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Shape memory polymer foams

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ABSTRACT

Recent advances in shape memory polymer (SMP) foam research are reviewed. The SMPs belong to a new class of smart polymers which can have interesting applications in microelectromechanical systems, actuators and biomedical devices. They can respond to specific external stimulus changing their configuration and then remember the original shape. In the form of foams, the shape memory behaviour can be enhanced because they generally have higher compressibility. Considering also the low weight, and recovery force, the SMP foams are expected to have great potential applications primarily in aerospace. This review highlights the recent progress in characterization, evaluation, and proposed applications of SMP foams mainly for aerospace applications.

Contents

1. Introduction

SMPs are smart materials that can respond to external stimulus (heat-induced, electricity-induced, light, magnetic field, water and solvent), changing their shape and then remember the original shape [1].

Shape memory is usually associated with metals alloy, such as copper-aluminium-nickel, nickel-titanium and iron-manganese-silicon, generally termed SMAs [2] but recently the synthesis of novel polymeric materials with thermally induced shape memory properties has been reported [3]. In SMPs the transition from temporary to permanent shape is generally obtained by an external gradient of temperature, in the range of a specific switching transition temperature.

SMPs possess several advantages over shape memory alloys, resulting in potential substitutes for lightness, low cost, high shape recovery, easy manufacturing, good biocompatibility. Furthermore, their physical (e.g. transition temperature) and mechanical properties can be tailored by small changes in chemical composition and structure [3].

Potential applications for SMPs exists in every area of daily life: from self repairing auto bodies to kitchen utensils, from switches to sensors, from intelligent packing to tools. They can be used also for heat shrinkable tubes, autoreparing and self-healing. Other potential applications are in the biomedical field: drug delivery, biosensor, biomedical devices. Moreover, since polymer can be made biodegradable, they can be used as short term implants where removal by surgery can be avoided [4]. In other fields they are very useful for microsystem components, smart textile and in aerospace for actuators and self deployable structures [1,4].

In foam form, the shape memory behaviour can be enhanced because foams generally have higher compressibility, even if mechanical stiffness and strength are generally reduced. Considering the low weight, and recovery force, the SMP foam are expected to have great potential applications mainly for actuators.

Recently, a concept called cold hibernated elastic memory (CHEM) utilizing SMPs in open cellular foam structures was

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proposed [5]. The effect of long-term storage in compressed cold hibernated elastic memory polyurethane foam was investigated and results show that polyurethane foam retains its shape memory properties even after being stored in a compacted state for a long period (complete strain recovery for a hibernation period of up to two months). These results are very interesting for space application because CHEM foams can be packed on Earth and then heated to recover its shape in space later.

However, SMP also have some drawbacks, such as low deformation stiffness, low recovery stress and to overcome these deficiencies, shape memory polymer composites (SMPCs) have been developed in many practical applications to satisfy this demand [1].

The results of studies on SMPCs indicate that they can have higher strength, higher stiffness and special characteristics determined by what fillers are added which can offer further advantages over SMPs [1,4]. SMPCs are expected to develop and have great potential applications mainly in aerospace applications in the near future as shown in [1,4,6–10]; remarkable research works are focusing on the design and evaluation of SMPC components such as foldable SMPC truss booms, SMPC hinges to actuate solar array deployment, systems for antenna and reflector deployment. Moreover, a morphing vehicle concept is developing by using both SMPs and SMPCs [1].

Interesting applications could be also for the marine field, by using a SMP core with self-healing properties in sandwich structures as shown in [11] and subsequently described in this paper.

This review highlights the recent progress in characterization, evaluation, and proposed applications of SMP foams, also taking into account some applications such as sandwich structures and filled foams.

Thermal-responsive SMPs foams are mainly investigated.

2. General mechanism of SMPs

The shape memory effect results from a combination of the polymer composition and morphology together with the applied processing and programming [3].

