Characteristics of a novel thermal-induced epoxy shape memory polymer for smart device applications

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Abstract

With the increasing demand for the application of electronic technology, high performance, multifunction and intelligent control have been the main developing trend of smart material. In this paper, a novel thermal-induced epoxy shape memory polymer (ESMP) is developed and utilized as substrate material for smart flexible electronic device. Owing to the advantage of thermal-induced ESMP, circuit substrate can be rigid-flexible controllable at different working temperature. Firstly, the ESMP samples are prepared and then the mechanical and shape memory characteristics are studied respectively. Secondly, the mechanical behaviors are analysed based on thin plate deflection theory and finite element simulation software on the engineering application. Meanwhile, corresponding experimental tests are designed and performed to corroborate the theory and simulation results. At last, ESMP based test circuit board is designed and manufactured. The electrical signals under large deformation are also measured and compared with typical circuit board. The results show that the prepared ESMP, as a smart material, has good reliability, flexibility and great application prospects in the field of intelligent devices.

1. Introduction

With the rapid development of the fifth generation (5G) networks and internet of things (IOT), intelligent devices present an increasingly attractive solution for numerous applications in fields such as military, medicine or consumer electronics [1–3]. Miniaturization and portability have always been an important trend for intelligent devices, meanwhile, there will be many opportunities and challenges including integrated circuits, packaging design, intelligent materials etc [4, 5].

In recent years, intelligent devices such as google project glass, apple watches, flexible displays has achieved great business success and gained great attention. However, most intelligent devices are either rigid or flexible, that is to say it has no ability to change rigidity when needed. In relation to different application scenario, bidirectional transformation of rigid-flexible capability is the trend of development for intelligent devices based on different working conditions. For example, in the initial working situation, intelligent devices show the rigid characteristics and keep the shape unchanged in state 1 as shown in figure 1. It can be flexible and can change shape at will when the working situation changed in state 2. Once it does not work, it can automatically change back to the original shape and convert to state 1 again. In the transformation process, it can maintain good and stable performance.

Shape memory polymer (SMP) are polymeric smart materials that have the ability to return from a deformed state to their original shape which have already been used for many applications such as deployable structure, temperature actuators and jet propulsion system [6–9]. SMP is an intelligent material, its mechanical performance (such as, flexibility, bending strength and so on) can be regulated continuously by external conditions. The characteristics of reciprocal transformation of rigidity and flexibility, lightweight, cheap for SMP can be used in intelligent devices. As a great potentials and broad prospects material, SMP have always been a research hotspot in recent years. At present, the research on SMP is mainly focused on the following aspects: (1) the study of principle and models of SMP including mechanics constitutive models, relaxation model [10, 11];
the preparation and performance testing of novel SMP including chemical, mechanics and electrical properties [12–14]; (3) the use of SMP such as actuators, MEMS devices, temperature sensors biomedical devices and so forth [15, 16]. The application of SMP has been a trend in the areas such as wearable electronics and soft robotics. Wang et al proposed a novel shape memory polymer composite which was fabricated by introducing silicon carbide whiskers into a shape memory epoxy. Although the shape recovery speed is high, the shape recovery ratio can be only 95% which is not entirely suited for intelligent devices [17]. Liu et al reported an SMP-based TENG to harvest biomechanical energy and detect biomechanical motion which SMP is used as thin film materials [18]. Xu et al designed and synthesized a healable and shape-memory dual-functional polymer with remarkably improved mechanical properties and stimuli responses [19]. Gaj et al introduced a green electrophosphorescent OLED produced on a shape-memory polymer substrate for flexible and conformable wearable electronic applications. The thickness of substrate is 500μm which is not properly size for plate [20]. In general, there are few investigations about the application of SMP on the smart devices as thin plate materials, particularly for the circuit substrate.

In this paper, a novel thermal-induced ESMP is developed in order to realize the rigid flexible conversion and maintain stable performance under different temperatures. At the same time, the thermomechanical properties and shape memory characteristics are investigated. Furthermore, based on the thin plate deflection theory, the differential equation of the thin plate of ESMP is derived and corresponding experiment is designed and proposed. Finally, a typical circuit is designed, simulated and manufactured based on the proposed thermal-induced ESMP. By contrast, FR-4 circuit board is manufactured as well. Both the electrical properties are tested which proved the possibility of prepared ESMP used for intelligent devices. Results and research method in this paper provide some theoretical and practical significance for the design of future smart electronic devices.

