Ponderomotive Force Generated by Microwaves During Sintering

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ABSTRAK

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I. INTRODUCTION

Many researchers have reported observations of "microwave effects" in a variety of material processes [1-3]. Microwave effect is sometime used to mark the enhancement of the processing rate when microwave heating is utilized such as enhancement of densification, atomic diffusion, chemical reaction rate [3]. In principle, the potential benefits of microwave heating, caused by the volumetric nature of microwave energy deposition which provides, in particular, a possibility of faster and more controllable temperature ramp-up and its selectivity which can provide concentration of energy deposition in the desired region result in precision heating. All the listed peculiarities of microwave heating can be treated as the thermal action of the electromagnetic field on matter. All microwave effects can be explained specifically to thermal and nonthermal effect.
Numerous experimental results suggest existence of a specific nonthermal action of microwaves on mass transport in crystalline solids [4]. The characteristics of porosity under microwave heating were found to differ considerably from those observed in a conventional sintering process under the same conditions. A direct influence of the microwave field on the transport phenomena in crystals was found in investigations of atomic diffusion [1], as well as in a study of the observation of a quasi-stationary electric current induced in a dielectric subjected to pulsed microwave irradiation [5]. However, the physical mechanisms of the effect are not completely clear. Some researchers proposed the additional driving force exist during microwave processing. Especially, Rybakov and Semenov proposed the first model being able to explain quantitatively the existence of an additional driving force for transport processes in ionic crystals subjected to a microwave field [4]. The basic idea was comparatively simple, based on the effect of rectification of the oscillatory vacancy drift near grain boundaries and interfaces. The additional driving force is known as ponderomotive force.

II. RESULTS OF MICROWAVE PROCESSING OF MATERIAL

Microwave enhanced sintering has been reported by several scholars [1-3,6-7]. It has received much attention because of the observed substantial decrease in sintering temperature and fast heating rates. Tian, et al., [6], have performed sintering of alumina at 1700 °C for 12 minutes. They reported that the sintered samples achieved 99.8% of theoretically density, with fine grain of 1.9 μm. The effect of microwave is not only in ceramic processing. Microwave enhanced drying have been also reported [8-9]. Some microwave enhancement results are shown in Fig 1 to 3.

![Fig. 1. Drying curves of cocoa beans in a microwave and in an electric furnace [8]](image-url)
Figure 2. Effect of microwave frequency and green sample in microwave sintering alumina [10]

Fig. 3 Reduction of open and closed porosity of silica xerogel upon MMW as compared to conventional sintering [2]

III. DISCUSSIONS
Because of all results are temperature activation process, they can be associated to enhancement of diffusion. Sintering lowers the surface energy of material by reducing surface area with concomitant formation of interparticle bonds. During sintering, high-energy free surfaces are replaced by lower energy sites such as grain boundaries or crystalline regions. The formation of these low-energy sites (neck region), and subsequent reduction in surface area. This reduction results in a decrease in the overall surface energy and known as driving force:

\[ \Delta G = \gamma_s dA \]  

(1)
where $G$ is free energy, $\gamma_s$ is specific surface energy, and $A$ is surface area. The stress associated with the curved surface as

$$\sigma = \gamma \left\{ \frac{1}{R_1} + \frac{1}{R_2} \right\}$$

(2)

where $R_1$ and $R_2$ are principal radii of curvature for this surface.

Flux of atom, $J$, is product of interatomic distance, reaction rate constant, and diffusing concentration.

$$[\text{Flux}] = -[\text{Transport coefficient}] \cdot [\text{Driving force}]$$

Diffusion path of mass transport during sintering of crystalline materials can occur by at least six mechanisms: vapor transport (evaporation/condensation), surface diffusion, lattice (volume) diffusion, grain boundary diffusion, and plastic flow [25].

![Figure 4. Possible atomic diffusion ways during sintering [10]](image)

The enhancement shown in Figure 1-3 reported by researchers is indicated that microwaves enhanced diffusion rate (mass transport flux) during processing.

For densification, by simplifying of diffusion process using two particle model the relation of densification to material transport parameters can be expressed by following equation:

$$\frac{\Delta \rho}{\rho_0} \approx \left( \frac{\Delta X}{L_0} \right)^3 = -\left\{D_0 \exp \left( -\frac{Q}{RT} \right) \right\} (\gamma_s \frac{dA}{n} dx) + z_iFE_{rms}cRT2\pi Vm2a33/2t3/2$$

(3)

Where $\rho$ = density, $L$ = material dimension, $Q$ = activation energy, $R$ is the universal gas constant, $T$ = temperature, $D_o$ is diffusion constant, $\gamma_s$ is specific surface energy, $z_i$ = charge on the ion, $F$ = Faraday constant = 9.65 kJ/ V, $E_{rms}$ = root mean square of the electric field of microwave, $A$ is the cross-sectional area over which diffusion occurs and $V_m$ is the molar volume of the material being transferred, $x$ is radius of neck, $a$ is radius of particle, and $t$ is time. Component $z_iFE_{rms}$ is microwave contribution on atomic transport during sintering. It is driving force generated by electric field of microwaves. It should enhanced atomic transport during sintering.

Application of ponderomotive effect was shown in experiment performed by Rybakov [11]. It was shown that a microwave field with the E-vector directed tangentially to a surface of a solid can develop a deformation-type instability. This results in the formation of a corrugated profile on that surface with
the spatial period on the order of 1 micrometer controlled period by adjusting the microwave power. However no direct experiment can demonstrate a ponderomotive force-driven mass transport up to now. One of important tasks in this field of research is now to demonstrate a ponderomotive force-driven mass transport in a direct experiment.

IV. CONCLUSION

A nonthermal action of microwaves which enhances diffusion in solids appears to be reasonable. As follows from the theoretical and experimental results obtained for ionic crystalline solids and drying it can be viewed in terms of an additional driving force (ponderomotive force). The experimental results on microwave sintering indicate supports the theory. However no direct experiment can demonstrate a ponderomotive force-driven mass transport up to now.

REFERENSI


