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Topical Review

Shape memory polymers and their composites in aerospace applications: a review

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Abstract
As a new class of smart materials, shape memory polymers and their composites (SMPs and SMPCs) can respond to specific external stimulus and remember the original shape. There are many types of stimulus methods to actuate the deformation of SMPs and SMPCs, of which the thermal- and electro-responsive components and structures are common. In this review, the general mechanism of SMPs and SMPCs are first introduced, the stimulus methods are then discussed to demonstrate the shape recovery effect, and finally, the applications of SMPs and SMPCs that are reinforced with fiber materials in aerospace are reviewed. SMPC hinges and booms are discussed in the part on components; the booms can be divided again into foldable SMPC truss booms, coilable SMPC truss booms and storable tubular extendible member (STEM) booms. In terms of SMPC structures, the solar array and deployable panel, reflector antenna and morphing wing are introduced in detail. Considering the factors of weight, recovery force and shock effect, SMPCs are expected to have great potential applications in aerospace.

Keywords: shape memory polymer (SMP), shape memory polymer composite (SMPC), aerospace, application

(Some figures may appear in colour only in the online journal)

Contents

1. Introduction

Shape memory polymer (SMP) is a type of macromolecular smart material that can respond to external stimulus by changing its macroscopic properties (such as shape and color) and then recover its original shape from its temporary shape [1–10]. Additionally, SMPs have the unique advantages of being lightweight and inexpensive and of having low density, good manufacturability, high shape deformability, good biodegradability and an easily tailorable glass transition temperature compared with shape memory alloys (SMAs) and shape memory ceramics [11–20]. Therefore, an increasing number of international researchers have been focusing on the development of the shape memory effect in polymers since the 1980s, particularly in the last few years [2, 8–10]. However, SMPs also have some drawbacks, such as low deformation stiffness and low recovery stress [21–23]. To overcome these deficiencies, shape memory polymer composites (SMPCs) have been developed in practical applications to satisfy demand, the results of studies on SMPCs indicate that SMPCs have higher strength, higher stiffness and certain special characteristics determined by what fillers are added, which can offer further advantages over SMPs [1–10, 21–29]. Meanwhile, some novel functional SMPs (functionally graded SMPs [30], multi-shape SMPs [31–36], two-way SMPs [37–40], self-healing SMP [41–43] and SMP foams [44–47]) have also been developed. Today, SMPs and SMPCs cover applications ranging from outer space to submarines (including aerospace [48–53], biomedicine [54–59], textiles [60–64] and automobiles [65–68]).

There are some excellent reviews about the development and application of SMPs and SMPCs, such as a review written by Wei *et al* on the research and development of shape memory materials (SMA, shape memory ceramics, SMP and SMPC) up to 1998, in which the properties of stimulus-induced phase transition of SMP are discussed in detail [13]; another excellent review written by Lendlein *et al* shows the multifunctionality of SMP and SMPC except shape memory effect based on different polymer network cross-linked structures, such as the properties of permeability, transparency and conductivity, and so on [2]. In addition, Leng *et al* give a summary of the fabrication, characterization, models, stimulus methods and application fields of SMP and SMPC, in which the stimulus methods and application fields are discussed in detail [8]; Xie has reviewed the recent development of SMP up to 2011, in which the main content is focused on all kinds of shape memory phenomena, such as conventional dual-shape SMP, triple-shape SMP, tunable multi-shape SMP, two-way SMP, and so on [34]; Hu *et al* give an extensive review of the concept, synthesis methods, stimulus methods, analysis models and applications (especially in textiles) of SMP and SMPC [10]. All of the above-mentioned reviews focus on some special interests or give an extensive summary. In this review, the applications of SMPs and SMPCs in the aerospace field are discussed in detail, including SMPC hinges, truss booms, reflector antennas, morphing structures, lunar habitats and mandrel fabrication. There is no doubt that SMPs and SMPCs will play an increasingly important role in aerospace in the future.

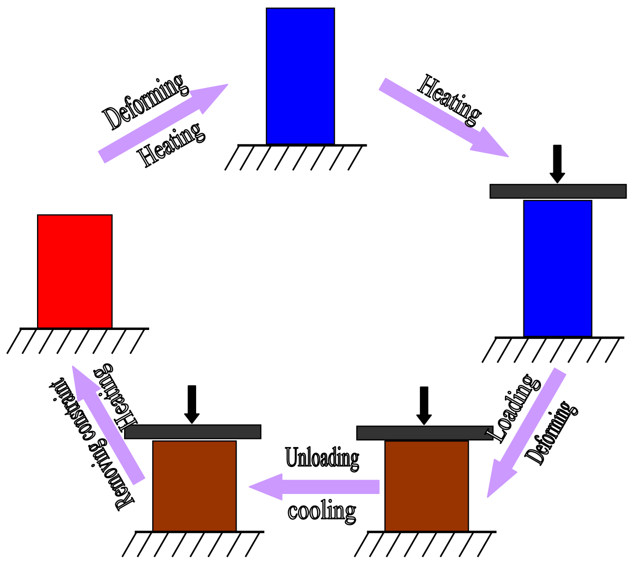


Figure 1. The typical thermomechanical cycle processing of a SMP/SMPC under compression testing.

2. General mechanism of SMPs and SMPCs

The main characteristics of SMPs and SMPCs are their variable material properties 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). Taking T_g for example, when the temperature is higher than T_g, the polymer is in the rubber state and is considered a viscous material; however, when the temperature is below T_g, the polymer is in the glass state and is considered an elastic material. Near the transition temperature, SMPs exhibit viscoelastic behavior, in which the polymer properties change rapidly and the elasticity modulus decreases by approximately two orders of magnitude [69–71]. In general, SMPs and SMPCs are commonly used in deployable structures. There are typical thermomechanical cycles of SMP or SMPC in the process of shape memory and recovery, as demonstrated in figure 1. The shape recovery process consists of the following steps. (1) Original step, fabricating the original shape of the SMP. (2) Heating step (above T_g), deforming the SMP to a pre-deformed shape. (3) Cooling step, reducing the temperature to a low temperature (below T_g) and removing the constraint. (4) Reheating step, increasing the temperature to the high-temperature state and recovering the original shape [1–10].

Based on the different molecular cross-linked architectures, SMPs/SMPCs can be classified into two types: thermoplastic and thermoset [2, 8, 72]. In the past few decades, research has mainly focused on thermoplastic SMPs/SMPCs, such as shape memory polyurethane (SMPU). Unfortunately, the components and structures made by thermoplastic SMPs lose their shape memory effect after several cycles. Therefore, thermoset SMPs/SMPCs with high material stiffness, high transition temperature and environmental durability are becoming the potential selection for the fabrication of space structures. In table 1, partial

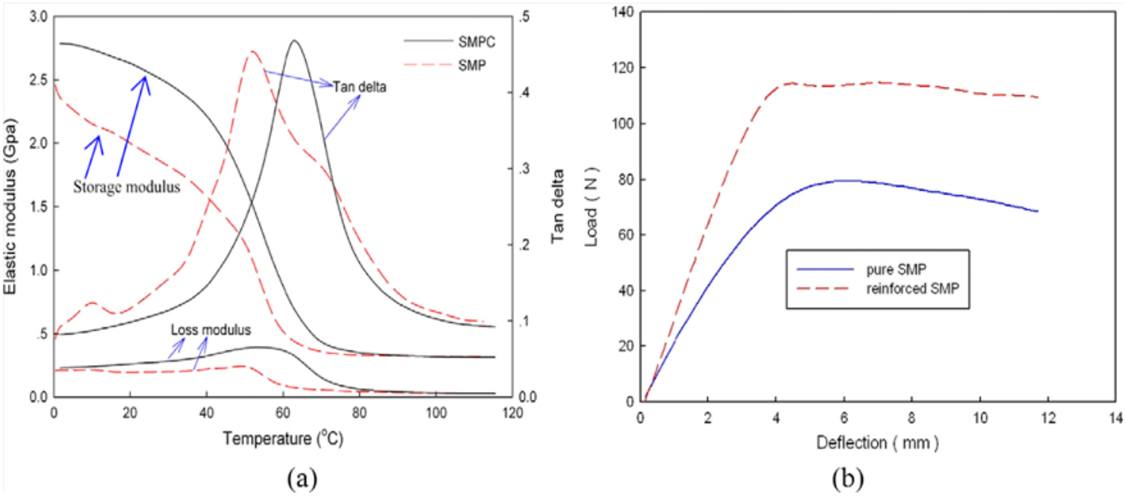


Figure 2. DMA testing of styrene-based SMPC. from [25]. Copyright ©2009, World Scientific.

Table 1. Partial list of currently available thermoset SMP matrix materials with broad tunable transition temperature.

Designers	Thermoset SMP matrix materials	Glass transition/deformation temperature (°C)
Xie and Rousseau [73]	Epoxy	30–89
Rousseau and Xie [74]	Epoxy	44–93
Leng *et al* [75]	Epoxy	37–96
Li and Larock [76]	Polystyrene	52–69
Zhang *et al* [77]	Polystyrene	63–74
Shumaker *et al* [78]	Polyaspartimide–urea	110–164
Biju *et al* [79]	Cyanate–ester–epoxy–poly(tetramethyleneoxide)	72/94
Xie *et al* [80]	Cyanate–ester	156.9–256.9
CTD [81]	CTD-400 cyanate–ester series	159–238
CRG [82]	Polystyrene	45–106
ILC [83]	TP series	53–108

research reported with broad tunable range of T_g is listed to show the thermomechanical behavior of different cross-linked structural thermoset SMPs and SMPCs.

