Surface control of cold hibernated elastic memory self-deployable structure

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ABSTRACT

A new class of simple, reliable, lightweight, low packaging volume and cost, self-deployable structures has been developed for use in space and commercial applications. This technology called "cold hibernated elastic memory" (CHEM) utilizes shape memory polymers (SMP) in open cellular (foam) structure or sandwich structures made of shape memory polymer foam cores and polymeric composite skins. Some of many potential CHEM space applications require a high precision deployment and surface accuracy during operation. However, a CHEM structure could be slightly distorted by the thermo-mechanical processing as well as by thermal space environment. Therefore, the sensor system is desirable to monitor and correct the potential surface imperfection.

During these studies, the surface control of CHEM smart structures was demonstrated using a Macro-Fiber Composite (MFC) actuator developed by the NASA LaRC and US Army ARL. The test results indicate that the MFC actuator performed well before and after processing cycles. It reduced some residue compressive strain that in turn corrected very small shape distortion after each processing cycle. The integrated precision strain gages were detecting only a small flat shape imperfection indicating a good recoverability of original shape of the CHEM test structure.

Keywords: Shape memory polymers, open cellular structures, glass transition temperature Tg, piezoelectric actuator.

1. INTRODUCTION

Experiments have confirmed the feasibility of an innovative, new class of very simple, reliable, low mass, low packaging volume, and low-cost self-deployable structures for space and commercial applications. The structure technology called "cold hibernated elastic memory" (CHEM) utilizes shape memory polymers (SMP) in open cellular (foam) structure or sandwich structures made of shape memory polymer foam cores and polymeric composite skins. The CHEM structures are self-deployable and are using the foam's elastic recovery plus their shape memory to erect a structure. In practice, the CHEM foams are compacted to small volume above their softening (glass transition) temperature Tg. They may then be stored below their Tg without constraint. Heating to a temperature above their Tg restores their original shape. The advantage of this exciting new technology is that structures when compressed and stored below Tg, are a small fraction of their original size and are lightweight. The CHEM processing cycle is illustrated in Figure 1 below.

The CHEM structures are under development by the Jet Propulsion Laboratory (JPL) (Ref. 1, 2 and 3) and industry Currently, the CHEM foam concept is well formulated, with clear space and commercial applications. One of many potential space applications is self-deployable multifunctional structures with embedded thin film electronics, sensors, actuators and power sources for solar arrays, antennas and solar sails. This space application requires a high precision deployment and surface accuracy during operation. The CHEM structure could be slightly distorted by the thermo-mechanical CHEM processing cycle of compaction, deployment and rigidization as well as by thermal space environment.

In this study, we evaluated the robustness of the Langley Research Center (LaRC) and Army Research Laboratory (ARL) Macro-Fiber Composite (MFC) actuators (Figure 2), potentially to be used for surface control of CHEM self-deployable structures. The major objective of this task was to assess the reliability of a flexible MFC piezocomposite actuator for surface control of CHEM self-deployable structures. The main components of the assessment were to evaluate the adhesive bonding for CHEM structure, use this information to fabricate experimental test structures with embedded actuators and then evaluate the performance of actuator and recoverability of original shape of the CHEM

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structure after thermo-mechanical processing cycles.