2. Preparation and properties of shape memory epoxy resin composites

2.1. Preparation of shape memory Epoxy Resin composites

The novel ESMP is developed in which methyl tetrahydrophthalic anhydride (MeTHPA) is used as curing agent and Tris (dimethylaminomethyl) phenol (DMP-30) is used as accelerator to cure hydro-epoxy resin which plays an important role in accelerating the reaction rate. Figure 2 shows the specific process of chemical reaction in curing process. The reagents used in the experiment are all analytically pure except hydrogenated epoxy resin. Hydrogenated epoxy resin is made by our laboratory. All the reagents and instruments are listed in table 1.

The formulation is designed as follows:

\[ X = \left( \frac{M}{n_{\text{anhydride}}} \right) \times K \]  

(1)

Where X is the quality of curing agent for 100 g hydrogenated epoxy resin (g) and M is the molecular weight (g mol⁻¹). K is the epoxy value of hydrogenated epoxy resin. \( n_{\text{anhydride}} \) is the number of anhydride groups in a molecule.

In a typical curing experiment, Hydrogenated epoxy resin and MeTHPA are mechanically mixed at 60 °C for 10 min, and then DMP-30 was added and mechanically mixed at 60 °C for 30 min. The mixture is degassed in a vacuum drying oven until most of the bubbles are removed at 80 °C, and then poured into a mold and cured at 80 °C for 2 h, followed by a middle-cure at 120 °C for 3 h and a post-cure at 150 °C for 2 h in electric thermostatic drying oven.

2.2. Performance testing of shape memory polymers

2.2.1. Thermomechanical test

The thermomechanical properties of the ESMP samples are characterized using a dynamic mechanical analyzer under single and dual bending modes. Sample dimensions are 28 mm × 13 mm × 3.5 mm. Figure 3 is the DMA
curves of ESMP sample. As shown, the glass transition temperature (Tg) is 80 °C, meanwhile, the storage modulus changes two orders of magnitude before and after Tg.

2.2.2. Shape memory test
Fold-bent test is a typical experiment for the measurements of shape memory characteristics. Firstly, the prepared samples are heated to 30 °C above Tg in the vacuum drying oven as shown in figure 4, deformed into a ‘U’ shape and then cooled down in cold water under constant external force to fix the temporary shape. Then the applied external force is removed after holding for several minutes. When the force is removed, a slight elastic recovery occurs, and the deformation angle changes to \( \theta_{fc} \). Finally, the ‘U’ shape samples are placed in the

Table 1. Reagents and Instruments.

| Reagents                  | Instruments/Type                                      |
|---------------------------|-------------------------------------------------------|
| Hydrogenated epoxy resin  | Vacuum drying oven/DZ-1BC                              |
| McTHPA;                  | Vacuum drying oven/DZ-1BC                              |
| PPGDGE                   | Electric thermostatic drying oven/ZT-072               |
| DMP-30                   | Electronic universal testing machine/CMT6303          |
| acetone                  | Dynamic mechanical analyser/InstrumentDMA Q800        |
|                          | Magnetic stirring apparatus/ZWC-08Y                    |

Figure 2. Principle of chemical reaction in curing process.

Figure 3. The DMA curves of ESMP.
vacuum drying oven 30 °C above Tg again. The time of shape recovery process and the final angle \( \theta_{\text{final}} \) are recorded.

The shape fixed rate \( (R_f) \) and shape recovery rate \( (R_r) \) are calculated using the following equations:

\[
R_f = \frac{\theta_{\text{fix}}}{\theta_{\text{max}}} \times 100\%
\]  

\[
R_r = \frac{\theta_{\text{max}} - \theta_{\text{final}}}{\theta_{\text{max}}} \times 100\%
\]  

Fold-bend test are performed nine times and the data are collected and processed. Figure 5 shows the shape memory test tool. The average of five samples are taken as final values to ensure the accuracy of the test. The results show that the shape fixed rate is 98.9%. As is shown in figure 6, the ESMP show full recovery within only 3 min, at the same time with the increase of fold-bent test times the recovery time decreases sharply. Meanwhile the shape recovery rate is almost 100%. Because, bond torsion occurs in a small range of free molecule chains and friction resistance reduced leading to the shape recovery ability increases.

