INTELLIGENT EXPANDABLE STRUCTURES BASED ON THE IMPROVED ACTIVATION OF SHAPE-MEMORY POLYMERS

Andrés Díaz Lantada, Pilar Lafont Morgado, Julio Muñoz-García, José Luis Muñoz Sanz
Javier Echavarri Otero and Juan Manuel Munoz-Guijosa
Grupo de Investigación en Ingeniería de Máquinas, E.T.S.I. Industriales, Universidad Politécnica de Madrid
c/ José Gutiérrez Abascal, nº 2, 28006, Madrid, Spain

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Abstract: Shape-memory polymers are active materials with thermomechanical coupling and a high capability to recover from high levels of deformation, which, combined with their low cost and density has favoured the appearance of numerous applications, particularly those linked to the Medical Industry. In many cases, these materials are of medical standard, which increases the chances of obtaining biocompatible devices.

In the last decade enormous progress has been made on many areas, regarding these materials, such as synthesis, characterization, activation, prototyping and others, aimed at improving their applicability. However, various spheres of action require additional in depth research to promote the production start-up of various shape-memory polymer-based devices that have had laboratory validation. One of these areas of improvement is linked to the activation systems of SMPs.

This work sets outs the possibility of obtaining a more homogeneous heating processes for an optimal activation of the "shape-memory effect", which promotes the geometric changes of such devices. These improvements are based on the development of net-shaped SMP structures to which silver thread is knitted for subsequent activation through Joule heating. First prototypes and trials are explained in detail, as well as the possible biomedical applications of this concept.

1 INTRODUCTION TO SHAPE-MEMORY POLYMERS (SMPS)

Shape-memory polymers (SMPs) are materials that show a mechanical response to external stimuli, usually to changes of temperature. When these materials are heated above their "activation" temperature, there is a radical change from rigid polymer to an elastic state that will allow deformations of up to 400%. If the material is cooled down after manipulation it retains the shape imposed; the said structure is "frozen" and returns to a rigid but "non-equilibrium" state. If the material is again heated above its vitreous transition temperature or "activation temperature" it recovers its initial non-deformed state. The cycle can be repeated numerous times without degrading the polymer and most suppliers can formulate different materials with activation temperatures ranging from –30 ºC to 260 ºC, depending on the application required. Of all the polymers developed that show shape-memory properties, those most worthy of mention due to their applicability are epoxy resins, polyurethane resins, cross-linked polyethilene, styrene-butadiene copolymers and other formulations (Lendlein, Kelch, 2002, Liu, 2007).

They are therefore active materials that present thermomechanical coupling and a high capability for recovery from deformation, (much greater than that shown by shape-memory metal alloys), which combined with their lower density and cost has favoured the appearance of numerous applications. Their properties permit applications for the development of sensing devices and actuators, especially for the aeronautics, automobile and medical industry.

Figure 1 shows a scheme of the training and actuation process of SMP structures.

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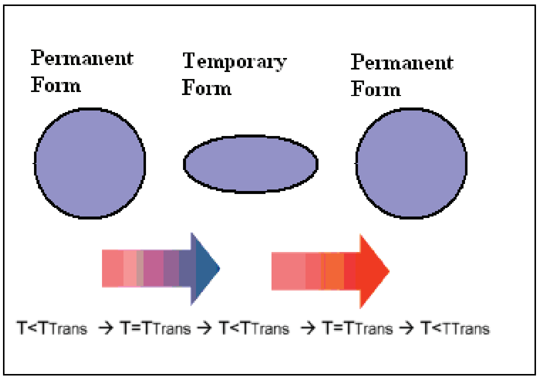

Figure 1: Training process of the shape-memory effect and recovery of permanent form.

2 POTENTIAL FOR BIODEVICES

2.1 Some Advantages

As polymers, SMPs can be easily conformed into different complex shapes and their properties designed or adapted to specific applications and can also be integrated with other microelectromechanical sensors (MEMS) to produce "intelligent" bioactuators and biodevices.