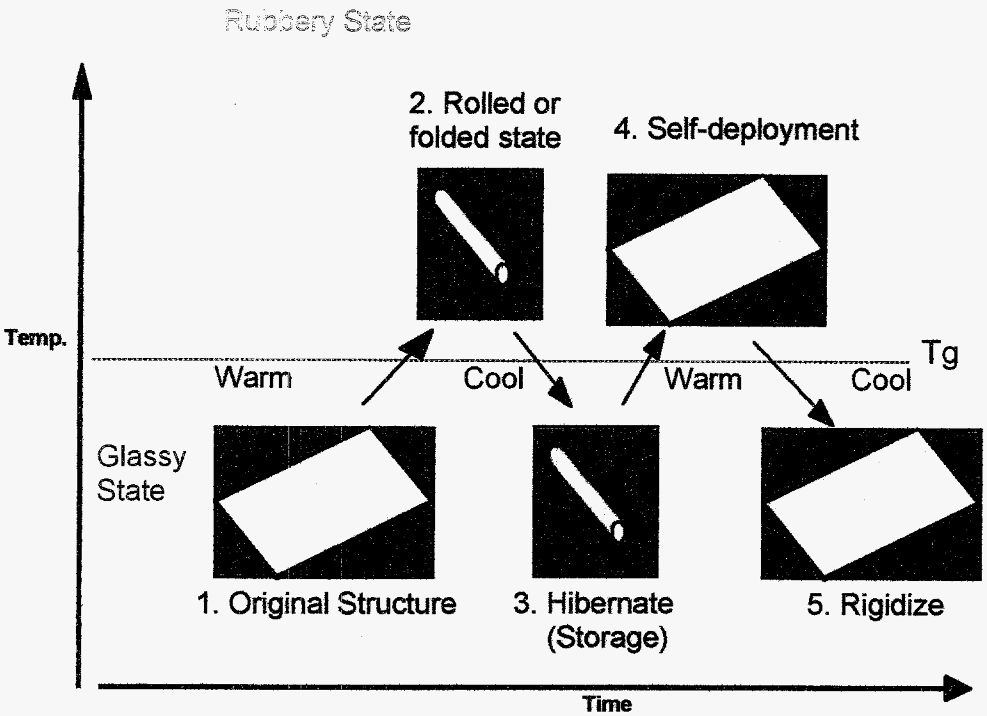

Figure 1: CHEM processing cycle

2. TEST STRUCTURE

Two experimental test structures with two different CHEM foam densities and one embedded MFC actuator in each set were planned to be fabricated. Two MFC II actuators were submitted by LaRC. The multi-layer structure design was selected for an experimental CHEM self-deployable test structure with integrated MFC actuator that is shown in Figure 3. Several different adhesives were tested and evaluated, and the best one was selected for fabrication of experimental test structures. Evaluation of adhesive bonding and fabrication of the test structure are described in following subsections.

2.1. Evaluation of adhesive bonding

The adhesive bonding were experimentally evaluated for:

- Actuator & Kapton film (5 mil Kapton & 2 mil Kapton)
- Kapton film & CHEM foam (2 mil Kapton & 0.375 inch thick foam)

Scotch-Weld 2216, Hysol 9361, RTV 615, regular Kapton tape and 3M pressure-sensitive adhesive tape were tested and evaluated for fabrication of test structures.

Table 1. Summary of results for Kapton to Kapton bonding

Adhesive	Visual before thermal cycling	Visual after thermal cycling	SAM	Shear Test Load (lbs)
Scotch-Weld 2216	Stiff, delaminated from 2 mil Kapton film	X	X	X
Hysol 9361	Stiff, delaminated from 2 mil Kapton film	X	X	X
RTV615	Flexible, delaminated from 2 mil Kapton film	X	X	X
1" wide 3M Scotch Kapton electrical tape	Flexible, flat adhesion	Flexible, periodic striations	Partially debonded at striations	21.9 ± 0.6
2" wide 3M pressure-sensitive Y966 tape	Flexible, flat adhesion	Flexible, periodic striations	Partially debonded at striations	27.5 ± 1.2

Notes: 3 samples of each adhesive were evaluated X – no further testing

The following conclusions and recommendation are drawn based on the test results.
Kapton to Kapton bonding. The results indicate that both the 1" wide 3M Scotch electrical tape and the 2" wide 3M pressure-sensitive adhesive tape have promising adhesive properties when bonded to 5 mil Kapton thin films. The 1" tape shows better uniformity in the bonding surface after thermal cycling, while the 2" tape has higher shear strength. The other adhesives tried were either too stiff (Hysol 9361 and Scotch-Weld 2216) and/or delaminated even before thermal cycling (RTV615). Therefore the two different adhesive tapes were used in the CHEM foam bonding trials.