To date, many research works have been carried out to investigate the thermomechanical behavior of SMPs and SMPCs, with various testing results (such as from uniaxial tensile, compression and three-point flexure tests); researchers explain the shape memory phenomenon and theory using two main approaches [84, 85]. One approach is based on viscoelastic theory. In the early years, Tobushi *et al* [86–88] investigated the thermomechanical behavior 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 a frictional element, which represents the slip mechanism due to internal friction. Their collaboration in series or in parallel can be used to represent viscoelastic properties of SMPU. The other approach is based on phase transition (frozen phase and active phase) theory. Liu *et al* [89, 90] developed a small strain and rate-independent thermomechanical constitutive model of epoxy SMP 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.

Moreover, SMPCs are considered to be a combination of the matrix materials (SMP) and the reinforcing materials; the reinforcing materials (such as carbon black, carbon nanotubes, short fibers and continuous fibers), which constitute some volume fraction of the matrices, are considered to have good compatibility with the matrices and strengthen the thermal, mechanical and other properties. As shown in figure 2, the glass transition temperature and storage modulus of styrene-based fiber-reinforced SMP are significantly higher than for pure SMP by dynamic mechanical analysis (DMA) [25].

3. Stimulus methods of SMPs and SMPCs

SMPs and SMPCs exhibit the shape memory effect as a result of various stimuli and polymer matrices [91–95]. For stimulus methods, heat-induced and electricity-induced SMPs and SMPCs are most typical. Additionally, light, magnetic field, water and solvent can also actuate the shape memory recovery of SMP and SMPC components and structures.

3.1. Thermal-responsive SMPs and SMPCs

Thermal-responsive SMPs and SMPCs are the earliest and most common type. Much research has focused on the thermomechanical behavior and applications of thermal-responsive SMPs and SMPCs [86–88, 96–100].

Tobushi *et al* investigated the thermomechanical behavior of SMPU with a small and large strain by tensile test and validated the good shape fixity ratio and shape recovery ratio of SMPU [86–88]. The free and constrained recovery of SMP also was investigated by Qi *et al*: a three-dimensional finite deformation constitutive model was used to simulate the loading/deformation process of compression test [96, 97]. Additionally, Gall *et al* compared the thermomechanical behavior of pure epoxy SMP resin with SMPC reinforced with nano-scale SiC by the three-point flexure test; the results showed that the SMPC owned higher elastic modulus and recovery force [98]. Moreover, Leng *et al* compared the deployment process of pure SMP with glass-fiber-reinforced SMP to validate the shape memory effect of SMPs and SMPCs [8]. In addition, Leng *et al* verify that SMPCs also exhibit certain functions due to the intrinsic properties of the filler, such as that the mechanical properties of SMPC reinforced with carbon particles are improved in addition to the change in electrical conductivity, except undergoing the shape memory effect similar to SMPs [8, 9].

The above-mentioned deploying process of thermal-responsive SMPs and SMPCs only occurs in a one-dimensional (1D) direction, and the process is relatively simple. Currently, SMPs and SMPCs can be used to simulate the deploying or packaging of relatively complex structures, such as solar arrays or morphing wing structure models, when the raw materials are selected effectively [2].

3.2. Electro-responsive SMPs and SMPCs

The electro-responsive SMPC is another type of common structures, in which electrically conductive fillers are incorporated into the SMP matrices to form electrically sensitive structures [101, 102]. Goo *et al* studied the shape recovery process of SMPU reinforced with multi-walled carbon nanotubes (MWNTs) to improve the mechanical properties and electrical conductivity [103, 104]. Hu *et al* fabricated SMPU composites reinforced with MWNTs to demonstrate the good shape recovery effect with different reinforcing phase volume fraction and the shape recovery stress trend under different thermomechanical cycles [105, 106]. Additionally, carbon nanopaper was selected as a new reinforcing material to investigate the electrical conductivity change of SMPs and SMPCs by Lv *et al* [107, 108].

Leng *et al* analyzed the change trends of electrical conductivity and electrical resistivity of a SMP reinforced with nanocarbon powders or fibers [109–115]. The SMPU experiment results showed that the micro-sized Ni powder formed chains under a weak external magnetic field, which can strengthen significantly the electrical conductivity in the chain direction [111]. Moreover, when a small amount of Ni powders was added to the SMP filled with carbon black, the electrical resistivity can reduce significantly when the Ni powders form chains; otherwise, the effect is slight [112]. Further, the electrical and thermomechanical properties of a SMPC filled with hybrid fibers were investigated by Leng *et al* [113–115]. Considering the relationship between strain and electrical resistivity with different temperature, electro-responsive SMPs can be fabricated to be smart strain structures or temperature sensors in application [116, 117].

3.3. Other stimulus methods of SMPs and SMPCs

In addition to the above-mentioned stimulus methods, light radiation, change of magnetic field and water/solvent will also play a role in future applications.

Light-responsive SMPs and SMPCs can be classified into two types: the intrinsically light-induced SMP, which is only sensitive to certain wavelengths of light and is independent of the temperature effect, and the indirect thermal actuation SMPC, which can effectively absorb infrared light and heat to actuate the structure to recover its original shape [2, 8]. The shape memory and recovery process of light-responsive SMPs and SMPCs has been investigated by Lendlein *et al* [118–120], Leng *et al* [121, 122] and Maitland *et al* [123–125].

Magnetic-responsive SMPCs are primarily composed of SMP matrices and magnetic fillers, such as Fe_2O_3, Fe_3O_4 and Ni particles; the shape memory effect can be actuated using an alternating external magnetic field [126–131].

Water/solvents can be used as plasticizers to reduce the glass transition temperature and trigger the shape recovery process at relatively low temperature compared to the original SMP/SMPCs [8]. Huang *et al* [132–134] and Lv *et al* [135, 136] investigated the plasticizing effect of water/solvents on polymer deformation.

4. Applications of SMPCs in aerospace

4.1. Space environment evaluation and related testing

Nowadays, much research is devoted to the SMP/SMPC applications in aerospace. However, space environment is extremely harsh, and many important factors must be considered when selecting structure materials in space environment, such as high vacuum, ultra-high or low temperature cycle effect, ultraviolet (UV) radiation, and so on; they can decrease the work effectiveness of solar arrays and increase the challenge component to normal work [137–139]. Some necessary testing must be done before application of SMPs and SMPCs in space-deployable structures. Fukher *et al* studied the influence of radialization on thermoset styrene SMP, in which the nanoindentation testing has been carried out to show the mechanical properties after radialization [140]. Leng *et al* investigated the influence of γ-radiation on the structures properties of epoxy SMPs by the DMA test and tensile test [141]. The results showed that the value of tensile strength reduced significantly after higher γ-radiation dosage, as shown in figure 3. Moreover, considering the ultra-high or low temperature of space environment, the thermoset shape memory cyanate polymer (SMCP) with a unique high glass transition temperature is investigated and discussed in relation to use in aerospace [142].

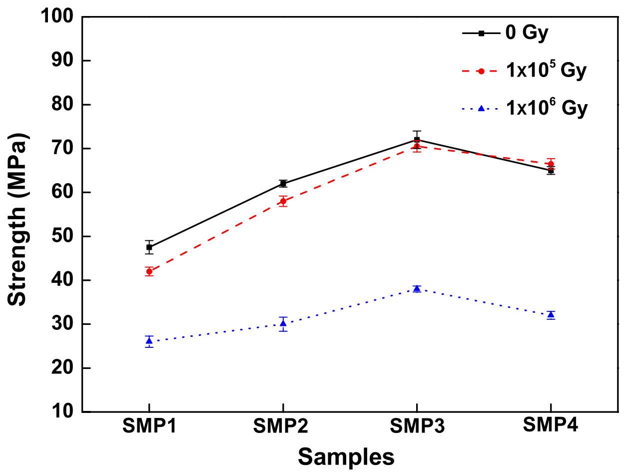


Figure 3. Tensile strength of epoxy-based SMPs before and after γ-irradiation [141]. Copyright 2013, Sage.

4.2. SMPC components in aerospace

In this section, several space-deployable components are introduced in detail, and a brief review concerning their development history and current application state are provided. Due to the traditional structures having some intrinsic disadvantages, such as high weight, high cost and high deployable shock effect, which will take up much room in spacecraft and decrease the effectiveness of aerospace missions, some new kinds of materials and structures have been developed to improve the effective space usage in the device. On the other hand, SMP/SMPC, which can be packaged and deployed with simple mechanical properties under a variety of external environments, is attracting more and more attention. Based on all the advantages of SMP/SMPC mentioned in section 4.1, there is no doubt that SMP/SMPC will be one of the best candidate materials for future aerospace engineering.

4.2.1. SMPC hinges. A hinge can usually be used as the driving device in the deployment process of space-deployable structures; there are many important factors to assess its effectiveness (such as shock effect and recovery precision). Traditionally, deployment has depended on a mechanical hinge or tape spring hinge [143]. However, the complex integrated systems of mechanical hinge and large shock effect of spring steel hinge increase the challenge of successful deployment and hinder their development in aerospace [144, 145]. To overcome this issue, Composite Technology Development Inc. (CTD) proposed a new type of hinge composed of elastic memory composite (EMC) materials to reduce the moving parts and shock effect, and results indicated that the novel hinge could provide good controlled deployment ability [146, 147].