3. Mechanical simulation and experiment

In engineering, ESMP can be made in varied sizes and shapes in accordance with the requirements. Among them, thin plates or even thin films are the most typical type. Compared with thin films, thin plates can resist bending, torsion and in-plane stress better. As a smart material, its working state and mechanics behavior should be investigated by theoretical and experimental methods in order to be closer to the engineering practice.

3.1. Thin plate deflection theory

The deflection differential equation of thin plate can be derived through a model shown in figure 7.

According to the assumptions of Kirchhoff thin plates theory[21], the normal orthogonality assumption leads to zero transverse shear strains \( \gamma_{xy} \) and \( \gamma_{yz} \), the following equations can be deduced.
Based on the assumptions that the points on the middle plane only move vertically, we deduce

\[
\begin{align*}
    u &= -\frac{\partial w}{\partial x} + f_1(x, y) \\
    v &= -\frac{\partial w}{\partial y} + f_2(x, y)
\end{align*}
\]  

(4) \hspace{1cm} (5)

Based on the assumptions that the points on the middle plane only move vertically, we deduce

\[
\begin{align*}
    (u)_{z=0} &= 0, \quad (v)_{z=0} = 0 \\
    f_1(x, y) &= 0 \\
    f_2(x, y) &= 0
\end{align*}
\]  

(6) \hspace{1cm} (7)

Based on geometric equation, the strain-displacement expressions can be given

\[
\begin{align*}
    \varepsilon_x &= \frac{\partial u}{\partial x} = -\frac{\partial^2 w}{\partial x^2} \\
    \varepsilon_y &= \frac{\partial v}{\partial y} = -\frac{\partial^2 w}{\partial y^2} \\
    \gamma_{xy} &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = -2\frac{\partial^2 w}{\partial x \partial y}
\end{align*}
\]  

(8)
Based on physical equation, the following equations can be expressed as

\[
\sigma_x = - \frac{Ez}{1 - \nu^2} \left( \frac{\partial^2 w}{\partial x^2} + \nu \frac{\partial^2 w}{\partial y^2} \right)
\]

\[
\sigma_y = - \frac{Ez}{1 - \nu^2} \left( \frac{\partial^2 w}{\partial y^2} + \nu \frac{\partial^2 w}{\partial x^2} \right)
\]

\[
\tau_{xy} = - \frac{Ez}{1 - \nu} \frac{\partial}{\partial x} \frac{\partial}{\partial y} w
\]

(9)

The equilibrium equations are of particular interest in Kirchhoff plate theory. Based on equilibrium equation and boundary condition, the following equations can be deduced

\[
\tau_{xx} = \frac{Ez^2}{2(1 - \nu^2)} \frac{\partial}{\partial x} \nabla^2 w
\]

\[
\tau_{yy} = \frac{Ez^2}{2(1 - \nu^2)} \frac{\partial}{\partial y} \nabla^2 w
\]

\[
\sigma_z = \frac{Et^2}{6(1 - \nu^2)} \left( \frac{1}{2} - \frac{z}{t} \right) \left( 1 + \frac{z}{t} \right) \nabla^4 w
\]

(10)

Finally, based on boundary conditions of thin plate, the differential equation of thin plate can be obtained

\[
\frac{Et^3}{12(1 - \nu^2)} \nabla^4 w = q
\]

(11)

Where \( w \) is the vertical displacement (deflection) of the points on the middle plane, \( E \) is the Young’s modulus, \( \nu \) is the poison constant, \( t \) is the plate thickness and \( q \) is the transverse load per unit area of thin plate. As equation (11) shows, the elastic surface differential equation of thin plate is fourth order partial differential equation. However, the Young’s modulus of ESMP varies greatly at different temperatures, especially before and after glass transition temperature in figure 3. In order to determine the boundary conditions and the deformation of ESMP thin plates, it is necessary to design experimental fixtures and develop corresponding simulation and experiments.

