SHAPE MEMORY EPOXY FOAMS AND COMPOSITES: RIBES_FOAM2 EXPERIMENT ON SPACECRAFT "BION-M1" AND FUTURE PERSPECTIVE

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Abstract

Shape memory epoxy foams and composites were tested in April 2013, on board the BION-M1 spacecraft through the Soyuz-2 launch vehicle, with the aim to study their behaviour in microgravity for future applications. The on-orbit Ribes_Foam2 experiment consisted in the heating of three samples in various configurations having different shapes (a prototype of actuator, a sheet of composite laminate and parallelepiped) packed on ground, to evaluate the shape recovery capabilities in the space environment. As expected, micro-gravity does not affect the ability of the foams to recover their shape but it poses limits for the heating system design because of the difference in heat transfer on earth and on orbit. In this work, the main results of the experiment are discussed. They have provided useful information for the development of actuators and deployable structure, highlighting future perspectives.

Introduction

Shape memory polymers (SMPs) are a new class of materials for aerospace applications as light actuators, structural parts with reduced size during transport, and expandable/deployable structures [1]. The shape memory effect can be observed by performing a typical thermo-mechanical cycle [2]. Firstly, the polymer is processed to receive its permanent shape. Secondly, it is heated and deformed in a new configuration that can be stored by cooling. Heating up the stored sample above a transition temperature it recovers its original shape. This concept has been also applied to open cellular (foam) structures and the presence of pores can magnify shape memory effects also in polymers with low memory properties. Moreover, the material can be packed in a very small volume because of pore collapsing, without generating any foam damage [3].

A new foaming process for thermosetting resin, called solid-state foaming, was proposed by the authors in order to obtain polymer foams [4-5]. This method is simpler than conventional foaming methods and gives homogeneous closed-cell foams with excellent mechanical properties and remarkable shape memory properties. In the solid-state foaming process, uncured thermosetting tablets are fabricated by pressing commercial powders in a steel mould at room temperature and used as foam precursors. The tablets foam when heated in an oven at high temperature. No blowing agent must be added because the foaming mechanism depends on the uncured resin boiling point.

Shape memory properties can be also given to composite materials and structures by using shape memory polymers (SMPs) matrices or integrating parts made of SMPs [6-7]. Some examples are reported in [7] where shape memory composite tubes and plates were fabricated by adding a shape memory layer between two carbon fibre reinforced skins. An optimal adhesion between the different layers was achieved thanks to the compatibility of the prepreg matrix and the shape memory material. Shape memory composite structures were also produced by joining composite shells with shape memory foams. Some mechanical, dynamic mechanical and shape recovery tests were performed to show the properties of such materials and structures. Results confirmed the ability of this class of materials to easily change their shape without affecting the mechanical stiffness of the recovered structures.

Thanks to their properties, epoxy foams by solid-state foaming were selected to build prototypes of actuators for space applications [5] and subsequently, prototypes of shape memory epoxy foams were selected for an experiment on the International Space Station (ISS) during the last mission of the Space Shuttle Endeavour [8-9]. Micro-gravity does not affect the ability of the foams to recover their shape but it poses strong limits for the heating system design because of the difference in heat transfer on earth and in orbit [8]. A full recovery of the foam samples was not achieved due to some limitations in the maximum allowable temperature on ISS for safety reasons: anyway a 70% recovery was also measured at a temperature of 110°C. On ground laboratory experiments showed that 100% recovery could be reached just by increasing the maximum temperature to 120 °C.

For the ISS experiment (I-FOAM) [8], a small equipment was designed and built to simulate the actuation of simple devices in microgravity conditions. Three different configurations were chosen according to previous studies (compression, flexure and torsion) [8]. The same equipment has been also used also in the following experiment (Ribes_Foam2) during the BION-M1 mission of the Soyuz spacecraft (20th of April 2013) in which for the first time a shape memory polymer composite (SMPC) sheet was also prototyped [9]. Results from this second experiment are discussed in this paper with the aim to highlight future perspective in the field.

