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Fusion Engineering and Design 81 (2006) 455–460
Fusion Engineering and Design
www.elsevier.com/locate/fusengdes

Breeder foam: an innovative low porosity solid breeder material

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Received 8 February 2005; received in revised form 13 June 2005; accepted 13 June 2005
Available online 18 January 2006

Abstract

Ceramic foam or cellular ceramics are proposed as a new solid breeder material configuration. Such cellular breeder materials would have an open cell structure consisting of a network of three-dimensional interconnected ligaments. Ceramic breeder foams could address some of the challenges facing packed breeder beds and potentially enhance thermal performance, increase breeding ratio, and improve structural reliability. Foam densities are not limited to those of mono-sized pebble beds, thermal conductivities are higher compared with similarly dense pebble beds; and morphology changes are expected to be much smaller and slower than in pebble beds. Heat transfer between breeder and coolant walls can be enhanced in principal, by bonding the stand-alone breeder foam to the structure. Correlations of thermo-mechanical properties of ceramic foams are reviewed to highlight the potential advantages of a foam configuration for solid breeders.

Keywords: Solid breeder; Ceramic foam; Cellular ceramic; Foam properties; Foam processing; Foam applications

1. Introduction

Solid breeder blanket concepts are typically based on pebble beds of beryllium and lithium ceramics, which serve as neutron multiplier and tritium breeding material, respectively. The large internal surface area and interconnected open porosity of pebble beds facilitate release and removal of transmutation gases (He, T). However, long term reliable performance of solid breeder pebble beds remains a field of intense R&D for fusion power reactor development [1–4]. The low thermal conductivity and wall-interface conductance of packed bed configurations result in characteristically thin bed thickness of a few centimeters. Furthermore, thermo-mechanical performance due to pebble movement, sintering, and pebble fracture or disintegration continue to pose significant challenges [4].

Ceramic breeder foams could address a number of solid breeder thermo-mechanical performance challenges, because foams can be tailored to have higher thermal conductivity, higher heat convection, improved wall-bed thermal conductivity, and stand-

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0920-3796/$ – see front matter
doi:10.1016/j.fusengdes.2005.06.374

alone structural rigidity. Furthermore, sintering in ceramic foams is not a major concern, because of the absence of high stress contact points. These features could reduce structural and Be material requirements in a breeder blanket. However, high density Li-ceramic foams have not been fabricated or researched for fusion applications. This paper is meant to address the feasibility of foam or cellular Li-ceramics for fusion applications. Several ceramic foam manufacturing techniques along with commercial applications are referred to. Density based correlations for thermal and mechanical properties of ceramic foams are given along with examples of high temperature creep performance of ceramic foams [5]. Stability of breeder foam materials in a neutron irradiation environment is not discussed, due to lack of any experimental data. Potential advantages of ceramic breeder foams for fusion blanket applications are highlighted in the conclusions.

2. Ceramic foam manufacturing and applications

Engineered foams have cellular structures which are categorized as either open cell or closed cell foams. Foam structures are an assembly of irregularly shaped prismatic or polyhedral cells connected to each other with solid edges (open cell) or with faces (closed cell). Engineered foams have been manufactures from polymers, metals, glasses, and ceramics. Ceramic foams are porous brittle materials with fully open, partially interconnected, or closed porosity. Ceramic foam manufacturing techniques can be classified into three general categories: sponge-replication, foaming agent based, or space holder method, which have been detailed earlier [6]. Fig. 1 shows examples of foams produced by these techniques.

Commercial ceramic foams offer a unique combination of properties, such as low density, high surface area to volume ratio, high stiffness to weight ratio, low thermal and electrical conductivity, and highly localized strain and fracture characteristics [7,8]. The high thermal shock resistance of ceramic foams makes them uniquely suitable for spreading flames, fuels, or coolants uniformly. Ceramic foams are use for a diverse range of applications, such as metal melt filtration, ion-exchange filtration, heat exchangers, catalyst support, refractory linings, thermal protection systems, diesel soot traps, flame rectifiers, and solar radiation collectors [6].

3. Ceramic foam structures and properties

Open cell ceramic foams exhibit high porosities (70–90%) with non-uniform spherical-like cells connected to each other by ligaments. The tortuosity of the foam is characterized in terms of the pore diameter, or pore per inch (PPI) density. Typical pore diameters range between a few microns to 2 mm and in commercial ceramic foams pore densities range between 10 and 100 PPI [9]. The interconnecting ligaments of low density foams provide an enormous surface area per unit volume, S_V. The exposed surface area of a 12% dense 80–100 PPI ceramic foam varies from 12.3×10^4 to 1.76×10^4 m^2/m(solid)^3, which is equivalent to that of a 60% spherical packed beds with diameters ranging 0.05–0.34 mm [10].