3.2. Finite element simulation

As is shown in figure 8(a), the fixture has several components including central hexagonal bolt, upper metal plate, middle metal plate, bottom metal plate, adjustable bar and flange. The designed fixture is good at support and fixation for ESMP thin plate and the strain and deformation of the plate can be also well controlled by adjusting the pre-tightening force of the hexagonal bolt. The type of bolt is M12 and bolt performance rating is 4.6 which means the tightening moment of the bolt is 36 to 45 N·M.

The finite element model of fixture and ESMP thin plate is established based on ANSYS Workbench software in figure 8(b), and the deformation of the ESMP thin plate under different temperature is particularly studied. The sizes of ESMP thin plate is 150°140°2.5 mm. Figure 9 shows the total deformation of the ESMP thin plate. When the external load is unchanged, with the decrease of elastic modulus, the maximum total deformation of the thin plate will increase from 0.57613 mm to 10.802 mm.

But there are two question deserves consideration. On one hand, the error diffusion and accumulation during finite element analysis because the rise of temperature leads to thermal expansion, which increases the total deformation as well. On the other hand, the change of modulus of ESMP is not a fast process which leads to the actual situation is not as good as simulation.
3.3. Experimental design and testing method

In order to verify the simulation results and how it works, the corresponding tests of ESMP thin plate are performed, using the same parameters. Figure 10 shows the fixture and ESMP thin plate. Under constant load and different temperatures, the strain of ESMP thin plate is measured with full-bridge resistance strain gauge for detecting.

Figure 11 shows the measurement circuit. In general, two basic forms of the resistance strain gauge are the bounded and the unbounded types. Bounded type with automatic temperature compensation is chosen as a measurement strain sensor. When the thin plate is deformed by external loads, the strain gauge will deform along with it. The resistance of the wire in the strain gauge will change because of its mechanical deformation, and the change of the resistance will reflect the deformation of the thin plate based on the following equations:

\[ \frac{\Delta R}{R} = K \times \varepsilon \]  \hspace{1cm} (12)

Where \( R \) is initial resistance of strain gauge, \( \Delta R \) is the resistance variation caused by elongation or compression, \( K \) is the proportional constant of strain gauge, \( \varepsilon \) is the strain. In this way, the strain measurement is transformed from the strain gauge to the resistance measurement. Based on theoretical mechanics theory, there is a typical equation:

\[ \frac{\sigma}{\varepsilon} = E \]  \hspace{1cm} (13)

Where \( \sigma \) is the stress, \( E \) is the Young’s modulus which have been already measured by DMA. The magnitude of stress can be controlled by the designed fixture in figure 10(a).

3.4. Experiment and results

The strain gauge is attached to the central part of ESMP thin plate after the stains and dust on the surface is removed. Before the test, test circuit connection and ground connection have to be completed correctly.
the ESMP thin plate is fixed on fixture and proper bolt pretension force is applied to generate original deformation. The fixture is placed in high-low temperature test box. The initial temperature is set at 20 °C, the temperature gradient is 1 °C/min, and the final temperature is set at 100 °C. The output voltage and the deformation of ESMP thin plate are recorded.

Figure 11 shows the deformation of ESMP thin plate under different temperature. As shown in figure 12(a), the deformation of the ESMP thin plate under certain pre-tightening force of the bolt is very small at 20 °C. Along with the rise of temperature, the deformation increases, especially from 60 °C to 100 °C. This is precisely because the modulus of ESMP decreases with the increase of temperature resulting in different deformation differences under the same load. The final shape is marked in red curve compared with the original shape (marked in black line) in figure 12(f) which value is well consistent with that of the finite element simulation in section 3.2.