The characteristics of SMPs are variable above and below the transition temperature (glass transition temperature (T_g) or melting transition temperature (T_m) based on the nature of the polymer configuration [1]. When the temperature is higher than T_g, the polymer is in the rubber state and is deformable, when the temperature is below T_g, the polymer is in the glass state and it can be considered an elastic material. Close to the transition temperature, SMPs exhibit viscoelastic behaviour. The polymer properties change rapidly and the elasticity modulus decreases.

The process of shape recovery can be divided into the following steps: (1) fabrication step of the original shape of the SMP, (2) heating step (above T_g), deforming the SMP in a new configuration, (3) cooling step, reducing the temperature to a temperature below T_g maintaining the constraint and finally removing it; reheating step, increasing the temperature above T_g in order to recover the original shape [12–15]. Fig. 1 shows this thermomechanical behaviour.

Based on the different molecular cross-linked architectures, SMPs can be classified into two types: thermoset and thermoplastic. In the recent past, research has mainly focused on thermoplastic SMP such as polyurethane (SMPU), while subsequently thermoset SMPs have been studied for their interesting properties, high material stiffness, high transition temperature and environmental durability, particularly interesting for the fabrication of space structures [1].

The shape memory phenomenon and theory can be explained by using two main approaches [16–18]. The first one is based on the viscoelastic theory. Tobushi et al. [19] investigated the thermomechanical behaviour of SMPU using this theory. In this model, the materials are assumed to be a combination of three types of basic elements: a spring, which represents elasticity properties, a dashpot, which represents viscous properties, and frictional element, which represents the slip mechanisms due to the internal friction. Their collaboration in series or in parallel can be used to represent the viscoelastic properties of SMPU. The second approach is based on phase transition (frozen phase and active phase theory). Liu et al. [20] developed a small strain and rate-independent thermomechanical constitutive model of epoxy SMP by using this theory. In this model, the internal variables are defined and the materials are commonly considered to own the state of active phase and frozen phase.

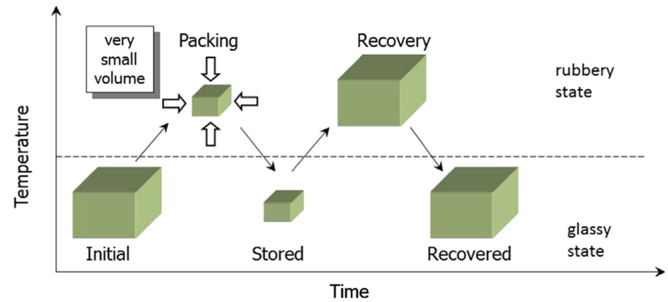

Fig. 1. Schematic representation of thermomechanical cycle for SMP.

3. Recent studies on SMP foams: characterization, evaluation, and possible applications

SMP foams have been extensively investigated in the last decade, mainly focusing the attention on the preparation, characterization and possible application.

In [21] the thermo-mechanical behaviour of epoxy shape memory polymer foams with an average relative density of nearly 20% was examined. These foams were deformed under conditions of varying stress, strain, and temperature. Various shape recovery tests were used to measure properties under different thermomechanical conditions. Tensile strain to failure was measured as a function of temperature to probe the maximum recovery limits of the foam in both temperature and strain space. Compression tests were performed to examine compressibility of the material as a function of temperature. These foams can be compacted as much as 80% and multiple cycles can be performed with full strain recovery. Micro-computed tomography scans of the foam at various compressed states were used to study foam deformation mechanisms. This analysis revealed the bending, buckling, and collapse of cells with increasing compression, in agreement with results from published numerical simulations.

In [5], the effect of long–storage in CHEM polyurethane foam was investigated. The foams were pre-strained at high temperature, above the glass transition temperature (nominal T_g=63 °C), to 80% and 93.4%, respectively, and then cooled to room temperature. After different periods of cold hibernation (up to two months), they were heated up at fixed length or against different constant loads.

The results show that the maximum stress exerted at fixed length strongly depends on the amount of pre-strain; expansion rate of 380% and 1273% from the hibernated size against a 1 N load (pre-strained by 80% and 93.4%, respectively) are achievable. However, upon further increases in load, the expansion is reduced dramatically. Moreover, the tested CHEM polyurethane foam maintains its shape memory properties even after being stored in