Liquid phase sintering in microgravity

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SINTERING is a phenomenon by virtue of which packed powders bond together when heated to temperatures in excess of approximately half the absolute melting temperature. Sintering and related phenomena are collectively grouped under the heading of powder metallurgy. One might be little aware of the impact of powder metallurgy on our modern life. Powder metallurgy is the most diverse manufacturing process, from building bricks to hi-tech aerospace titanium alloys. To illustrate the diversity, consider the use of tungsten lamp filaments, oil-less bearings, automotive transmission gears, armour piercing projectiles, electrical contacts, nuclear power fuel elements, orthopaedic implants, high temperature filters, friction materials, turbine components, dental amalgams, superalloy components for jet engines, high performance cemented carbide tools, amorphous and metastable alloys, all of which are fabricated using powder metallurgy. The success of this processing approach has derived from the economic benefits and the ability to fabricate unique/ difficult to process materials.

Liquid phase sintering (LPS) is a subclass of the sintering processes involving particulate solid along with a coexisting liquid during some part of the thermal cycle. Presence of liquid during sintering gives this process an advantage over other sintering processes. The presence of liquid provides both a capillary force and transport medium that leads to rapid consolidation and sintering[1–3]. The capillary attraction due to wetting liquid gives rapid compact densification without the need of an external force. As the starting material is in a powder form, a near net shape fabrication is possible, and complete melting is not necessary. All these features make LPS a very attractive fabrication process for commercial production. LPS is a widely used fabrication process for high performance metallic and ceramic (glass–ceramic) materials. It is particularly useful for high melting point materials for which fabrication by melting is not feasible.

During LPS there are at least three phases coexisting – vapour, liquid and solid; and these are associated with their specific interfaces and energies. Presence of three phases coupled with solubility, viscosity and diffusivity factors makes the analytical treatment of the process very difficult. An important parameter in the LPS process is gravity. Gravity induces separation of the solid and liquid phases due to the density differences between the two[4–7]. Consequently, the microstructure evolves differently in gravity than the way it would in its absence. This difference in microstructure affects the sintering kinetics and thus affects the material properties. Therefore, for a better understanding of the process of LPS it is of interest to quantify and understand the effect of gravity on microstructural evolution during LPS. For this purpose, it is necessary to perform LPS experiments in the absence of gravity or in reduced gravity (e.g. microgravity environment as of a sounding rocket or space station) and compare the results to those of experiments done under normal gravity.

One of the first experiments on LPS in reduced gravity was performed in 1983 by Rossito[8]. The low gravity environment was produced by sounding rocket *TEXUS-8*, launched from ESRANGE, Kiruna, Sweden on 13 May 1983. Since then many researchers around the world have performed LPS experiments in reduced gravity and microgravity environments of sounding rockets, space labs and shuttle missions. Although these experiments have increased our understanding of the phenomenon of LPS, many more issues remain unresolved. On the other hand, these experiments have sometimes shown some anomalous outcomes that have questioned some of our basic understanding of the phenomenon. For example, it was concluded by Ekbom *et al.*[9] in their study that the particle growth rate under microgravity is initially faster, although in another independent research[10], just the opposite was observed. Both the studies were done on same system but with very different volume fractions. Another anomalous observation was reported by Xue *et al.*[11] in which extensive pore formation and metamorphosis was observed. Probably the biggest finding about LPS in microgravity is due to Liu and German[12] who found that the Young's equation ($\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos\theta$, where γ_{SV}, γ_{SL} and γ_{LV} are tensions of the solid–vapour, solid–liquid and liquid–vapour interfaces and θ is the contact angle for a liquid drop on a solid) is not applicable in general under microgravity conditions. A reanalysis of several derivations of Young's equation reveals errors. The resulting configuration could only be described by a three-vector force balance.

Thus microgravity LPS experiments can provide a unique opportunity for studying the problems of pore formation and metamorphosis, effect of capillary forces and Brownian motion. They would also provide solutions to problems of Young's equation and three-phase equilibrium. This will increase our understanding of the effect of gravity on the fundamental process of LPS, which is of both fundamental and practical interest in materials processing.

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