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ORIGINAL RESEARCH ARTICLE

3D printing soft robots integrated with low-melting-point alloys

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Abstract

Soft robots are developed and applied in aspects such as grasping delicate objects. Their inherent flexibility also enables applications that are unattainable by humans, especially those in life-threatening environments. However, the object grasping performed by most pneumatic soft robotics during transportation requires continuous external power/force, a highly energy-consuming process, particularly for long-distance transportation. In this paper, we propose a low-melting-point alloy (LMPA)-integrated soft robot, manufactured by material extrusion additive manufacturing, requiring no power/force for holding objects during the moving process and thus presenting energy-saving characteristics. The working principles of the LMPA-integrated soft robot are as follows: (1) The LMPA is injected inside the soft robot using material extrusion. (2) The LMPA is heated to above its melting temperature so that the soft robot can change its shape. (3) At this stage, the soft robot is able to grasp an object. (4) While the soft robot is holding or grasping the object, the LMPA is cooled down to room temperature so that it turns into a solid state, and from this point onward, the soft robot can hold the object without relying on extra power for object grasping. (5) Once the soft robot arrives at the destination, the LMPA will be melted again to change the shape of the soft robot for releasing the grip and/or getting ready for another object grasping. In summary, this paper presents a case study of soft grippers, using 3D printing, specifically material extrusion, for fabricating an LMPA-integrated soft robot.

Keywords: Additive manufacturing; 3D printing; Soft robot; Soft gripper; Energy consumption; Smart manufacturing

1. Introduction

Distinct from subtractive manufacturing and formative manufacturing methodologies, additive manufacturing (AM) encompasses a range of technologies commonly referred to as 3D printing, a method that joins materials to create parts from 3D model data, typically in a layer-by-layer manner.[1-4] The versatility of 3D printing is evident across various domains, including aerospace,[5-8] medicine,[9-14] marine engineering,[15-19] food,[20-23] functional structures,[24-27] and bioscience.[28-32] In the realm of soft robotics, 3D printing plays a pivotal role due to its capacity to construct intricate designs.[33-35]

Soft robots, characterized by their flexibility and adaptability,[36] have been increasingly deployed in applications ranging from delicate object manipulation to operation in hazardous environments where human intervention is not feasible.[37] The inherent compliance of soft robots allows them to interact with their surroundings and handle objects with varying degrees of flexibility. However, a significant limitation persists in the operation of pneumatic soft robots: they often require continuous external power or force to maintain their grip on objects during transportation,[38] leading to unnecessary energy consumption. This is particularly problematic for long-distance transportation, where maintaining a sustained grip results in considerable energy consumption.

To address this challenge, Tang *et al.*[39] explored the use of elastic instabilities to enhance the performance of soft robots. They designed a bistable hybrid soft actuator inspired by the spine of a cheetah, utilizing a pre-tensioned linear spring and soft pneumatic actuators to achieve rapid and high-force movements. The bistable mechanism enables the actuator to switch between two stable states, providing dynamic operating regimens for high-speed crawling and swimming. Wang *et al.*[40] introduced an inflatable particle-jamming gripper that combines positive pressure and partial filling to enhance grasping performance. The gripper adapted its shape to objects through particle jamming, presenting significant compliance and robust grasping capabilities. The particle jamming technique offers a robust way to lock the gripper's shape. Li *et al.*[41] presented a vacuum-driven soft gripper based on an origami "magic-ball" structure. The gripper used negative pneumatic pressure (vacuum) to achieve significant grasping force while maintaining compliance. The vacuum-driven approach provides an effective method for locking the gripper's shape. Faber *et al.*[42] investigated the folding mechanism of the earwig wing, which remained open through a bistable locking mechanism and rapidly self-folds without muscular actuation. Inspired by this biological system, they developed a spring origami model that enables programmable morphing functionalities through precise design and fabrication. However, the fabrication processes involved in these studies are complex.

