APPLICATIONS OF SHAPE MEMORY ALLOYS IN SPACE ENGINEERING: PAST AND FUTURE

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ABSTRACT

In this paper the over-thirty-years history of space applications of shape memory alloys (SMA) is summarized. Our experience is illustrated by detailed examples, such as the first launch of TiNi to an Earth orbit in 1982, when thermomechanical pipe couplings on the orbital station Salyut-7 were tested for their hermetic durability; the use of TiNi wire actuators to deploy two ring-shaped constructions of 20m in diameter on the spacecraft Progress-40 in 1989; assembling a large truss Sofora using special thermomechanical couplings with TiNi sleeves in 1991, and others. In conclusion the future of shape memory alloys in space engineering is considered, that is believed to be single- and multiplex-action drives, various kinds of thermomechanical couplings, thermosensors, intelligent composites, devices for active damping of vibrations of large structures, micromechanisms.

1. PAST

One of the first suggestions as to the use of TiNi in space engineering were deployable constructions. It was proposed to make most of them wholly of the material with shape memory which served both as functional and construction material. The main problem then was how to ensure the required geometrical dimensions of the objects after their deployment. This problem still remains unsolved. The next stage in the development of applications of materials with shape memory were technical solutions where the SMA was used only as a functional material. One of the first examples of such application can be considered a model of wire actuators of the flaps of the instrument container for the satellite Nimbus [1]. These actuators were made of TiNi wire that contracted when the temperature in the section increased, and thus opened the flaps allowing the release of heat radiation. As the temperature decreased, the biasing spring strained the wire because of plasticity induced by direct martensitic transformation, and replaced the flaps.

As for deployable constructions, it has been generally acknowledged that shape memory materials give maximum efficiency when used as a working body in drives for deployment of various kind of constructions made of regular materials. This has found a wide utility in the open space due to the main condition of the latter – zero gravity (by the way, similar conditions are found in the hydromedium). The constructions used combine high specific working capacity with high safety, allowing cosmonauts to work in the immediate proximity to the unfolding object. Shape memory actuators allow easy control of the deployment process, obviating the need to install various kinds of dampers for shock suppression which are normally used with ordinary springs when the construction is unfolded by means of accumulated elastic energy. One of the first products was a drive for transforming a parabolic antenna from its transportation configuration into the operation shape. The drive had three working elements of TiNi with the diameter of 2 mm that operated by torsion [2]. Most of the wire drives developed, however, operate in tension-contraction mode, as in this case the optimal combination of the force and displacement exerted is achieved for the task fulfilled. Such drives are usually larger than the springs operating by torsion or bending, but this disadvantage can be easily overcome by adjusting the long working wire into the parts of the construction to transform. The most common solution in this case is when the wire element rounds the hinge connecting the unfolded construction parts [3-14]. Some other kinds of working bodies are also used, for example, a cylindrical spiral made of wire prestrained in the martensitic state, that, when heated, unwinds along the rails on the cylindrical shaft and rotates the outgoing unit of a quite space-saving drive [15-16]. Or we could mention a rod working by torsion [17].

Another wide area of application of SMAs in space technique is suggested by the necessity to damp vibration in constructions. Excellent damping ability of these alloys has always attracted designers. In addition to the usual passive damping, the possibility of active suppression and control of vibration in various objects has been increasingly investigated for the last ten years. Thus, investigations are now underway, whether it can be possible to use SMA drives for long trusses intended for use in the open space, and for other objects with the vibration band reaching several dozen hertz [11, 18-21]. Of great interest to researchers are also composite materials with embedded SMA-elements which could serve as actuators for damping and control of vibrations [22-31] or be used for changing the stress and shape of the object made of these materials [32-34]. SMAs have future also in production of locking and release devices [9,10, 35-39]. Substitution of pyrotechnical materials, that have so far been commonly used in these devices, with shape memory materials would eliminate shock-load during release, allow less strict requirements for storage and performance check of the devices, as well as repeated use of the device and the working element.

However, only a small number out of the designed devices, including those mentioned above, have been used and tested in the open space. These devices are described in detail below.

The first “launch” of TiNi to an Earth orbit can be considered to have happened in 1982, when thermomechanical pipe couplings on the orbital station Salyut-7 were tested for their hermetic durability [4]. A special pneumatic section containing the couplings was fixed on the station’s outer surface, and after a year in the space it still retained its hermetic characteristics. Already in November 1988 similar thermomechanical couplings became part of the propulsion system on the Soviet shuttle Buran.

