters (211).



(Caption appears on following page)

Figure 7 (Figure appears on preceding page)

(a) Configuration for SPS of complex shapes via a multiple-punch approach with sacrificial material for target geometry. (b) The complex shape-deformed interface approach is used for flash SPS. (c) Before-and-after UHS images of 3D-printed SiOC and some thin-walled complex SiOC structures with different repeating units after the UHS process. (d) Optical images of 3YSZ samples after UHS for different dwell times. (e) Comparison of rapidly sintered and conventionally sintered 3D-printed turbocharger engine rotors. Panel *a* adapted with permission from Reference 206; copyright 2016 Acta Materialia. Panel *b* adapted with permission from Reference 166; copyright 2021 Elsevier. Panel *c* adapted with permission from Reference 46; copyright 2020 The Authors. Panel *d* adapted from Reference 122 (CC BY 4.0). Panel *e* adapted from Reference 67; copyright 2022 The Author(s) (CC BY-NC 4.0). Abbreviations: CS, conventional sintering; F, force; R.D., relative density; RS, rapid sintering; SPS, spark plasma sintering; UHS, ultrafast high-temperature sintering.

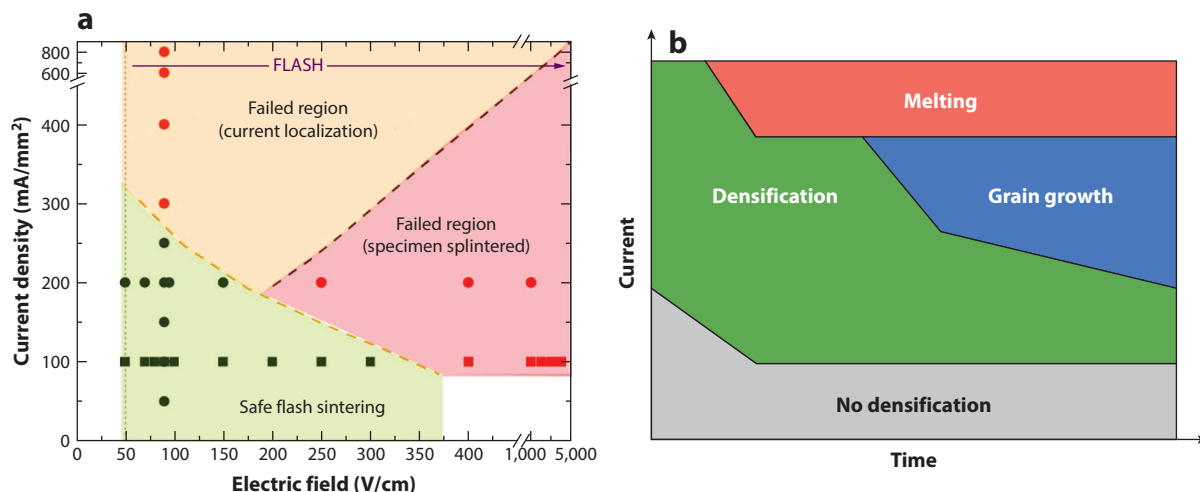


Figure 8

(a) Processing map for flash sintering of gadolinium-doped ceria. Panel adapted with permission from Reference 207; copyright 2021 The Authors (CC BY-NC 4.0). (b) Proposed processing map for ultrafast high-temperature sintering.

5. CONCLUSIONS

Different rapid sintering techniques are being developed at the lab scale, while other mature techniques such as FF are already extensively employed at the industrial level. Rapid heating offers a set of crucial advantages such as refined microstructures, improved sintering kinetics, reduced carbon footprints from sintering, development of out-of-equilibrium materials with reduced space charges/segregations or line defect concentrations, and consolidation of volatile compounds.

Key challenges remain, including developing homogeneous heating and microstructures and integrating complex shapes and nonconventional sintering (such as those achievable by AM). More specifically, such issues challenge techniques where volumetric direct heating is employed, such as in FS and MWS. Different approaches are being explored to mitigate such limitations, including the use of cascade susceptors, thermal insulation, or current ramps.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

L.K. expresses his sincere gratitude to Prof. Dr. Ender Suvacı for the invaluable and insightful discussions.