Compared to other shape-memory alloys used in numerous medical devices, SMPs show a far greater capability for changing their geometry during activation. They are also much cheaper to synthesise and their large scale mass production costs are reduced by using technologies such as injection moulding. All this makes them very versatile active materials with a high potential for industry, provided they overcome some of the limitations set out in the following sections.

2.2 Proposed Devices

Bellow are explained some specific proposals for developing medical devices based on the use of shape-memory polymers, most of which have undergone in vitro laboratory testing. After undergoing in vitro testing and meeting the requirements for official approval, in some cases their commercialisation is subject to their attaining the goals described at the end of this paper.

Self-expanding Stents. Like the stent designed by Boston Scientific Corporation using the polymer from CRG Industries known as "Veriflex" under its trade-name, to treat the problems arising when the arteries become narrow or obstructed and also for removing obstructions from other "tube-shaped" body parts, like the uretheres and the bronchial tubes. The stent is inserted in its temporary form (reduced) and the body's own heat causes it to dilate and become attached to the artery. They may be used to replace stents based on shape-memory alloys such as Nitinol, once the appropriate biocompatibility studies have been carried out. Developments of self-expanding stents have also been carried out by using injected polyurethane (Wache, 2003).

Intelligent Sutures. Like those developed at the Forschungszentrum in Karlsruhe by Lendlein's team and at the M.I.T. by Langer's team, which have a temporary linear shape and a permanent shape in the form of a knot, with the change in geometry being activated by the body's own temperature. They have numerous applications in minimally invasive surgery and, as they are biodegradable, they have additional advantages over the use of textile sutures and metal clips (Lendlein, Kelch, Langer, 2002, 2005).

Thrombectomy Devices. With the recent discovery that the thermal effect of shape-memory can be activated by a laser, part of whose energy is absorbed by the polymer, devices with special geometries have been proposed for removing clots (Wilson, 2006). The polymer is shaped in a spiral mould and then heated and stretched to give it its temporary shape. When the laser light passes through the polymer, the shape-memory effect is activated and the device recovers its spiral shape trapping the clot which can then be removed.

Active Catheters. By using shape-memory polymers for the distal point of catheters together with a subsequent activation of the memory effect by laser light or body heat, different drugs and antitumoral agents can be released. The presence of an active catheter point can also help reach zones that are difficult to access in minimally invasive surgery tasks (Yackaki, 2007).

Drug Release Devices. If biodegradable shape-memory polymers are used for implantable medical devices, drug supply reservoirs can be incorporated into the device itself. After implant, the polymer begins to be absorbed by the organism and the drug is released. Patents have been taken out in this respect for self-expanding coronary stents or intra-urethral stents (Boston Scientific Co. and Surmodics Inc.). The possibility of obtaining temporary geometries with micro-reservoirs for drug storage has also been studied. The drugs would then be released on activation of the shape-memory effect by body heat (Gall, 2004).

Active Annuloplasty Rings. Aimed at obtaining a progressive postoperative treatment of mitral insufficiency, they are based on the use of a polymeric ring with heating resistances distributed around the inside to activate the shape-memory effect by Joule effect. This activation must allow the cross section of the mitral ring to be gradually reduced and, therefore, the mitral insufficiency improved.

3 CHALLENGES RELATED TO THE ACTIVATION PROCESS

One aspect where most progress has been made in the last years is the activation of the memory effect by various methods, especially:

Joule Effect Activation. Based on distributing heating resistances at the core of the polymer where the passing of an electric current generates the necessary heat.

Light or Laser Activation. Based on projecting a laser through a shape-memory material with a similar absorption frequency to that of the laser used, which produces heating (Lendlein, 2005, Wilson, 2006)

Magnetic Activation. Based on heating by induction of magnetic or metallic microparticles, distributed at the core of the polymer while it is being conformed to its shape (Buckley, 2006). However, the biocompatibility of the associated devices needs to be further optimised.