The tape spring hinge is one kind of stored strain energy hinge, in which the tape spring can be metal, plastic or composite. The first use of the tape spring hinge dates back to the 1960s. Vyvyan *et al* conceived the self-actuating, self-locking tape spring and introduced the general geometrical configuration in 1968 [148]; Schwartz *et al* conceived a flexible tape spring hinge to hinder the shock effect, in which rubber material can be applied to the metal tape spring to improve the stored strain energy and bending characteristics [149]. In addition, Chiappetta *et al* conceived a tape spring hinge in which the metal tape spring was replaced by composite materials with two tape springs in the equal sense [150]. Besides the experimental research, theory analysis has also attracted attention. Pellegrino *et al* assumed the tape spring as a curved shell spring in some methods and analyzed the tape spring mechanical properties in the equal sense and opposite sense under moments [151–153]. The early EMC hinge prototype is an improvement on the design of tape spring hinges, replacing the tape spring by EMC material to reduce impact during space structural deployment. Although the early EMC hinge design can meet some real project requirements, it is only a preliminary design, and there is much room for improvement, such as in the shape of the EMC tapes and the two end fixture devices.

Figure 4. The early SMPC hinge prototype. Reused from [154] with permission from the authors.

The early EMC hinge prototype is similar to the hinge invented by Chiappetta *et al* in which the two EMC tapes are in parallel, as shown in figure 4. The experiment results show that when the two EMC tapes have a relatively long distance between each other, a high strain region will be present near the end fixture. This phenomenon will lead to local bucking and damage of the hinge after several cycles; when the distance is too short, the structural stiffness will significantly decrease [154]. To solve this drawback, the geometrical configuration of the prototype can be changed. Based on the equal stiffness rule in the lateral and longitudinal direction of hinge, the tapes in the opposite sense configuration with a half-angle of 120° would be most optimal. However, a half-angle of 90° is usually suitable for design for convenient manufacture; in terms of the design of the end fixture, considering the local buckling and strain distribution rule, parabolic footprint geometry would be ideal to replace rectangle and circle end fixture design [154]. Today, SMPC hinges are increasingly applied in space-deployable structures, and there are several different types to be selected. In addition to the aforementioned EMC hinges, Leng *et al* have developed a type of SMPC hinge reinforced with carbon fibers (figure 5) [8, 155, 156]. This hinge consists of three parts: (1) two circular curved thin shells in the opposite sense, (2) two end fixture devices, (3) two resistor heaters stuck to the surfaces (surface-bonded resistor heater) of the thin shells in the axial direction to actuate the deformation recovery using electricity. To verify the feasibility of this type of SMPC

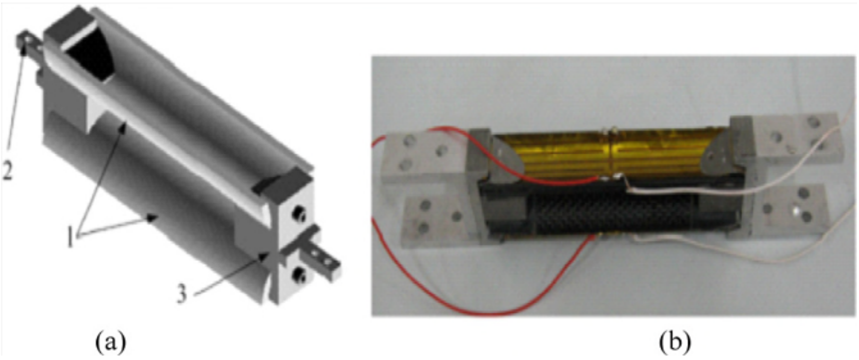


Figure 5. Epoxy-based SMPC hinge reinforced with carbon fiber: (a) illustration prototype of the hinge and (b) real-scale hinge design. Reprinted from [8], Copyright 2011, with permission from Elsevier.

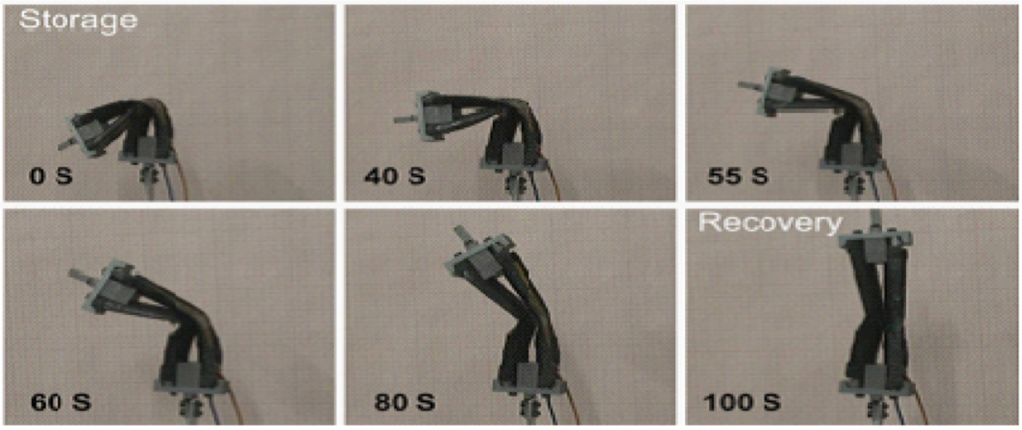


Figure 6. The shape recovery process of SMPC hinge actuated by direct current [156].

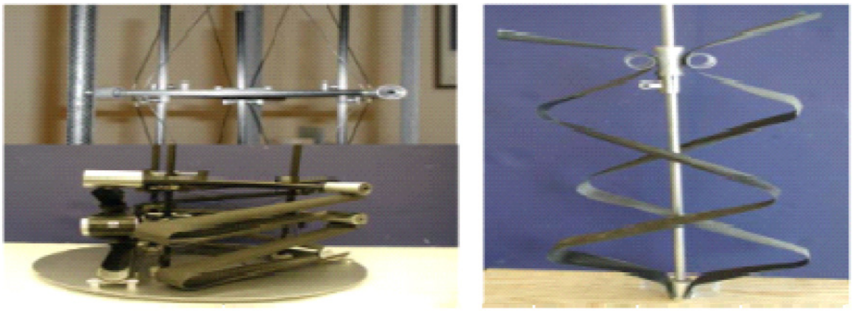
hinge, a recovery experiment was performed, in which the bending angle was as high as 140° initially. The recovery process is illustrated in figure 6. The shape recovery ratio is nearly 100%. The velocity varies during the deployment process, with the early stage and final stage being slower than the middle stage, which helps to reduce the shock effect in the deployable structure [156].

4.2.2. SMPC booms. Booms are the main components to support the tip payloads in satellites. Traditionally, the design of a space deployable boom has involved complex assembly and control mechanism and high weight because the materials selected are mostly metals. To overcome this problem, researchers have explored many methods. Today, the existing deployable booms can be divided into two classes: classical traditional booms and novel SMPC booms.

The classical traditional space-deployable booms include tubular, extendible booms and collapsible truss booms actuated by motor. The disadvantages have been listed above [157–161]. In contrast, the novel SMPC not only has simple structure, but also packages and deploys without mechanical devices. Therefore, the unique characteristics of SMPCs have aroused increasing interest for space-deployable structures. The novel types of SMPC booms can be divided into foldable truss booms, coilable truss booms and storable tubular extendible member (STEM) booms. The longeron is the main component of the SMPC boom, which provides the deployable driving force and undergoes the tip payloads at the end of deployment.

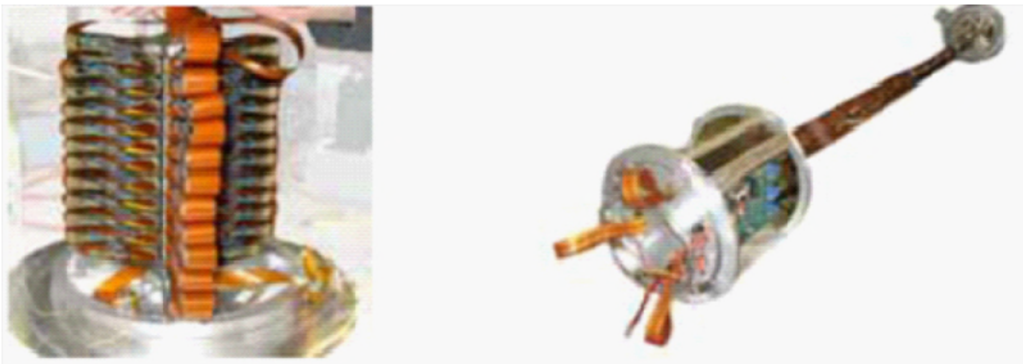
(1) *Foldable SMPC truss booms*. CTD has developed a new type of EMC space-deployable boom under the funding of the Air Force Research Laboratory (APRL) for the United States Air Force Academy (USAFA) FalconSat-3 mission [162, 163]. Two types of boom configurations have been selected as possible best candidate structures. One is a two-longeron truss boom, which will form a tubular-shaped boom after deployment, and the other is a three-longeron truss boom, which will be extensible to a space triangle-shaped truss boom. The prototype is shown in figure 7 [162].