Figure 12(a) depicts relationship between output voltage and temperature. It can be seen that the output voltage does not change significantly between point A and point B. This is because with the increase of temperature, the molecular chain segment as a switch structure gets certain energy, the micro-Brownian motion is activated, and the volume expansion of epoxy resin occurs with the increase of temperature, and the chain segment obtains certain free space. From the point of macroscopic view, the elastic modulus of thin plates does not change much at this stage. As the temperature keeps rising, the output voltage is decreasing from point B to point C. With the increase of energy obtained from molecular chains, the micro-Brownian motion becomes more obvious. Under external loads, the deformation of materials increases, and the expanded free volume and the loose free volume between the original network chains are compressed. The materials change from glass state to high elastic state. Although the temperature continues to rise, the free space of the chain segment is limited and cannot grow indefinitely, the output voltage remains unchanged after point C. Through analyzing the experimental data and matching work, a relation curve based on gaussian curve fitting is acquired from the experiment and finally obtain the relation between the change rate of Young’s Modulus and heating time in figure 12(b). It not only illustrates that the change rate of Young’s Modulus of ESMP can firstly increase and then
decrease with the increasing of heating time but also present a single peak curve which appears in 42 min approximately at 180 Mpa/min. At this time, the internal molecular chains of ESMP are curled, and the rapid stretching speed reaches the maximum under the action of external forces. After that, the change rate of Young’s Modulus decreases significantly and reaches 31.3 Mpa/min in 52 min at point C. The modulus of ESMP has been reduced by two orders of magnitude during the whole temperature rise process.

4. Circuit design and electrical experiment

In order to test and verify the feasibility of ESMP for smart electronic device, an ESMP based circuit board and corresponding FR-4 PCB are designed and manufactured. The work including the design of the representative Resistor-Capacitance (RC) circuit and PCB plate making is completed. Finally, two kinds of printed circuit boards are applied the same load to measure the real-time electrical signal, which verifies the reliability of ESMP as an intelligent electronic device in the case of deformation.

4.1. Experiment and results

In linear electronic circuits, there are often DC and AC components, which can be superimposed on each other. The designed circuit schematic diagram is shown in figure 13.

In this paper, point A and B are selected for electrical performance test. As shown in figure 13, R1 and R3 are connected in series, R2 and R4 are connected in series, and then in parallel, forming a bridge circuit. When the input DC voltage is U0, the voltage of point A can be measured which can be divided by the relation of resistance as follows:
\[ U_a = \frac{(R_1 + R_2)(R_3 + R_4)}{R_7 + \frac{R_3 + R_4}{(R_1 + R_2)(R_3 + R_4)}} \times \left( \frac{R_2}{R_2 + R_4} - \frac{R_3}{R_2 + R_3} \right) \]
\[ U_0 = \frac{1}{5} U_a \]  

(14)

For point B, \( U_b \) can be deduced as the following equations:

\[ U_b = \frac{R_7}{R_7 + \frac{R_3 + R_4}{(R_1 + R_2)(R_3 + R_4)}} = \frac{1}{2} U_0 \]  

(15)

In figure 15(b), the equivalent impedance of the capacitor \( Z \) can be calculated:

\[ Z = \frac{1}{2\pi fC} \]  

(16)

Where \( f \) is the frequency of input AC signal, \( C \) is the capacitance for capacitor. Assuming the signal frequency is 10KHz, the equivalent impedance of both capacitors is 15.9Ω which value is two orders of magnitude smaller than other resistors and can be regarded as open circuit. When the effective value of input AC voltage is \( U_1 \), \( U_a \) and \( U_b \) can be calculated as the following equation based on circuit analysis theory:

\[ U_a = \frac{1}{5} U_1 \]
\[ U_b = \frac{1}{2} U_1 \]  

(17)

4.2. Circuit board production and test

In mass production for typical circuit board, Copper foil and base plate are usually bonded by hot-pressing process through prepreg solidification. However, in the early stage of the experiment, during the hot-pressing curing of ESMP thin plate and copper foil, the failure of copper cladding is caused by the fracture of the thin plate due to its brittleness.

Finally, the following method is adopted to complete the ESMP based PCB. At room temperature, the surface of ESMP thin plate is washed with water, then dried, and coated with ethyl cyanoacrylate on one side. The thickness of the adhesive layer is uniform. The adhesive surface is overlapped with the coarsening surface of copper foil with the thickness of 35 micrometer, and placed between two specular steel sheets. The pressure is kept between 40 and 50 kg cm\(^{-2}\). The copper clad sheet can be obtained at room temperature for 24 hours. After copper coating, the hacksaw blade and drilling machine are used to remove redundant copper and drill 0.8 mm diameter holes based on the circuit diagram in figure 13. Finally, the electronic components are welded. Meanwhile, FR-4 circuit board is also manufactured and welding the components as a reference group, figure 14 depicts PCB layout. The FR-4 based circuit board is shown in figure 15(a). Similarly, the layout of in SMP based circuit board is highly marked in figure 15(b). Compared with the former, ESMP based circuit board has the same thickness of copper foil and the same distribution of electronic components.

