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Research on Application of Shape Memory Polymers to Space Inflatable Systems

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Abstract

Inflatable and deployable structure technology enables launch vehicles with limited fairing sizes to transport huge structures to space. However, because of the complex mechanism required to form desired shapes, a non-negligible number of malfunctions have occurred. Although some deployable and inflatable structures have been put to practical use, they were too complex and heavy.

We have focused on Shape Memory Polymers (SMPs) that can be inflated and deployed simply and reliably. SMPs are lighter, cheaper, and larger in recovery volume ratio than shape memory alloys. This technology will thus be applicable to space robotics.

1. Introduction

The technology of inflatable and deployable structures enables launch vehicles with limited fairing sizes to transport huge structures to space. However, because of their complex mechanisms for forming desired shapes, a non-negligible number of malfunctions have occurred. Though some deployable and inflatable structures were employed, they were too complex and heavy.

We have focused on Shape Memory Polymers (SMPs), which are lighter, cheaper, and larger in recovery volume ratio than Shape Memory Alloys (SMAs). Characteristics of SMPs and SMAs are compared in Table 1.

Table 1 Characteristics of SMPs Compared with Shape Memory Alloys

	Shape Memory Polymers	Shape Memory Alloys
Recovery volume	400~500%	7%
Recovery power	Small	Large
Density	1 g/cm^3	6.5 g/cm^3
Workability	Good (Thermoplastic)	Poor
Resistance to space environment	Low	High
Cost	$50 /kg	$1000 /kg

Effect of SMPs

The shape memory effect of SMPs is due to their glass transition function. Figure 1 illustrates the concept of shape memory effect of SMPs, which are rubbery and flexible above the Glass Transition Temperature (T_g), and glassy and rigid below it. SMPs can be inflated and deployed simply and reliably.

To maintain precise performance and stiffness, the

T_g of SMPs should be above the temperature of the SMP structure in orbit.

Application of SMPs to space structures

Figure 2 presents an example of SMPs applied as solar paddles. SMPs can be employed in large space structures, such as solar paddles, antennas, and radiators. While SMAs are used for actuators as part of whole structure, SMPs, owing to their large recovery volume and light weight, are suitable for application to the whole structure and making it an actuator.

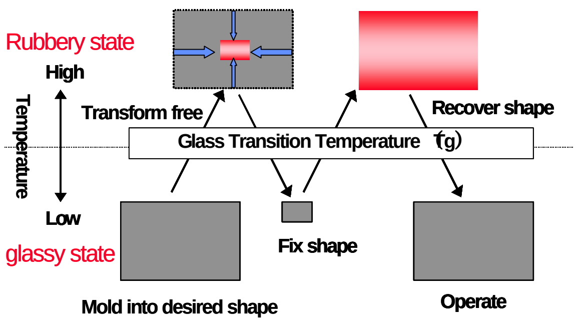

Fig. 1 Concept of SMP's Shape Memory Effect

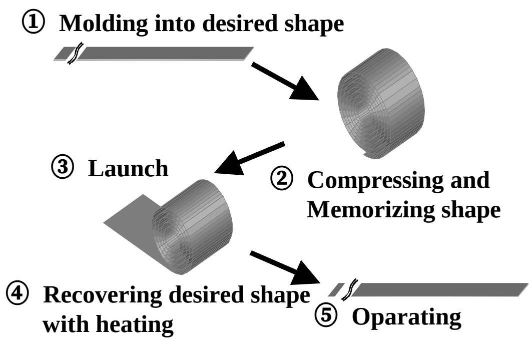

Fig. 2 Application of SMPs to Space Structure (ex. Solar Paddles)

2. Experimental

Polyurethane-based SMP "DiAPLEX®,"[(1)-(4)] manufactured by Mitsubishi Heavy Industries and being the only SMP put into practical use, was chosen as a sample material. DiAPLEX has many features; it is light, clear, colorable, highly corrosion resistant, and workable, and allows flexible T_g selection. Figure 3 illustrates the basic synthesis process of SMPs.