Starsys Research Corporation (SRC) verified the feasibility of EMC truss booms and selected the best structures. The results indicated that each model has some drawbacks during the deployment process. The moving of the two-longeron truss boom and the fastening of the three-longeron truss boom are potential failure factors to successful deployment: finally, the low-moving-part design and light weight of the two-longeron truss boom led to its selection as the preliminary baseline model for the FalconSat-3 mission [162, 163]. However, the structure must be improved to eliminate the drawbacks before implementing this design. After a series of designs, fabrications, measurements and evaluations, the SMPC boom of FalconSat-3 mission was developed, as shown in figure 8. The final truss boom included three semi-cylindrical EMC longerons packaged into a ‘z shape’ for



(a) (b)

Figure 7. The preliminary SMPC booms design of FalconSat-3 mission: (a) three-longeron truss boom and (b) two-longeron truss boom. Reused from [162] with permission from the authors.



(a) (b)

Figure 8. The proposed FalconSat-3 three-longeron EMC tubular boom: (a) the packaged configuration and (b) the deployed configuration. Reused from [144] with permission from the authors.

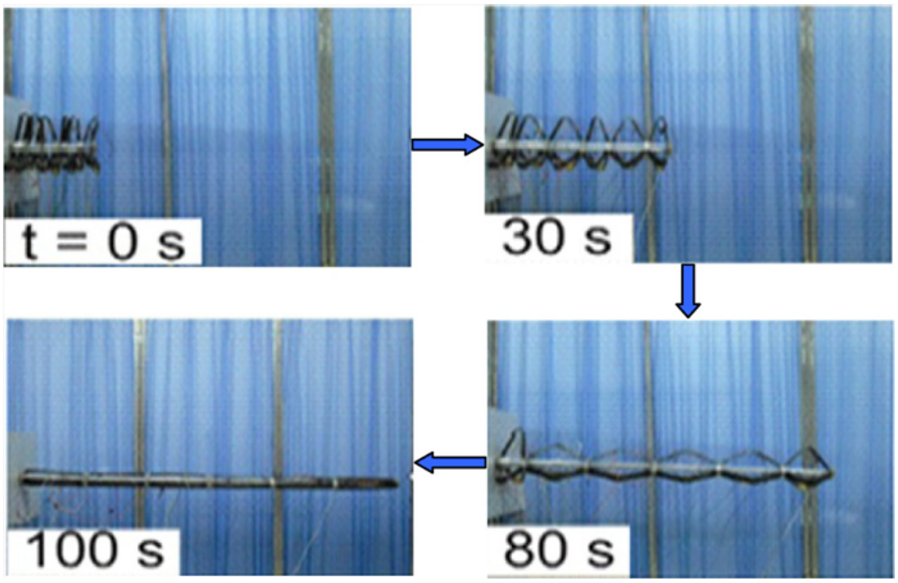
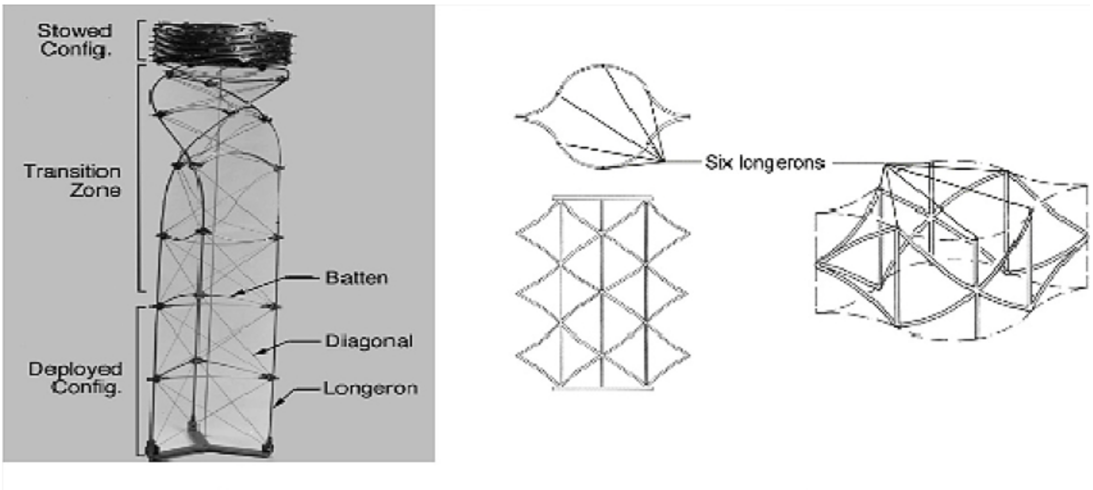


Figure 9. The deployment process of epoxy-based SMPC truss boom.

launch in the vehicle, and a series of resistor heaters embedded into the EMC longeron to actuate deployment in orbit [144].

Recently, Leng *et al* developed a novel type of SMPC truss boom, which consists of 18 pieces of laminate tapes with a semi-cylindrical section in the equal sense, one extendable central bracket, which includes six levels of short hollow rods that assume good contact area without friction with each short rod containing three laminate tapes with an angle of 120° to each other, and a resistor heater stuck to the concave surface centerline along the axial direction of every laminate tape. The boom is packaged into a 'M-shape' before the experimental evaluation; when performing the experiment, the boom will



(a) (b)

Figure 10. Coilable truss boom, (a) three-longeron boom and (b) six-longeron boom. Reused from [164] with permission from the authors.

gradually deploy with increasing time. The recovery process is presented in figure 9. The structure is very different from the CTD production. First, the sections are in the equal sense, which is related to the deployable recovery force, and second, the structure is divided into some small parts.

(2) *Coilable SMPC truss booms*. The coilable truss boom is another advanced deployable boom, which consists of simple structure and low weight in some respects, simultaneously. However, high strain energy and large relaxation phenomena exist in the stowed state. Nowadays, there are two types of configurations: three-longeron and six-longeron coilable truss booms (figure 10) [164]. The longeron of the boom can be bent or stowed in a small volume and provide stiffness and strength after deployment [164, 165]. The methods of deployment mainly consist of free deployment, cable deployment and tubular deployment.

The three-longeron coilable truss boom is a free-deployment boom, which is typically composed of longeron, lateral batten and diagonal members. S2-glass/epoxy is the main material to fabricate the longeron due to the deformation and mechanical properties. However, the boom will store lots of strain energy and be a safety challenge, when packaged by twisting the boom into a helical or snake shape for launch [164]. To overcome the drawback of high strain energy, the fiber-reinforced composite concept was considered to fabricate the longeron; the results indicated that the EMC longerons can significantly reduce the weight of the boom and the packaged strain energy while simultaneously maintaining the high strain capability [164–166]. There is no doubt that the boom will have a promising future in improving the performance of all types of packaged structures.

(3) *SMPC STEM booms*. The SMPC STEM boom is the other kind of advanced boom extant since the early stages of space exploration, and is of lower weight, higher packaging strain and stronger specific modulus than the traditional STEM boom. Additionally, the SMPC STEM boom has a simpler structure and larger cross-section compared with conventional SMPC booms. To date, some prototype booms have been fabricated by using STEM technology. In this section, the deployment and packaging technology for a seven meters horizontal SMPC STEM boom (figure 11) will be introduced, and some important factors of the system will be considered [167, 168], such as fabrication technology, assembly technology and deployment-control technology. As to the material fabrication technology, the modification of SMPC component ratio and the curing methods are sensitive to the shape memory effect of the structure. In addition, the final space-deployable boom is usually composed of some small member sections; lap joints are a key part to assemble these sections. Moreover, a deployment control system is imperative for deployment of the structure, which essentially consists of support structure, heater, driving motor and computer controller [168].

Due to SMPC hinges/booms needing to undergo flexural deformation and have minimal strain, the bending mechanical properties and deployment dynamics must be considered in aerospace application [169]. CTD Co. has reported the microbuckling response of reinforced EMC laminates. The results show that the fiber microbuckling can undergo higher flexural deformation without damage at high temperature and store the deformation state at low temperature. When the EMC material is reheated, the microbuckling gradually disappears and the original shape is gradually recovered [170, 171]. Lan *et al* have also investigated the post-microbuckling mechanics of fiber-reinforced SMPC undergoing flexural deformation by considering the material deformation and mechanical properties (figure 12) [172].

4.3. Structures based on SMPC components in aerospace

4.3.1. Solar arrays and deployable panels. Solar arrays are the main energy generation subsystems in space-deployable structures to obtain energy in space and are commonly packaged in the vehicle before launch; once in-orbit, the solar array is released to deploy and collect energy, and its work efficiency is dependent on a large deployment area, reliable

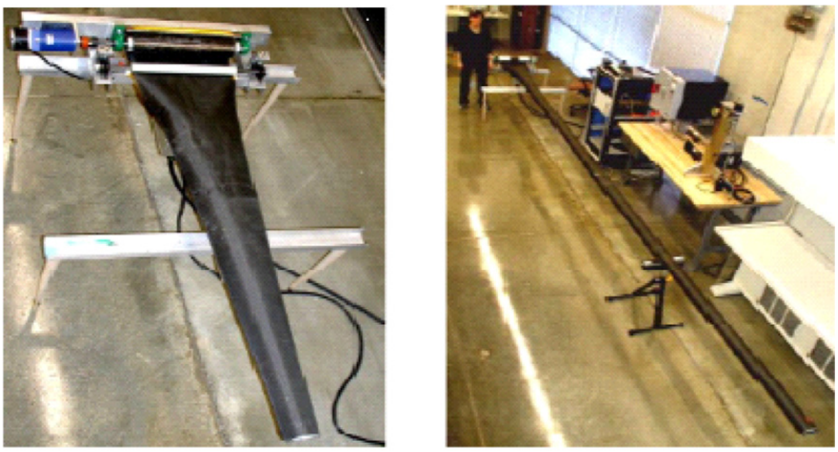


Figure 11. EMC STEM deployed system: (a) partial deploying state and (b) the deployed state. Reused from [168] with permission from the authors.