1. Materials and methods

1.1 Materials and samples production

A commercial epoxy resin (3M ScotchkoteTM 206 N), which is available as an uncured green powder, has been used for the samples production. The solid-state foaming process has been used for the foam preparation [4]. Tablets with a weight of 4g and a diameter of 20 mm were made by compaction at room temperature of the resin powder in a steel mold. The tablets were foamed by using a muffle at 320°C for 8 min. Both foaming and successive cooling were performed in air. The final epoxy foam density was about 0.36 g/cm^3 with a foaming ratio close to 4. Two foam blocks were extracted by machining from the initial cylindrical foams. The first block (24x8x8 mm^3) was used for the compression configuration, and the second block (nominal size 14x8x8 mm^3) for the actuator. The memory step was made by heating the samples in an aluminum mold having the cavity equal to the sample cross section (8x8 mm^2); this way buckling was avoided during compression by a piston of the same size. The compression load was kept on the piston during the mold cooling. At the end of the memory step, a 50% reduction was obtained for the height of both samples whereas the other two sizes remained unaltered.

For the first time, a SMPC sheet was also prototyped for the on-orbit experiment. The composite laminate was produced by using the same epoxy resin in a molding process with a hot parallel plate press. A low pressure (5 MPa), a plate temperature of 150 °C and a molding time of 15 min were applied. Two polyamide flat molds were used to avoid the direct contact of the composite sheets with the plates. After molding, composite sheets were post-cured in oven for 1 h at 150 °C. Composite sheets consisted of two layers of dry carbon fiber fabric with a shape memory epoxy resin interlayer. After production, a small sample (nominal size 24x10x0.4 mm^3) was cut and heated for the memory step. A 180°C folding was performed with a bending diameter of 2.5 mm.

The strategies for the development of the samples were discussed in [9]. In Figure 1, the image of the samples is shown.

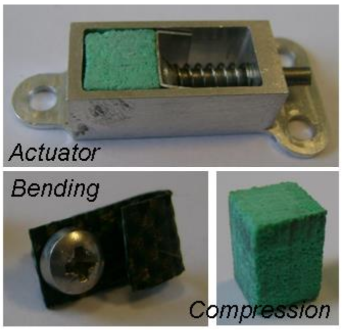

Fig. 1 The samples of the Ribes_Foam2 experiment.

1.2 The apparatus for the on board experiment.

The apparatus for the experiment in microgravity was an autonomous device placed in a proper container (namely BIOKON by Kayser Italia) which had already flew in other space missions. It consisted of a top case, with the front panel and the battery pack, and a lower chamber, with the control unit including heating system, camera, and experiment unit and data acquisition system.

The experiment unit was composed of a sample house, a heating plate, a heater, thermocouples, optical sensors (only for the compression configuration) and the unit walls. Three thermocouples were inserted in the aluminium plate to monitor the temperature evolution during heating. The sample with the compression configuration was placed in a rectangular box where three optical sensors allowed measuring its height. This rectangular box was made in aluminium as well to improve the foam heating: in fact, during recovery, this sample moves its end far from the heating plate with the risk of a poor performance. During the on-ground preliminary tests, samples were heated up to a temperature in the range between 90 and 120 °C and then kept at this temperature for a settable time.

Temperature data loggers, optical sensors (for the compression configuration) and the camera (for the other two configurations) were used to measure the foam recovery as a function of time and temperature. The heating plate was opportunely thermally insulated by means of plastic spacers and a base plate. The unit external walls were made of thermally insulated foam, except for the top external surface which was made of polycarbonate to permit the image acquisition. Figure 2 shows the apparatus and Figure 3 shows the view of the samples integration before flight. More details of the equipment can be found in [11].

Fig. 2 The apparatus of the experiment Ribes_Foam2.

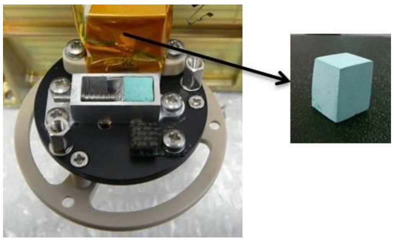

Fig. 3 View of samples integration before flight.

1.3 The experiment Ribes_Foam2.

As above mentioned, the on-orbit experiment consisted in the heating of three samples in various configurations having different shape, packed on ground, to evaluate the shape recovery capabilities in the space environment.

The main goal of the experiment was to achieve the maximum material recovery, and for this reason the recovery temperature was fixed to 120°C. Higher temperatures were not possible because of energy limitations of the batteries. In fact, being a flight without astronauts, it was necessary to turn-on the experimental apparatus before the flight. The related energy consumption had to be taken into account. A Russian Soyuz rocket launched the Bion-M1 space capsule into orbit from Baikonur Cosmodrome (Kazakhstan) on 19th of April, 2013. The Ribes_Foam2 experiment was performed on 20th of April but the system was already switched-on 102 hours before (more than 4 days). Data acquisition of temperature, time, status of the optic sensors, and images by the camera was correctly performed. Data and samples were collected and provided to the authors for further analysis.