LITERATURE CITED

1. Carter CB, Norton MG. 2007. *Ceramic Materials: Science and Engineering*. New York: Springer
2. Biesuz M, Grasso S, Sglavo VM. 2020. What's new in ceramics sintering? A short report on the latest trends and future prospects. *Curr. Opin. Solid State Mater. Sci.* 24(5):100868
3. Orton C, Hughes M. 2013. *Pottery in Archaeology*. Cambridge, UK: Cambridge Univ. Press
4. Bender W, Böger HH. 2007. A short history of the extruder in ceramics. In *Extrusion in Ceramics*, ed. F Händle, pp. 85–128. Berlin: Springer
5. Bordia RK, Kang S-JL, Olevsky EA. 2017. Current understanding and future research directions at the onset of the next century of sintering science and technology. *J. Am. Ceram. Soc.* 100(6):2314–52
6. Rahaman MN. 2007. *Sintering of Ceramics*. Boca Raton, FL: CRC Press
7. German RM. 2013. History of sintering: empirical phase. *Powder Metall.* 56(2):117–23
8. Yu M, Grasso S, Mckinnon R, Saunders T, Reece MJ. 2017. Review of flash sintering: materials, mechanisms and modelling. *Adv. Appl. Ceram.* 116(1):24–60
9. Biesuz M, Sglavo VM. 2019. Flash sintering of ceramics. *J. Eur. Ceram. Soc.* 39(2):115–43
10. Guillon O, Gonzalez-Julian J, Dargatz B, Kessel T, Schierning G, et al. 2014. Field-assisted sintering technology/spark plasma sintering: mechanisms, materials, and technology developments. *Adv. Eng. Mater.* 16(7):830–49
11. Galotta A, Sglavo VM. 2021. The cold sintering process: a review on processing features, densification mechanisms and perspectives. *J. Eur. Ceram. Soc.* 41(16):1–17
12. Grasso S, Biesuz M, Zoli L, Taveri G, Duff AI, et al. 2020. A review of cold sintering processes. *Adv. Appl. Ceram.* 119(3):115–43
13. Vakifahmetoglu C, Karacasulu L. 2020. Cold sintering of ceramics and glasses: a review. *Curr. Opin. Solid State Mater. Sci.* 24(1):100807
14. Grasso S, Sakka Y, Maizza G. 2009. Electric current activated/assisted sintering (ECAS): a review of patents 1906–2008. *Sci. Technol. Adv. Mater.* 10(5):053001
15. Chaim R, Chevallier G, Weibel A, Estournès C. 2018. Grain growth during spark plasma and flash sintering of ceramic nanoparticles: a review. *J. Mater. Sci.* 53(5):3087–105
16. Ibn-Mohammed T, Randall CA, Mustapha KB, Guo J, Walker J, et al. 2019. Decarbonising ceramic manufacturing: a techno-economic analysis of energy efficient sintering technologies in the functional materials sector. *J. Eur. Ceram. Soc.* 39(16):5213–35
17. Ndayishimiye A, Sengul MY, Bang SH, Tsuji K, Takashima K, et al. 2020. Comparing hydrothermal sintering and cold sintering process: mechanisms, microstructure, kinetics and chemistry. *J. Eur. Ceram. Soc.* 40(4):1312–24
18. German RM. 1996. *Sintering Theory and Practice*. New York: Wiley
19. Olevsky EA. 1998. Theory of sintering: from discrete to continuum. *Mater. Sci. Eng. R* 23(2):41–100
20. Guillon O, Rheinheimer W, Bram M. 2023. A perspective on emerging and future sintering technologies of ceramic materials. *Adv. Eng. Mater.* 25(18):2201870
21. Hansen JD, Rusin RP, Teng M-H, Johnson DL. 1992. Combined-stage sintering model. *J. Am. Ceram. Soc.* 75(5):1129–35
22. Coble RL. 1961. Sintering crystalline solids. I. Intermediate and final state diffusion models. *J. Appl. Phys.* 32(5):787–92
23. Herring C. 1950. Effect of change of scale on sintering phenomena. *J. Appl. Phys.* 21(4):301–3
24. Su H, Johnson DL. 1996. Master sintering curve: a practical approach to sintering. *J. Am. Ceram. Soc.* 79(12):3211–17
25. Wang J, Raj R. 1990. Estimate of the activation energies for boundary diffusion from rate-controlled sintering of pure alumina, and alumina doped with zirconia or titania. *J. Am. Ceram. Soc.* 73(5):1172–75

26. Zhao J, Harmer MP. 1992. Effect of pore distribution on microstructure development: III, model experiments. *J. Am. Ceram. Soc.* 75(4):830–43
27. Gorynski C, Geiß J, Anselmi-Tamburini U, Winterer M. 2024. Structural and compositional gradients in alternating current sintered aluminum-doped zinc oxide. *Acta Mater.* 270:119855
28. Booske JH, Cooper RF, Freeman SA. 1997. Microwave enhanced reaction kinetics in ceramics. *Mater. Res. Innov.* 1(2):77–84
29. Rybakov KI, Olevsky EA, Krikun EV. 2013. Microwave sintering: fundamentals and modeling. *J. Am. Ceram. Soc.* 96(4):1003–20
30. Link G, Miksch S, Thumm M, Takayama S. 2007. Microwave sintering techniques - more than just a different way of heating? In *Advanced Processing and Manufacturing Technologies for Structural and Multifunctional Materials*, ed. T Ohji, M Singh, pp. 55–66. Hoboken, NJ: Wiley
31. Olevsky EA, Maximenko AL, Grigoryev EG. 2013. Ponderomotive effects during contact formation in microwave sintering. *Model. Simul. Mat. Sci. Eng.* 21(5):055022
32. Chaim R. 2016. Liquid film capillary mechanism for densification of ceramic powders during flash sintering. *Materials* 9(4):280
33. Holland TB, Anselmi-Tamburini U, Quach DV, Tran TB, Mukherjee AK. 2012. Effects of local Joule heating during the field assisted sintering of ionic ceramics. *J. Eur. Ceram. Soc.* 32(14):3667–74
34. Olevsky EA, Froyen L. 2009. Impact of thermal diffusion on densification during SPS. *J. Am. Ceram. Soc.* 92(s1):S122–32
35. Biesuz M, Sglavo VM. 2019. Microstructural temperature gradient-driven diffusion: possible densification mechanism for flash sintering of zirconia? *Ceram. Int.* 45(1):1227–36
36. Jongmanns M, Wolf DE. 2020. Element-specific displacements in defect-enriched TiO₂: indication of a flash sintering mechanism. *J. Am. Ceram. Soc.* 103(1):589–96
37. Raj R, Kulkarni A, Lebrun J-M, Jha S. 2021. Flash sintering: a new frontier in defect physics and materials science. *MRS Bull.* 46(1):36–43
38. Raj R, Wolf DE, Yamada CN, Jha SK, Lebrun J-M. 2023. On the confluence of ultrafast high-temperature sintering and flash sintering phenomena. *J. Am. Ceram. Soc.* 106(7):3983–98
39. Biesuz M, Pinter L, Saunders T, Reece M, Binner J, et al. 2018. Investigation of electrochemical, optical and thermal effects during flash sintering of 8YSZ. *Materials* 11(7):1214
40. Jha SK, Charalambous H, Wang H, Phuah XL, Mead C, et al. 2018. In-situ observation of oxygen mobility and abnormal lattice expansion in ceria during flash sintering. *Ceram. Int.* 44(13):15362–69
41. Mishra TP, Neto RRI, Speranza G, Quaranta A, Sglavo VM, et al. 2020. Electronic conductivity in gadolinium doped ceria under direct current as a trigger for flash sintering. *Scr. Mater.* 179:55–60
42. Dong Y. 2024. Redox enhanced slow ion kinetics in oxide ceramics. *J. Am. Ceram. Soc.* 107(3):1905–16
43. Dong Y, Qi L, Alvarez A, Li J, Chen I-W. 2022. Enhanced mobility of cations and anions in the redox state: the polaronium mechanism. *Acta Mater.* 232:117941
44. Dong Y, Wang H, Chen I-W. 2017. Electrical and hydrogen reduction enhances kinetics in doped zirconia and ceria: I. Grain growth study. *J. Am. Ceram. Soc.* 100(3):876–86
45. Rheinheimer W, Phuah XL, Wang H, Lemke F, Hoffmann MJ, Wang H. 2019. The role of point defects and defect gradients in flash sintering of perovskite oxides. *Acta Mater.* 165:398–408
46. Wang C, Ping W, Bai Q, Cui H, Hensleigh R, et al. 2020. A general method to synthesize and sinter bulk ceramics in seconds. *Science* 368(6490):521–26
47. Biesuz M, de Beauvoir TH, De Bona E, Cassetta M, Manière C, et al. 2024. Ultrafast high-temperature sintering (UHS) versus conventional sintering of 3YSZ: microstructure and properties. *J. Eur. Ceram. Soc.* 44(7):4741–50
48. Kocjan A, Logar M, Shen Z. 2017. The agglomeration, coalescence and sliding of nanoparticles, leading to the rapid sintering of zirconia nanoceramics. *Sci. Rep.* 7(1):2541
49. Ji W, Parker B, Falco S, Zhang JY, Fu ZY, Todd RI. 2017. Ultra-fast firing: effect of heating rate on sintering of 3YSZ, with and without an electric field. *J. Eur. Ceram. Soc.* 37(6):2547–51
50. Kim D-H, Kim CH. 1993. Effect of heating rate on pore shrinkage in yttria-doped zirconia. *J. Am. Ceram. Soc.* 76(7):1877–78
51. Biesuz M, Spiridigliozzi L, Frasnelli M, Dell'Agli G, Sglavo VM. 2017. Rapid densification of samarium-doped ceria ceramic with nanometric grain size at 900–1100°C. *Mater. Lett.* 190:17–19