Support Technologies. Progress in the field of wireless communications means that devices can now be remotely activated, which is promoting the appearance of new active implantable biodevices.

One of the main problems of using Joule effect activation lies in the fact that distributing punctual heating resistances among the polymer leads usually to a decrease of mechanical resistance and to important temperature differences along the structure during activation.

On the other hand, “light / laser activation” is normally limited to tubular / linear structures and “magnetic activation” usually implies problems due to the important magnetic fields needed for heating.

We propose and explain in the following chapters some improvements for SMP activation, obtained by substituting punctual heating resistances by silver-cloth thread knitted along the structure and used as single Joule effect heating element.

4 IMPROVING ACTIVATION: DISTRIBUTING HEAT

As previously stated our objective is to obtain SMP structures with an improved distribution of heating element(s) for a better controlled and more homogeneous activation of “shape-memory effect”.

Figure 2 shows the prototype of a net-shaped SMP structure with the heating silver-cloth thread already knitted to it. Such thread was acquired from the MUTR (www.mutr.co.uk) special materials facilities.

For manufacturing the prototypes (directly from 3D CAD files with part geometry) a laser stereolithography “SLA-3500” machine was used to polymerise a 3D Systems epoxy resin sold under the trade name of Accura 60. A total electrical resistance of around 40 Ω was measured between ends of the thread, which proves to be an acceptable value for activating the whole structure through Joule effect heating.

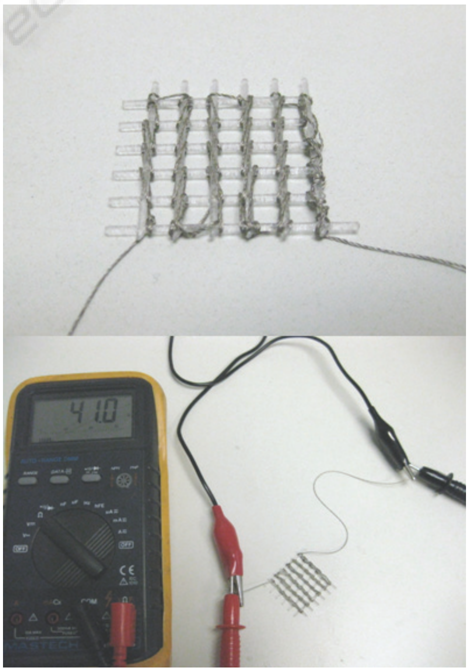

Figure 2: Prototype of net-shaped SMP structure with knitted silver-cloth thread for improving activation. (Resistance around 40 Ω).

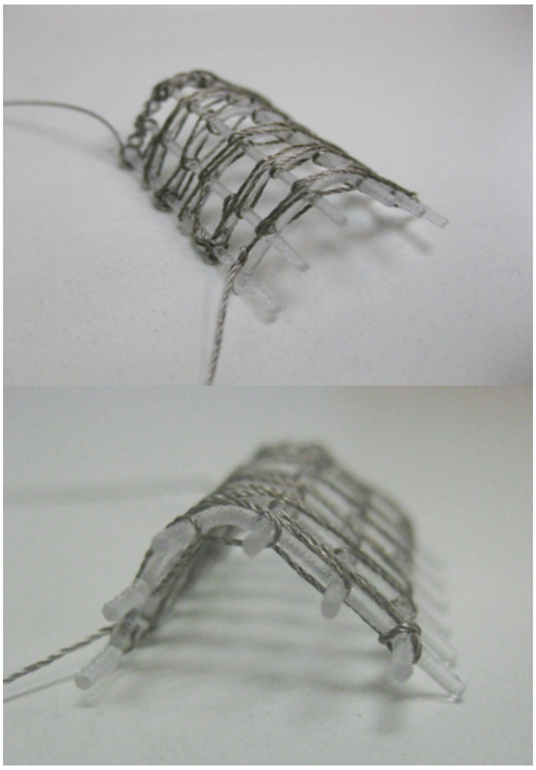

Figure 3: Temporary form obtained through heating, imposing a 90º deformation between extremes of the structure and finally cooling down.