An experiment on deploying a large space structure (LSS) with the help of TiNi wire drives was first conducted in the framework of the project Krab [5,8] which included also a study of dynamical characteristics of deployed large transformable ring-shaped constructions at maneuvering of the spacecraft, and correlation of real parameters with the calculated ones. Two ring-shaped LSSs were installed in folded state on the outer surface of the spacecraft Progress-40, namely, on the section for refueling equipment. Each of the LSSs consisted of rods connected by hinges. In unfolded state it was a rectilineal polygon with the diameter of its inscribed circle equal to 20 m. To unfold the carcass from its transportation state into the operating one 78 drives were used made of TiNi wire of 2 mm in diameter. Heated by electric current, this wire produced a moment of force in the hinge coupling. The weight of one such LSS was 58 kg. The experiment was carried out from March, 3 to March, 5 1989 controlled from the Earth, as follows. After unloading and departure of the cargo spacecraft Progress-40 from the orbital station Mir to the distance of 70-80 m a command was given to shoot off the cover of the first container. Then power was supplied to the drives of one carcass. It was being deployed for 5 minutes, and its shaping took another 10 minutes. Then the same operations were applied to the other LSS. The two following days were dedicated to observation of the constructions’ conduct at maneuvering of the spacecraft. The crew of the Mir orbital station, A.Volkov, S.Krikalyov and V.Polyakov, video-taped and photographed the experiment the successful completion of which has proved that SMA drives can work reliably in conditions of open space. They have a simple design, small weight and dimensions, allow easy remote control, and thus are superior to other existing drive types.

The aim of another space experiment, called Sofora, was to approbate the developed technique of assembling truss constructions in open space with the help of thermomechanical couplings, the main element of which is a sleeve made of a shape memory alloy [6-8]. This technique allows assembling trusses of large sizes by automatic manipulators as well as manually. It should be noted that the types of couplings normally used on earth, present a number of disadvantages when assembling is done in the space. Thus, to tighten a nut a point of rest is needed, that is not always available, or special instruments, short of saying that the operation is quite a problem for a cosmonaut wearing a space suit. By the way, most nuts used in space have a different shape than those we are accustomed to. Riveting also requires particular pressing equipment. The disadvantages of weld-couplings are great power consumption, dangerousness of welding, and the difficulty of checking welding quality in the space. Ordinary fasteners have proved to be good in use, but they have big weight and require high accuracy in manufacturing of all their numerous parts.

The Sofora experiment included manual assembling of a truss with 14.5 m in length, the cross section of 0.5x0.5m, and the weight of 90 kg. The truss consisted of standard units – square diaphragms and V-shaped elements – that had been folded for transportation and then deployed at assembling. The rods of the V-shaped elements of one cell running through holes in a diaphragm were fixed in the fittings of V-shaped elements of the following cell by compressing them with a sleeve made of TiNi. For compression the sleeve was heated to the required temperature with a special installation-and-heating device with filament lamps. The Sofora experiment was carried out in July 1991 on the Mir station by cosmonauts A.Artsebarsky and S.Krikalyov. After the cargo was delivered to the orbit by the spacecraft Progress-M8, and preliminary work was carried out in the Kvant-2 modular, all equipment was transferred to the outer surface of the Kvant astrophysical modular. There, after having made four walks in space with the total duration of 22 hours, the cosmonauts assembled the truss and fastened it on the surface of the modular Kvant. 84 thermomechanical couplings were assembled. In September 1992 an outside propulsion unit was delivered to the Mir station and installed on the top of the truss Sofora by both members of the crew, A.Soloviev and S.Avdeev. To make the work easier, the truss had a hinge in its middle, which allowed it to operate as a crane arm. This propulsion unit was meant for control of the station's tangential orientation and was substituted with a new one after its operation life expired in 1998. The weight of the unit is 750kg, and the weight of the cargo delivered to the orbit, including the unit, the truss and equipment for its assembling, is about 1000kg.

Under the Rapana program [6,9] a transformable truss with a length of 5 m, the cross section of 0.3x0.4 m, and the weight of 13 kg was designed and constructed. The truss consisted of five units, each of them having four carbon-plastic panels connected together by hinges. Diagonal parts of the units were folding links with wire drives. Like in the Krab construction, TiNi wire of 2 mm in diameter was used here, and the drive was activated by heating with electric current. But unlike the Krab's drive, which has two identical hinge-connected links, the drive of the Rapana truss consists of two hinge-connected links that differ in length. This difference in design was determined by the kinematics of truss deployment. In addition, a release device with a TiNi wire drive was designed to hold the belt tightening the package with the truss in its transportation configuration with the force of 50 kg. The device released the package immediately before the truss deployment. During the space experiment Rapana in September 1993 cosmonauts V.Tsibliev and A.Serebrov installed the folded truss Rapana on the outer surface of the modular Kvant next to the Sofora truss, where, upon start of power supply, the Rapana truss transformed into its operation configuration. Then investigation equipment was installed on the truss by the cosmonauts.