In this paper, we propose an innovative solution that aligns with sustainability and energy-efficiency principles, utilizing a two-nozzle extrusion 3D printer to achieve integrated printing of a soft gripper that has the function of lock in place. Our approach involves integrating low-melting-point alloys (LMPA) into soft robots. LMPAs, which include elements such as tin (Sn), indium (In), bismuth (Bi), and gallium (Ga), can transition between solid and liquid states at relatively low temperatures (generally below 300°C).[43] The advantages of LMPA include ease of handling, good thermal and electrical conductivity, reusability, and mechanical strength. LMPA usually incorporates low-melting-point elements.[44] The applications of LMPA include bionics,[45] clean energy applications,[46] thermal management,[47] biomedical applications,[48] and electromagnetic shielding.[49]

In this study, we attempted an innovative methodology for designing and fabricating a soft robotic gripper embedded with LMPA using material extrusion 3D printing, specifically fused deposition modeling.[50,51] This approach leverages the state-changing properties of LMPA to create a soft robot that can transition between a pliable, soft state, and a rigid, solid state. The basic operating principle involves heating the LMPA above its melting point to allow the soft robot to change its shape for holding and grasping objects. While holding or grasping the object, the LMPA is cooled to room temperature so that it turns into a solid state to enable the robot to continue holding the object without consuming additional power.

By utilizing 3D printing techniques, we can precisely control the placement and integration of LMPA within the soft robot, ensuring optimal performance. The proposed grippers that can maintain a grip without continuous energy input represent a significant advancement in soft robotics, addressing issues in both energy efficiency and mechanical strength. Furthermore, the incorporation of LMPA into soft robots can enhance their operational capabilities. The solidified LMPA not only maintains the grip but also improves the structural rigidity of the robot, enabling it to handle heavier objects and operate in more demanding environments. This dual functionality of LMPA providing both flexibility and rigidity opens new possibilities for the design and application of soft robots.

2. Materials and methods

2.1. Design of soft grippers

To facilitate a comprehensive evaluation, two types of soft grippers were designed: A pure thermoplastic polyurethane (TPU) soft gripper and an LMPA-integrated TPU soft gripper. Both grippers were engineered to possess identical dimensions and functional characteristics, enabling a direct comparison of their performance. The design process was meticulously executed using SolidWorks 2022.

In our designed LMPA-integrated soft gripper, the LMPA serves a similar function in both pneumatic and cable-driven soft robots. The primary purpose of the LMPA is to enhance stiffness and enable shape locking through phase transition, which is beneficial in both actuation mechanisms. In this work, we utilized a cable-driven soft gripper as a case study example. The cable and the tip of the soft gripper are fixed together. The cable passes through the interior of the gripper and exits through the center of the soft gripper. Upon actuation, the cable induces bending in the gripper due to its uneven structural design. The fundamental operational concept of the designed gripper involves the contraction of the arms to grasp components when subjected to wire tightening, as illustrated in Figure 1A. This mechanism ensures that the gripper can securely hold objects of varying shapes and sizes, making it suitable for a wide range of applications. Detailed dimensions and structural features of the pure TPU soft gripper and the LMPA-integrated TPU soft gripper are depicted in Figure 2.

2.2. Materials

The primary material used for fabricating the soft grippers was TPU, sourced from Polymaker LTD (China). TPU was chosen due to its excellent flexibility, durability, and compatibility with 3D printing processes. The TPU filament had a diameter of 1.75 mm, suitable for precise extrusion through the 3D printer nozzle.

For the LMPA-integrated gripper, an LMPA was used to fill the interior of the gripper. The LMPA, supplied by Dongguan Houjie Dingtai Metal Materials LTD (China), consisted of a composition of tin 12.5%, bismuth 50%, lead 25%, and cadmium 12.5%, with a melting point of 70°C. This specific alloy was selected due to its suitable melting point, ease of handling, and excellent thermal and mechanical properties.