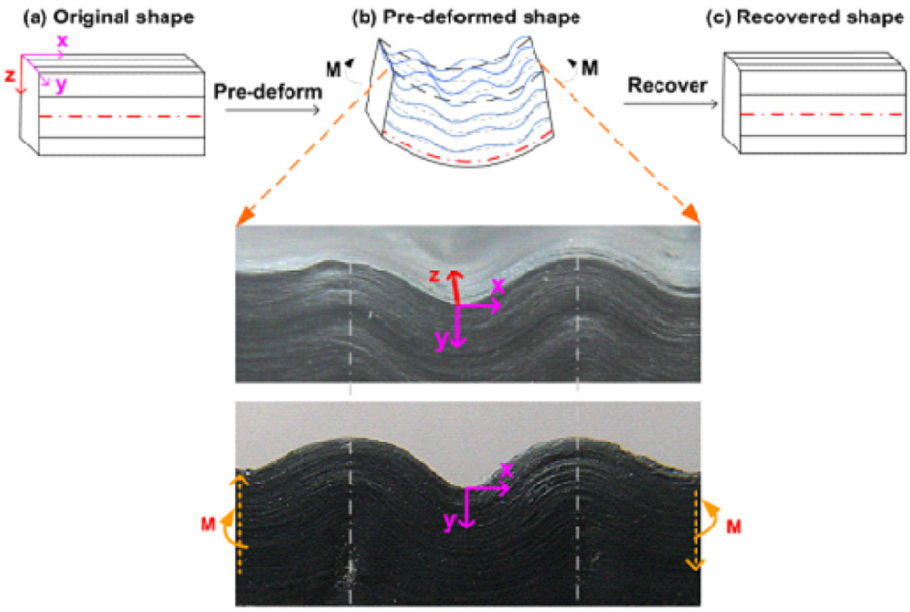


Figure 12. Shearing microbuckling deformation of SMPC laminate. Reused from [172], Copyright 2013, with permission from Elsevier.

stiffness and lightness of weight. Today, solar array structures have different forms, such as rigid, semi-rigid and flexible types [173–179].

Lan *et al* have developed a type of carbon-fiber-reinforced SMPC hinge to actuate solar array deployment and performed an experiment to simulate the deployment process in a zero-gravity environment [156]. The solar array is heated above transition temperature and bent to a pre-deformed angle under an external force, then maintains the force and is allowed to cool to room temperature; after that the prototype is reheated to the same temperature at the same voltage and recovers its original position in 80 s. The deployment process is illustrated in figure 13.

The feasibility of the deployable technology of advanced SMPC solar arrays has been verified by the experiment of the RoadRunner satellite (250 kg) [144], in which two solar arrays located at the two ends of the satellite are selected as experimental components (figure 14). The configuration of the two solar arrays is the same; however, the hinge materials are different from each other, with one being an EMC hinge and the other being a conventional steel tape-spring hinge [174]. A series of experiments, including a gravity-off load deployment test and a random vibration test, were performed to validate the feasibility of using an EMC hinge to deploy the solar array without damage. The results indicate that the EMC hinge can replace the traditional metal material on some non-critical deployable parts of satellite to increase the work mission [144, 174].

CTD has also designed a type of solar array with low-moving parts, a simple structure and low cost (figure 15).

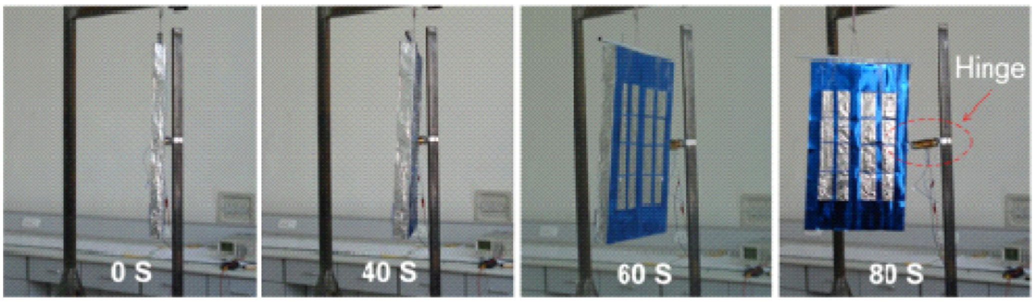
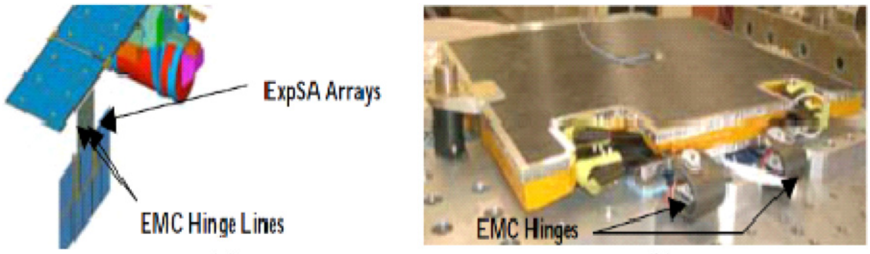


Figure 13. Shape memory process of a solar array prototype actuated by an SMPC hinge [156].



(a) (b)

Figure 14. RoadRunner experiment: (a) deployed state and (b) packaged state [144].

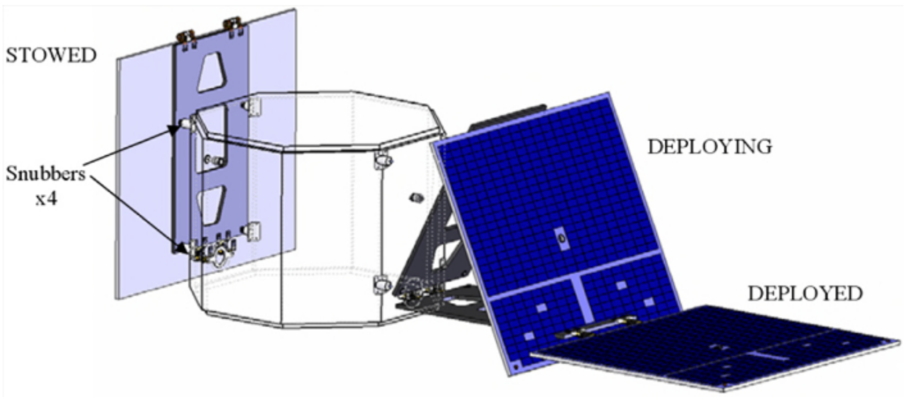


Figure 15. CTD solar array design. Reused from [175] with permission from the authors.

A special mission of the structure is to advance the Operationally Responsive Space (ORS) technology and validate the advantages of the new design to better adapt different types of missions for future small satellites. The key factor of achievement is the use of EMC hinges. The hinge is designed to drive and damp the deployment of the solar array and to lock the shape of array after deployment without driving and locking devices as seen in traditional mechanically deployed arrays [175].

EMC hinges have also been applied to the deployable panels of the Intelligent Nanosat Operations Satellite (DINO Sat) fabricated by a cooperative effort of JPL and CTD *et al* (figure 16). These hinges were designed to link the main part of the satellite and two deployable panel wings on the two ends; the wings can control the yaw direction of the satellite by the deployment or packaging of the EMC hinge [144].

As the main energy generation component, the design and architecture of solar arrays are important factors to improve the efficiency of collecting energy. In the above-mentioned structures, the deployment of solar arrays and panels are actuated by SMPC hinges; the deployed cells are limited and relatively small, so the power output is appropriate to space mission. Due to these drawbacks, another kinds of solar array, called Roll-out And Passively Deployed solar ARray (RAPDAR), has been developed by CTD [176–178]. In brief, RAPDAR consists of two EMC longerons/booms and several pieces of thin-film photovoltaic (TFPV) solar arrays, in which the booms actuate the solar array deployment and become the support structures of the solar array, as illustrated in figure 17 [176]. Due to the lower power-conversion efficiency compared with other kinds of solar arrays, the RAPDAR requires larger deployable areas to provide an equal total energy [177]. The use of EMC material can overcome this drawback, as demonstrated in the STEM boom section; similarly, the booms can be stowed before launch in the high-temperature state and the structure can be released and deployed by temperature or current, once in