52. Biesuz M, De Bona E, Manière C. 2024. Fast firing of 3 mol% yttria-stabilized zirconia: on the effect of heating rate on sintering. *J. Am. Ceram. Soc.* 107(10):6596–606
53. Dong J, Pouchly V, Biesuz M, Tyrpekl V, Vilémová M, et al. 2021. Thermally-insulated ultra-fast high temperature sintering (UHS) of zirconia: a master sintering curve analysis. *Scr. Mater.* 203:114076
54. Ji W, Zhang J, Wang W, Fu Z, Todd RI. 2020. The microstructural origin of rapid densification in 3YSZ during ultra-fast firing with or without an electric field. *J. Eur. Ceram. Soc.* 40(15):5829–36
55. Zhang J, Meng F, Todd RI, Fu Z. 2010. The nature of grain boundaries in alumina fabricated by fast sintering. *Scr. Mater.* 62(9):658–61
56. Luo W, Pan J. 2015. Effects of surface diffusion and heating rate on first-stage sintering that densifies by grain-boundary diffusion. *J. Am. Ceram. Soc.* 98(11):3483–89
57. Ji W, Zhang J, Wang W, Fu Z, Todd RI. 2020. The microstructural origin of rapid densification in 3YSZ during ultra-fast firing with or without an electric field. *J. Eur. Ceram. Soc.* 40(15):5829–36
58. Rheinheimer W, Phuah XL, Porz L, Scherer M, Cho J, Wang H. 2023. The impact of flash sintering on densification and plasticity of strontium titanate: high heating rates, dislocation nucleation and plastic flow. *J. Eur. Ceram. Soc.* 43(8):3524–37
59. Salamon D, Kalousek R, Zlámál J, Maca K. 2016. Role of conduction and convection heat transfer during rapid crack-free sintering of bulk ceramic with low thermal conductivity. *J. Eur. Ceram. Soc.* 36(12):2955–59
60. Kermani M, Dong J, Biesuz M, Linx Y, Deng H, et al. 2021. Ultrafast high-temperature sintering (UHS) of fine grained α -Al₂O₃. *J. Eur. Ceram. Soc.* 41(13):6626–33
61. Porz L, Scherer M, Huhn D, Heine L-M, Britten S, et al. 2022. Blacklight sintering of ceramics. *Mater. Horiz.* 9(6):1717–26
62. Biesuz M, Dong J, Fu S, Liu Y, Zhang H, et al. 2019. Thermally-insulated flash sintering. *Scr. Mater.* 162:99–102
63. Bradbury WL, Olevsky EA. 2010. Production of SiC–C composites by free-pressureless spark plasma sintering (FPSPS). *Scr. Mater.* 63(1):77–80
64. Salamon D, Shen Z. 2008. Pressure-less spark plasma sintering of alumina. *Mater. Sci. Eng. A* 475(1):105–7
65. Salamon D, Kalousek R, Maca K, Shen Z. 2015. Rapid grain growth in 3Y-TZP nanoceramics by pressure-assisted and pressure-less SPS. *J. Am. Ceram. Soc.* 98(12):3706–12
66. Kuscer D, Kocjan A, Majcen M, Meden A, Radan K, et al. 2019. Evolution of phase composition and microstructure of sodium potassium niobate-based ceramic during pressure-less spark plasma sintering and post-annealing. *Ceram. Int.* 45(8):10429–37
67. Hofer A-K, Kocjan A, Bermejo R. 2022. High-strength lithography-based additive manufacturing of ceramic components with rapid sintering. *Addit. Manuf.* 59:103141
68. Singh KK, Subrahmanyam AV. 1976. Fast firing of ceramics—a review. *Trans. Indian Ceram. Soc.* 35(1):26–30
69. Moertel H. 1977. Porcelain for fast firing. *Ceramurg. Int.* 3(2):65–69
70. Kudrina AP, Gul'ev GE, Kulichenko VA, Sorokin NA, Sobolev SK, et al. 1971. Temperature distribution in a 130-ton converter lining of tarred brick during fast firing with coke in an oxygen jet. *Refractories* 12(9):636–39
71. Shaw MJ. 1971. Some experiments in fast firing of aluminous refractories. *The Refractories Journal*, Febr., p. 8
72. Leaver NE, Mistler RE. 1972. A gas-fired roller hearth kiln for fast firing high alumina substrates. *Am. Ceram. Soc. Bull.* 51(11):845–46
73. Locsei BP. 1974. Spherical and cylindrical porous mullite-corundum materials produced by fast-firing. *Interceram* 23(4):257–60
74. Hsueh C-C, Mecartney ML, Harrison WB, Renee M, Hanson B, Koepke BG. 1989. Microstructure and electrical properties of fast-fired lead zirconate-titanate ceramics. *J. Mater. Sci. Lett.* 8(10):1209–16
75. Baumgartner CE. 1988. Fast firing and conventional sintering of lead zirconate titanate ceramic. *J. Am. Ceram. Soc.* 71(7):C-350–53