3.1. Mechanical and thermal properties

Foam property correlations are expressed as a function of the relative density (ρ^*/ρ_s); where ρ^* is the density of the cellular solid and ρ_s is the density of the solid from which the foam is made. In general, a relative density of 0.3 is the cut-off value between low-density foams and higher density micro-cellular ceramics. The relative density of foams is expressed in terms of unit cell geometric features, such as ligament length and thickness.

Table 1 lists correlations based on the relative density for thermal and mechanical properties of open cell foams, such as stiffness (E^*), the elastic collapse stress (σ^*_{el}), the plastic collapse stress (σ^*_{pl}), the crush strength (σ^*_f), and the fracture toughness (K^*_{IC}). Fig. 2 shows the variation in relative crush strength as a function of relative density for ceramic foams [11]. Foams made of low density engineering ceramics such as alumina offer comparatively high strengths – up to 80 MPa crush strength and 25 MPa modulus of rupture [12].

3.2. Thermal conductivity

The primary operating limitations of a sphere packed solid breeders are due to low thermal conductivity caused by small pebble-to-pebble contact

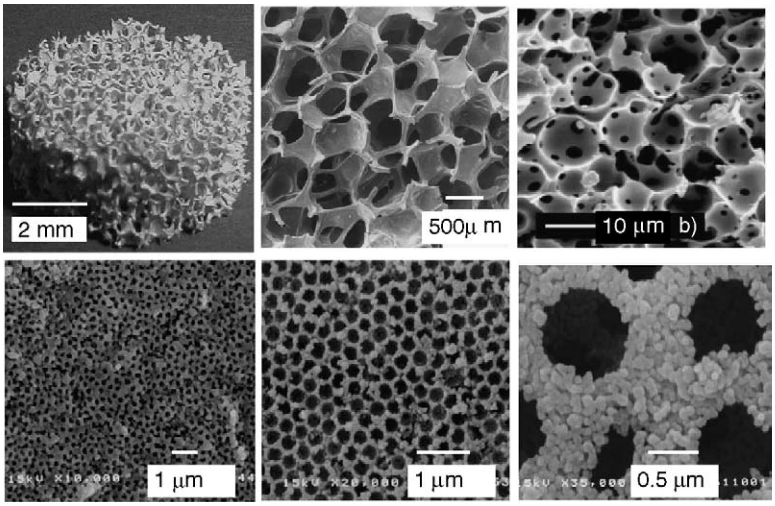

Fig. 1. Ceramic foam examples; (a) TiO_2 foam: positive replicated of polyurethane foam [19]; (b) pyrolyzed ceramic SiC–Si_3N_4 composite foam [7]; (c) micro-cellular SiOC foam using a foaming agent and pre-ceramic polymer [9]; Placeholder techniques, SEM of macro-porous ceramic material prepared using suspended ceramic nano-particles with polymer spheres: (d) γ-Al_2O_3, (e) TiO_2, (f) 3Y-TZP [20].

areas (Fig. 3a). At 25 °C bulk Li_4SiO_4 has a thermal conductivity of about 2.8 W/m K, which decreases to about 0.25 W/m K in a 62% volume fraction sphere packed configuration. Based on the correlation given in Table 1, 62% dense Li_4SiO_4 foam could have a thermal conductivity as high as 0.63 W/m K, which is almost a factor of 2.5 times higher than that of a sphere packed bed.

The packing fraction of a monosphere sized bed is limited to ∼64%. However, foam structures are not inherently limited in density and it is feasible that foams with densities above 80% can be developed [13,14]. At room temperature, 80% dense Li_4SiO_4 foam could have a thermal conductivity of ∼0.78 W/m K, or a factor of about three times higher than that of a 62% sphere packed bed.

Table 1
Correlations for mechanical and thermal properties of low density open cell foams [6,8]

Property	Formula
Density	$\frac{\rho^*}{\rho_s} = C_1\left(\frac{t}{l}\right)^2$
Stiffness	$\frac{E^*}{E_s} \approx 1.0\left(\frac{\rho^*}{\rho_s}\right)^2$
Elastic collapse stress	$\frac{\sigma^*_{el}}{E_s} \approx 0.05\left(\frac{\rho^*}{\rho_s}\right)^2$
Plastic collapse stress	$\frac{\sigma^*_{pl}}{\sigma_y} \approx 0.3\left(\frac{\rho^*}{\rho_s}\right)^{3/2}$
Crushing strength	$\frac{\sigma^*_f}{\sigma_{fs}} \approx 0.2\left(\frac{\rho^*}{\rho_s}\right)^{3/2}$
Fracture toughness	$\frac{K^*_{IC}}{\sigma_{fs}} \approx 0.65\sqrt{\pi l}\left(\frac{\rho^*}{\rho_s}\right)^{3/2}$
Creep	$\frac{\dot{\varepsilon}^*_f}{\dot{\varepsilon}_0} \approx \frac{0.6}{n+2}\left(\frac{1.7(2n+1)}{n}\frac{\sigma^*}{\sigma_0}\right)\left(\frac{\rho_s}{\rho^*}\right)^{(3n+1)/2}$
Thermal conductivity	$\frac{\kappa^*}{\kappa_s} \approx 0.35\left(\frac{\rho^*}{\rho_s}\right)$