In the US, where shape memory effect in TiNi had been first discovered, and a lot of suggestions on its application in space technologies made, the first actual launch of a shape memory alloy to the space took place only in 1994. The effect was used in four release devices Frangibolt holding folded solar panels at launch the spacecraft Clementine [37]. The release device consisted of a bolt made of a high-strength titanium alloy, a sleeve made of TiNi, and a heater. The bolt featured ring turning which allowed to reduce the bolt's net section locally. The sleeve, precompressed along its axe, pushed the nut and one of the two parts when heated, and destroyed the bolt along the turning, thus releasing the package. The sleeve was heated by a special device that embraced it tightly covering all outer surface of the sleeve. Heating spirals in the device were embedded in an elastic polymeric case which followed the sleeve's contraction in diameter, when the sleeve's shape memory worked for the release process.

In December 1996 SMAs were tested outside the Earth's orbit, when the automatic interplanetary station Pathfinder carrying a mars rover Sojourner set off to Mars. The rover featured a SMA drive which was a TiNi wire of 30 mm in length and 0.15 mm in diameter, operating by bend. In July 1997 the drive removed a thin glass panel with mars dust, unshielding a photoelement in the device that determined dust content in the planet's atmosphere by the difference in sun radiation intensity.

Our twenty years of experience of using materials with shape memory in space systems have been an evidence of their high efficiency, reliability, and advantages in the situations where standard methods are unapplicable. Besides special equipment for space purposes, other devices with shape memory effect can be used in space systems. It should be added, that some technical solutions unacceptable on earth for economical reasons, can become the only reasonable choice in the space, eliminating all the barriers that it had seemed impossible to overcome. And it should be also noted, that all technical solutions proposed for use of SMAs in space systems are valid for use on earth as well.

2. FUTURE

Like in every branch of science, future of shape memory materials in space systems is essentially based on the accumulated experience and the present general development of fundamental and applied sciences.

Many space designers are eager to create SMA-devices that would work under force of the Sun's heat. Over 10 years ago, when in the framework of the Sofora project (1985-1991) we were designing a truss and choosing a shape memory material for the thermomechanical coupling, we kept also in view the solution where the sleeve was actuated by the Sun's heat. But, however, this solution was rejected due to insufficient reliability. Our choice then was a material with the temperature of martensitic recovery transformation equal to 80 °C, which ensured, on the contrary, that the Sun would not activate the sleeve. For the time since, the progress in physical metallurgy of SMAs, and the knowledge gained from experience on the Mir station and other space vehicles allow the hope that in the near future the technology of SMA-devices will be able to switch to the use of Sun radiation. It seems to us highly possible that in some years a satellite entering the Earth's shadow will, for example, close the shutters of its instrument section and open them upon coming out on the Earth's day-side without consuming a bit of its own power. This would take us past the only, although not so significant disadvantage of SMAs, which is a relatively small efficiency of martensitic transformations. The coefficient of transformation of heat energy to mechanical work at shape recovery is estimated not to exceed 10 %. At spacecraft with large power stock such as orbital stations low efficiency is not a problem. But it should be taken into consideration in designing devices for small satellites.

The emergence of such alloys as TiNiNb, TiNiHf, and other new materials has brought about a new era for thermomechanical couplings. The assembling of the Sofora truss was carried out by means of a unique for that time method of rod coupling. Now it could have been completed using TiNiNb in a standard coupling design. The resources and technological effectiveness of thermomechanical couplings have grown notably higher. And it should be added, that the scope of tasks on construction and repair of pipe and rod systems to be implemented in the open space will be growing wider with the development of orbital construction technologies. A better solution here, than thermomechanical couplings, is hard to find.

Technologies for obtaining thin films and membranes, that have lately experienced active development, and use of SMA in micromechanisms could contribute a lot to space systems as well (microvalves, micropumps, microsensors, etc.).

Advantages of various actuators made of shape memory alloys cannot be overestimated. They allow to avoid shock loading, have simple design and are easy to operate.

Thus, the future of shape memory alloys in space applications is now believed to lie in their use as a construction material for single- and multiplex-action drives, thermomechanical couplings of various types, thermosensors, intelligent composites, micromechanisms, and devices for active damping of vibrations in elongate objects. In most areas of application of SMAs, outlined in the last part of this paper, The Rocket and Space Corporation ENERGIA together with the Research Institute of Mathematics and Mechanics at the St-Petersburg State University have their own projects of devices for future spacecrafts, based on the rich previous experience.

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