76. Laughner JW, Calnan FJ, Borglum B, Falter LM. 1986. Centrifugation and fast firing of a commercial BaTiO₃ powder. In *Proceedings of the Sixth IEEE International Symposium on Applications of Ferroelectrics*, pp. 381–83. Piscataway, NJ: IEEE
77. Mostaghaci H, Brook RJ. 1983. Production of dense and fine grain size BaTiO₃ by fast firing. *Trans. J. Br. Ceram. Soc.* 82(5):167–70
78. Mostaghaci H, Brook RJ. 1986. Microstructure development and dielectric properties of fast-fired BaTiO₃ ceramics. *J. Mater. Sci.* 21(10):3575–80
79. Powers RW, Mitoff SP, King RN, Bielawski JC. 1981. A beta-alumina fabrication scheme with some special features. *Solid State Ion.* 5:287–90
80. Kassarijan MP, Fox BH, Biggers JV. 1985. Fast firing of a lead-iron niobate dielectric ceramic. *J. Am. Ceram. Soc.* 68(6):C-140
81. Leriche A, Cambier F, Brook RJ. 1986. Study of some factors influencing the microstructural development of mullite-zirconia composites obtained by reaction sintering. In *Special Ceramics 8*, ed. SP Howlett, D Taylor, pp. 167–77. Stoke-on-Trent, UK: Inst. Ceram.
82. Johnson DW, Ghate BB. 1986. Scientific approach to processing of ferrites. In *Advances In Ceramics*, Vol. 15: *Fourth International Conference on Ferrites*, ed. FY Wang, pp 27–38. Columbus, OH: Am. Ceram. Soc.
83. Oliveira RC, Volnistem EA, de Melo MAC, Cótica LF, Santos IA, et al. 2023. On the enhanced dielectric and magnetic properties of BiFeO₃ ceramics sintered under meta-stable conditions. *Appl. Mater. Today.* 32:101790
84. Karacasulu L, Karakaya M, Adem U, Sglavo VM, Biesuz M, Vakifahmetoglu C. 2024. Fast-firing of potassium sodium niobate (KNN). *Open Ceram.* 17:100541
85. Bhandari S, Hanzel O, Veteška P, Janek M, De Bona E, et al. 2024. From rapid prototyping to rapid firing: on the feasibility of high-speed production for complex BaTiO₃ components. *J. Am. Ceram. Soc.* 107(10):6562–73
86. Panda PC, Mobley WM, Raj R. 1989. Effect of the heating rate on the relative rates of sintering and crystallization in glass. *J. Am. Ceram. Soc.* 72(12):2361–64
87. Karacasulu L, Tomasini A, Vakifahmetoglu C, Biesuz M. 2025. Fast firing technique for Martian regolith simulant: advancing ISRU capabilities. *Icarus* 433:116521
88. Hotza D, García DE, Castro RHR. 2015. Obtaining highly dense YSZ nanoceramics by pressureless, unassisted sintering. *Int. Mater. Rev.* 60(7):353–75
89. Rahaman MN. 2017. *Ceramic Processing and Sintering*, Vol. 1. Boca Raton, FL: CRC Press
90. Dole SL, Prochazka S, Doremus RH. 1989. Microstructural coarsening during sintering of boron carbide. *J. Am. Ceram. Soc.* 72(6):958–66
91. Zuo F, Wang Q, Yan Z-Q, Kermani M, Grasso S, et al. 2022. Upscaling ultrafast high-temperature sintering (UHS) to consolidate large-sized and complex-shaped ceramics. *Scr. Mater.* 221:114973
92. Liang Y, Xiang S, Zhang X. 2022. Ultrafast high-temperature heating in air. *J. Eur. Ceram. Soc.* 42(9):4030–39
93. Wu J, Kermani M, Zhu D, Li J, Lin Y, et al. 2022. Carbon free ultra-fast high temperature sintering of translucent zirconia. *Scr. Mater.* 210:114476
94. Luo R-X, Kermani M, Guo Z-L, Dong J, Hu C-F, et al. 2021. Ultrafast high-temperature sintering of silicon nitride: a comparison with the state-of-the-art techniques. *J. Eur. Ceram. Soc.* 41(13):6338–45
95. Li HW, Zhao YP, Chen GQ, Li MH, Wei ZF, et al. 2023. SiC-based ceramics with remarkable electrical conductivity prepared by ultrafast high-temperature sintering. *J. Eur. Ceram. Soc.* 43(5):2269–74
96. Zuo F, Deng Y-N, Liu Z-X, Li Q, Grasso S, et al. 2024. Enhancing densification rate and the unusual 4H-SiC polytype stabilization in ultrafast high-temperature sintering of α -SiC. *J. Eur. Ceram. Soc.* 44(2):610–16
97. De Bona E, Manière C, Sglavo VM, Biesuz M. 2024. Ultrafast high-temperature sintering (UHS) of ZrB₂-based materials. *J. Eur. Ceram. Soc.* 44(1):567–73
98. Mondal S, Lombard JDS, Gollapudi S, Tallon C, Li J-F, Viehland D. 2023. Ultrafast high-temperature sintering of ZrB₂. *J. Am. Ceram. Soc.* 107:11–15
99. De Bona E, Karacasulu L, Vakifahmetoglu C, Sglavo VM, Biesuz M. 2024. Ultrafast high-temperature sintering (UHS) of WC and WC-containing ZrB₂. *J. Alloys Compd.* 986:174102