Table 2. Summary of results for Kapton to CHEM foam bonding.

Adhesive/CHEM foam combination	Visual before thermal cycling	Visual after thermal cycling	SAM	Peel Test (lb/in)
Electrical tape to low density foam	Uniform	Some striations visible	Debonded small striations	0.14±0.03
Pressure sensitive tape to low density foam	Uniform	In 1 sample a partial crack in foam at bonded line.	Bright strings	0.73±0.09
Electrical tape to high density foam	Uniform	2 out of 3 samples delaminated before end of 10 thermal cycles, 1 sample loosely attached after 10 thermal cycles – wide striations of debonded area	Large areas that are debonded	0.11±0.03
Pressure sensitive tape to high density foam	Uniform	1 samples cracked in half at the bond to no bond line during thermal cycling	Fairly uniform bonding	1.0±0.2

Notes: 3 samples of each adhesive were evaluated

Kapton to CHEM foam bonding. These results indicate the 2" wide 3M pressure-sensitive adhesive tape has better peel strength than the 1" wide 3M Scotch electrical tape to both the high and low density CHEM foams. The high-density, more rigid foam has slightly higher peel strength.
Final recommendations. 3M pressure-sensitive adhesive tape was recommended for bonding of the MFC actuator to the CHEM foam and Kapton film.

2.2 Fabrication of test structures

Two CHEM foam materials with the Tg (glass transition temperature) of 60°C and two different densities (0.035 and 0.070 g/cm^3) were utilized for fabrication of test structures. Two MFC II actuators, identified as 368 and 369 were submitted by the Electronic Systems Branch, NASA LaRC. Additional data on the actuator is given in Table 3 below.

Table 3 MFC II actuator data

368	UNPOLED	POLED
C	10.595 nF	12.585 nF
D	.0988	.1072
/Z/	14.95 kΩ	12.57 kΩ
θ	-84.34°	-83.86°
L	2.390 H	2.013 H
Q	10.1	9.3
369	UNPOLED	POLED
C	10.200 nF	12.221 nF
D	.0581	.0683
/Z/	15.57 kΩ	13.00 kΩ
θ	-86.65°	-86.06°
L	2.482 H	2.073 H
Q	17.2	14.6

Serial Number	MFC 368,369
Date of Manufacture	September 2001
Ceramic Type	CTS Wireless 5A
Ceramic Thickness	.005"
Electrode Pattern/Type	MFC II
Epoxy	Loctite E120HP
Fabrication Representative	James W. High

The CHEM foam was cut to the substrate size of 10" long x 4" wide x 0.375" thick and then blown off with compressed air. This eliminated debris from the bonding surface. Later, MCF actuators were bonded to the foam substrates. A double-sided 3M pressure-sensitive adhesive tape was used during fabrication. It was selected during previous experimental evaluation. Surface preparation and bonding were conducted per the procedure developed early in this program. Next, the actuator and CHEM foam substrate were enclosed (bonded) by the 2 mil Kapton film. Finally, two precision strain gages, submitted by LaRC, were attached to the surface of test structure (Figure 4).

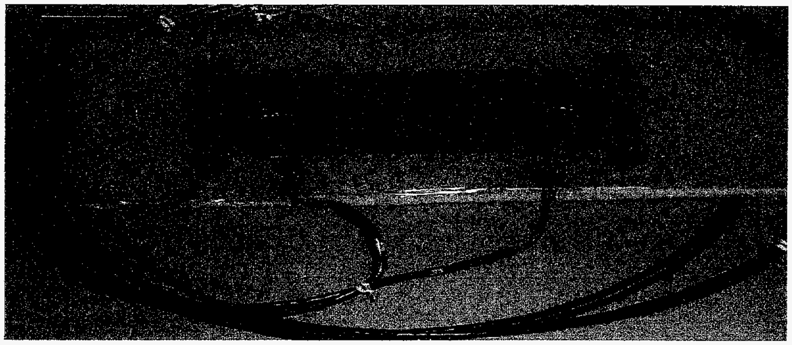

Figure 4 Test structure

The gages were oriented to measure strains in the longitudinal direction. Unfortunately, during fabrication, one of actuators was damaged and only one test structure with low density CHEM foam substrate was completely fabricated, tested and evaluated. Visual and low magnification examination of this test structure indicated good mechanical integrity before testing and evaluation .

