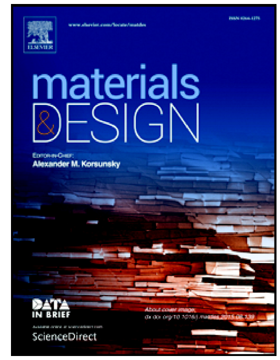
Accepted Manuscript



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PII: S0264-1275(17)31091-2
DOI: doi:10.1016/j.matdes.2017.11.059
Reference: JMADE 3536

To appear in: *Materials & Design*

Received date: 15 September 2017
Revised date: 16 November 2017
Accepted date: 26 November 2017

Please cite this article as: Haoyuan Ren, Dafang Wu, Junning Li, Wenjun Wu , Thermal insulation characteristics of a lightweight, porous nanomaterial in high-temperature environments. The address for the corresponding author was captured as affiliation for all authors. Please check if appropriate. Jmade(2017), doi:10.1016/j.matdes.2017.11.059

Thermal insulation characteristics of a lightweight, porous nanomaterial in high-temperature environments

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Abstract: Thermal-insulating nanomaterials with excellent thermal insulation performance are one type of thermal protection material used in spacecraft. In this study, the high-temperature insulation characteristics of a lightweight, porous aluminum oxide (Al_2O_3) nanomaterial were studied through experimentation using a self-developed thermal testing system for high-speed spacecraft, and were calculated by numerical simulation. The results showed that in a 1200 °C front-surface, high-temperature environment, an Al_2O_3 nanomaterial sheet with a thickness of only 10 mm could reduce the temperature by over 70% while exhibiting stable thermal insulation performance. This demonstrates that the Al_2O_3 nanomaterial has excellent high-temperature insulation performance. The scanning electron microscopy (SEM) images showed that, after the temperature exceeded 1200 °C, the aggregation and growth of the Al_2O_3 nanoparticles accelerated, and single Al_2O_3 nanoparticles and voids increased significantly in size; in addition, the fibers inside the material started to melt, and the cracks started to increase considerably in number, depth, and width. Furthermore, a significant contraction and bending deformation occurred at the edges of the Al_2O_3 nanomaterial sheet; therefore, the Al_2O_3 nanomaterial is suitable for use in a thermal environment below 1200 °C. The results provide an important reference basis for the design of thermal protection systems for spacecraft.

Keywords: nanomaterial; thermal insulation performance; experimental study; numerical simulation

1 Introduction

High-speed spacecraft face extremely adverse aerodynamic thermal conditions in high-Mach-number flight and thus require efficient thermal protection. Both the weight and thickness requirements for thermal insulation materials for high-speed spacecraft are strict, and thermal protection systems (TPSs) must be produced using lightweight, efficient thermal insulation materials [1–3]. Currently, it is generally accepted that nanomaterials are the solid materials having the lowest thermal conductivity [4–5]. The thermal conductivity of thermal-insulating nanomaterials can reach as low as 0.013 W/m·K, far lower than that of still air [6]. In addition, thermal-insulating nanomaterials also have other excellent properties, such as low density and high-temperature resistance and, thus, are a type of near-ideally efficient thermal insulation materials.

Researchers in China and elsewhere have extensively studied the thermal insulation performance of nanomaterials [7–9]. Hoseini et al. [10] provided a theoretical method for determining the thermal conductivity of aerogels and analyzed the effects of porosity and the thermal conductivity of fibers on aerogels. Hurwitz et al. [11] studied the changes in the internal structure of nano-aerogels with temperature and developed a boehmite-structured aerogel that could maintain its structural porosity and performed steadily under high-temperature conditions. Huang et al. [12] investigated experimentally the structural behaviors of silica aerogel under temperatures of 950-1200°C based on scanning electron microscopy, Brunauer-Emmett-Teller analysis, Fourier transform infrared spectroscopy, and X-ray diffraction patterns and explored the possibility of using silica aerogel under even higher temperature condition. Bi et al. [13] designed a three-dimensional numerical model that could calculate the heat conduction properties of porous nano-aerogels by simulating their typical ordered internal structures; in addition, they introduced the size effects of aerogel particles and pores into the numerical model to improve the prediction accuracy for the effective thermal conductivity. Bialls et al. [14] established a nanoscale heat transfer model for an organic aerogel and calculated the effective thermal conductivity of the organic aerogel by comprehensively considering radiant and conductive heat transfer. Through experimentation, Yang et al. [15] studied a silicon dioxide (SiO_2) nanomaterial using the non-steady-state step plane heat source method and determined the values of several parameters (e.g., thermal conductivity, thermal diffusivity, and specific heat capacity) at various temperatures. Zhou and Feng et al. [16] numerically simulated the transient heat transfer process of a nano-SiO_2 aerogel using the implicit finite-difference method, as well as determined the internal temperature-time relationship of the material and the thermal insulation parameters of the material.

With the speed of hypersonic vehicles increasing constantly, the high-temperature environments resulting from aerodynamic heating are becoming increasingly harsh. Temperatures at the thermal boundaries of some parts of a hypersonic vehicle exceed 1000°C. Therefore, research focusing on the determination of the thermal insulation performance and operating temperature limits of lightweight, efficient thermal-insulating nanomaterials under high-temperature conditions is of great importance to the safe and reliable design of TPSs for spacecraft. However, to date, there have been no reports presenting research on the thermal insulation performance of thermal-insulating nanomaterials in a high-temperature environment up to 1400 °C.

In this work, the high-temperature insulation performance of an aluminum oxide (Al_2O_3) nanomaterial was experimentally studied using a self-developed aerothermodynamics test simulation system for high-speed aircraft. The dependence of the internal structure of the nanomaterial on temperature was observed by scanning electron microscopy (SEM). Suitable operating temperature limits for the nanomaterial were determined based on the test results concerning the growth and variation of nanoparticles