100. Zhang B, Hu M, Zhong F, Zhang S, Yang Z, et al. 2024. Ultrafast high-temperature sintering and densification of ZrC-based ceramics. *J. Eur. Ceram. Soc.* 44(10):5569–78
101. Sun Y, Zhao L, Guo R-F, Shen P. 2023. Cr₃C₂ assisted ultrafast high-temperature sintering of TiC. *J. Eur. Ceram. Soc.* 43(13):5458–65
102. Che T, Mao H-R, Guo R-F, Shen P. 2023. Ultrafast synthesis and pressureless densification of multicomponent nitride and carbonitride ceramics. *Ceram. Int.* 49(19):31530–38
103. Guo R-F, Mao H-R, Shen P. 2023. Ultra-fast high-temperature synthesis and densification of high-entropy diborides and diboride-carbide ceramics. *J. Eur. Ceram. Soc.* 43(14):5763–73
104. Mao H-R, Dong E-T, Jin S-B, Qiu X-M, Shen P. 2022. Ultrafast high-temperature synthesis and densification of high-entropy carbides. *J. Eur. Ceram. Soc.* 42(10):4053–65
105. Karacasulu L, Hérisson de Beauvoir T, De Bona E, Cassetta M, Vakifahmetoglu C, et al. 2025. Ultrafast high-temperature sintering of yttria-stabilized zirconia in reactive N₂ atmosphere. *J. Eur. Ceram. Soc.* 45(2):116879
106. Lin Y, Luo N, Quattrocchi E, Ciucci F, Wu J, et al. 2021. Ultrafast high-temperature sintering (UHS) of Li_{1.3}Al_{0.3}Ti_{1.7}(PO₄)₃. *Ceram. Int.* 47(15):21982–87
107. Ihrig M, Mishra TP, Scheld WS, Häuschen G, Rheinheimer W, et al. 2021. Li₇La₃Zr₂O₁₂ solid electrolyte sintered by the ultrafast high-temperature method. *J. Eur. Ceram. Soc.* 41(12):6075–79
108. Guo M, Dong Q, Xie H, Wang C, Zhao Y, et al. 2022. Ultrafast high-temperature sintering to avoid metal loss toward high-performance and scalable cermets. *Matter* 5(2):594–604
109. Mishra TP, Wang S, Lenser C, Jennings D, Kindelmann M, et al. 2022. Ultra-fast high-temperature sintering of strontium titanate. *Acta Mater.* 231:117918
110. Boldrini S, Ferrario A, Fasolin S, Miozzo A, Barison S. 2023. Ultrafast high-temperature sintering and thermoelectric properties of n-doped Mg₂Si. *Nanotechnology* 34(15):155601
111. Reavley MJ-H, Guo H, Yuan J, Ng AYR, Ho TYK, et al. 2022. Ultrafast high-temperature sintering of barium titanate ceramics with colossal dielectric constants. *J. Eur. Ceram. Soc.* 42(12):4934–43
112. Zhao X, Wu W, Bai Y, Wu Y, Liu J, et al. 2024. Microstructure evolution and densification behavior of ultrafast high-temperature sintered Li_{6.5}La₃Zr_{1.5}Ta_{0.5}O₁₂ ceramics. *J. Power Sources* 613:234913
113. Li Q, Du H, Zhao X, Zhao F, Zhang Y, et al. 2024. Densification and microstructure evolution of NaNbO₃ ceramic via ultrafast high-temperature sintering. *Ceram. Int.* 50(11):18907–14
114. Miranda JL, Ribeiro C, Tkach A, Senos AMOR, Vilarinho PM. 2024. Ultrafast high-temperature sintering of potassium-sodium niobate: processing and properties. *J. Eur. Ceram. Soc.* 44(15):116701
115. Guo R-F, Mao H-R, Zhao Z-T, Shen P. 2021. Ultrafast high-temperature sintering of bulk oxides. *Scr. Mater.* 193:103–7
116. Zhao Z-T, Guo R-F, Mao H-R, Shen P. 2021. Effect of components on the microstructures and properties of rare-earth zirconate ceramics prepared by ultrafast high-throughput sintering. *J. Eur. Ceram. Soc.* 41(11):5768–73
117. Meng F, Ye F, Luo T. 2024. The high-temperature CMAS corrosion behavior of high-entropy (La_{0.2}Nd_{0.2}Sm_{0.2}Eu_{0.2}Gd_{0.2})₂Hf₂O₇ hafnate thermal barrier coating material with fluorite structure. *J. Eur. Ceram. Soc.* 44(4):2460–70
118. Ye F, Luo T, Meng F, Guo L. 2024. Structure, thermal and mechanical properties of mid-entropy thermal barrier ceramic (Y_{0.3}Gd_{0.3}Yb_{0.4})₄Hf₃O₁₂ prepared by ultrafast high-temperature sintering. *Ceram. Int.* 50(1):181–87
119. Wu J, Lin Y, Hu C, Grasso S, Zhu D, et al. 2023. Ultra-fast high-temperature sintering of transparent MgAl₂O₄. *Ceram. Int.* 49(11):19537–40
120. Bai Y, Li J, Lu H, Liu J, Ma C, et al. 2023. Ultrafast high-temperature sintering of high-entropy oxides with refined microstructure and superior lithium-ion storage performance. *J. Adv. Ceram.* 12(10):1857–71
121. Zhao Y, Zu Y, Wang K, Wang Y, Fu X, et al. 2024. Toughening of (MgCoNiCuZn)O through addition of ZrO₂(3Y) prepared by ultrafast high-temperature sintering. *Ceram. Int.* 50(13):22327–35
122. Bhandari S, Manière C, Sedona F, De Bona E, Sglavo VM, et al. 2024. Ultra-rapid debinding and sintering of additively manufactured ceramics by ultrafast high-temperature sintering. *J. Eur. Ceram. Soc.* 44(1):328–40