Both two groups are checked with an oscilloscope probe, and the multimeter is used to confirm that signal paths are connected properly. The DC input voltage is 5 V. The waveforms of point A of different PCBs are measured through two channel which CH1 connects the output of FR-4 circuit board and CH2 connects the output of ESMP based circuit board respectively. The two curves coincide completely which means the circuit is under a proper working condition. AC input is generated by waveform generator with sine wave which frequency is 1 kHz and output amplitude is 5 V. The voltage measurement of test points is shown in table 2. Tests show that the output waveform can meet the design specifications, which proves the design is correct and feasible.

4.3. Experiment and results

As shown in figure 16, the two fixtures with FR-4 based circuit and ESMP based circuit board are placed in the upper and lower layers of high-low temperature test box respectively. The same bolt pretension force is applied to generate original deformation, respectively. Similarly, the initial temperature is set at 20 °C, the temperature gradient is 1 °C/min, and the final temperature is set at 100 °C. The output voltage and the deformation of ESMP based circuit board are recorded.

On one hand, for FR-4 based circuit board, there is no obvious deformation in figure 17(a) and output signal is trending to the normal value with the change in temperature. This is because the temperature is far below the glass transition temperature of FR-4 based circuit board. On the other hand, the deformation of ESMP based circuit board can be measured in based on equation (12) and (13). The relationship between deformation, heating time and output voltage of two test points for the ESMP based circuit board is shown in figure 18.
initial deformation caused by the pre-tightening force of the bolt is about 0.57 mm. The maximum deformation of the ESMP based circuit board increases with the increase of time. The M point reaches the highest value, and remains unchanged after that. The maximum deformation is about 17.28 mm which is about 30 times of the initial deformation. The photo of ESMP based circuit board after temperature test is shown in figure 17(b).

During the test, the output voltage of point a and point B is stable at 1 V and 2.5 V even if such large deformation occurs respectively.

The ESMP based circuit board are taken out of the high-low temperature test box and then cooled to room temperature. After that, we place it in a high and low temperature box of 100 °C without the fixture. The ESMP based circuit board recovers to their original shape within 3 min, and the output voltage of point A and point B is also normal through measurement. This fully verifies the feasibility of the new proposed ESMP as the substrate material (especially as thin plate) in the flexible circuit, and also shows that it has great application potential.
5. Conclusions

In this paper, we have developed a novel thermal-induced epoxy shape memory polymer for future smart electrical device which can automatically change in shape along with the working temperature. We have
investigated the mechanical properties including DMA and shape memory test. At the same time, the mechanics behavior based on thin plate deflection theory are studied and corresponding simulation and experiment are carried out as well. Additionally, using proposed epoxy shape memory polymer, an ESMP based test circuit board and corresponding reference FR-4 based circuit board for both AC and DC signal are designed, manufactured and tested. The results show that the prepared ESMP has good mechanical properties and shape memory capacity in more complex environment. Meanwhile, we confirm that the proposed thermal-induced ESMP can be a smart material with great potentials for flexible electronics devices. In addition, it still has stable signal output at different temperatures and very strong deformation recovering ability compared with traditional rigid circuit board based on the test results. ESMP has the broad prospects for development in the future, and is likely to become the shape of things to come. Results and research method in this paper provide some theoretical and practical significance for the design of flexible electronic devices. The interfacial effects caused by the bending and re-shaping of the ESMP based test circuit board as well as the lifetime of these devices, will be the focus of future work.

