A SHAPE MEMORY POLYMER BASED SELF-HEALING SYNTACTIC FOAM

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Thermoset polymer based syntactic foams have been widely used in high performance foam cored sandwich structures such as auto, ship, aircraft, train, tank, pressure vessel, etc. due to their high specific strength and stiffness, corrosion resistance, and tailor-ability. It is well known that foreign object impact is not uncommon for composite sandwich structures. Subjected to an impact load, the thermoset syntactic foam core would be significantly damaged in the form of macro-cracking, microballoon crushing, microcracking, etc., leading to a considerable reduction in residual load carrying capacity. This cannot be avoided because of the brittleness of the thermoset polymer and the lack of ability to self-heal internal damage. In order to maintain the structural capacity under impact, it is desired to develop a new syntactic foam which is able to absorb more impact energy and to repair internal damage autonomously, repeatedly, efficiently, and at molecular length-scale. We believe that the shape recovery functionality of shape memory polymers (SMP) can be used for the purpose of self-repairing impact damage. In the current study, a novel shape memory polymer based syntactic foam was proposed, fabricated, tested, and characterized as composite sandwich core.

The thermoset SMP has a glass transition temperature (T_g) of 62°C. The foam was fabricated by dispersing 40% by volume of glass microballoons (density 0.14g/cm^3, average diameter 85μm) and 0.15% by volume of multi-walled carbon nanotubes (density 2.1g/cm^3, diameter 20-30nm, and length 20-30μm) into the SMP matrix. The foam was prepared with the assistance of an ultrasound mixer and a three-roll mill. Figure 1 shows a TEM picture of the distribution of the multi-walled carbon nanotubes in the polymer matrix. After curing, the foam cored sandwich panels with a dimension of 152.4mm × 101.6mm × 12.7mm were prepared for impact and self-healing tests. We used the foam cored sandwich panels instead of the neat foam panels to evaluate the self-healing efficiency because (1) the foam will be used as sandwich core in practice, and (2) a sandwich having a thick core and thin skin would represent the actual working environment for the foam and evaluate core-dominated impact response. The sandwich panels were fabricated using the vacuum assisted resin infusion molding (VARIM) system. The skin was made of the same SMP reinforced by one ply of woven roving E-glass fabric. The cured thickness of the skin was 0.736mm. The smart syntactic foam core was cured in an industrial oven at 79.4°C for 24 hours, 107.2°C for 3 hours, followed by a curing cycle of 121.1°C for another 3 hours. The sandwich panel was post-cured following the same curing cycle mentioned above. It is noted that the first three steps for the shape fixity of the foam core was associated with the post-curing of the sandwich in this study. During the post-curing, the sandwich panel was still assembled with the vacuum system at a pressure of 0.05MPa. The difference between this study and the typical programming was that we used stress controlled programming (stress was constant instead of strain). After post-curing, the sandwich slab was cooled down to room temperature while holding the pressure. Once the sandwich reached room temperature, the vacuum system was removed and the stress was removed. In order to evaluate the shape recovery behavior of the foam, a free shape recovery step was also implemented. The four-step thermo-mechanical cycle by a fully gauged programming is shown in Fig. 2. From Fig. 2, the shape fixity rate of the foam is 99.0% and the shape recovery rate is 97.6%. It is also seen that at about 62°C (glass transition temperature of the SMP), the shape recovery process (step 4 in Fig. 2) shows a corresponding transition. This echoes the DSC test results which show that the foam has a glass transition temperature around 62°C. Once the temporary shape was obtained, a low velocity impact test with a hammer weight of 6.64kg and velocity of 3m/s was conducted on the sandwich panels using an instrumented impact machine. The impact was conducted at room temperature. Immediately before and after impact, ultrasound C-scan was used to visualize the damage. After that, the impact damaged panel was heated up to 121.1°C to heal the damage and C-scan was again used to visually see the healing result. This impact-healing cycle was repeated seven times at the same impact location. It is found that the maximum impact force, impact duration, initiation energy, and propagation energy are recovered after each healing, which is supported by the C-scan image, showing the disappearance of the impact damage after each healing cycle; see Figure 3. An SEM observation also confirmed the effect of shape recovery on closing microcracks. An anti-buckling compression after impact (CAI) test was conducted. It was found that the 7th round impact reduced the compressive strength by 18.6%; after healing, almost all the lost bearing capacity was recovered (99.7%); see Figure 4. A strain-controlled 1-D compression test was also conducted on the pure smart foam specimens at room temperature. It was found that the constitutive behavior of the smart foam is similar to conventional syntactic foams, i.e., an almost linear behavior until yielding (at a strain about 0.1mm/mm), followed by a very long plateau (ending at a strain about 0.6mm/mm), and finally strain hardening (at a strain greater than 0.6mm/mm). Because the plateau range is very long compared to conventional syntactic foams, it is suggested that the uniqueness of the smart foam persists in not only its ability to heal the damage but also its ability to absorb energy without disintegration; see Figure 5. We also investigated the temperature rising during impact. We tested the smart foam cored sandwich at room temperature. It is found that, with an incident energy of 29.9J, the maximum temperature rising is only 2.5°C, suggesting that the foam under impact is still glassy; see Figure 6. In addition to the conventional foam cored sandwich structure, the smart foam has been integrated with advanced grid stiffened sandwich structure. Because of the confinement provided by the grid skeleton to the smart foam during shape recovery, better healing efficiency has been achieved.