Once the prototypes had been fabricated, and the heating thread knitted to the structure, the “in vitro” heating was carried out to verify the designed heating system and show that it is possible to exceed the glass transition temperature that leads to the “shape-memory effect” being activated.

This was controlled using a thermographic IR camera marketed under the name of “Flyr Systems Thermacam E300” with its accompanying “Thermacam Reporter 8.0” analytical software which enables the thermographs taken to be more exactly and thoroughly analysed.

A remarkable fact for the trials is to verify that no short-circuit appears during the training process, which limits the attainable size reduction. When bending and reducing structure size during training, the heating thread can separate slightly from the polymeric material and promote such problems.

Therefore, fixing points for the heating element have to be taken into account from the design stage, so as to improve final performance. Another option consists of totally embedding the heating element within the polymeric structure during manufacture, but that leads to additional problems when casting or injecting into the moulds.

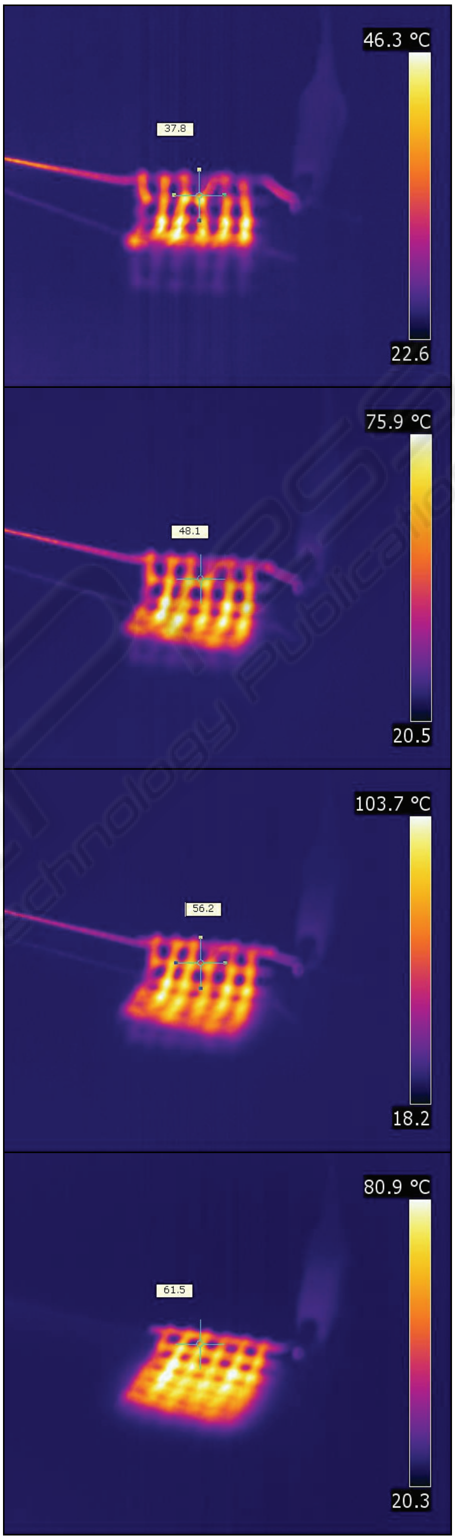

Figure 4: Recovery process by distributed heating. (View using IR thermography). Total recovery time → 20 seconds. Images taken every 5 seconds (image corresponding to t=0 not included).

