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FABRICATION OF VERY-LOW-DENSITY, HIGH-STIFFNESS CARBON FIBER/ALUMINUM HYBRIDIZED COMPOSITE WITH ULTRA-LOW DENSITY AND HIGH STIFFNESS

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Fabrication of a composite material with ultra-low density and high stiffness in microgravity is the objective of the present investigation. The composite structure to be obtained is a random three-dimensional array of high modulus, short carbon fibers bonded at contact points by an aluminum alloy coated on the fibers. The material is highly porous and thus has a very low density. The motivation toward the investigation, simulation experiments, choice of the component materials, and on-flight experiment during ballistic trajectory of a NASDA rocket, are described herein.

Introduction

Structural materials in space are desired to possess high specific strength, stiffness, and resistance to buckling. Also it is desirable that the materials be fabricated on-orbit. Such requirements can be met, in principle, by a material such as a finely foamed, metal-ceramic composite where the macroscopic buckling load can be raised by an increase in the second moment of area of the cross section at a constant mass, while the microscopic buckling at the metal walls between small cavities is prevented by fine ceramic particles or fibers dispersed in the metal matrix. Fabrication of such materials was our original proposal for the current FMPT project. However, preliminary investigation revealed two difficulties to overcome, which are: (a) to confine cavities to an isolated fine state in a molten metal even under microgravity since metals have generally very low viscosity and very high surface tension in the molten state and (b) to find a suitable constituent which will act as a foaming agent in a molten metal and is yet safe in carrying out the fabrication.

An alternate method to obtain a similar type of structure which would have the properties stated above was then proposed. The structure consists of short high modulus ceramic fibers and a small amount of filler metal of relatively low density. The fibers are aligned as random three-dimensional arrays and are bonded at contact points by the metal that is coated on the surface of the fibers. Such a structure is highly porous and cavities are surrounded by the metal walls to resemble the structure of the foamy hybrid composite in the original proposal. The fabrication procedure in this case involves fiber coatings with a metal or an alloy encapsulation of chopped fibers and heating the material to a temperature above the melting point of the metal coating, followed by cooling to ambient temperature. The procedure is simple and thus has an advantage for possible on-orbit fabrication. Microgravity during fabrication is essential for two reasons: (a) keeping short fibers in a random three-dimensional configuration instead of collapsing to near two-dimensional configuration under the effect of gravity, and (b) keeping the molten metal from slipping down and separating away along the direction of gravity due to a difference in densities of the fibers and the metal.

Simulation Experiment

In order to provide a better picture of the structure under consideration, results of a simulation experiment are briefly shown. In the experiment, nylon threads to 0.8 mm in diameter are used as fibers which are coated with wax to a thickness of some 0.2 mm. The coated threads are chopped into pieces of 5 mm in length and then heated in a Pyrex glass container until the wax coatings melt. To simulate a microgravity environment, coated threads are placed in an aqueous solution of alcohol of which the density is adjusted to be that of the wax. Upon heating and subsequent cooling, the threads are bonded at contact points. Figure 1a shows composites obtained under the microgravity simulation, and Figure 1b shows those prepared under the effect of gravity. In Figure 1a, a random three-dimensional array of the short threads bonded at contact points is achieved, whereas in Figure 1b the wax has separated from the nylon threads and is deposited at the bottom of the container. The difference is clearly seen when the height of the specimen is compared because the same amount of materials was used for each case of fabrication.

Choice of Component Materials

A high modulus carbon fiber was chosen for this experiment and an aluminum alloy was developed as a coating substance for the fibers. An aluminum-based alloy was selected because of its relatively low density and its moderate melting temperature where fabrication is practical and feasible with non-expensive, simple electric furnaces. It was recognized, however, that the wettability between carbon fiber and pure aluminum is known to be extremely poor. However, the wettability between them is known to be improved at temperatures above 1273 K due to the formation of aluminum carbide (Al_4C_3) at the interface [2,3]. The chemical reaction is also known to occur even at lower temperatures, at 773 K for example, upon prolonged exposure [2-7]. At any rate, the occurrence of the carbide formation has been known to cause severe degradation of the fiber strength. In the present investigation, therefore, a systematic investigation was first undertaken to improve the compatibility between carbon fiber and aluminum by alloying the aluminum.

Aluminum alloys containing a small amount of various alloying elements (up to 5 at%) were prepared by arc-melting under an argon atmosphere. These alloys were coated onto the carbon fiber surface by vacuum deposition. The fibers were then heated to 1073 K in vacuum encapsulated silica tube to melt the alloys. After cooling the surface of the fibers was examined by scanning electron microscopy to judge the degree of wettability. As is shown in Figure 2a, the surface of the fibers coated with pure aluminum has a number of metal droplets indicating the poor wettability. It was found that when addition of such elements as thallium, indium, and lead by only 1 at% was made, the wettability was significantly improved as shown in Figure 2b for the case of lead addition. Moreover, tensile tests of the coated fibers after the heat treatment revealed that room temperature strength of the fiber was not deteriorated by such alloy coatings. Through the investigation, a wetting reagent which could be added to aluminum was found so that the composite fabrication under consideration became realistic. Details of the investigation are describe elsewhere [8].