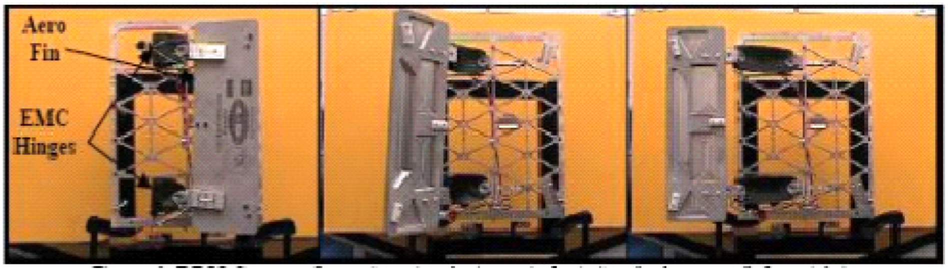
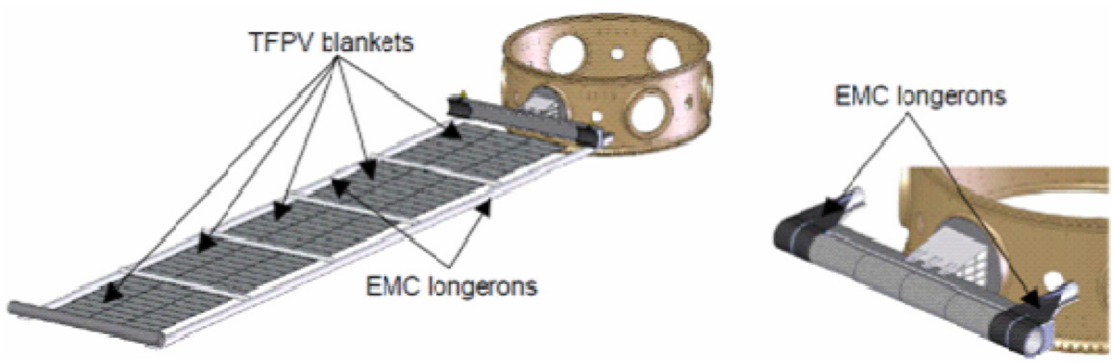
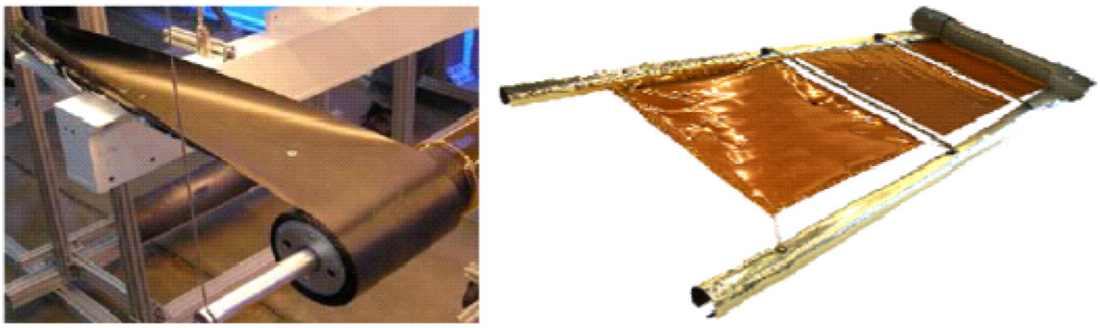


Figure 16. DINO Sat aero fin deployment process [144].



(a) (b)

Figure 17. Schematic of RAPDAR concept: (a) deployed configuration, and (b) stowed configuration. Reused from [176] with permission from the authors.



(a) (b)

Figure 18. The deployment model of EMC boom: (a) EMC boom and (b) partially deployed model of solar arrays supported by the EMC boom. Reused from [177] with permission from the authors.

orbit [176–179]; the deployment processing is illustrated in figure 18 [177].

4.3.2. SMPC reflector antennas. The antenna is the important communication tool between the satellite and Earth in space, which can provide necessary information about space matter. Two main parameters measure the deployable antenna working properties: the reflector aperture and precision. However, the two parameters are contradictory in certain ways—the structure would be very complex if the two parameters could be satisfied simultaneously [180]. In addition, the weight and packaged volume of the deployable antenna are also considered in the design.

Researchers have proposed several types of structure models, such as the wrap-rib deployable antenna [181], the rigid-rib deployable antenna [182], the hinged-rib deployable antenna [183] and the tension truss antenna [184, 185]. All the aforementioned antennas have some drawbacks concerning the weight, reflector aperture or surface precision. As one of the ideal advanced materials, SMPCs can overcome these drawbacks and play an increasingly important role in space deployable antennas.

Yang *et al* developed a new type of mesh-surface antenna deployed using SMPC tapes, as demonstrated in figure 19. The structure essentially consists of six pieces of SMPC thin shell tapes, six tape linkers, six guided ribs, a steel supporter and six resistor heaters. The ground deployment experiment

(a) (b)

Figure 19. The space deployable mesh-surface antenna model: (a) deployed SMPC antenna and (b) packaged SMPC thin shells. Reused from [186] with permission from the authors.

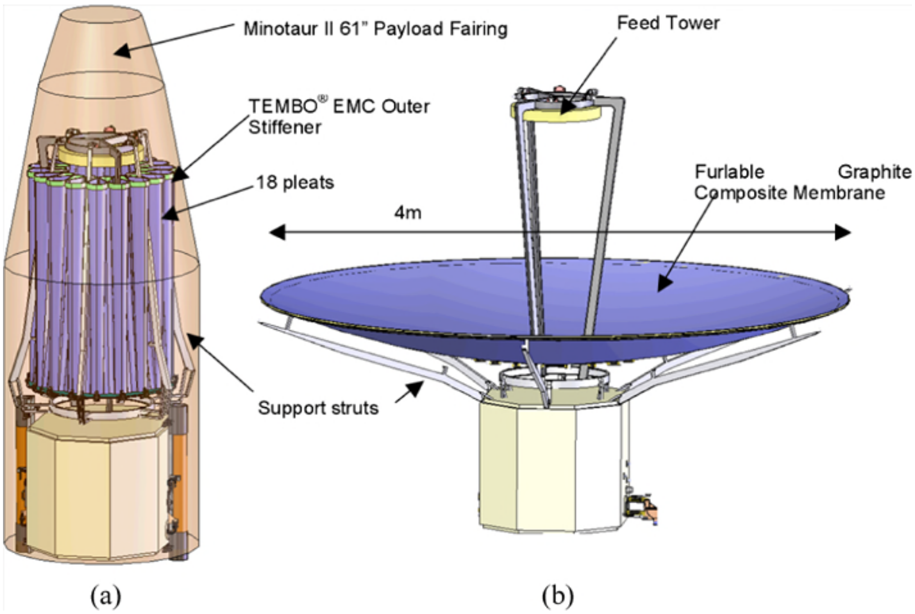


Figure 20. Solid-surface reflector developed by CTD: (a) the stowed state and (b) the deployed state. Reused from [188] with permission from the authors.

was performed using the heating of electricity. The results indicate that the SMPC antenna can be stowed into a small volume and be deployed completely by heating. Compared with traditional SMAs and mechanically deployable antennas, the structure is more lightweight and reduces the stowed strain energy; however, the surface precision is not significantly improved [186, 187].

CTD has developed a high-frequency solid-surface deployable reflector to better meet the requirement of future satellite missions in aerospace engineering, which mainly include: furlable graphite composite membrane, support struts and EMC outer stiffener, as shown in figure 20 [188]. The EMC stiffener is the key element of the reflector, which can provide deployment force for the reflector and become the important supporting structure after deployment. The result shows the EMC stiffener with high strain capability can be packaged into the stowed configuration under high temperature and return to the deployed shape without large shock effect, when reheated above the EMC transition temperature [188].

Harris Company has been considering using the concept of SMPCs to design a new type of smart solid-surface deployable reflector called the Flexible Precision Reflector (FPR) and has created some models for deployment experiment, as shown in figure 21; the structure consists of two parts: the outer stiffener fabricated using an EMC material and a thin film surface reflector in the middle part. The structure is packaged in stowed configuration, which can be actuated to deploy in some manner, such as by using light or temperature change [189].

The inflatable antenna is an important type of deployable reflector, which is fabricated using flexible materials [190–194]. The antenna is packaged into a small volume before launch. When the spacecraft is in space, the antenna

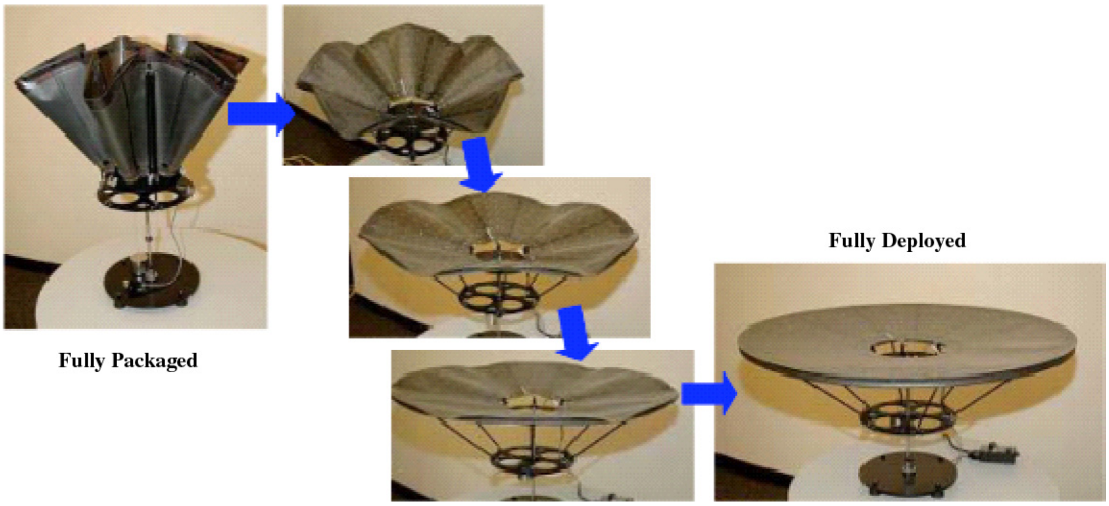


Figure 21. The deployment stages of Breadboard deployment. Reused from [189] with permission from the authors.

