A soft sandwich structure enables voltage-induced actuation of liquid metal embedded elastomers

Cite as: AIP Advances 10, 015016 (2020); https://doi.org/10.1063/1.5129352
Submitted: 27 September 2019 . Accepted: 23 December 2019 . Published Online: 08 January 2020

Yin Wang, Geng Sun, Juancheng Yang, Ling Zhang, and Jinxiong Zhou

NEW

AVS Quantum Science
A new interdisciplinary home for impactful quantum science research and reviews

NOW ONLINE
A soft sandwich structure enables voltage-induced actuation of liquid metal embedded elastomers

Cite as: AIP Advances 10, 015016 (2020); doi: 10.1063/1.5129352
Submitted: 27 September 2019 • Accepted: 23 December 2019 • Published Online: 8 January 2020

Yin Wang,1,2 Geng Sun,1 Juancheng Yang,2 Ling Zhang,2 and Jinxiong Zhou2,a)

AFFILIATIONS
1 State Key Laboratory Base of Eco-hydraulic Engineering in Arid Area, Xi’an University of Technology, Xi’an 710048, China
2 State Key Laboratory for Strength and Vibration of Mechanical Structures, Shaanxi Engineering Laboratory for Vibration Control of Aerospace Structures, School of Aerospace, Xi’an Jiaotong University, Xi’an 710049, China

a)Author to whom correspondence should be addressed: jxzhouxx@mail.xjtu.edu.cn

ABSTRACT
Dispersing liquid metal droplets in a soft elastomer matrix yields a composite, called liquid metal embedded elastomer (LMEE), with less modified stiffness but noticeably increased relative permittivity. Stretching and applying voltage through the thickness of the elastomer composite directly, it is vulnerable to the loss of being an insulator due to the conductive pathway formed during prestretching. Here, we describe a very simple sandwich structure that enables electromechanical actuation of LMEE. It consists of two very high bonding tapes as skins and a layer of LMEE as the core, making the sandwich all polymeric and thus stretchable. The electromechanical performance of a LMEE made of Ecoflex and Galinstan at various mass ratios was systematically measured. For a typical circular actuation made of the sandwich structure, a 90% areal actuation strain was achieved. Our efforts pave the way for various applications of LMEE.

© 2020 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5129352

The dielectric elastomer (DE) has emerged as one of the electroactive polymers for a broad range of applications including actuators,1–4 sensors,1–5 generators,6–8 loudspeakers,9,10 acoustic metamaterials,11–13 and soft machines.14–16 Commonly used DE materials include commercial very high bonding (VHB) tapes by 3M Company, silicone rubbers, and natural rubbers. These DE materials have relative permittivity ranging from 2 to 12.7,20 rendering high voltage up to 10 kV, for actuation of a DE membrane with thickness around 1 mm. It is highly desirable to develop DE materials with increased dielectric constants but low moduli. Previous efforts aiming at an increase in the permittivity of DE adopt incorporation of ceramic particles into the elastomer matrix. Although incorporating particles with high permittivity increases the overall dielectric constants of the composite, the strategy on the other hand makes the composite stiff and results in a dramatic decrease in breakdown strength in the particle-elastomer interface. Very recently, Majidi et al.21,22 proposed to embed liquid metal such as Galinstan into the elastomer matrix, resulting in a composite called a liquid metal embedded elastomer (LME) which has increased relative permittivity but remains stretchable with a negligible change in stiffness. This is a promising candidate of DE for potential applications. The use of LME as sensors has been successfully demonstrated.23 Besides its potential of replacing conventional DE materials for future applications, this elegant solid-liquid composite system also poses very interesting mechanics problems of Eshelby inclusion, constitutive law, and numerical simulation of a representative volume element (RVE) of a solid-liquid element.24,25

LMEE is an aggregate of an infinite number of small conductive droplets and a continuous crosslinked polymer matrix. These droplets are randomly distributed, and some walls between small agglomerative droplets are very thin. These thin walls may become thinner or even rupture under combined prestretch and electrical loading, forming a conductive pathway and rendering LMEE ineffective as an insulator. The direct usage of bare LMEE
in this manner frequently causes disabled functioning of LMEE as a DE in practice. Therefore, deliberate structure of LMEE as an actuator is needed to realize voltage-induced deformation, which is rarely reported in the literature (in the earlier work by Majidi,\textsuperscript{21,22} they did not demonstrate voltage-induced actuation). Recently, Pan \textit{et al.}\textsuperscript{26} performed experiment on an annular dielectric elastomer actuator and a cone generator composed of a LMEE layer and demonstrated enhanced performance of the LMEE-elastomer composite. In this work, we propose a simple yet effective trilayer structure by sandwiching the LMEE between two layers of VHB tapes, making the system all soft, dielectric, and polymeric.

