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Experimental and computational studies on the thermal behavior and fire retardant properties of composite metal foams

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ABSTRACT

A comprehensive experimental and computational evaluation of thermal behavior and fire retardant properties of composite metal foams (CMFs) is reported in this study. Thermal behavior characterizations were carried out through specific heat, effective thermal conductivity, and coefficient of thermal expansion analyses using differential scanning calorimetry, high temperature guarded-comparative-longitudinal heat flow technique, and thermomechanical analyzer (TMA), respectively. The experimental results were compared with analytical results obtained from, respectively, rule of mixture, Brailsford and Major's model, and modified Turner's model for verification. United States Nuclear Regulatory Commission (USNRC) standards were employed as regulatory standards and criteria for fire retardant property study. The results revealed a superior thermal resistance and fire survivability of CMFs compared to 304L stainless steel. A physics-based three-dimensional model accounting for heat conduction was built using Finite Element Analysis to validate the reliability of the experimental results. The model led to a good reproduction of the experimentally measured data when comparing CMF to bulk stainless steel. This research indicates that one of the potential applications of lightweight CMFs can be in nuclear spent fuel casks replacing conventional structural and radiation shielding materials with demonstrated benefits of excellent thermal isolation, fire retardant, light weight and energy absorption capabilities.

1. Introduction

Spent fuel nuclear transportation casks are commonly used as containers for transporting radioactive waste materials from nuclear power plants to fuel reprocessing plants or disposal sites. A typical nuclear cask uses forged 304L steel as an outer shielding layer to attenuate gamma rays, and beech or spruce encased in stainless steel shells as an impact limiter to absorb impact energy. The increasing need for lightweight, radiation shielding, high-energy absorption, and heat resistance nuclear casks has sparked an interest towards multifunctional materials. *Composite Metal Foam (CMF) is a* new type of metal foam that can be produced by filling the vacancies around a random loose collection of preformed metallic hollow spheres with a solid metallic matrix either by casting or powder metallurgy (PM) techniques with the aim of increasing the foam's strength and energy absorption. The presence of the matrix strengthens and stabilizes the sphere walls, reducing the possibility of their buckling under loading and resulting in a stronger material with a much greater energy absorbing capability. The properties of composite metal foams can be altered by their processing technique, variation of the size and wall thickness of the hollow spheres as well as the matrix and sphere materials. This new metallic foam has shown up to 7–8 times higher energy absorption compared to any other metal foam made from similar materials and almost two orders of magnitude higher energy absorption under loading compared to the bulk materials that they are made of [5,21].

Composite metal foam (CMF) fulfills the requirements needed to replace the current cask designs as characterized by its low density, high specific stiffness and strength, extraordinary radiation attenuation efficiency, and good energy absorption capability [3,4,6,13,15,22]. However, thermal behavior and heat transfer mechanisms for CMF and its actual performance under fire exposure have not been studied before. Such information is critical to provide guidance to determine the feasibility of application of CMFs in many structures with potential heat and fire exposure such as

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nuclear casks. In order to address these requirements, thermal characterizations including specific heat, effective thermal conductivity (ETC), and coefficient of thermal expansion (CTE) of CMFs were investigated in this work. Specific heat of CMFs was tested by Differential Scanning Calorimetry, and compared with theoretically calculated values obtained through rule-of-mixture. The ETC was measured by means of high temperature guarded-comparative-longitudinal heat flow technique, and verified by Brailsford and Major's model. The CTE was experimentally studied using a thermomechanical analyzer (TMA), and validated via modified Turner's model. Flame test was also performed in accordance with United States Nuclear Regulatory Commission (USNRC) standard [49 CFR 173.398(d)] [23], in which CMF was subjected to a fully engulfing fire with an average flame temperature of 800 °C for a period of 30 min. A physics-based three-dimensional model was carried out using Finite Element Analysis to secure the credibility of the experimental results.