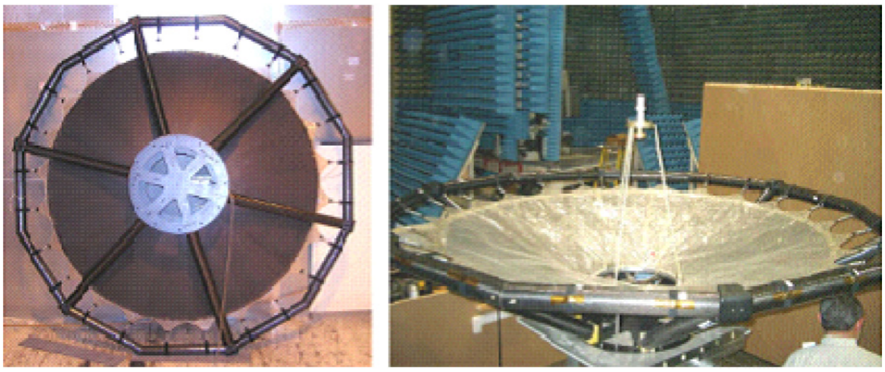


Figure 22. SMPC reflector for the hybrid inflatable antenna [191]. Reused with permission from the authors.

is released, inflated and hardens because of the physical or chemical effect. NASA successfully completed the in orbit experiment in 1996, the reflector provide sufficient surface reflector precision [190]. Today, SMPCs are considered for the fabrication of the main parts of the inflatable antenna to eliminate the air pressure leakage issue. A SMPC reflector model (2-m diameter) has been fabricated to validate the feasibility of SMPC as the supporting structure of a hybrid inflatable antenna, as shown in figure 22 [191]. These SMPC materials can significantly improve the structure application probability, via shape deformation and mechanical properties, and reduce the structural weight and cost effectively.

Yang *et al* have designed a class of inflatable reflectors to verify the good deployment mechanism [186]. The structure is fabricated using a carbon-fiber-reinforced SMPC material, with a parabolic-shaped surface and a 50-cm aperture. The four resistor heaters are stuck to the surface of the reflector and are used to actuate the structural deployment. The experimental results demonstrate that the structure can be deployed under the actuator of electricity and that it has a high surface precision. However, some drawbacks also need to be overcome such as the difficulty of fabrication technology, large heating area and insufficient deployed–packaged ratio [186].

Recently, NASA has been developing a new type of radar antenna under the Earth Science Technology Program, which has a large deployable aperture and good emergency response ability; its shape is the Sunflower model, as shown in figure 23 [194]. After many fabrication, examinations and evaluations, the results demonstrate that the key factors of the production program rely on the application of SMPs and SMPCs in the design of rigidizable-inflatable (RI) structures at reasonable cost. The SMPC antenna not only satisfies the complex structure demand but is also lightweight and exhibits high reflector precision [194].

4.3.3. Morphing structures. The idea of morphing an aircraft's shape is far from new. The design inspiration originates from birds flying free in the air and changing their flight posture according to the air flow [195, 196]. However, traditional aircraft can only carry out a single missions in a flight, such as an F-17 being used for attack mission, or Boeing 747 used for long-distance transport mission [197]. To improve flight performance, morphing vehicles were introduced to overcome this problem and efficiently alleviate

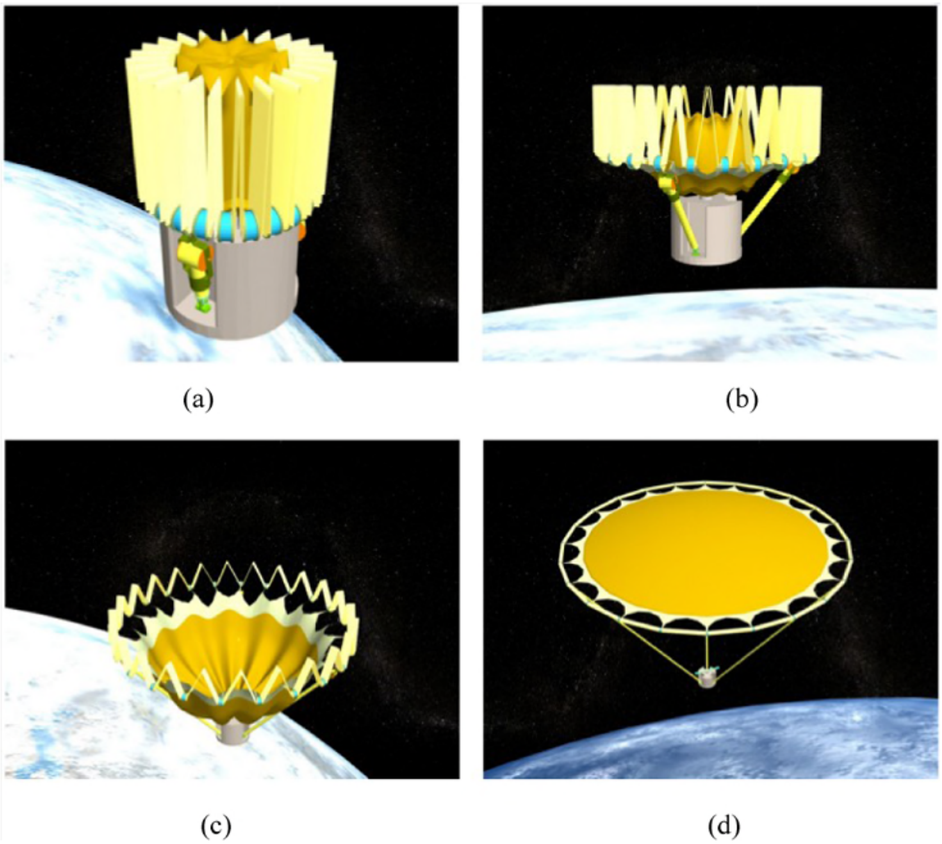


Figure 23. The deployment process of Sunflower reflector model: (a) the stowed state, (b) and (c) partial deployed state and (d) fully deployed state. Reused from [194] with permission from the authors.

structural deterioration [198, 199]. Today, researchers are greatly interested in designing new types of morphing wing skin; one of the branches involves SMPs and SMPCs, which can change their shape according to the temperature or other external stimulus and maintain normal efficiency.

Lockheed Martin has proposed a z-shape morphing vehicle concept and verified its flight properties through ground and wind tunnel tests of unmanned air vehicles (UAV) [200, 201]. Cornerstone Research Group (CRG) has improved the manufacture technique of SMPs for seamless skin: the wing skin can deform based on the packaging or deploying states of the hinge using SMPs at the conjunction parts [202].

Yu *et al* proposed the concept of a morphing wing consisting of SMPs/SMPCs and compared the deployment process of carbon-fiber-reinforced SMPs (CF-SMPs) with SMA-wire-reinforced SMP composites (SMA-wire-SMP) and elastic steel-slice-reinforced SMP composite (ESS-SMP) [203]. The results indicated that the SMA-wire-SMP and ESS-SMP have larger recovery speed than CF-SMPs due to the different reinforced materials. In addition, Yin *et al* developed the concept of a variable-camber wing and performed a related experiment to measure the deformation mechanism. The fiber Bragg grating (FBG) was selected to measure the deflection of the wing, as illustrated in figure 24 [204]. Bearing in mind that SMPCs possess variable mechanical properties under high/low temperature, the variable stiffness styrene-based SMPC tube reinforced with carbon fiber was fabricated and embedded into the flexible silicon rubber skin. Experimental results showed that the variable-stiffness SMPC tube had significant effect on the deformation of the morphing skin: with increase of time, the deflection gradually grows [205, 206], as illustrated in figure 25. Moreover, Garcia *et al* give a good summary of the UAV morphing concepts, design, technologies and development state, especially in terms of technologies; many methods are described in detail to explain their advantages and disadvantages [207].

4.3.4. Expandable lunar habitat. If space exploration is conducted for a long time, a special shelter or habitat is needed to maintain basic life and avoid damage from ultraviolet radiation. To solve this problem, the development of space-deployable technology becomes important; its aim is to better reduce the occupied room in spacecraft and maximize the work volume in space. SMP/SMPC is one of the advanced materials to satisfy the purpose, as it can be packaged and stowed in a smaller volume and deployed using some stimuli in space to function [208, 209].

