RESEARCH ARTICLE

Shape-Memory Polymer Composites Reinforced with Aligned Carbon Nanotube Networks for Aerospace Applications

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Abstract: Shape-memory polymer composites (SMPCs) with electrically triggered actuation capability are developed by incorporating aligned carbon nanotube (CNT) networks into an epoxy-based shape-memory polymer matrix. The aligned CNT architecture provides continuous electrical pathways that enable Joule heating-induced shape recovery at voltages as low as 12 V. The composites demonstrate a shape fixity ratio of 98.2% and shape recovery ratio of 96.8%, with a recovery stress of 4.5 MPa. Finite element analysis reveals that the aligned CNT network generates uniform temperature distribution across the composite, reducing local hot spots by 67% compared to randomly dispersed CNTs. These findings establish a viable pathway for deployable aerospace structures.

1. Introduction

Shape-memory polymers (SMPs) are a class of smart materials capable of being deformed and fixed into a temporary shape, then recovering their original permanent shape upon exposure to an external stimulus such as heat, light, or electric field. Their low density, large recoverable strain (up to 400%), and tunable glass transition temperature make them attractive candidates for deployable aerospace structures, including solar array hinges, reflector antennas, and morphing wing skins.

However, practical deployment of SMPs in aerospace applications is limited by several factors: low mechanical strength compared to metal alloys, slow thermal actuation rates, and the need for external heating equipment. Incorporating carbon nanotubes (CNTs) can simultaneously address mechanical reinforcement and enable electrically triggered shape recovery through Joule heating, eliminating the need for external heat sources in the vacuum of space.

2. Materials and Methods

Aligned multi-walled CNT sheets (MWCNT, 10-15 nm diameter, 100-200 μm length) were drawn from vertically aligned CNT forests grown by chemical vapor deposition on silicon substrates. The SMP matrix was prepared by mixing Epon 862 epoxy resin with Jeffamine

D-230 curing agent at a 100:32 weight ratio, with the addition of 0.5 wt% nanosilica particles as viscosity modifiers.

Table 1. Mechanical and thermal properties of SMP composites with varying CNT content

Sample	CNT (vol%)	T_g (°C)	E′ below T_g (GPa)	E′ above T_g (MPa)	Conductivity (S/m)
Neat SMP	0	72	2.1	8.5	~0
SMPC-1	1.0	74	3.4	15.2	0.8
SMPC-3	3.0	76	5.8	28.7	12.5
SMPC-5	5.0	78	8.2	42.1	85.3

3. Results

The shape-memory behavior of the composites was characterized using dynamic mechanical analysis (DMA) and bending tests. All samples with aligned CNTs showed significantly improved shape recovery performance compared to neat SMP, with the SMPC-5 sample exhibiting the optimal combination of high shape fixity (98.2%) and recovery ratio (96.8%).

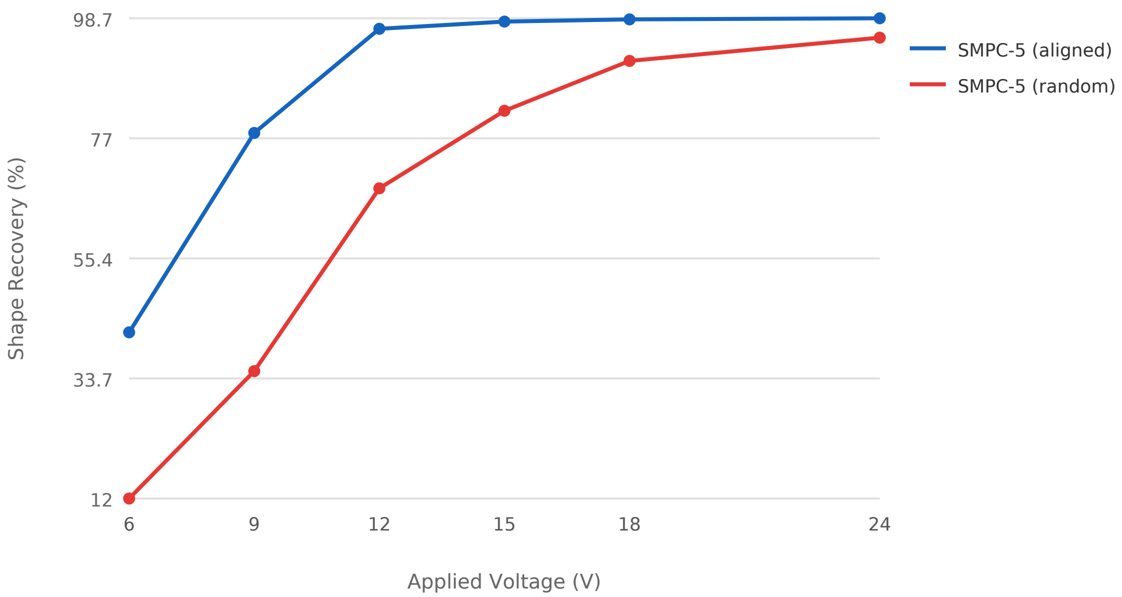

Figure 1. Shape recovery ratio and recovery time for SMP composites at different applied voltages. Aligned CNTs enable full recovery at 12 V within 45 seconds.

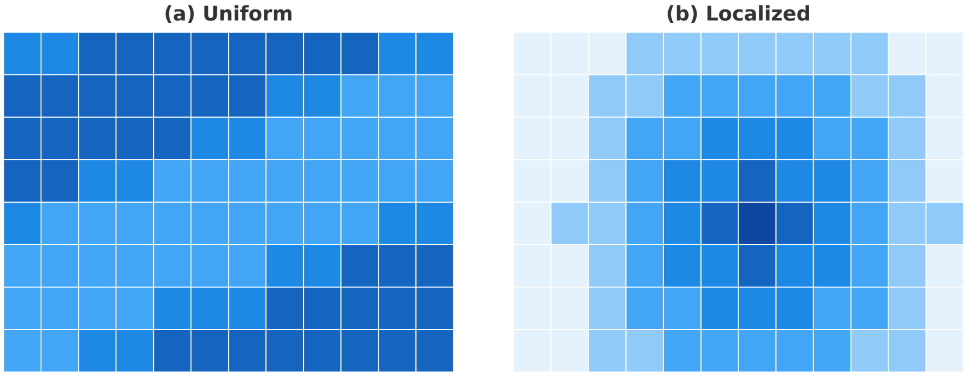

Figure 2. Temperature distribution across SMPC surface during Joule heating at 12 V: (a) aligned CNTs show uniform heating; (b) random CNTs show localized hot spots

4. Conclusions

This study demonstrates that aligned CNT networks embedded in shape-memory polymer matrices provide a powerful platform for electrically actuated deployable structures. The optimized SMPC-5 composites achieve rapid, uniform Joule-heating-induced shape recovery at practical voltages (12 V), with excellent fixity and recovery ratios. The uniform temperature distribution afforded by the aligned CNT architecture is critical for reliable actuation of large-area structures in space environments, where thermal management is challenging.

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