3. TESTING AND ASSESSMENT STUDIES

3.1 Test procedure

The following evaluation & reliability assessment were conducted during these studies

- performance/capabilities of MCF actuator
- recoverability of original shape of the CHEM foam substrate
- integrity of test structure

After each CHEM thermo-mechanical processing cycle (RT to 80°C), the test structure was linked to the test assembly (Figure 5) and the performance of MFC actuator was evaluated. Two precision strain gages performed the assessment of deployment/original shape restoration of foam substrate, identified some flatness imperfection in μstrains and then the actuator corrected the surface distortion caused by the CHEM cycles. In addition, a visual and low magnification examination of test structure were conducted to find out the mechanical integrity after each cycle.

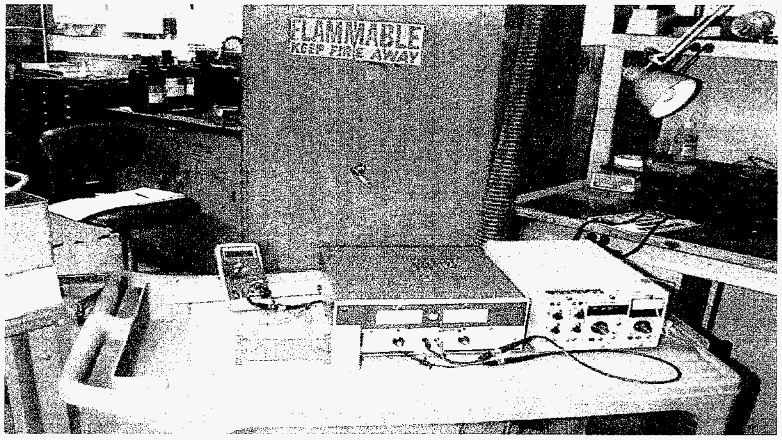

Figure 5 Test assembly

3.2 Thermo-mechanical processing cycle

The CHEM thermo-mechanical processing stages are illustrated in Fig. 6. They were as follows:

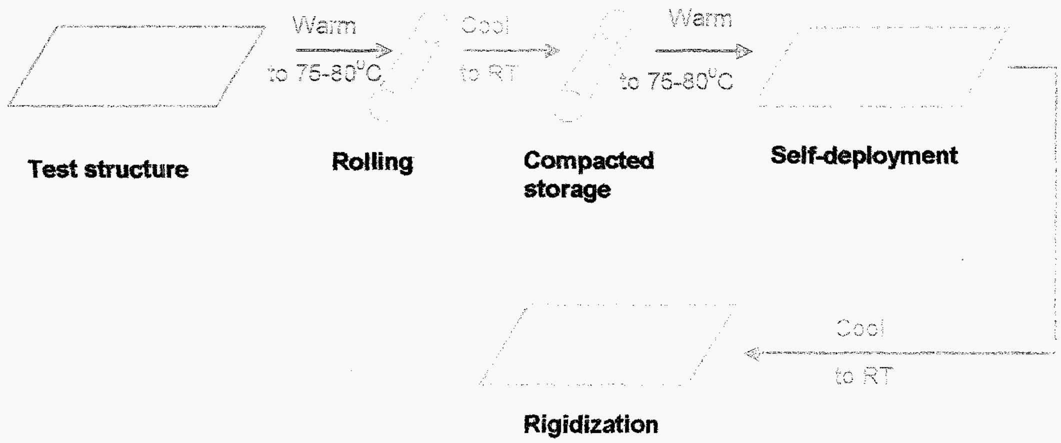

Figure 6 CHEM thermo-mechanical processing cycle

• Heating & rolling
The test structure was put into the oven , heated up to 80°C in air, stayed at this temperature for 5 minutes and rolled on a 1″ diameter metal rod.
• Compacted storage
Compacted, rolled structure was taken out from the oven, cooled to room temperature (RT) to "freeze" it in its rolled state for at least 15-20 minutes.
• Deployment
"Frozen" rolled structure was put into the oven at 80°C for heat-activated deployment/shape restoration of the test structure.
• Rigidization
After full deployment, the test structure was taken out from the oven and cooled to RT for rigidization
Three (3) CHEM thermo-mechanical processing cycles were conducted during this investigation

3.3 Test assembly

The test assembly is illustrated in Figure 7 below. Main elements in the test assembly were:

- Test structure

Cold hibernated elastic memory (CHEM) foam structure with embedded MFC actuator and two gages oriented to measure strains in the longitudinal direction.

- DC power supply

KEPCO Model APH1000M: supplied up to 1000 V to the actuator electrode

- Conditioner & amplifier

Strain Gage Conditioner and Amplifier 2100 System: a multi-channel system for generating conditioned high-level signals from strain gage inputs for display

- Output display

Strain output display in mV, later converted to μstrain (ppm)

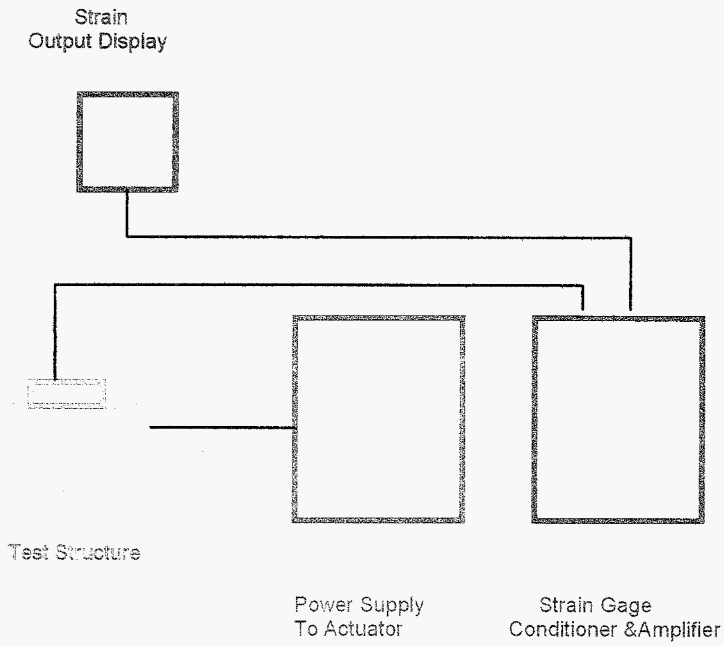

Figure 7 Schematic of test assembly

3.4 Evaluation/assessment results

Actuator performance before processing cycles

A voltage DC up to 1000V was supplied to the MFC actuator to find out its actuation capability in the test CHEM foam structure. An applied voltage produced in-plane electric fields that subsequently created in-plane actuation of the piezoceramic material. First a voltage was gradually increased to 1000 V, later decreased to 0 (zero) and measurements of strain actuation were taken at each 100 V increment. This strain actuation cycle was repeated three times to find out if the actuator's performance could be reproduced consistently. The strain reading was in mili-volts that later was converted to µstrain (ppm). The strain actuation data are presented in Figure 19 below.