C_1 (∼1) is a constant which depends on cell geometry, E the Young's modulus, l the strut length and t the strut thickness, n the diffusional flow parameter; subscripts: f is the foam, s the solid, fs the failure strength, y the yield.

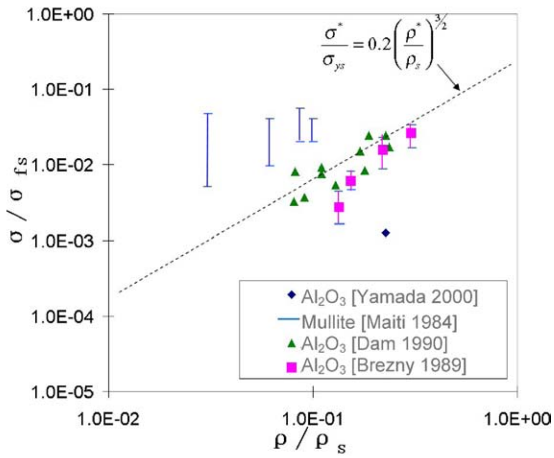

Fig. 2. Variation of relative crushing strength as a function of relative ceramic foam density (dotted line is based on alumina solid fracture strength) [11].

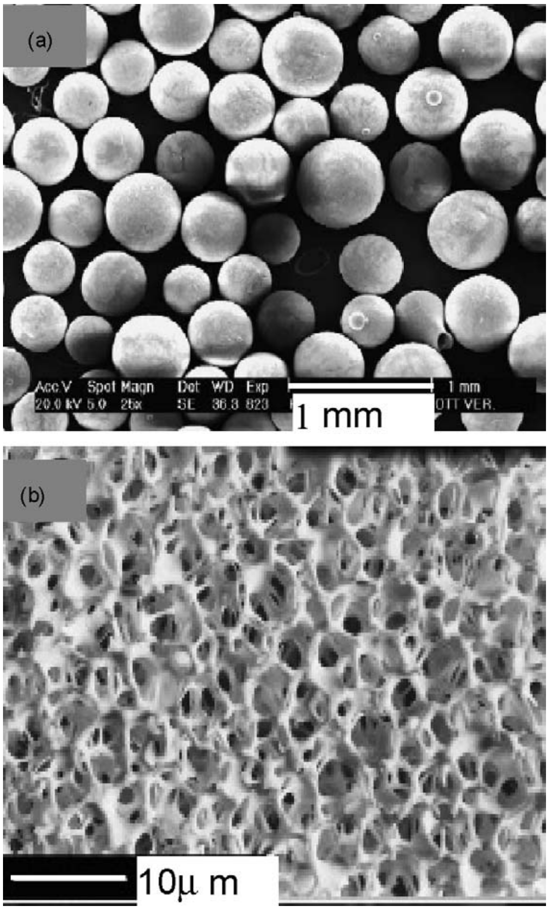

Fig. 3. Samples of (a) Li_3SiO_4 pebbles and (b) Al_2O_3 foam [1,21].

3.3. Breeder wall interface thermal conductivity

One of the critical blanket design issues is heat conduction across the interface between solid breeders and actively cooled structures. Foams are free-standing structures and therefore offer the potential of being bonded to structures. Bonding could significantly improve thermal conductance between breeder and coolant wall, however significant material challenges have to be overcome in developing reliable ceramic foam-to-metallic bonds. Tungsten foam has been bonded to structures using chemical vapor deposition to deposit a tungsten face sheets onto the foam [15].

3.4. Thermal creep

In reactor creep models of sphere packed solid breeder beds are complex, in that creep depends on elastic (ε_e), thermal expansion (ε_{th}), swelling (ε_{sw}), thermal creep (ε_c), and on time-dependent plastic (ε_{pl}) components. Reimann and Worner have shown that Li_4SiO_4 experiences thermal creep strains of the order of 3% at 850 °C after 100 h at 2.2 MPa uniaxial load [16]. At high temperatures thermally induced loads are continuously released by creep of a packed bed. However, cyclic operation can result in partial sintering, breeder-wall separation/contact cycles, and fragmentation of pebbles [1].

