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Microwave enhanced reaction kinetics in ceramics

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Abstract Numerous observations have been reported in the literature of enhanced mass transport and solid-state reaction rates during microwave heating or processing of a variety of ceramic, glass, and polymer materials. These empirical observations of microwave enhancements have been broadly called the “microwave effect”. In the past, these claims have been the source of significant controversy, due in part to the lack of a credible and verifiable theoretical explanation. Moreover, certain notable microwave heating experiments have failed to observe any resolvable reaction or transport rate enhancements. This paper describes a series of recent experimental and numerical investigations that have established the fact that strong microwave electric fields induce a (previously unknown) nonlinear driving force for (ionic) mass transport near surfaces and structural interfaces (e.g., grain boundaries) in ceramic materials. This driving force can influence reaction kinetics by enhancing mass transport rates in heterogeneous solid-state reactions. Most of the previously reported observations regarding “microwave effects” (both for and against) are consistent with the characteristics of this newly identified microwave-induced driving force.

Keywords Microwave processing · Microwave effect · Ponderomotive force · Ionic transport · Nonthermal · Sintering

Introduction

Understanding the microscopic physical mechanisms by which microwave fields influence the properties of mate-

rials plays a crucial role in the development of materials technologies employing microwave radiation. For example, heat processing of materials with microwave or RF radiation is usually a complex process involving the conversion of temporally-coherent electromagnetic field energy into thermal kinetic motion of atomistic particles (molecules, atoms, ions, electrons). Increased acceptance of the reliability, safety, and benefits of microwave processing is one important consequence of a thorough, fundamental understanding of microwave-materials interactions.

Microwaves came of age with the development of radar during World War II. At that time it was discovered that microwave energy from radar could dry large ceramic bodies. However, serious efforts to process ceramics with microwave energy did not appear until the late 1960's [1, 2] and early 1970's [3, 6]. In recent years, many researchers have studied high-temperature processing of ceramics such as firing, sintering, joining, and melting [7-16]. The initial stimuli for their efforts were the unique benefits that microwave heating could provide that conventional furnace heating could not. These potential benefits included more precise and controlled volumetric heating, faster ramp-up to temperature, lower energy consumption, and improved quality and properties of the processed materials.

As it turned out, results from experimental investigations of microwave processing of materials have periodically suggested the existence of a controversial, unexplained nonthermal interaction between high-strength microwave fields and ceramic materials. This nonthermal interaction was unanticipated, lacked a credible or verifiable explanation, and was broadly termed a “microwave effect.” For high-temperature reaction experiments involving thermally-activated chemical diffusion, the common manifestation of the microwave effect was (is) to enhance the process kinetics either by reducing the temperature or the time necessary to complete the reaction.

Generally, the response of the scientific community was to propose two competing explanations for the apparent microwave effect: (1) that researchers observing

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