123. Alemayehu A, Biesuz M, Javan KY, Tkach A, Vilarinho PM, et al. 2023. Ultrafast high-temperature sintering of gadolinia-doped ceria. *J. Eur. Ceram. Soc.* 43(11):4837–43
124. Kabir A, Lemieszek B, Karczewski J, De Bona E, Varenik M, et al. 2024. Ultrafast high-temperature sintering (UHS) of cerium oxide-based compound. *Open Ceram.* 17:100551
125. Biesuz M, Karacasulu L, Vakifahmetoglu C, Sglavo VM. 2024. On the temperature measurement during ultrafast high-temperature sintering (UHS): Shall we trust metal-shielded thermocouples? *J. Eur. Ceram. Soc.* 44(5):3479–85
126. Cologna M, Rashkova B, Raj R. 2010. Flash sintering of nanograin zirconia in <5 s at 850°C. *J. Am. Ceram. Soc.* 93(11):3556–59
127. Biesuz M, Sglavo VM. 2016. Flash sintering of alumina: effect of different operating conditions on densification. *J. Eur. Ceram. Soc.* 36(10):2535–42
128. Cologna M, Francis JSC, Raj R. 2011. Field assisted and flash sintering of alumina and its relationship to conductivity and MgO-doping. *J. Eur. Ceram. Soc.* 31(15):2827–37
129. Zapata-Solvas E, Bonilla S, Wilshaw PR, Todd RI. 2013. Preliminary investigation of flash sintering of SiC. *J. Eur. Ceram. Soc.* 33(13):2811–16
130. Sortino E, Lebrun J-M, Sansone A, Raj R. 2018. Continuous flash sintering. *J. Am. Ceram. Soc.* 101(4):1432–40
131. Johnson SL, Venugopal G, Hunt AT. 2018. Flame-assisted flash sintering: a noncontact method to flash sinter coatings on conductive substrates. *J. Am. Ceram. Soc.* 101(2):536–41
132. Saunders T, Grasso S, Reece MJ. 2016. Ultrafast-contactless flash sintering using plasma electrodes. *Sci. Rep.* 6(1):27222
133. Johnson SL, Venugopal G, Hunt AT. 2018. Flame-assisted flash sintering: a noncontact method to flash sinter coatings on conductive substrates. *J. Am. Ceram. Soc.* 101(2):536–41
134. Dong J, Wang Z, Zhao X, Biesuz M, Saunders T, et al. 2020. Contactless flash sintering based on cold plasma. *Scr. Mater.* 175:20–23
135. Jalali SIA, Raj R. 2022. Touch-free flash sintering with magnetic induction within a reactor activated by the usual flash method. *J. Am. Ceram. Soc.* 105(11):6517–22
136. Çetinkaya Z, Raj R. 2024. Processing map for touch-free flash sintering of a whiteware ceramic. *J. Am. Ceram. Soc.* 107(9):5720–27
137. Jones GM, Biesuz M, Ji W, John SF, Grimley C, et al. 2021. Promoting microstructural homogeneity during flash sintering of ceramics through thermal management. *MRS Bull.* 46(1):59–66
138. Das S, Durygin A, Drozd V, Sozal MSI, Cheng Z. 2024. Reactive flash sintering of TiZrN and TiAlN ternary metal nitrides. *J. Eur. Ceram. Soc.* 44(4):2037–51
139. Tyagi PK, Jha SK. 2024. Flash sintering improves the densification and mechanical properties of high entropy oxides used in anodic applications. *Materialia* 33:101967
140. Yoon B, Campos JV, Lavagnini IR, Avila V, Gardner JM, et al. 2024. Phase evolution during conventional and reactive flash sintering of (Mg,Ni,Co,Cu,Zn)O via in situ X-ray diffraction. *J. Am. Ceram. Soc.* 107(2):785–96
141. Xu C, He J, Chen Z, Zhao G, Cai S, et al. 2024. Two-step reactive flash sintering of high entropy pyrochlore: densification, grain growth, and microstructural homogeneity. *J. Am. Ceram. Soc.* 107(2):797–802
142. Campos JV, Lavagnini IR, Zallocco VM, Jesus LM, Rodrigues ACM. 2024. Ultrafast crystallization and sintering of Li_{1.3}Al_{0.3}Ti_{1.7}(PO₄)₃ glass through flash sinter-crystallization. *J. Am. Ceram. Soc.* 107(3):1806–21
143. Deng H, Biesuz M, Vilémová M, Kermani M, Veverka J, et al. 2021. Ultrahigh temperature flash sintering of binder-less tungsten carbide within 6 s. *Materials* 14(24):7655
144. Sglavo VM, De Bona E, Mazo I. 2024. Flash sintering of metal-like ceramics: a short overview. *Ceram. Int.* 50(19):37356–65
145. Zhang D, Xiang S, Liang Y, Li T, Tang C, et al. 2024. Ultrafast fabrication of W/Cu composites using flash sintering. *Mater. Chem. Phys.* 321:129501
146. Eskandariyun A, Das S, Dubois D, Saedian K, Durygin A, et al. 2024. Effects of processing conditions on flash sintering of commercial ZrN. *J. Am. Ceram. Soc.* 107(6):3735–50