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References

[1] Agiwal M, Roy A and Saxena N 2016 Next generation 5G wireless networks: a comprehensive survey IEEE Communications Surveys & Tutorials 18 1617–55
[2] Chen M, Ma Y, Li Y, Wu D, Zhang Y and Youn C-H 2017 Wearable 2.0: enabling human–cloud integration in next generation healthcare systems IEEE Commun. Mag. 55 54–61
[3] Palatella M R, Dohler M, Grieco A, Rizzo G, Torsner J, Engel T and Laidl I 2016 Internet of things in the 5G era: enablers, architecture, and business models IEEE J. Sel. Areas Commun. 34 510–27
[4] Sheng Z, Yang S, Yu Y, Vasilakos A V, McCann J A and Leung K K 2013 A survey on the ietf protocol suite for the internet of things: standards, challenges, and opportunities IEEE Wirel. Commun. 20 91–8
[5] Guererro-Ibáñez J A, Zeadally S and Contreras-Castillo I 2015 Integration challenges of intelligent transportation systems with connected vehicle, cloud computing, and internet of things technologies IEEE Wirel. Commun. 22 122–8
[6] Eisenhauser J D, Ruehe S I, Al a M, Carlson A, Ferreira P M and Kim S 2015 The use of shape memory polymers for MEMS assembly J. Microelectromech. Syst. 25 69–77
[7] Jo MJ, Choi H, Kim G H, Yu W-R, Park M, Kim Y, Park J K and Youk J H 2018 Preparation of epoxy shape memory polymers for deployable space structures using flexible diamines Fibers Polym. 19 1799–805
[8] Lee J H, Hinchet R, Kim S K, Kim J S and Kim J-W 2015 Shape memory polymer-based self-healing triboelectric nanogenerator Energy & Environmental Science 8 3605–13
[9] Meng Q and Hu J 2009 A review of shape memory polymer composites and blends Composites Part A: Applied Science and Manufacturing 40 1661–72
[10] Chai Q, Huang Y, Kirley T and Ayres N 2017 Shape memory polymer foams prepared from a heparin-inspired polyurethane/urea Polym. Chem. 8 5039–48
[11] Zhao Q, Qi H J and Xie T 2015 Recent progress in shape memory polymer: New behavior, enabling materials, and mechanistic understanding Prog. Polym. Sci. 49 79–120
[12] Chen B, Yuan L, Guo S, Li J and Guo Y 2018 Preparation and mechanism of shape memory bismaleimide resins with high transition temperature, high toughness and good processability J. Mater. Sci. 53 10796–811
[13] Zhang X, Li X, Xu C, Zhong Y, Dai Y, Qi P, Xie A T, Basile V, Taylor C and Liang P 2017 Programmable macroporous photonic crystals enabled by swelling-induced all-room-temperature shape memory effects Adv. Funct. Mater. 27 1703322
[14] Maeda S, Wakiyama S, Yamada Y and Kawai S 2016 Proposal of pneumatic rubber meshes with shape-memory polymer reinforcement fibers realizing desirable motion 2016 IEEE Int. Conf. on Robotics and Biomimetics (ROBIO) (Piscataway, NJ) (IEEE) pp 1221–6
[15] Ortega J M, Benett W J, Small W, Wilson T S, Maitland DJ and Hartman J 2017 Shape-memory polymer foam device for treating aneurysms Google Patents
[16] Xie M, Wang L, Gu J, Guo B and Ma P 2015 Strong electroactive biodegradable shape memory polymer networks based on star-shaped polylactide and aniline trimer for bone tissue engineering ACS Appl. Mater. Interfaces 7 6772–81
[17] Wang Y, Tian W, Liu X and Ye J 2017 Thermal sensitive shape memory behavior of epoxy composites reinforced with silicon carbide whiskers Applied Sciences 7 108
[18] Liu R, Kuang X, Deng J, Wang Y C, Wang A C, Ding W, Lai Y C, Chen J, Wang P and Lin Z 2018 Shape memory polymers for body motion energy harvesting and self-powered mechanosensing Adv. Mater. 30 1705195
[19] Xu W, Wong M-C, Guo Q, Jia T and Hao J 2019 Healable and shape-memory dual functional polymers for reliable and multipurpose mechanical energy harvesting devices Journal of Materials Chemistry A 7 16267–76
[20] Gaj P, Wei A, Fuentes-Hernandez C, Zhang Y, Reit R, Voit W, Marder S R and Kippenen B 2015 Organic light-emitting diodes on shape memory polymer substrates for wearable electronics Org. Electron. 25 151–5
[21] El-Zafrany A, Debbih M and Fadhil S 1994 A modified Kirchhoff theory for boundary element bending analysis of thin plates *Int. J. Solids Struct.* **31** 2885–99