2. Materials processing and sample preparation

2.1. Materials processing

The hollow spheres used in this study were produced by Hollomet in Germany, using a powder metallurgy process. All spheres were made of 316 stainless steel (except that the carbon content is slightly higher than 316 stainless steel) and have two major nominal outer diameter sizes of 2 and 4 mm. The average outer diameter, wall thickness and porosity percentage of all spheres are presented in Table 1. The spheres are designed in a way to maintain a constant ratio of sphere wall thickness to outer diameter in all spheres and have a low percentage of porosities within the sphere walls. This was to make sure the samples were all uniform and that the resulting data would be repeatable and reliable. Aluminum A356 casting alloy (TriAlCo, Inc), and 316L stainless steel powder (North American Hoganas High Alloys LLC) with particle size sieved to −325 mesh (95%) and −200/+325 mesh (5%) were used as the matrix material in manufacturing CMFs. The chemical compositions of hollow spheres is given in Table 2 while that of Aluminum A356 alloy, and 316L stainless steel are given in Table 3. Aluminum-steel composite metal foams (Al-S CMFs) consisting of steel hollow spheres and a solid aluminum A356 alloy matrix were processed through gravity casting technique, whereas steel–steel composite metal foams (S–S CMFs) comprised of steel hollow spheres closely packed in 316L stainless steel powder were manufactured through powder metallurgy technique. More details of manufacturing procedures of CMFs can be found elsewhere [13,22].

2.2. Sample preparation

2.2.1. Samples for specific heat analysis

Specific heat was studied on (4 mm sphere) S–S CMFs and (4 mm sphere) Al-S CMFs. 50 mg metal filings from each sample were obtained through milling the sample surface without using any lubricant in order to keep the filings clean and dry.

2.2.2. Samples for effective thermal conductivity analysis

Three CMF samples were selected to study the effect of sphere size and matrix material on thermal conductivity and compared with the properties of 316L stainless steel and Aluminum A356 available in literature:

- Composite metal foams with 2 mm steel hollow spheres and 316L stainless steel matrix [(2 mm sphere) S–S CMF]
- Composite metal foams with 4 mm steel hollow spheres and 316L stainless steel matrix [(4 mm sphere) S–S CMF]
- Composite metal foams with 4 mm steel hollow spheres and Aluminum A356 matrix [(4 mm sphere) Al-S CMF]

These samples were cut using a Buehler Isomet 4000 linear precision saw to nominal dimensions of 2.54 × 2.54 × 2.54 cm. The specimen ends (top and bottom surfaces as illustrated in Fig. 1) were prepared to be flat and parallel to each other, and perpendicular to the sides within 25 μm per 25 mm accuracy. Both surfaces were finished using a progression of 240, 600, and 1200 grit papers at a wheel speed of 90 rpm for S–S CMFs and 70 rpm for Al-S CMFs in order to improve the flatness, parallelism and thickness uniformity of the samples. Physical properties of the CMF samples are summarized in Table 4.

2.2.3. Samples for coefficient of thermal expansion analysis

Two S–S CMF samples with respectively sphere sizes of (2 mm sphere) and (4 mm sphere) were used to evaluate the coefficient of thermal expansion (CTE):

Table 2
Chemical compositions of 2 mm and 4 mm stainless steel spheres used in processing CMFs (wt%).

	2 mm diameter	4 mm diameter
C	0.68	0.58
Mn	0.13	0.15
Si	0.82	1.14
Cr	16.11	17.34
Ni	11.53	12.28
Mo	2.34	2.28
P	–	0.009
S	–	<0.003
Cu	–	0.04
Co	–	0.02
Fe	balance	balance

Table 3
Chemical compositions of matrix materials used in processing CMFs (wt%).

Element	316L stainless steel	Aluminum A356
C	0.03	–
Mn	2.00	0.28
Si	1.00	7.01
Cr	16.00–18.00	0.02
Ni	10.00–14.00	–
Mo	2.00–3.00	–
Cu	–	0.11
Fe	balance	0.50
Mg	–	0.39
Ti	–	0.09
Zn	–	0.06
Al	–	balance

Table 1
Geometrical characteristics of 2 mm and 4 mm stainless steel hollow spheres.

Sphere diameter (mm)	Sphere wall porosity (%)	Sphere density (g/cm^3)	Sphere wall thickness t (mm)	Sphere outer radius R (mm)	t/R
2	8	2.03	0.104	1.02	0.1023
4	6	2.24	0.196	1.76	0.1111