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Emerging challenges in solid-state sintering science and technology

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Major research challenges in the field of solid-state sintering are noted following the authors' recent paper (J. Am. Ceram. Soc. 2017. Vol. 100. P. 2314–2352). They are highlighted in the areas of (i) modeling and simulation (mesoscale as well as macroscale), (ii) microstructural evolution with respect to interface structure, (iii) novel sintering techniques, and (iv) solutions for practical systems.

Keywords: solid-state sintering, modeling and simulation, microstructural evolution, novel techniques, sintering research.

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Introduction

Sintering, one of the oldest human technology, has been developed and utilized since the prehistoric era with firing of potteries. Systematic studies in this field, however, started only from the 1940's [1—3]. A remarkable body of scientific knowledge has since been accumulated and tremendous technical developments have been achieved. Sintering is a key technique for fabricating numerous novel materials and components, and an important technology in modern industry.

Recently, in a centennial feature article of the Journal of the American Ceramic Society, technological as well as fundamental developments in sintering were reviewed and future research directions and areas were suggested [4]. This note summarizes the suggested future research challenges of solid-state sintering in commemoration of the centennial birth of the late Professor Grigorii Valentinovich Samsonov.

Challenges in sintering research

1. Modeling and simulation of sintering

Modeling and simulation have been key subjects of sintering since early scientific studies to understand sintering fundamentals and sintering phenomena. In addition modeling and simulations have been essential in predicting the effect of process variables on sintering kinetics and microstructure development. This aspect has been critical in technologically implementing sintering as a controlled and predictable manufacturing process. With respect to the scale they treat, studies in this area can be categorized into two groups, mesoscale (the level of particles, grains, and pores) and macroscale (continuum scale, the level of components) studies.

Many of the mesoscale modeling and simulations on densification have been for simple and ideal systems with no grain growth, for example, two-particle systems and regularly packed mono-sized systems [5—8]. They provide a good physical basis of observed sintering phenomena. These systems assume that the grain boundary and the surface are a perfect atom source and sink, where the kinetics is linearly proportional to the driving force. Recent investigations, however, show that this assumption is valid only for systems with rough (atomically disordered) interfaces. For even partially faceted (atomically ordered) systems, the kinetics can be nonlinear with respect to the driving force (see section 2). Modelling and simulation studies that take into account the effect of the interface structure should be carried out to better understand the sintering phenomena in real systems.

Another issue in the mesoscale modeling and simulation studies is that the systems they consider are far from real systems, where particles have a given size distribution and grain growth takes place during densification. Although there have been analyses on microstructural evolution during sintering, they are for ideal systems with regularly spaced pores and simple pore/boundary interactions [9—12]. Studies should take into account particle size distribution and packing, pore/grain structure, and microstructural evolution in order to be realistic.

Macroscale modeling and simulation studies are based on continuum mechanics. They can predict the macroscopic sintering behavior of powder compacts fairly well and are utilized in optimizing the manufacturing of components, in particular those with complex shapes, multi-materials and multi-layered systems [13—18]. There is, however, need for improving the predictability of densification in connection with microstructure and microstructural evolution, and also with the interface structure. With advances in simulation capability, the shape change of the compact can be better predicted and its damage and fracture can be well controlled. The usability and predictability of simulation will further be improved through integrated studies with experiments.

2. Interface structure and microstructural evolution during sintering

Recent investigations show the critical effects of the interface structure, either rounded (atomically disordered) or faceted (straight, atomically ordered), on densification and grain growth [19, 20]. For (even partially) faceted systems, which account for most systems, there are critical driving forces for densification and grain growth with appreciable kinetics [21, 22]. It has also been shown that the difference in limiting density and the difference in microstructural evolution in the same system are due to the degree of faceting and hence the difference in their critical driving forces [21, 23].

The studies thus far on the effects of the interface structure on densification and grain growth have been performed for systems with average thermodynamic and kinetic properties of the boundaries. In reality, however, the properties are different from boundary to boundary for the same driving force. More quantitative and detailed studies on the properties and kinetics for individual boundaries as well as an ensemble of boundaries should be performed in order to better describe the sintering kinetics and phenomena. They may include (i) characterization and calculation (theory) of grain boundaries, their structural transition, and their motion, (ii) theory development of densification and simulation of microstructural evolution for faceted systems, and (iii) revisiting the effects of other parameters, such as impurities and second phase particles.

3. Development and application of novel techniques

There have been significant advances in developing novel sintering techniques, including pressure-assisted techniques and electric field/current-assisted techniques. Novel techniques with modification of thermal cycles have also been developed [24, 25]. The pressure-assisted techniques are well established and utilized to fabricate materials with low sinterability [26, 27]. The electric field/current-assisted techniques are being developed and provide remarkable enhancement of densification [28—35]. Their fundamentals including the underlying mechanisms, however, are not yet well understood. Process control also is required to fabricate products with uniform microstructure and properties. In addition to the sintering technique itself, additive manufacturing, a powder processing technique, has garnered notable attention in both academia and industry because of its versatility and convenience in making sintered parts of complex shapes. To increase the application of this technique, solutions to sintering issues of the processed powder compacts will be critical.

4. Solutions for practical systems

Numerous components for various applications are fabricated by sintering. In many cases, the components have either very complex shapes, layered structures, films on substrates, multi-phases or combinations of these. To solve practical issues in fabricating such components a sound understanding and solid control of sintering for the specific system as well as powder processing of the components are necessary. Although macroscale continuum theories have provided qualitative guidance for sintering these complex systems, there is a need for predictable quantitative theory and simulations. In most cases, this will require multi-scale theories and simulations. In addition, with a reduction of powder size to a nano-scale, which is the current trend, greater control of particle packing, grain growth, and densification during sintering than that for micron-sized powders is necessary. In sintering of layered compacts or films on substrates, the finite geometry aspects, including the size and thickness ratio, aspect ratio of the layer, and free edge effects, have not been extensively analyzed and are not yet well understood. Accordingly, many technical and fundamental studies are needed for individual systems and components.

Remarks

We have briefly described current and emerging challenges and directions in sintering research. There may, however, be other challenges that are omitted in this note but warrant consideration. We hope that by overcoming the challenges described herein and others as well, the sintering science and technology will further be developed and continuously make critical contributions to modern and future industry and society.

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