147. Bamidele EA, Mahmoud MM, Raj R. 2024. Current rate flash sintering of nickel at ambient temperature in <1 min. *J. Am. Ceram. Soc.* 107(6):3659–65
148. Bechteler C, Todd RI. 2023. Lattice modification of ZrO_{2-8} and formation of rocksalt structure ZrO and Zr(O,N) after DC electrical loading of 3YSZ. *J. Eur. Ceram. Soc.* 44(2):1044–52
149. Jo S, Kindelmann M, Jennings D, Balice L, Sohn YJ, et al. 2024. Flash-induced defects in single-crystal 8YSZ characterized by TEM, XRD, and Raman spectroscopy. *J. Am. Ceram. Soc.* 107(9):5786–800
150. Li J, Cho J, Ding J, Charalambous H, Xue S, et al. 2024. Nanoscale stacking fault-assisted room temperature plasticity in flash-sintered TiO_2 . *Sci. Adv.* 5(9):eaaw5519
151. Seko M, Kayukawa S, Inagaki S, Tokunaga T, Yamamoto T. 2024. Variation of grain boundary dihedral angles caused by voltage-to-current-based flash treatment in fully stabilized yttria-doped zirconia polycrystals. *J. Ceram. Soc. Jpn.* 132(2):63–67
152. Raj A, Jha SK. 2024. Hyperdoping: doping TiO_2 beyond thermodynamic limits using flash sintering. *J. Eur. Ceram. Soc.* 44(15):116720
153. Hérissou de Beauvoir T, Ghomari Z, Chevallier G, Flaureau A, Weibel A, et al. 2021. Flash spark plasma sintering of 3YSZ: modified sintering pathway and impact on grain boundary formation. *J. Eur. Ceram. Soc.* 41(15):7762–70
154. Mazo I, Monclus MA, Molina-Aldareguia JM, Sglavo VM. 2024. Fracture resistance of binderless tungsten carbide consolidated by spark plasma sintering and flash sintering. *Open Ceram.* 17:100533
155. Masuda H, Morita K, Tokunaga T, Yamamoto T, Yoshida H. 2022. Anelasticity induced by AC flash processing of cubic zirconia. *Acta Mater.* 227:117704
156. Mazo I, Monclus MA, Molina-Aldareguia JM, Sglavo VM. 2023. Does flash sintering alter the deformation mechanisms of tungsten carbide? *Acta Mater.* 258:119227
157. Zhao R, Shao G, He H, Liu D, Han D, et al. 2023. Mechanical behavior of ZrO_2 ceramics in the post-flash stage. *Mater. Sci. Eng. A* 867:144724
158. Masuda H, Tokunaga T, Yamamoto T, Yoshida H. 2024. Optical and mechanical properties of rutile TiO_2 subjected to AC flash processing. *Scr. Mater.* 246:116088
159. Cho J, Li Q, Wang H, Fan Z, Li J, et al. 2018. High temperature deformability of ductile flash-sintered ceramics via in-situ compression. *Nat. Commun.* 9(1):2063
160. Li Y, Xu C, Huang R, Zhao X, Wang X, Jia Z. 2023. Mechanism analysis of arc-induced flash sintering of 3YSZ at room temperature. *J. Eur. Ceram. Soc.* 43(15):7033–40
161. Bechteler C, Gibson A, Falco S, Kirkpatrick A, Todd RI. 2024. Plasma formation during flash sintering of boron carbide – part I: plasma characteristics. *Ceram. Int.* 50(19):37241–50
162. Zhu Y, Zhou H, Huang R, Yan N, Wang X, et al. 2022. Gas-discharge induced flash sintering of YSZ ceramics at room temperature. *J. Adv. Ceram.* 11(4):603–14
163. Nunes FC, Alves MFRP, Olhero SM, Lévaro NRM, Pallone EMJA, Santos C. 2024. Abnormal grain growth inhibition of extrusion-based 3D-printed 3Y-TZP ceramics sintered by flash sintering. *Ceram. Int.* 50(7):11273–82
164. Hagen D, Beaman JJ, Kovar D. 2020. Selective laser flash sintering of 8-YSZ. *J. Am. Ceram. Soc.* 103(2):800–8
165. Hagen D, Beaman JJ, Kovar D. 2023. Mechanisms responsible for the onset of selective laser flash sintering of 8-YSZ. *J. Am. Ceram. Soc.* 106(8):4592–604
166. Manière C, Lee G, Olevsky EA. 2022. Flash sintering of complex shapes. *Appl. Mater. Today* 26:101293
167. Molina-Molina S, Gil-González E, Durán-Olivencia FJ, Valverde JM, Perejón A, et al. 2022. A novel multi-phase flash sintering (MPFS) technique for 3D complex-shaped ceramics. *Appl. Mater. Today* 26:101274
168. Chandrasekaran S, Ramanathan S, Basak T. 2012. Microwave material processing—a review. *AIChE J.* 58(2):330–63
169. Falciglia PP, Roccaro P, Bonanno L, De Guidi G, Vagliasindi FGA, Romano S. 2018. A review on the microwave heating as a sustainable technique for environmental remediation/detoxification applications. *Renew. Sustain. Energy Rev.* 95:147–70
170. Meloni E, Iervolino G, Palma V. 2023. Basics of microwave heating and recent advances. In *Advances in Microwave-Assisted Heterogeneous Catalysis*, ed. J Hu, BM Reddy, pp. 1–24. Cambridge, UK: R. Soc. Chem.

171. Karayannis VG. 2016. Microwave sintering of ceramic materials. *IOP Conf. Ser. Mater. Sci. Eng.* 161:012068
172. Agrawal D. 2006. Microwave sintering of ceramics, composites and metallic materials, and melting of glasses. *Trans. Indian Ceram. Soc.* 65(3):129–44
173. Shang X, Zhai D, Zhang F, Wei C, Chen J, et al. 2019. Electromagnetic waves transmission performance of alumina refractory ceramics in 2.45 GHz microwave heating. *Ceram. Int.* 45(17):23493–500
174. Amini A, Latifi M, Chaouki J. 2021. Electrification of materials processing via microwave irradiation: a review of mechanism and applications. *Appl. Therm. Eng.* 193:117003
175. Mohanty A, Patel DK, Panigrahi SK. 2024. Susceptor based design strategies for enhancing microwave hybrid heating capability via experimental analysis, 3D multi-physics simulation and parametric optimization. *Int. J. Therm. Sci.* 196:108674
176. Marinel S, Renaut N, Savary E, Macaigne R, Riquet G, et al. 2018. Tuning, impedance matching, and temperature regulation during high-temperature microwave sintering of ceramics. *Adv. Mater. Sci. Eng.* 2018(1):4158969
177. Valverde C, Rodríguez-García M-M, Rojas E, Bayón R. 2024. State of the art of the fundamental aspects in the concept of microwave-assisted heating systems. *Int. Commun. Heat Mass Transf.* 156:107594
178. Zhou X, Pedrow PD, Tang Z, Bohnet S, Sablani SS, Tang J. 2023. Heating performance of microwave ovens powered by magnetron and solid-state generators. *Innov. Food Sci. Emerg. Technol.* 83:103240
179. Marinel S, Savary E, Gomina M. 2010. Sintering of CuO and ZnO in a single mode microwave cavity with shrinkage control. *J. Microw. Power Electromagn. Energy* 44(1):57–63
180. Bykov YV, Egorov SV, Ereemeev AG, Kholoptsev VV, Rybakov KI, Sorokin AA. 2015. Flash microwave sintering of transparent Yb:(LaY)₂O₃ ceramics. *J. Am. Ceram. Soc.* 98(11):3518–24
181. Bykov YuV, Egorov SV, Ereemeev AG, Plotnikov IV, Rybakov KI, et al. 2018. Flash sintering of oxide ceramics under microwave heating. *Tech. Phys.* 63(3):391–97
182. Manière C, Lee G, Torresani E, Gerling JF, Yakovlev VV, et al. 2020. Flash microwave pressing of zirconia. *J. Am. Ceram. Soc.* 103(8):4110–21
183. Manière C, Zahrah T, Olevsky EA. 2017. Inherent heating instability of direct microwave sintering process: sample analysis for porous 3Y-ZrO₂. *Scr. Mater.* 128:49–52
184. Manière C, Harnois C, Riquet G, Grippi T, Behar-Lafenetre S, Marinel S. 2023. Rapid microwave sintering of centimetric zirconia: scalability and electromagnetic-thermal-fluid-dynamic simulation. *J. Am. Ceram. Soc.* 106(2):848–59
185. Riquet G, Grippi T, Harnois C, Marinel S, Manière C. 2023. Flash microwave sintering of zirconia by multiple susceptors cascade strategy. *J. Eur. Ceram. Soc.* 43(11):4896–905
186. Orrù R, Licheri R, Locci AM, Cincotti A, Cao G. 2009. Consolidation/synthesis of materials by electric current activated/assisted sintering. *Mater. Sci. Eng. R* 63(4):127–287
187. Vasylyk O, Borodianska H, Sakka Y, Demirskyi D. 2016. Flash spark plasma sintering of ultrafine yttria-stabilized zirconia ceramics. *Scr. Mater.* 121:32–36
188. Grasso S, Saunders T, Porwal H, Cedillos-Barraza O, Jayaseelan DD, et al. 2014. Flash spark plasma sintering (FSPS) of pure ZrB₂. *J. Am. Ceram. Soc.* 97(8):2405–8
189. Grasso S, Saunders T, Porwal H, Milsom B, Tudball A, Reece M. 2016. Flash spark plasma sintering (FSPS) of α and β SiC. *J. Am. Ceram. Soc.* 99(5):1534–43
190. Olevsky EA, Roling SM, Maximenko AL. 2016. Flash (ultra-rapid) spark-plasma sintering of silicon carbide. *Sci. Rep.* 6(1):33408
191. McKinnon R, Grasso S, Tudball A, Reece MJ. 2017. Flash spark plasma sintering of cold-Pressed TiB₂-hBN. *J. Eur. Ceram. Soc.* 37(8):2787–94
192. Zou J, Grasso S, Liu L-F, Ma H-B, Reece M, Binner J. 2018. Flash spark plasma sintering of HfB₂ ceramics without pre-sintering. *Scr. Mater.* 156:115–19
193. Manière C, Lee G, Olevsky EA. 2017. All-materials-inclusive flash spark plasma sintering. *Sci. Rep.* 7(1):15071
194. Zapata-Solvas E, Gómez-García D, Domínguez-Rodríguez A, Todd RI. 2015. Ultra-fast and energy-efficient sintering of ceramics by electric current concentration. *Sci. Rep.* 5(1):8513
195. Manière C, Riquet G, Marinel S. 2019. Dielectric properties of flash spark plasma sintered BaTiO₃ and CaCu₃Ti₄O₁₂. *Scr. Mater.* 173:41–45

