Observations on the Role of Electric Fields in the Synthesis and Processing Materials

Zuhair A. Munir*

Department of Materials Science and Engineering, University of California,
Davis, CA 95616, USA.

*zamunir@ucdavis.edu

Highlights

- Field activation in material processing.
- Fundamental studies on the SPS process.
- Model study of role of current in SPS.
- Nano-structured functional oxides.

The phenomenal success of the spark plasma sintering (SPS) process is manifested by the remarkable increase in the number of yearly publications dealing with the topic, a number approaching one thousand by the latest count. The success of the process is attributed variously to a number of parameters, among the most important of which is the application of an electrical field.

The effect of an electric field on the synthesis and processing of materials has been a topic of investigations for many decades. Field effects have been investigated on such processes as crystal nucleation, growth, and orientation[1,2], phase transformations[3], oxidation[4], crystalline defect distribution[5] and mobility[6], evaporation and sublimation[7], self-propagating high-temperature synthesis (SHS)[8], dissolution in liquid metals[9], and crystallization of metallic glasses[10].

The presentation will highlight results of investigations on some of the above, leading to fundamental investigations on the role of current in the SPS process.

The sublimation rate from (100)-oriented surfaces of single crystals of alkali halides was substantially increased (up to ~ 60%) when an electric field was applied parallel to the surface. A temperature-dependent threshold field was needed to see the effect[7,11]. In the case of SHS reactions, observations have shown that the imposition of the field increased the reaction temperature and the velocity of the reaction (combustion) wave, and altered the mechanism of the reaction, and thus the nature of the product[8].

The effect of a current on interfacial reactions was investigated in electromigration and SPS experiments. The imposition of the current had a marked influence on the kinetics of reactions at metal/metal[12] and metal/non-metal[13] interfaces. The current strongly enhanced the kinetics of the formation and growth of the intermetallic phases, decreasing the effective activation energy, and reducing the incubation time for the nucleation of the product phase[11,13]. Under electromigration and SPS conditions, the direction of the DC current had no influence on the kinetics of mass transport, as long as a product compound is formed, e.g., intermetallic or ceramic phase[12,13]. However, the current direction had a definite effect when no compound was formed, e.g., when a solid solution is formed[14].

Positron annihilation spectroscopy (PAS) analyses showed that the application of the current decreased the activation energy of migration (annealing out) of point defects in an intermetallic phase[6]. The application of a current on metallic glasses was shown to induce crystallization with the size and volume fraction of the resulting crystallites being dependent on the magnitude of the imposed current[10].

Fundamental investigations were also carried out on the spark plasma sintering (SPS) process. These included the nature of the pattern of the pulsed DC current and the effect of its direction[13]. Modeling studies, elucidating the nature of the formation of a product under simulated SPS conditions, were also carried out[15]. Direct evidence of the role of the current in sintering in the SPS, using a model copper spheres-to-plate geometry, was provided[16].

The effect of the applied pressure on the densification and grain growth of functional oxides, including nanocrystalline yttria-stabilized (cubic) zirconia (YSZ) was investigated in the SPS[17-19]. An increase in pressure resulted in a decrease in the sintering temperature needed to achieve a given high density. Concomitant with a decrease in temperature is a significant decrease in grain growth. Highly dense (98+%) YSZ with a grain size of < 20 nm was prepared[20]. Evidence suggests that with such a small grain size, nano-YSZ conducts protonically at room temperature[21].

References

[1] D. Kashchiev, *Phil. Mag.* 25 (1972) 459-70.
[2] C. Schalansky and Z. A. Munir, *J. Cryst. Growth,* **97** (1989) 310-318.
[3] H. Conrad, *Mater. Sci. Eng.,* A287 (2000) 227-237.
[4] D. N. Modlin and W. A. Tiller, *J. Electrochem. Soc*., **132** (1985) 1659-1663.
[5] Y. K. Min et al., *Phil. Mag*.**71** (1995) 815-829.
[6] J. E. Garay, et al., *Appl. Phys. Lett*, **85** (2004) 573-575.
[7] Z. A. Munir and T. T. Nguyen, *Phil. Mag*., **47** (1983) 105-117.
[8] Z. A. Munir, *Metall.Trans*., **A27** (1996) 2080-2085.
[9] J. Zhao, et al., *Acta Mater*., **55** (2007) 5592-5600.
[10] T. B. Holland, et al., *J. Appl. Phys*., **95** (2004) 2896-2899.
[11] Z. A. Munir and A. A. Yeh*, Phil. Mag.,* **A56** (1987**)** 63-71.
[12] N. Bertolino, et al., *Scripta Mater.*, **44** (2001) 737-742.
[13] W. Chen, et al., *Mater. Sci. Eng*., **A394** (2005) 132-138.
[14] J. Zhao, et al., *J. Appl. Phys*., **102** (2007) 114902/1-114902/7.
[15] E. M. Carrillo-Heian, et al*., Acta Mater*., **50** (2002) 3331-3346.
[16] J. M. Frei, et al., *J. Appl. Phys*., **101** (2007) 114914/1-114914/8.
[17] U. Anselmi-Tamburini, et al., *Scripta Mater*., **54** (2006) 823-828.
[18] D. V. Quach, et al., *Key Engin. Mater*., **484** (2011) 107-116.
[19] D. V. Quach, et al., *Acta Mater*., **58** (2010) 5022-5030.
[20] H. J. Avila-Paredes, et al., *J. Mater. Chem*., **20** (2010) 990-994.
[21] S. Kim, et al., *Adv. Mater*., **20** (2008) 556-559.

Keywords
Review; Field effects in materials processing; Fundamental investigations on SPS.