Figure 1(a) shows schematically the process of synthesizing a piece of LMEE. It is similar to the procedure by Majidi \textit{et al.}\textsuperscript{21} with minor modifications. The process consists of the following four steps: stirring and mixing uncured Ecoflex with Galinstan liquid metal (Ga 68.5%, In 21.5%, Sn 10% in weight ratio) using an automatic mixer for 30 min; putting the silicone-Galinstan emulsion into the vacuum box for 10 min to remove the bubbles during the mixing process; pouring the emulsion on an automatic coating
machine (MSK-AFA-1000-H, HeFei Kejing), scraping the emulsion into a thin film with a thickness of 1 mm, curing the film at a room temperature of 25 °C, and heating it for 2 h at 80 °C, and detaching the film from the surface of the coating machine. Figure 1(b) presents the picture of the synthesized LMEE membrane stretched by hand. Figure 1(c) gives the optical microscope images of the LMEE with two different resolutions. The Galinstan/silicone mass ratio of this LMEE is 1:2, and it is clearly seen from the images that Galinstan droplets (the black regions) are dispersed uniformly in the Ecoflex matrix.

Figure 2(a) plots the stress-strain curves of LMEE for various Galinstan/silicone mass ratios, 1:2, 1:1, 2:1, and 3:1. Also shown in the picture is the pure Ecoflex curve in green for comparison. Calculating the elastic moduli of pure Ecoflex and LMEE with different mass ratios (1:2, 1:1, 2:1, and 3:1) yields moduli of 34, 39, 43, 52, and 50 kPa, respectively. Incorporating liquid inclusions into a soft elastomer matrix would slightly increase the stiffness of the elastomer composite due to the stiffening effects of the small droplets. Our measurement coincides with experiments reported previously, and the stiffening effects are explained theoretically in Ref. 27. We then performed experiment on the measure of relative permittivity vs frequency for the LMEE using a LCR Hitester (HIOKI 3532-50). The tested frequency was ramped from 5 Hz to 5000 Hz, covering all the possible working frequencies of the LMEE.

As mentioned previously, applying mechanical and electrical loading directly on a piece of bare LMEE membrane would cause formation of a conductive pathway and loss of function of LMEE. This point is schematically illustrated in Fig. 3(a). To solve this issue, we came up with a simple sandwich structure shown in the right picture in Fig. 3(b), where a piece of LMEE with a thickness of 1 mm is sandwiched by two VHB4905 layers, each with a thickness of 0.5 mm. The sandwich trilayer was then coated with carbon grease as electrodes. With such a simple sandwich structure, we can easily pre-stretch it and fabricate a circular actuator, as shown in the left picture in Fig. 3(b).

The circular actuator is adopted here because it is widely used in DE community to demonstrate the effectiveness and working principles of DE.1,13,28,29 Figure 3(c) shows the experimental images of the actuator in the states of voltage off (left) and voltage on (right). Setting the prestretch to a fixed value, \( \lambda_p = 3 \), we performed systematic measurements on the voltage-induced actuation of the circular actuator made of LMEE with various mass ratios, 1:2, 1:1, 2:1, and 3:1, respectively. The actuation of pure Ecoflex was also measured and shown here by a green curve for comparison. The results are presented in Fig. 3(d). For such a typical actuator design with pre-stretch \( \lambda_p = 3 \), a maximum areal actuation strain of 92% was achieved for the highest mass ratio of 3:1 used in this experiment. From Fig. 3(d), we note that the difference between the actuation curves of LMEE and that of pure Ecoflex is small for low voltages, but this difference becomes dramatic if the applied voltage is above 6000 V. This implies that the effect of embedding liquid metal droplets into an elastomer is pronounced for high voltage actuation and large deformation.

In summary, we describe a very simple yet effective way to realize voltage-induced deformation of LMEE. The proposed sandwich structure avoids the issues if otherwise bare LMEE is used, which enables systematic measurements on electromechanical actuation of LMEE. Using a circular actuator as a typical example, we demonstrate that an areal strain of up to 92% is attainable. The advantage of LMEE becomes pronounced for high voltage and large deformation. Compared with traditional DE materials, LMEE opens the door to incorporate other liquid metals with low melting temperature into an insulative elastomer matrix to yield new DE materials. Moreover, it could be possible to vary the environment temperature to tune the liquid metals to transform between solid and liquid states, giving rise to a material with variable-stiffness property. The results pave the way for various applications of LMEE. Applications of LMEE for actuators, sensors, generators, and variable-stiffness devices and soft robots are expected.
FIG. 3 Voltage-induced actuation of a LMEE circular actuator. (a) The schematic illustrating the formation of a conducting pathway under combined prestretching and applied voltage. (b) A sandwich structure proposed (right) and the circular actuator (left) made of this sandwich structure. (c) Pictures of the circular actuator in voltage off (left) and voltage on (right) states. (d) Systematic measurements on voltage-induced actuation of the circular actuator with pre-stretch $\lambda_p = 3$.