ILC Dover Company has teamed with NASA Langley Research Center to develop a type of inflatable expandable lunar habitat; the framework of the structure is composed of SMPCs, and the structure achieves the purpose of self-deployment and high extensive area. In addition, the model

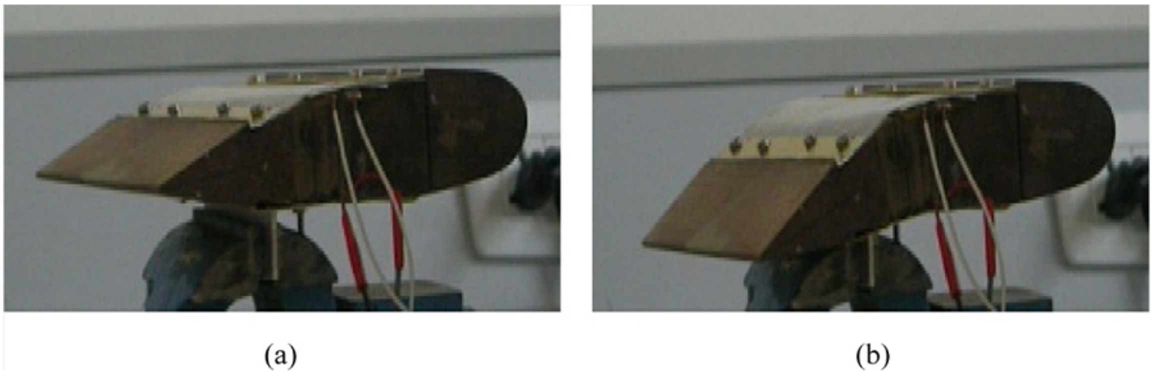


Figure 24. The deformation photograph of the variable-camber wing: (a) the original configuration and (b) the morphing configuration. Reused from [204], with permission from SPIE.

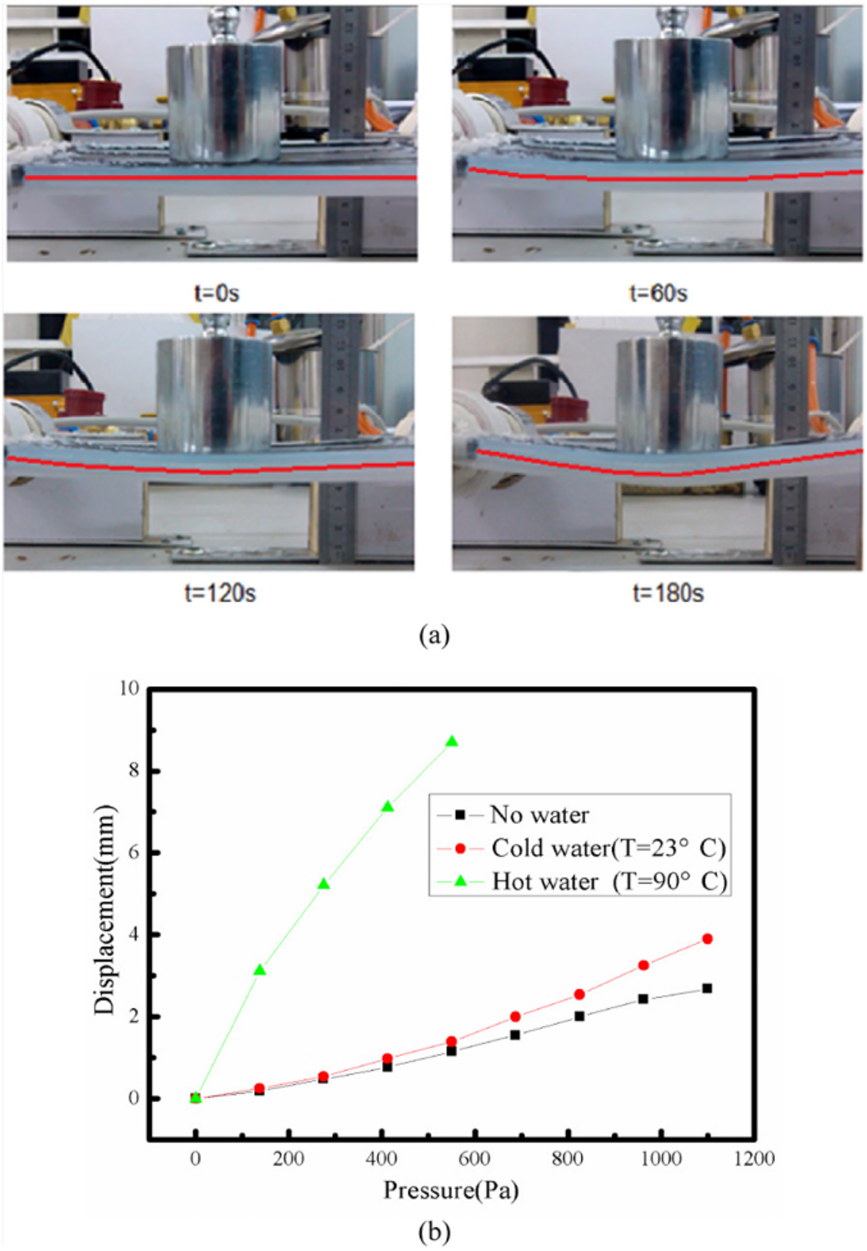


Figure 25. The deformation of morphing skin embedded into variable stiffness SMPC tube: (a) SMPC skin heating system, and (b) experimental curve of stress versus deformation of morphing skin [206].

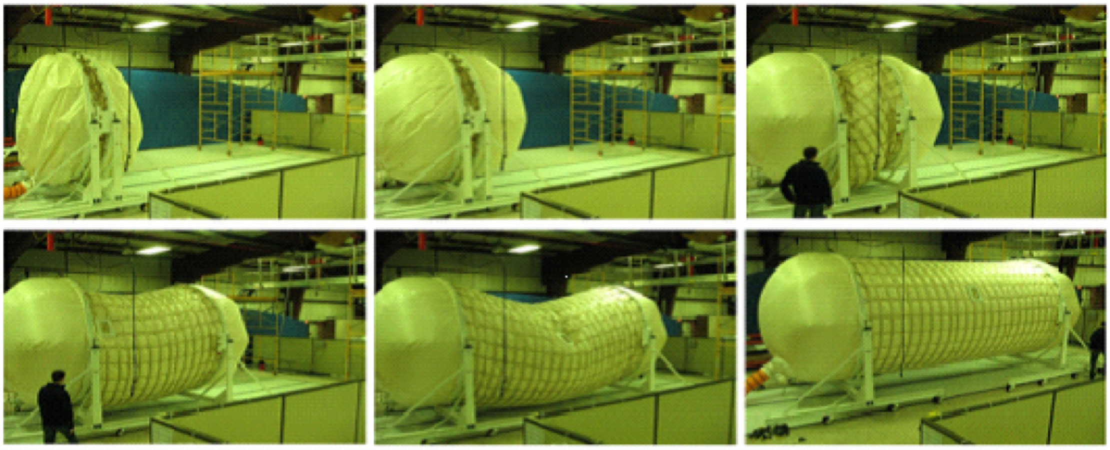


Figure 26. The deployment testing of expandable lunar habitat. Reused from [209] with permission from the authors.

was fabricated and the deployable process of the structure was examined in a ground experiment, as demonstrated in figure 26; the results indicated that the materials have good recovery properties under the air pressure deploying test [209]. Also, CRG has developed a self-constructing infrastructure for future moon and Mars missions to reduce the labor burden [210].

4.3.5. SMP and SMPC mandrels. Traditionally, there are two methods to overcome the fabrication problem of complex-curved structures: multi-piece metal mandrels and water-soluble mandrels. Although multi-piece metal mandrels can successfully satisfy the design precision, a significant amount of time, labor, energy, and cost is required to design, fabricate, assemble and demold these structures; on the other hand, the fabrication of water-soluble mandrels is relatively complexity. The main steps consist of preparing water-soluble materials (sand or salt) and a rigid support rod; forming pre-deformation shape of the structures; filament winding and curing; injecting water into the mandrel to dissolve the sand or salt; finally, the structure can be formed after cleaning the internal impurity [82]. Some companies (such as CTD) have fabricated linerless composite tanks using this method and analyzed the mechanical properties [211–213]. The disposable usage and residual noxious materials severely hinder the development of water-soluble mandrels. However, SMP mandrels or SMPC mandrels reinforced with a high strain fiber have the advantages of variable stiffness based on external temperature, a lower product cost, reusable usage and an easy demolding process, which is becoming a new developing direction of complex-curved structural manufacturing techniques.

CRG has fabricated a bottle-shaped mandrel and air-duct-shaped mandrel and verified the technique feasibility of SMP [82, 214–216]. Different types of SMP materials reinforced with fibers were produced to satisfy the various work environments in the company. Recently, Leng *et al* has investigated the mechanical properties of thermoset styrene SMP bottle-shaped mandrels and air-dust-shaped mandrels [217]. The results demonstrate the good deformation and reusable usage properties of the SMP mandrels: the structures have good shape fixity and good shape recovery ratio after several cycles, and the deformation and demolding process are easily controlled with temperature.

5. Conclusions

As one kind of advanced smart material, SMPs and SMPCs are playing an increasingly important role in the aerospace field. In this review, a number of research findings have been introduced to show the current and potential applications of SMPCs in aerospace. Remarkable research works are focusing on the design and evaluation of SMPC components, such as SMPC hinge and boom. Different types of components have been developed to better meet the need of space deployable structures, such as solar arrays and deployable panels, reflector antennas and morphing structures.

The variable stiffness under different external stimuli is the most striking characteristic of SMPs and SMPCs. SMPC hinges/booms can be packaged and deployed to realize the shape fixity and shape recovery of components and structures, which can provide deploying force and damping during the deployment process and lock the shape at the end of deployment to support the deployed structures. However, there are some challenges to the applications of SMPC in aerospace, such as the limited types of high-temperature SMPC suitable for the harsh space environment.

Considering their unique advantages of light weight, low cost, low density, high strength–weight ratio, low part count, simple design, good manufacturability, high shape deformability and an easily tailorable glass transition temperature, SMPs and SMPCs are expected to develop in multiple dimensions and have great potential applications in aerospace in the near future.

Acknowledgments

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