As seen in the Figure 8, the MFC actuator integrated with CHEM test structure generated a peak actuation strain of approximately 40 µstrain (part-per-million) in the longitudinal direction under the voltage of 1000 V. Therefore, the ratio of strain per volt was ~ 0.04. The actuator demonstrated a consistent performance. A small variation in µstrain output and negative strain-voltage hysteresis (-4.8 to –8.4 µstrain) during three voltage cycles were caused likely by the visco-elastic deformation and shape memory polymer behavior of CHEM structure. It was found that one hour after the test, the CHEM test structure was still slightly moving towards a positive strain direction and was closed to 0 µstrain. It appears it takes more time in the hard/hibernated state of CHEM structure for individual molecule chains aim at degrading the µstresses for some sort of rearrangement until an equilibrium value is attained. That in turn could cause the residue µdeformation (µstrain) to disappear completely.

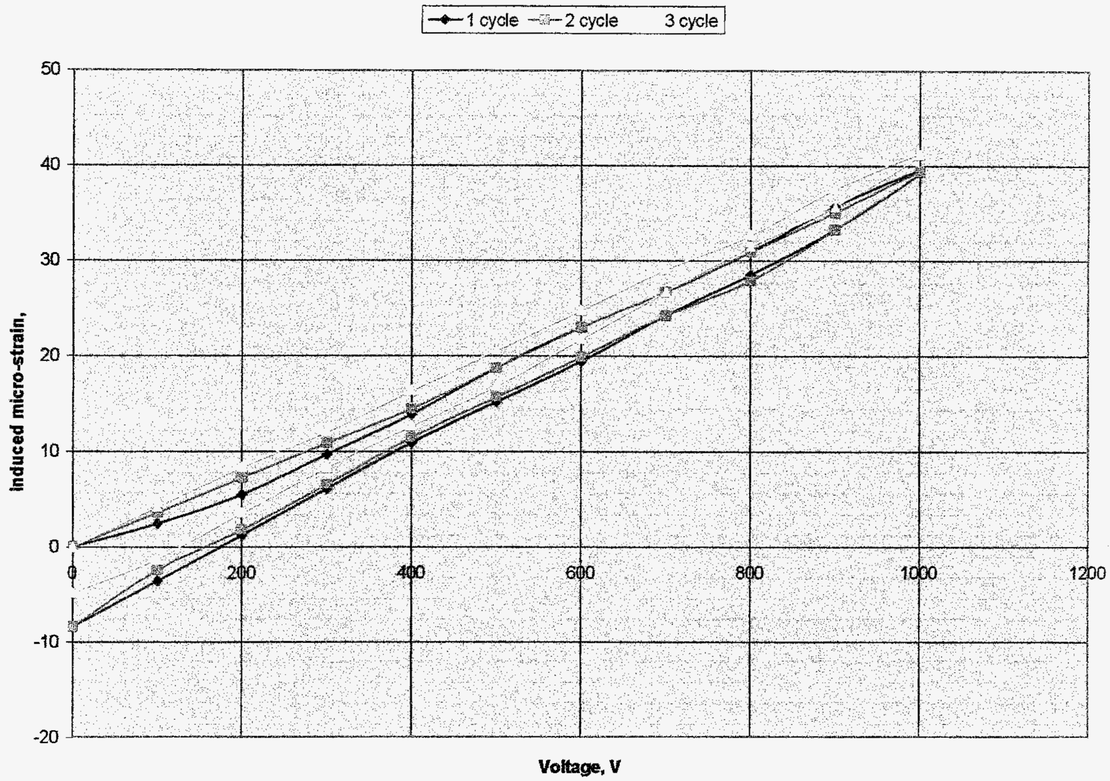

Figure 8 Actuation performance of MFC actuator integrated with CHEM test structure

Recoverability of original shape assessment

The recoverability of original flat shape of the CHEM test structure was assessed after each thermo-mechanical processing cycle. Approx. 27% strain in compression was introduced during the rolling/bending stage on the structure's side where a MFC actuator and strain gages were embedded.

After shape restoration and rigidization, two precision strain gages were sensing a flat shape imperfection by detecting the residue μstrain. Recoverability of original shape results are presented in Table 4 below.