2. Results, discussion and future perspectives.

The experiment unit is shown in Figure 4 before and after the flight in microgravity. It is evident the recovery of the SMPC sheet and the movement of the SMP actuator. In the figure, it is also reported the status of the foam sample with the compression configuration: the sample is inside the aluminum housing and after the flight is visible through the holes for the optic sensors. The first hole of the sample housing was at 13 mm from the base and the other two holes were 3 mm spaced in height. The second hole is not visible in the figure because it is located on the opposite side. Being the initial height of the deformed foam about 12 mm, its end was 1 mm far from the beginning of the first hole. During the experiment, all the optic sensors registered the sample recovery.

Shape recovery of the SMPC laminate and the actuator can be also evaluated during time thanks to the camera.

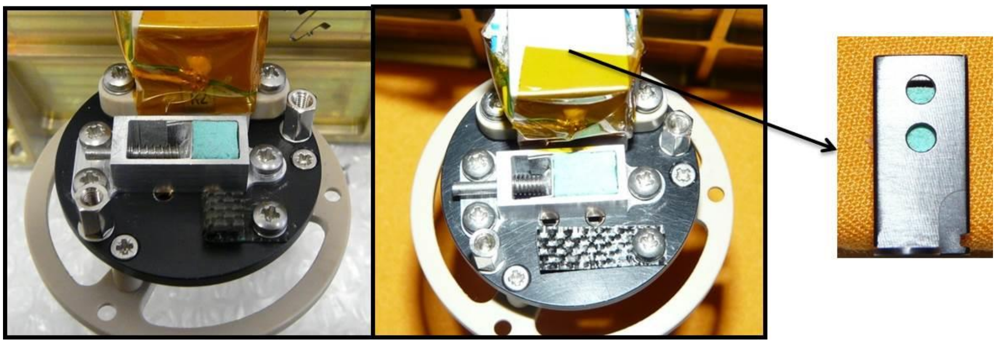

Fig. 4 The experiment unit before and after the flight in microgravity.

The maximum temperature reached during the experiment was 111,7 °C, even if the set temperature was 120°C. Unfortunately, the launch was delayed and the charge of the battery was not sufficient to heat as previously fixed. The sample with compression configuration recovered almost his initial shape (recovery of about 90%). In fact, the three optical sensors for detecting the shape recovery were activated after about 34 min, 38 min, and 48 min respectively. The corresponding temperature of the heating plate was 107°C, 109°C and 111°C. The sheet of composite laminate recovered his shape and also in this case a detachment from the heating plate was evident as in the previous experiment onboard of the ISS [8].

Instead, Figure 5 shows the prototype of actuator before and after the experiment in microgravity. It is clearly evident the actuation. The spring stiffness is 2.1 N/mm and so it is possible to infer the value of the actuation load as a function of the time, analyzing the video recorded on orbit.

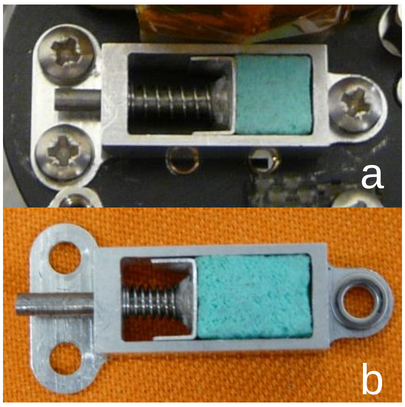

Fig.5 The prototype of actuator: a) before and b) after the microgravity experiment.

In fact, from the video the shape evolution of two samples during heating in the time can be evaluated. It is visible that, after 20 min, the SMPC laminate already started to recover the shape whereas a time of 40 min is necessary to observe a significant displacement of the actuator end. That is due to the higher thermal conductivity and the lower thickness of the composite sample in comparison with the foam. Moreover, the foam sample into the actuator was pre-loaded by the spring: a displacement of 2 mm was applied to the spring for a resultant load of 1.16 N which tended to avoid the length recovery of the foam block.