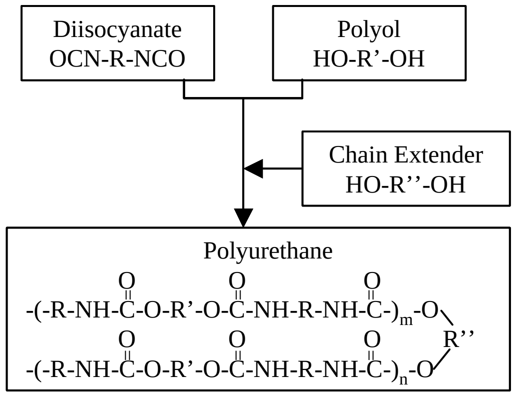

Fig. 3 Basic synthesis process of SMPs

Two types of samples were prepared. One is a deployable carbon-fiber-reinforced SMP (FR-SMP) manufactured by hot pressing (Fig. 4). FR-SMP is designed to increase the rigidity and recovery power of SMPs. The other sample type is foam (SMP-Foam) for inflatable structures. SMPs can be foamed by means of CO_2 generated by reaction of polyol and H_2O.

In addition, we attempted to raise T_g of resin for FR-SMP before preparing samples.

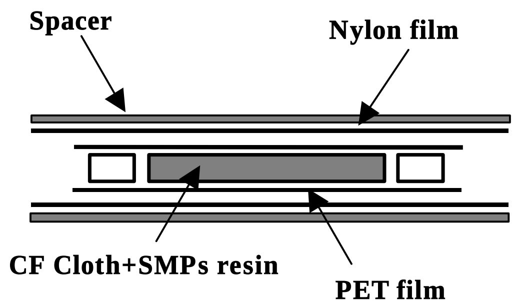

Fig. 4 Manufacturing FR-SMP by Hot Pressing

Our previous research revealed that SMPs' shape memory properties are preserved up to 50 equivalent solar days (ESD) of UV irradiation.[(5)]

Atomic oxygen (AO) and electron beam (EB) irradiated samples were also prepared in order to determine the resistance of SMPs to other potentially damaging constituents of the space environment. AO fluence was 1×10^{20} cm^{-2}, almost equivalent to 10 days of irradiation in low Earth orbit; the EB fluence was 2×10^{16} cm^{-2}, almost equivalent to 10 years of irradiation in geostationary orbit.

Dynamic viscoelasticity tests were conducted to estimate the shape memory properties. The dynamic viscoelasticity of SMP samples was investigated at temperatures between 223K and 473K, in torsion for FR-SMP and compression for SMP-Foam. SMPs are judged to have good shape memory properties when the storage modulus (G') determined in dynamic viscoelasticity tests has two phases, and the difference in storage moduli between them is largely decoupled above and below T_g. Three-point bending tests were also performed to judge FR-SMP's mechanical properties.

Outgassing of the samples was also evaluated with ASTM E 595.

Additionally, parabolic antenna models were made from SMP-Foam by numerically controlled cutting in order to evaluate workability.

3. Results and Discussion

Raising T_g

The space environment heats space structures. For example, solar paddle surfaces can reach 330K. The original T_g of FR-SMPs was 328K, T_g must be raised for SMPs to maintain stiffness after deployment or inflating. We therefore altered the SMPs composition and T_g reached 368K. Figure 5 shows the storage modulus of high T_g FR-SMP.

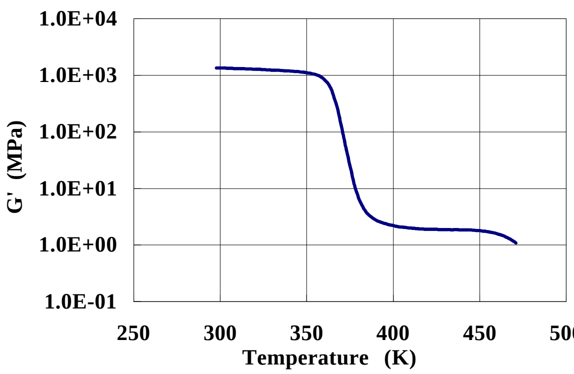

Fig. 5 Storage modulus of high T_g FR-SMP

Resistance of SMPs to space environment

Figure 6 illustrates changes in the storage modulus of FR-SMP as a function of irradiation. The irradiated sample curves closely match that of the unirradiated sample, and so satisfy the conditions of having good shape memory properties.