Acknowledgement

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Reference:

1. Li G and John M. *Composites Science and Technology*, 68: 3337-3343, (2008).

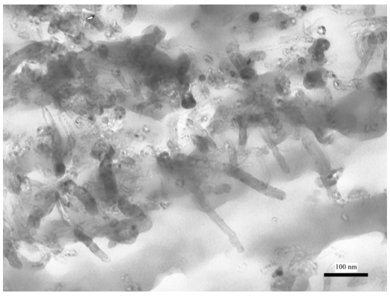


Fig. 1 TEM picture of carbon nanotubes in SMP matrix

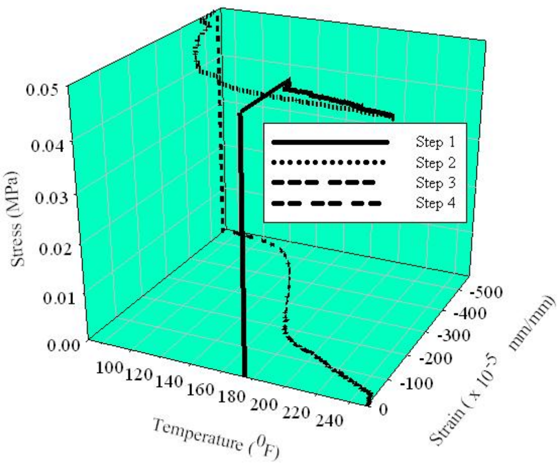
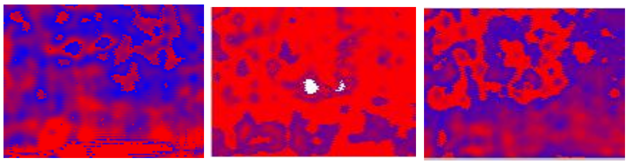


Fig. 2 Four-step thermomechanical programming



(a) Original (b) After 7th impact (c) After 7th healing

Fig. 3 Ultrasound C-scan images

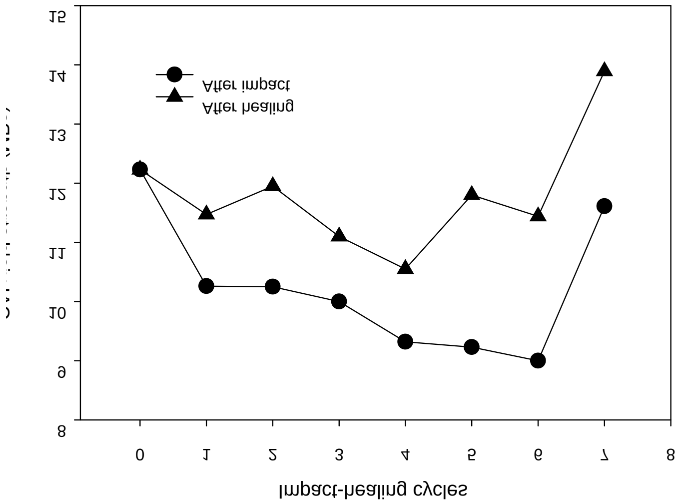


Fig. 4 Change of CAI yield strength with impact-healing cycles

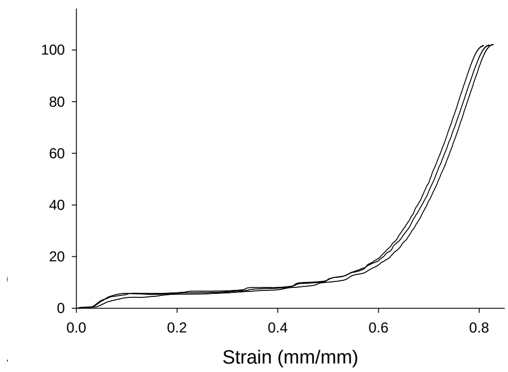


Fig. 5 Typical compressive stress – strain curves for the foam material

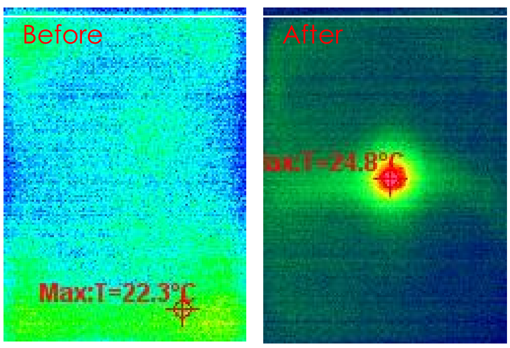


Fig. 6 Temperature rising