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Recent Progress in Scalable Nanomanufacturing

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As the size of materials becomes close to 10 nm, materials exhibit a unique electronic band structure that is not observed in traditional bulk materials. The modified band structure offers new opportunities for future technological innovation because it exhibits unprecedented electrical, optical and magnetic properties that are absent in their bulk counterparts. Fabrication and manufacturing of such novel nanomaterials have been significantly improved in the past few years. The section sponsored by the Nanomaterials Committee in the January issue of *JOM* has a unique combination of short review papers and research papers on the scale-up and integration of nanomaterials into functional architectures and bulk systems for engineering applications.

A paper written by Graeve et al. shows recent progress and current status of spark plasma sintering (SPS) which is beneficial in manufacturing of bulk materials comprised of nanosize grains. Manufacturing of nanostructured bulk material has been a daunting challenge, since the dramatic growth of nanocrystals is accompanied by the densification during the sintering. SPS addresses this trade-off between densification and grain growth. In this paper, principles of SPS sintering and materials prepared by SPS are summarized, showing that various materials (metal, ceramics and polymers) can be sintered without substantial growth of nanosize particles in SPS. In addition, SPS has an economic benefit over other sintering techniques such as hot press, reducing equipment cost and electricity consumption, and increasing a throughput rate. Technical and economical strengths of SPS indicate that SPS may pave a way toward commercialization of bulk nanostructured materials. Therefore, interest in SPS continues to grow in academic and industrial communities. Currently remaining tasks for the commercialization of SPS are near-net and net-shape forming, scalability, and high-throughput systems, and several groups are working to solve these problems.

Two-dimensional (2-D) dimensional materials are very attractive, since electrons confined in 2-D planes produce intriguing responses to external optical, electrical, magnetic, and thermal stimuli. Graphene is a well-known 2-D material which exhibits extremely high charge carrier mobility of $\sim$200000 cm^2 V^{-1} s^{-1}, thermal conductivity of $\sim$5000–8000 W m^{-1} K^{-1}, Young's modulus of $\sim$1100 GPa and fracture strength of $\sim$125 GPa. To exploit the excellent mechanical and functional properties, a scalable manufacturing technique must be developed. Chopra et al. have reviewed the progress of graphene synthesis techniques in two papers, with one focused on a chemistry-based method and the other focused on a vapor phase-based method. As discussed in these two review papers, there are four different groups of methods which enable large-scale production: exfoliation, epitaxial growth, chemical vapor deposition, and reduction of graphene oxides. In the early stage of the graphene study, the exfoliation of graphite using transparent adhesive tape, sonication, and chemical intercalation was widely used. The exfoliation method looks promising for high-throughput production of reasonable quality graphene. In relatively small-scale production of the high-quality graphene, vacuum processes such as epitaxial growth and chemical vapor deposition are preferred. These two review papers also state that successful application of graphene in industry will depend on the integration of the graphene with other materials as well as the development of large-scale production techniques.

Metal oxides have played a central role in many electronic, optical and magnetic devices such as optical fibers, random access memory, capacitors, sensors, and magnetic media. Chen et al. report that the dielectric constant of TiO_2 film can be controlled by engineering nanopores in the film. Since the dielectric constant of nanoporous TiO_2 film was easily tuned by filling the nanopores with gas, this

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porous material was tested for a gas sensing application. The sensor is based on the refractive index change and evanescent field interaction in hydrogen-sensitive cladding. When gas was adsorbed in the nanopores of the film, the dielectric constant was lowered and the refraction rule of the optical signal changed. Because of these properties, the optical signal propagation and the gas adsorption were correlated and the type and content of ambience gas was detected optically. In Chen's approach, the sol–gel method was used to fabricate nanoporous TiO_2. This nanoporous film was then coated on silica fibers, followed by laser scribing of an optical pattern for optical gas sensing. Given the affordable nature of the sol–gel method and the laser scribing, it is concluded that fabrication of the optical sensors built on the nanoporous metal oxide film is certainly scalable at large scales.

The following papers being published under the topic of Scalable Nanomanufacturing provide excellent details and research on the subject. To download any of the papers, follow the url http://link.springer.com/journal/11837/67/1/page/1 to the table of contents page for the January 2015 issue (vol. 67, No. 1).

- "Spark Plasma Sintering as an Approach to Manufacture Bulk Materials: Feasibility and Cost Savings" James P. Kelly and Olivia A. Graeve
- "Progress in Large-Scale Production of Graphene Part 1: Chemical Methods" Yuan Li and Nitin Chopra
- "Progress in Large-Scale Production of Graphene Part 2: Vapor Methods" Yuan Li and Nitin Chopra
- "Scalable Fabrication of Metal Oxide Functional Materials and Their Applications in High-Temperature Optical Sensing" Aidong Yan, Zsolt L. Poole, Rongzhang Chen, Paul Leu, Paul Ohodnicki, and Kevin P. Chen