Figure 7 depicts changes in breaking load and deflection of FR-SMP in three-point bending tests as a function of irradiation. Three-point bending test results differ among the samples. The EB-irradiated sample had slightly reduced ductility, but the AO-irradiated sample had increased ductility and strength. This phenomenon is considered to result from active cross-linking after the molecular chain of SMP is cut by AO irradiation.

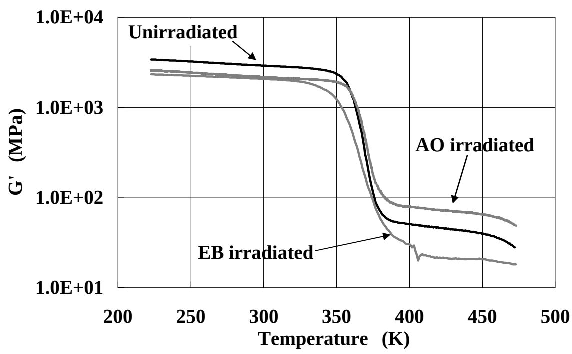

Fig. 6 Change in storage modulus of FR-SMP as a function of irradiation

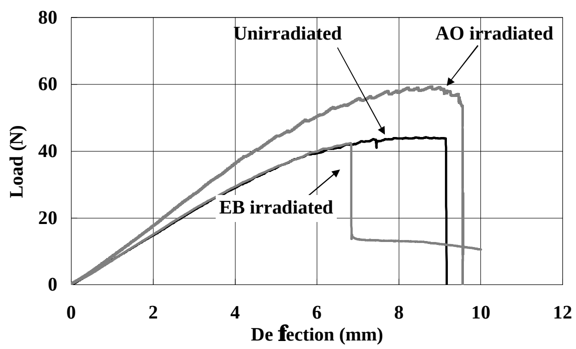

Fig. 7 Change in breaking load and deflection of FR-SMP in three-point bending test as a function of irradiation

In addition, SMP-Foam samples nearly get the same results of FR-SMPs'.

Antenna models of SMPs

Figure 8 presents 20-cm-diameter parabolic antenna models made of SMP-Foam by numerically controlled cutting. SMP-Foams are easy to cut to various shapes.

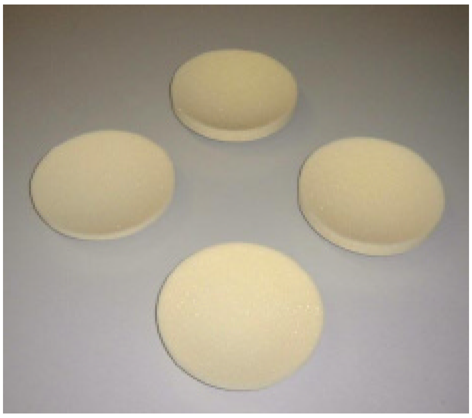

Fig .8 Parabolic antenna models made of SMP-Foam

Outgassing of SMPs

Table 2 lists measured SMP out-gassing data. The total mass loss of SMP-Foam does not satisfy the recommended value. For use in space, SMP-Foam should decrease its total mass loss. In this respect, FR-SMP has good out-gassing properties.

Table 2 Out-gassing Data of SMPs

Samples	FR-SMP	SMP-Foam
Total Mass Loss (TML) (%)	0.678	3.582
Collected Volatile Condensable Materials (CVCM) (%)	0.001	0.057
Water Vapor Regained (WVR) (%)	0.158	0.16
Judgment*	Passed	Failed

* PASSED: TML≦1% and CVCM≦0.1%

4. Conclusion

In this research, we succeeded in raising the shape-recovery temperature T_g of SMPs to facilitate their precise control. SMPs retain their shape-memory properties even in the space environment.

In the future, we will conduct various experiments to assess the performance of SMPs, including heating methods, with structure models such as solar paddles.

SMP application has the potential for realizing larger and more reliable space structures.

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