This research was supported by the Natural Science Foundation of China (Grant Nos. 11702215 and 11972277) and the Natural Science Basic Research Plan in Shaanxi Province of China (Grant Nos. 2017JQ5062 and 2018JQ1029), Fund of the Youth Innovation Team of Shaanxi Universities.

REFERENCES

1. R. Pelrine, R. Kornbluh, Q. Pei, and J. Joseph, Science 287, 836 (2000).
2. J. A. Anderson, T. A. Gisby, T. G. Mckay, B. M. O’Brien, and E. P. Calius, J. Appl. Phys. 112, 041101 (2012).
3. E. Acome, S. K. Mitchell, T. G. Morrissey, M. B. Emmett, C. Benjamin, M. King, M. Radakovitz, and C. Keplinger, Science 359, 61 (2018).
4. P. Brochu and Q. Pei, Macromol. Rapid Commun. 31, 10 (2010).
5. J. Y. Sun, C. Keplinger, G. M. Whitesides, and Z. G. Suo, Adv. Mater. 26, 7608 (2014).
6. M. A. McEvoy and N. Correll, Science 347, 1261689 (2015).
7. T. Li, H. Luo, L. Qin, X. Wang, Z. Xiong, H. Ding, Y. Gu, Z. Liu, and T. Zhang, Small 12, 5042 (2016).
8. H. Zhang and M. Wang, Soft Rob. 3, 3 (2016).
9. S. Bauer, S. Bauer-Gogonea, I. Graz, M. Kaltenbrunner, C. Keplinger, and R. Schwödiauer, Adv. Mater. 26, 149 (2014).
(10) R. Kornbluh, R. Pelrine, H. Prahlad, A. Wong-Foy, B. McCoy, S. Kim, J. Eckerle, and T. Low, Proc. SPIE 7976, 797605 (2011).
(11) T. G. McKay, S. Rosset, I. A. Anderson, and H. Shea, Smart Mater. Struct. 24, 015014 (2015).
(12) J. Huang, S. Shian, Z. Suo, and D. R. Clarke, Adv. Funct. Mater. 23, 5056 (2013).
(13) C. Keplinger, J. Y. Sun, C. C. Foo, P. Rothemund, G. M. Whitesides, and Z. Suo, Science 341, 984 (2013).
(14) N. Hosoya, S. Baba, and S. Maeda, J. Acoust. Soc. Am. 138, EL424 (2015).
(15) Y. Tang, S. Ren, H. Meng, F. Xin, L. Huang, T. Chen, C. Zhang, and T. Lu, Sci. Rep. 7, 43340 (2017).
(16) G. Gu, J. Zou, R. Zhao, and X. Zhu, Sci. Rep. 3, eaat2874 (2018).
(17) D. Rus and M. T. Tolley, Nature 521, 467 (2015).
(18) C. Majidi, Soft Rob. 1, 5 (2014).
(19) T. Cheng, G. Li, Y. Liang, M. Zhang, B. Liu, T. Wong, J. Forman, M. Chen, G. Wang, Y. Tao, and T. Li, Smart Mater. Struct. 28, 015019 (2019).
(20) L. J. Romasanta, M. A. Lopez-Manchado, and R. Verdejo, Prog. Polym. Sci. 51, 188 (2015).
(21) M. D. Bartlett, A. Fassler, N. Kazem, E. Markvicka, P. Mandal, and C. Majidi, Adv. Mater. 28, 3726 (2016).
(22) N. Kazem, T. Hellebrekers, and C. Majidi, Adv. Mater. 29, 1605985 (2017).
(23) Z. Yu, J. Shang, X. Niu, Y. Liu, P. Dhanapal, Y. Zheng, H. Yang, Y. Wu, Y. Zhou, Y. Wang, D. Tang, and R. Li, Adv. Electron. Mater. 4, 1800137 (2018).
(24) N. Cohen and K. Bhattacharya, Int. J. Non-Linear Mech. 108, 81 (2019).
(25) R. W. Style, J. Wettlaufer, and E. Dufresne, Soft Matter 11, 672 (2015).
(26) S. J. A. Koh, T. Zhou, X. Zhao, W. Hong, J. Zhu, and Z. Suo, Polym. Phys. 49, 504 (2011).