Table 4 Recoverability of original shape after cycles

Thermo-mechanical cycle #	**Residue strain %**		
	Original shape	**Rolled state**	**Recovered shape**

1	~ 0	~ - 27	- 0.0206
2	~0	~ - 27	- 0.0103
3	~ 0	~ - 27	- 0.0094

The data from Table 4 indicated a good recoverability of original flat shape of the CHEM test structure. After heating & rolling on a 1″ diameter metal rod and cold hibernation storage at room temperature (RT), we were able to recover an original flat shape and structure's condition by heating above the glass transition temperature Tg and cooling to RT. Only a small amount of residue compressive strain was left indicated a tiny flat shape imperfection. As seen in the Table 4, a residue compressive strain was getting smaller in each following thermo-mechanical processing cycle, reducing from 0.0206 to 0.0094 after 3 cycles. This is in agreement with previous studies of CHEM structures and shape memory polymers (Ref. 4, 5 and 6).

Reduction of distortion by MFC actuator

After each assessment of original shape's recoverability, the MFC actuator was activated to reduced some small flat shape imperfection brought in during thermo-mechanical cycles. A voltage up to 1000 V was supplied to the actuator to introduce tensile stresses and reduce residue compressive stresses that caused this small flat shape distortion. A reduction of flat shape imperfection is presented in Table 5 below.

Table 5 Reduction of flat shape imperfection

Thermo-mechanical cycle No.	**Residue strain %**		
	After cycle	**After actuation 1000 V**	**Correction**
1	- 0.0206	- 0.0154	+ 0.0052
2	- 0.0103	-0.0054	+ 0.0049
3	- 0.0094	- 0.0043	+ 0.0051

The objective of this testing was to find out the actuator's capability to reduce a flat shape distortion introduced during thermo-mechanical cycles. As seen in the Table 5, the MFC actuator integrated with the CHEM test structure could reduce the residue strain of approx. 50 μstrain under the voltage of 1000 V. Therefore, the actuator's performance and capability to reduce a shape distortion was ~ 0.05 μstrain per volt.

As previously occurred during these studies, it was detected by precision strain gages that one hour after the actuation, the CHEM test structure was still slightly moving and oscillating between a positive and negative strain areas. It appeared the actuation created a new state of stresses and individual molecule chains needed more time for the rearrangement until an equilibrium value was attained. This micro-instability subject matter was not investigated further because it was not part of the objective of this program.

Visual examination of test structure

The test structures were visually examined at low magnification after each thermo-mechanical cycle. It appeared the test structure survived all three processing cycles including the actuation of the MFC actuator before and after each cycle. Visual examination did not show the presence of apparent debonding or delamination. In general, the test structure looked solid with enough mechanical integrity to withstand more processing cycles and actuation activities.

4. CONCLUSIONS

The multi-layer structure design was selected for an experimental CHEM self-deployable test structure with an integrated MFC actuator. Several adhesives were evaluated and the best one was chosen for fabrication of the test structure. The performance of actuator and recoverability of original shape were assessed after thermo-mechanical processing cycles. Here are the major conclusions of this investigation:

1. Visual examination, SAM evaluation and peel test results after thermo-mechanical cycles indicated that the 3M pressure-sensitive Y966 adhesive tape was the best adhesive material for this purpose and was selected for fabrication of the test structure.

2. The test structure survived all three processing cycles including the actuation of the MFC actuator before and after each cycle.

3. MFC actuator integrated with the CHEM test structure performed well before and after cycles. It consistently generated a peak actuation strain of approx. 40 μstrain under the voltage of 1000 V before cycles. After each processing cycle, it reduced the residue compressive strain by approximately 50 μstrain after each processing cycle.

4. Precision strain gages were sensing a small flat shape imperfection by detecting some residue compressive μstrain indicating a good recoverability of original shape of the CHEM test structure. The residual compressive μstrain was further decreased in each subsequent processing cycles.

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