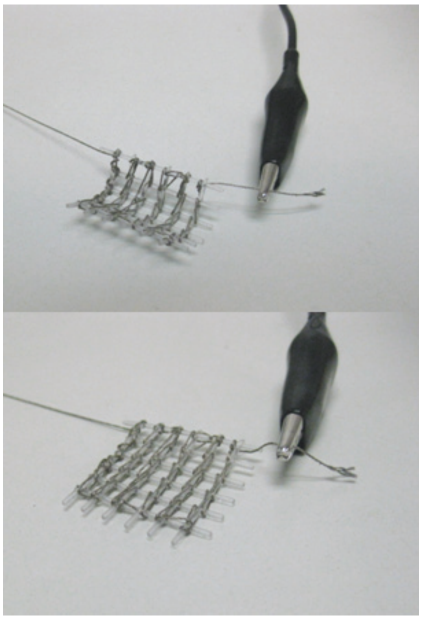

Figure 5: Recovery process by distributed heating.

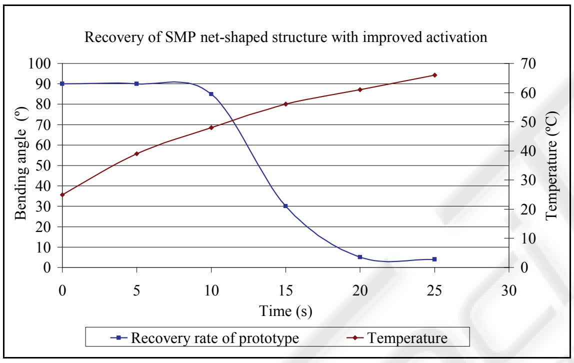

Figure 6: Recovery process (from 90º to 0º) as a function of time and temperature.

The results show a remarkable homogeneous heating of the net-shaped structure and the possibility of going beyond the glass transition temperature of the polymer, so as to activate the "shape-memory effect" and the subsequent geometrical changes.

Additionally, as Figure 5 shows, it is important to mention that the presence of the silver-cloth thread for Joule heating does not limit the "shape-memory effect training" capability or the ability to recover its original shape through subsequent heating above glass transition temperature. The mismatch between original shape "A_0" and final shape "A_f" after activation fulfills the relation:

$$[A_0 - A_f] / A_0 < 4\%.$$

5 IMPROVING RESULTS AND CONCLUSIONS

While the new capabilities brought by these materials give rise to expectations that many medical devices will become more effective, considerably great effort still needs to be put into research and development, so as to obtain robust and effective actuators based on these materials.

Some advances linked to obtaining a more homogeneous heating for improving activation have been explained. First prototypes of net-shaped SMP structures with silver-cloth thread knitted to them for Joule activation have helped to validate the proposal.

It should be mentioned that although the activation temperature of the materials used of around 50-55 ºC could not give rise to safe intracorporeal devices, there are shape-memory polymers whose activation temperatures are closer to human body temperature which could be subjected to a process similar to the one described here.

The choice of this material was influenced by its availability in the UPM's Product Development Laboratory and by its good processing properties, as well as its suitability for prototype manufacturing directly from 3D CAD models, through "laser stereolithography". Future work will be focused to the search and application of SMP formulations with improved biocompatibility and more suitable activation temperatures.

Additionally, once having obtained the prototypes in end materials, different surface deposits can be used by means of physical or chemical steam deposition technologies (particularly the new DLC "diamond like carbon") coatings, as well as textile coatings to ensure the biocompatibility of the device and facilitate its implantation.

At the same time other medical grade metals and alloys will be studied as heating coils, so as to obtain final more appropriate prototypes for "in vitro" trials. The use of such "in vitro" trials, together with results from simulations, will help to prepare "in vivo" studies in a more confident way.

Non-medical applications of this kind of "SMP-based devices" or "SMP-based smart structures", with similar or more complex geometries, can also be promoted by the possibilities supplied by distributed threads for Joule activation. Infrared (IR) thermography proves to be a useful tool for validating the capabilities of new concept prototypes and as a support for design tasks.

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