Flight Experiment

A flight experiment was carried out in August 1983 using a NASDA TT-500A-13 rocket. The details of the materials preparation and the fabrication experiment are as follows.

Carbon fibers of a high modulus type being approximately 7 to 8 μm in diameter were coated on the surface with an Al-1 at% Tl alloy to a thickness of 1 μm using a vacuum evaporation technique. The coated fibers were cut into short pieces of 0.5 to 1 mm in length and vacuum encapsulated in a silica tube with an inner diameter of 10 mm. Prior to the encapsulation, a piece of lid made of silica pipe was welded onto the inner wall of the tube to slightly compact the materials. The height of the specimen in the silica tube was then ca. 15 mm. The whole specimen capsule, ca. 45 mm in length as shown in Figure 3, was then packed in a graphite container and placed in an electric furnace. The TT-500A rocket provided a microgravity environment for 6 min during its ballistic trajectory and the heat treatment of the specimen was scheduled for this time period. The maximum temperature was scheduled to be 1023 K for 2 min while the melting point of the aluminum alloy was about 943 K.

Unfortunately, during the on-flight experiment temperature control of the electric furnace was unsuccessful and the temperature went up to above 1743 K. Examination of the retrieved specimen showed obvious damage on the surface of the fibers due to the overheating and the whole composite was found to be brittle. This is probably due to the chemical reaction between the fiber and aluminum alloy to form Al_4C_3 and also due to partial evaporation of the aluminum alloy . SEM observation, however, revealed the structure of the specimen to be a random three-dimensional configuration of the short fibers and the contact-point bonding was mostly successful making the entire specimen rigid.

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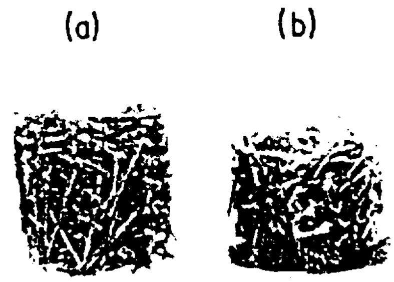

Figure 1. Structure of Nylon threads-wax composites fabricated under (a) microgravity simulation and (b) the effect of gravity.

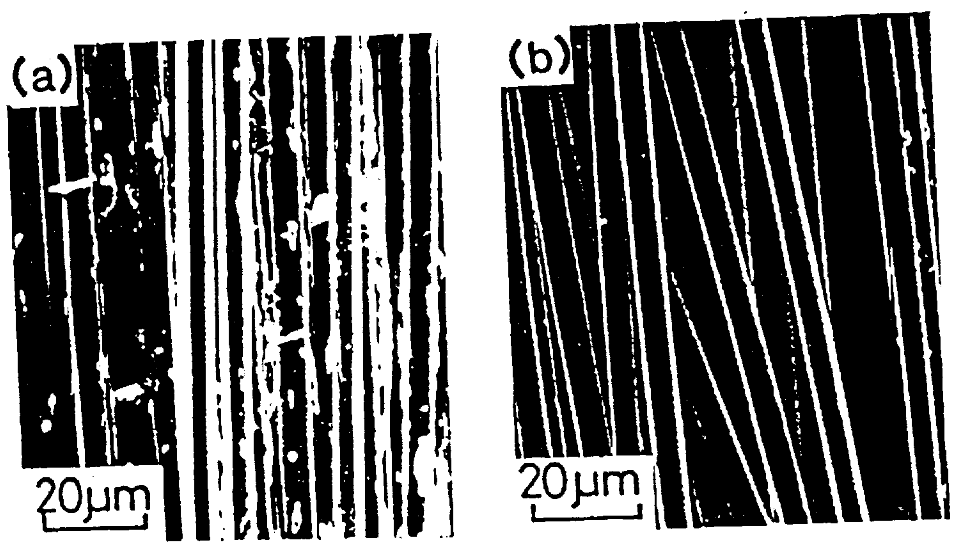

Figure 2. Scanning electron micrographs of carbon fibers after heating at 1073 K for 30 min coated with (a) pure aluminum and (b) Al-1 at% Pb alloy.

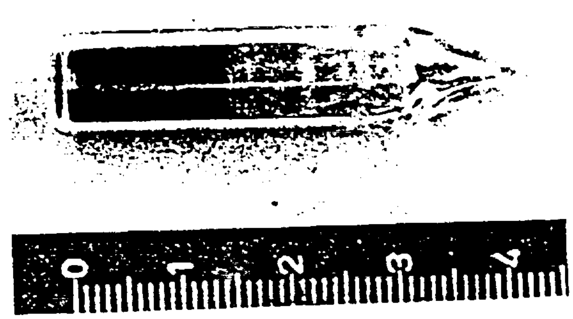

Figure 3. Appearance of the specimen capsule for the in-flight experiment.