A breeder-foam would have an entirely different behavior, foremost due to absence of material realignment, such as caused by initial loading of pebble beds. Furthermore, the creep behavior of the ceramic foams was shown to follow that of bulk ceramics except at much lower stresses [5]. Compressive creep of 30% dense open-cell Al_2O_3 1200 and 1500 °C was shown to occur by diffusional flow for strain rates between 10^{-8} and $10^{-6}\,s^{-1}$ for stresses in the range 20–100 kPa. The activation energy for steady state creep of foam was typical of that for dense Al_2O_3 [5]. At 2 MPa the creep strain rate of 80% dense Li_4SiO_4 at 900 °C is less than $6 \times 10^{-10}\,s^{-1}$ [17]. Based on similar creep behavior between foams and bulk ceramic materials [5], at 900 °C and 2 MPa loading a 80% relative dense Li_4SiO_4 foam would have a creep strain of less than 0.02% compared with 3% for a sphere packed bed.

4. Structural integrity and fragmentation

Dell'Orco et al. [1] have demonstrated that breeder pebble beds exposed to several MPa of loading undergo large elastoplastic deformations along with considerable bed height reduction due to bed compaction. Cyclic thermal loading of the pebble beds resulted in pebble fragmentation. The "point-to-point" contact between pebbles introduced large stress concentrations during thermal loading. Such stress concentrations are not inherent to foam structures. For pebbles sintering and fragmentation is a concern, while in foams localized cracking of individual ligaments may occur. Crush strengths of open cell 30% dense Al_2O_3 foams are as high as 80 MPa [12]. The crush strength of foams increases with relative density (see Fig. 2) [11]. To avoid foam fracture, the combined thermal expansion plus swelling induced loads would have to be kept below the foam crush strength.

As long as burn-up does not result in disintegration of the breeder material itself, the macroscopic geometry of a foam breeder structure should be maintainable with minimal internal damage.

5. Tritium release

Tritium release depends among other things on the available open surface area of the breeder material. The geometric surface areas, S_v, of commercial 12.6% relative dense foams with 30 PPI have been measured to be of the order of 0.423×10^4 m^2/m^3, which is close to that of a spherical packed bed, 0.582×10^4 m^2/m^3 made of 0.5 mm diameter pebbles having a relative density of about 60% [18]. In order to maintain such large surface areas in a 60% relative dense foam the pore density would have to be doubled to about 60 PPI and the pore diameter reduced to about 0.1 mm [6]. Such foams would have ligament thicknesses of about 0.13 mm, which means that the maximum tritium diffusion path length is reduced by a factor of 3 from that of 0.5 mm pebbles. Tritium release rates in equivalently dense foam structures would significantly increase due to shorter diffusion path lengths.

6. Swelling and helium-retention

At 3 at.% ^{6}Li-burnup the volumetric swelling ($\Delta V/V_0$) of Li_4SiO_4 has been measured to be about 0.4, 2.7, and 2% at 500, 700, and 900 °C, respectively [17]. Helium retention of Li_4SiO_4 was reported to decrease with increasing temperatures. At 1 at.% burn-up of ^{6}Li, helium retention was 0.7, 0.6, and 0.06% at 500, 700, and 900 °C, respectively [17]. Helium release rates in breeder foam structures are expected to be higher, because diffusion path lengths in foams are smaller than those in pebbles beds. Thus swelling, due to helium retention in breeder foam ligaments could be less. However, because of lack of any data on ceramic foam structures in an irradiation environment, this would have to be verified experimentally.

7. Conclusions

A number of solid breeder packed bed challenges could be addressed by developing a foam or cellular breeder configuration. The existence of an interconnected network of open porosities and ligaments provides continuous thermal conduction paths and large internal surfaces for tritium and helium release. Low density ceramic foams are produced commercially for a wide variety of applications in severe environments. Thermal, mechanical, creep, swelling, and tritium retention related properties of ceramic foam materials were briefly discussed. Although many challenges lie ahead in the development of solid breeder foams, the potential benefits of improved thermal performance could result in increased tritium breeding ratios suggests that breeder foam configurations would be beneficial for fusion power reactors.

Acknowledgments

The authors would like to thank Prof. Peter Greil and Dr. Jurgen Zeschky (Univ. Erlangen-Nuernberg, Germany), Prof. Paolo Colombo (University of Bologna, Italy), Dr. Havard Haugen (Technische Universitat Munchen, Germany), and Dr. Jon Binner (Loughborough University, UK) for their comments and many suggestions regarding ceramic foam for fusion applications.

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