196. Jang Y-R, Joo S-J, Chu J-H, Uhm H-J, Park J-W, et al. 2021. A review on intense pulsed light sintering technologies for conductive electrodes in printed electronics. *Int. J. Precis. Eng. Manuf. Green Technol.* 8(1):327–63
197. Gilshtein E, Pfeiffer S, Rossell MD, Sastre J, Gorjan L, et al. 2021. Millisecond photonic sintering of iron oxide doped alumina ceramic coatings. *Sci. Rep.* 11(1):3536
198. Chen A-N, Wu J-M, Liu K, Chen J-Y, Xiao H, et al. 2018. High-performance ceramic parts with complex shape prepared by selective laser sintering: a review. *Adv. Appl. Ceram.* 117(2):100–17
199. Zhang Y, Nie J, Chan JM, Luo J. 2017. Probing the densification mechanisms during flash sintering of ZnO. *Acta Mater.* 125:465–75
200. Porz L, Scherer M, Muhammad QK, Higuchi K, Li Y, et al. 2022. Microstructure and conductivity of blacklight-sintered TiO₂, YSZ, and Li_{0.33}La_{0.57}TiO₃. *J. Am. Ceram. Soc.* 105(12):7030–35
201. Scherer M, Ameres M-G, Rheinheimer W, Frömling T, Rödel J, Fulanović L. 2023. Blacklight sintering of BaTiO₃ ceramics. *J. Eur. Ceram. Soc.* 43(12):5406–11
202. Scheld WS, Ebert JN, Scherer M, Fulanovic L, Porz L, et al. 2024. Blacklight sintering of garnet-based composite cathodes. *J. Eur. Ceram. Soc.* 44(5):3039–48
203. Manière C, Borie F, Marinel S. 2020. Impact of convection and radiation on direct/hybrid heating stability of field assisted sintering. *J. Manuf. Process* 56:147–57
204. Yang B, Cho J, Phuah XL, Wang H, Zhang X. 2021. Flash sintering of additively manufactured 3YSZ gears. *J. Am. Ceram. Soc.* 104(8):3828–32
205. Dong Y. 2017. On the hotspot problem in flash sintering. arXiv:1702.05565 [cond-mat.mtrl-sci]
206. Manière C, Durand L, Weibel A, Chevallier G, Estournès C. 2016. A sacrificial material approach for spark plasma sintering of complex shapes. *Ser. Mater.* 124:126–28
207. Mishra TP, Lenser C, Raj R, Guillon O, Bram M. 2021. Development of a processing map for safe flash sintering of gadolinium-doped ceria. *J. Am. Ceram. Soc.* 104(9):4316–28
208. Trombin F, Raj R. 2014. Developing processing maps for implementing flash sintering into manufacture of whiteware ceramics. *Am. Ceram. Soc. Bull.* 93(6):32–35
209. Karacasulu L, Vakifahmetoglu C. 2023. Cold sintering assisted two-step sintering of potassium sodium niobate (KNN) ceramics. *Mater. Sci. Eng. B* 297:116709
210. López R, González F, Cruz MP, Villafuerte-Castrejon ME. 2011. Piezoelectric and ferroelectric properties of K_{0.5}Na_{0.5}NbO₃ ceramics synthesized by spray drying method. *Mater. Res. Bull.* 46(1):70–74
211. de Abreu MG, Pallone EMJA, Ferreira JA, Campos JV, de Sousa RV. 2021. Evaluation of machine learning based models to predict the bulk density in the flash sintering process. *Mater. Today Commun.* 27:102220