MECHANICAL BEHAVIOR OF LIGHTWEIGHT CERAMICS

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ABSTRACT

The current understanding of the mechanical behavior of lightweight ceramics is reviewed. It is shown that these materials may have considerable potential in structural applications. To capitalize on this potential, it is clear that several challenges need to be met. These include establishing a clear understanding of the relationship between microstructure and mechanical behavior in these materials, developing new and innovative techniques for their fabrication and devising appropriate techniques for their engineering design.

INTRODUCTION

The majority of scientific studies into the mechanical behavior of ceramics have invariably emphasized materials close to theoretical density. Indeed, most structural applications of materials, with the exception of wood, utilize dense materials. Conversely, Nature invariably uses fibrous or cellular materials in such applications and presumably these represent a careful evolutionary optimization. As pointed out by Ashby [1], cellular materials permit the simultaneous optimization of stiffness, strength and overall weight. There are a wide range of man-made lightweight materials, with polymeric foams being the most familiar group. Within the field of ceramics there are several examples, including fibrous and foamed materials that are used for thermal insulation and open cell materials, that are used for filtering molten metals. As these materials represent a rather new class of ceramics, it is reasonable to expect they may have a wide range of potential applications that are not yet fully explored. Currently, these materials are not chosen for their structural attributes but for some other special quality. It is, however, still important to maximize the strength of such materials for an optimum design. For example, the tiles used for the thermal protection system (TPS) of the space shuttles were chosen for their high temperature capability, low thermal conductivity, low coefficient of thermal expansion and weight, and yet prior to the first flight their mechanical behavior and its understanding was a critical issue [2-4].

MICROSTRUCTURES OF LIGHTWEIGHT CERAMICS

For the purposes of this paper, let us consider lightweight ceramics
as having fractional densities $\rho / \rho_s < 0.5$, where $\rho$ and $\rho_s$ are the densities of the lightweight and solid materials respectively. For thermal insulation purposes, values of $\rho / \rho_s$ are often $< 0.1$ and rigid materials with values as low as 0.03 have been fabricated [5]. There are two broad categories of lightweight ceramics, i.e., fibrous or cellular, which reflects the nature of their microstructure. The fibrous materials generally consist of a tangled network of fibers, whereas the cellular materials consist of a relatively regular array of cells. For the cellular materials, there is generally a further sub-classification into closed or open cells, depending on whether the faces of the cell are present or not. These various classes of lightweight ceramics are illustrated by some examples in Fig. 1.

The microstructures of the fibrous materials are often anisotropic. This is usually a result of the processing, in which fiber slurries are pressed and filtered. As the fibers will prefer to lie perpendicular to the pressing direction and/or gravity, this preferred orientation will persist in the final microstructure. This leads to anisotropy in the properties of these materials. The tiles used on the TPS of the space shuttle are transversely isotropic, i.e., they are isotropic in one principal plane but possess a different set of properties for the direction perpendicular to this plane. Thus, when studying the mechanical behavior of these materials, it is essential to be aware of the anisotropy of strength, fracture toughness and the elastic constants [6,7]. Cellular ceramics tend to be relatively isotropic and are often produced by foaming techniques (closed cell) or by using reticulated polymeric foams as a skeleton (open cell). An alternative approach to producing closed cell ceramics is by the sintering or bonding of hollow spheres [8-10].

In terms of microstructural and engineering design, it is crucial to develop relationships between the microstructural parameters, e.g., cell size, fiber diameter, cell wall thickness, etc., and the mechanical properties, e.g., fracture toughness, strength and the elastic constants, especially with respect to variations in $\rho / \rho_s$. A powerful scientific approach to accomplish this, is to model the microstructure using an idealized arrangement of micro mechanical unit cells.

MICROMECHANICAL MODELS

There has been a variety of attempts to model cellular and fibrous materials. Let us first consider cellular materials, for which there is an extensive literature, mainly in the field of polymer science [11-18]. In these studies, the first assumption is that the mechanical behavior of the cellular material can be analyzed by considering the deformation of a particular unit cell. There has been a wide variety of cells chosen, including open and closed cubic [12,14] and various dodecahedrons [16-18]. These latter cells are chosen to reflect the morphology of foams, as this is often the approach to fabricating cellular materials. This type of approach has been discussed by Patel and Finnie [17]. During foaming, the pressure difference between adjacent cells is expected to be small due to diffusion. This implies the reduction of surface area should be the overriding factor in establishing the final geometry. This behavior is equivalent to that of soap bubbles, for which surfaces can only meet in two ways [19]. That is, either three surfaces meet along a curve at angles of $120^\circ$ or six surfaces (four edges) meet at a vertex with angles of $109.47^\circ$. There is no regular polyhedron that meets these requirements as well as being able to fill space. Kelvin [20] showed, that if the edges of a truncated octahedron were curved, both the required angles and the compatibility conditions could be satisfied. This polyhedron is called the minimum area tetrakaidecahedron. In actual foams, however, such curvature