Analyzing the heating system, it is therefore possible to perform shape recovery also by using a single heated surface if a proper housing is used and this fact is particularly important for designing deployable structures and actuators. For the latters, it was found that a low actuation rate (about 0.2 mm/min) can be achieved, with a resultant loading speed about 0.1 N/mm, by using a very small SMP foam (14x8x8 mm^3). These characteristics are very promising to design small-size actuators for self-deployable structures where other shape memory materials (e.g. shape memory alloys, SMA) cannot be used for the excess in the actuation rate. Another possible application could be the fine regulation of the position of shields, mirrors, and other structures of satellites.

The development of new advanced materials and their testing in microgravity is therefore a challenge to make successful the next generation of space exploration missions. For example, the possibility to realize on orbit, under microgravity conditions, material foaming with a homogenous distribution of the pores and therefore enhanced properties could enable new capabilities. In this perspective, a fundamental step would be better understand the behavioural properties of such material exposed to the space environment, testing the stability and durability of SMP foam and devices and the deployment of a complex structure with several folding operations by using an electric current or the Sun exposure. This type of foam may be an enabling technology for building future spacecrafts components for long-term space flight or for light actuators. Moreover, the above mentioned self-deployable structures, with the integration of composite materials and parts made of SMPs, could be used for the deployment of solar sails or of systems for the capture of space debris and for deorbiting, ongoing researches of the authors. All that could open new frontiers for space exploration.

Conclusions

The experiments Ribes_Foam 2 has shown the ability of solid state epoxy foams and composites to recover their shape in microgravity.

In previous studies, it has been shown that the micro-gravity poses limits for the heating system design because of the difference in heat transfer on earth and on orbit. The Ribes_foam2 experiment has taken into account this difference by using filled materials (e.g. carbon fiber composites), by improving the contact of the foam samples with the heated walls, and increasing the maximum temperature necessary to obtain the full recovery of the samples. A higher recovery was registered with a maximum up to 90% only by increasing the heating time whereas the maximum temperature remained almost unaltered.

Fort the first time, the actuation of a very small SMP foam has been studied. The characteristics are very promising to design small-size actuators for self-deployable structures where other shape memory materials (e.g. shape memory alloys, SMA) cannot be used for the excess in the actuation rate.

All of these aspects could become very significant for the behavior of complex multifunctional structures in which shape memory epoxy foams and composites are integrated.

References

1. *Y. Liu, H. Du, L. Liu, J. Leng, Shape memory polymers and their composites in aerospace applications: a review, Smart Mater. Struct. 23 (2014) 023001 (22p).*
2. *Lendlein A and Kelch S, 2002, Shape-memory polymers Angew. Chem. Int. Edn 41 2034–2057.*
3. *Sokolowski W. M. and Hayashi S., Applications of cold hibernated elastic memory (CHEM) structures, Proceedings of the SPIE - The International Society for Optical Engineering 5056 (2003) 534-44.*

4. *F. Quadrini, E.A. Squeo, Solid-State Foaming of Epoxy Resin, Journal of Cellular Plastics 44 (2008) 161-173.*
5. *Quadrini Fabrizio, Santo Loredana, Squeo Erica Anna, Shape memory epoxy foams for space applications, Materials letters, Vol.69, 2012, pp.20-23.*
6. *L. Santo, F. Quadrini, L. De Chiffre, Forming of shape memory composite structures, Key Eng. Mat., 554-557 (2013), 1930-1937.*
7. *Fabrizio Quadrini, Polymer matrix composites with shape memory properties, Materials Science Forum, (2014) Volumes 783 – 786,pp. 2509-2516.*
8. *L. Santo, F. Quadrini, E. A. Squeo, F. Dolce, G. Mascetti, D. Bertolotto, W. Villadei, P. L. Ganga, V. Zolesi, "Behavior of shape memory epoxy foams in microgravity: experimental results of STS-134 mission", Microgravity - Science and Technology, vol. 24 issue 4 (2012), p. 287 – 296.*
9. *L. Santo, F. Quadrini, G. Mascetti, F. Dolce, V. Zolesi, Mission STS-134: Results of Shape Memory Foam Experiment, Acta Astronautica, 91 (2013) pp. 333-340.*
10. *Loredana Santo, Recent Developments in the Field of Shape Memory Epoxy Foams, Materials Science Forum, (2014) Volumes 783 – 786, pp. 2523-2530.*
11. *A, Donati et al., Ribes Precursor Paylod on Bion-M1, Proceedings of 64th International Astronautical Congress, Beijing, China. IAC-13-A2.3.2.*