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Electric Field Assisted Sintering and Related Phenomena Far From Equilibrium

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ENERGY COUPLED TO MATTER RESEARCH FOR FIELD-ASSISTED PROCESSING

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Energy Coupled to Matter (ECM) is an emerging technology area that goes beyond the traditional limits of materials research by exploring the use of applied physics-based fields and their influence over material structures, phase development, processing, properties, and responses over multiple length scales (i.e. from atomic to macroscale). The U.S. Army Research Laboratory (ARL) defines ECM as fundamental research to discover, explore, and exploit interactions between materials and intense energy fields in order to enable significant property enhancements and unique property combinations that overcome traditional engineering tradeoffs, and allow for responsive on-demand structure-property modifications. These field-material interactions can produce outcomes that are otherwise unattainable, expanding materials-by-design and processing/manufacturing science capabilities beyond the current state-of-the-art.

The use of ECM for field-assisted processing has led to advances in materials development. The application of external electromagnetic (EM) fields to materials using techniques such as electric field-assisted sintering, flash sintering, microwave sintering, and high magnetic field processing has led to rapid production and improved properties. These methods have a few things in common, in that they use EM fields to contribute energy to heat treatment of materials, enabling full densification at lower temperatures (i.e. by hundreds of ^{o}C) and shorter times (i.e. from hours to second) as compared to conventional methods. The ability to rapidly densify materials under less extreme temperature conditions exemplifies one of the major advantages of ECM, as a smaller final grain size (i.e. nanoscale) can be preserved, resulting in enhancement of a number of physical and mechanical properties that are relevant to Army applications (i.e. strength, hardness, fracture toughness, etc.).

As one example of successful ECM research at ARL, field-assisted processing has been used to investigate the development of transparent ceramics for laser host and protective system applications. In particular, single-mode microwave sintering has been explored, using a specially designed cavity as a waveguide to separate the electric and magnetic field components, enabling exposure of the material to pure electric or magnetic fields at microwave frequencies. By comparing conventional pressure-less sintering to two different types of microwave sintering, multi-mode and single-mode, the effect of different types of microwave fields on the sintering behavior of erbium-doped Al_2O_3 was studied. For single-mode microwave sintering, the percentages of electric and magnetic fields that the sample was exposed to during sintering were varied by adjusting the position of the sample along the chamber. Results shown in Table I suggest that the microwave sintering parameters had a profound influence on densification and rare earth migration/phase stability. Sintering in single-mode with a 30%E:70%H mixed field produced samples with significantly higher density than other samples sintered at 1400°C (and equal to samples conventionally sintered at 1700°C). These samples also contained the least amount of unwanted second phase, indicating that more Er formed a solid solution with Al_2O_3. Our findings suggested that the magnetic component may play a critical role in the processing of weakly magnetic materials such as Al_2O_3, and that the dopant material (rare earth in this case) may play an important role in the material response to EM fields.

Table I. Microwave sintering conditions for baseline (BL), multi-mode (MM), and single-mode (SM) samples.

Sample	Temp (°C)	Microwave Conditions	Density (g/cm^{3})	Peak Height Ratio	Equivalent Vol%* $Er_3Al_5O_{12}$
BL	1400	No microwave	2.80	7.31	2.62
BL-HT	1700	No microwave	3.88	7.32	2.61
MM	1400	Multimode	2.93	7.30	2.62
SM-100:0	1400	Single Mode 100%E:0%H	2.75	7.38	2.59
SM-60:40	1400	Single Mode 60%E:40%H	2.64	7.69	2.45
SM-30:70	1400	Single Mode 30%E:70%H	3.88	8.23	2.25