INL/CON-25-82797-Revision-0

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June 2025

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Idaho National Laboratory

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http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

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Keywords: Ceramics, debinding, additive manufacturing, modeling, simulation

INTRODUCTION

Microwave-assisted debinding offers an economical approach to processing 3D-printed engineering ceramics [1]. Ceramic parts produced with photopolymer-based additive manufacturing techniques require thermal debinding to remove polymers that bind ceramic particles during the printing process. Microwave-assisted debinding significantly reduces processing times and offers energy savings over conventional thermal treatments due to higher heating rates and more uniform heating. Finite-element modeling of the debinding process allows for the optimization and prediction of temperature distribution, stress development, and potential defects, leading to improved process control and material quality.

METHODOLOGY

Microwave processing enables volumetric heating by directly transferring microwave energy to the 3D printed part, leading to efficient and rapid binder removal. This occurs at the molecular level through friction between molecules, caused by dipolar rotation and the movement of conducting ions in an electric field. After debinding the green parts, sintering is required to densify the ceramic material, enhancing its mechanical strength and structural integrity. Conventional debinding and sintering processes use standard furnaces and thermal treatments, typically resulting in long operating times and high energy consumption. Canillas et al. [2] conducted a comparative study in which alumina printed parts were debound and sintered using microwave and/or conventional heating in an electric furnace. They found that both debinding methods achieved similar relative densities and that microwave debinding did not introduce additional defects compared to conventional thermal debinding. However, microwave processing reduced debinding time by 70%. Microwave sintering resulted in lower densification due to the lower achievable temperatures compared to conventional thermal sintering and therefore is not used in our research.

The microwave source used in our research is a high-power, large format microwave oven operating at 2.45 GHz with a maximum power of 2100 watts (Model BP-210, Microwave Research Associates, Carol Stream, IL). Microwave energy enters the process cavity through four mode stirrers—two positioned above and two below the cavity—to ensure

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uniform heating. The standard low temperature floor has been replaced with a high temperature ceramic rod floor. Absorbent materials can be directly heated, while low loss (such as alumina) or reflective materials require a susceptor [3]. A susceptor, which is a microwave-absorbent material at room temperature, initiates heating until the sample's dielectric loss increases, allowing for direct microwave heating. Silicon carbide (SiC)-coated alumina/silicate composite muffles can be inserted within the internal cavity to provide hybrid heating of the samples (Figure 1). Power can be controlled either manually or by a process controller. Regulating the incident power is crucial because uncontrollable heating rates can cause rapid decomposition of the photopolymer and produce a large volume of gas, potentially damaging the green ceramic body.

Figure 1. Microwave unit with SiC coated muffle.

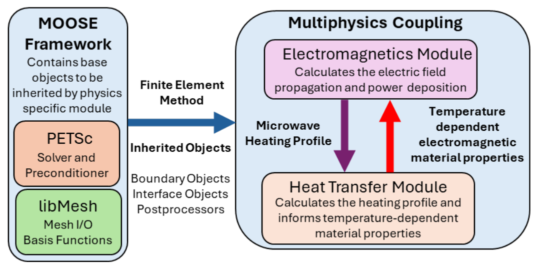

Figure 2. Structure of MOOSE application.

Idaho National Laboratory's Multiphysics Object-Oriented Simulation Environment (MOOSE) is an open source multiphysics framework based on the finite element method [4] that is employed to simulate debinding scenarios and offer insights to guide the optimization of microwave furnace parameters for improved process outcomes. Electromagnetic and heat transfer modules are internally coupled within MOOSE (Figure 2), which can provide the electric field, power deposition, and material heat profiles [5]. The primary coupling mechanism between the two physics domains is the temperature dependent electromagnetic material properties, the conductivity and dielectric coefficients, in the two primary equations of:

$$\nabla \times \left(\nabla \times \vec{E}\right) = \mu_0(\omega^2 \varepsilon_0 \varepsilon_r - j\omega\sigma)\vec{E} \tag{1}$$

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-\kappa \nabla T) = Re\left(\sigma \vec{E} \cdot \vec{E}^*\right) \tag{2}$$

where $\vec{E}$ is the electric field, $\vec{E}^*$ is the complex conjugate, μ_0 is the permeability of free space, ε_0 is the permittivity of free space, ε_r is the relative material dielectric coefficient, ω is the angular drive frequency of the system, σ is the electrical conductivity, ρ is the sample density, C_p is the specific heat capacity, T is the sample temperature, and κ is the thermal conductivity. Equation 1 is the electromagnetic wave equation used with the assumption that the electric field propagation response occurs on time scales much faster than the temperature propagation of the sample. Equation 2 is the heat transfer equation, with the right-hand side term representing the power deposition into the sample by the microwaves. To represent the mode stirrers, a modified port boundary condition is employed.

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On short time scales during the startup of the microwave system where the diffusion of the temperature in the material can be neglected, the temperature growth, power deposition, and magnitude of the electric field can be calculated directly by:

$$\frac{\rho C_p \partial T}{\partial t} = \frac{P}{V} = \omega \varepsilon_0 \varepsilon'' E_{RMS}^2 \quad (3)$$

where P is the power supplied by the microwave, V is the volume of the sample, ε'' is the complex component of the material dielectric coefficient, and E_{RMS} is the root mean square of the electric field. Assuming that the magnitude of the electric field is only determined by the power supplied by the microwave system, this calibration method provides a measure of the unique electric field magnitude per each microwave power setting of P. To account for inherent losses in the system, such as ohmic losses in the cavity walls and impedance mismatch, calorimetry measurements from inferred thermal readings of water are correlated to the applied power. These temperature measurements through inferred thermal readings, power measurements, and magnitudes of the electric field will assist in the validation of the model.

RESULTS AND DISCUSSION

Microwave debinding enhances ceramic manufacturing efficiency and quality, advancing high-performance component production for industrial applications. The MOOSE model under development predicts debinding behavior by considering interactions with temperature and electric fields, and accounts for the microscale evolution of the part over time when exposed to microwaves.

CONCLUSION

Microwave debinding produces ceramic parts faster and with significant energy savings compared to conventional thermal debinding, promising efficient production of customized components. Additionally, the development of an open source modeling tool will benefit the microwave research community.

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