2.3. Manufacturing process

The manufacturing of the soft grippers was carried out using a customized 3D printer from Polarbear 3D (China). This printer was modified to include an additional nozzle specifically for injecting LMPA, as shown in Figure 3. This dual-nozzle setup allowed for the simultaneous printing of TPU and injection of LMPA, streamlining the fabrication process.

Key printing parameters for TPU were meticulously calibrated to ensure optimal print quality and structural

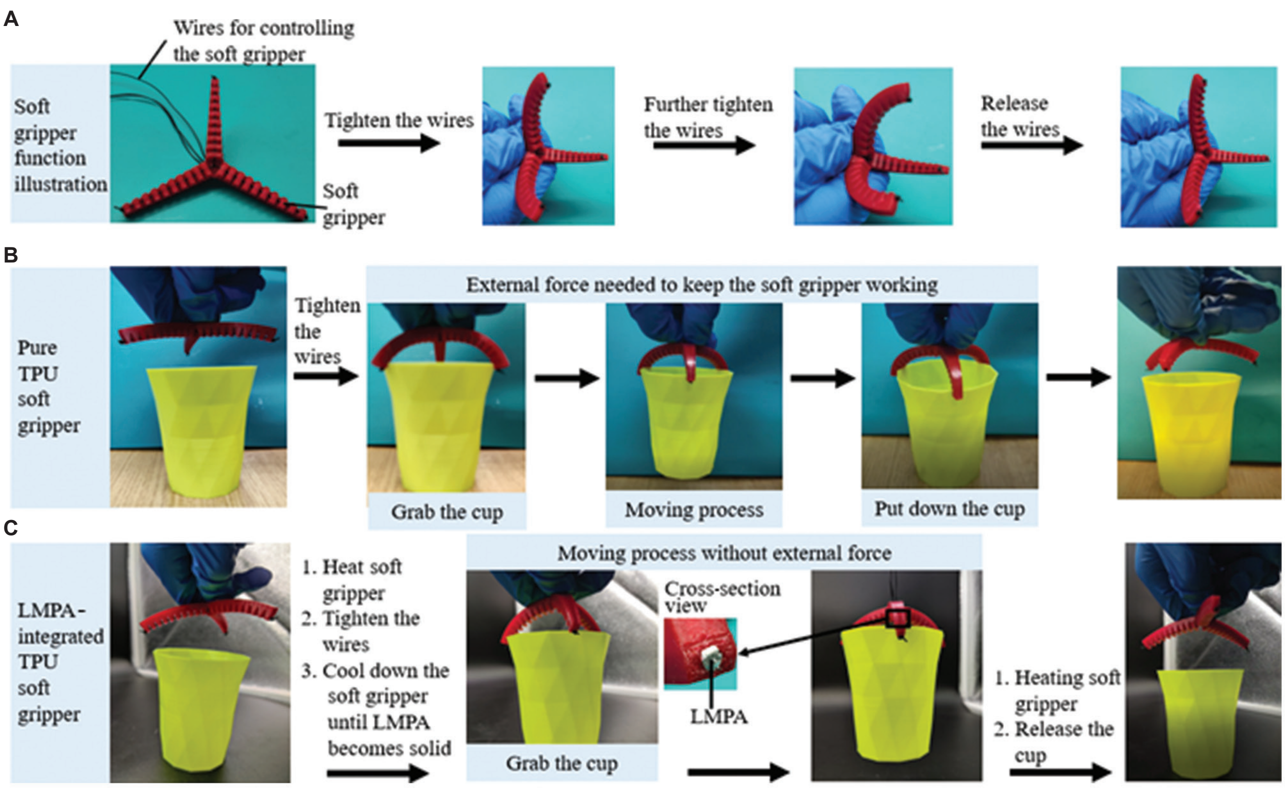

Figure 1. Working principle of soft robots integrated with low-melting-point alloys. (A) Soft gripper function illustration; (B) working process of the pure TPU soft gripper; (C) working process of the LMPA-integrated TPU soft gripper
Abbreviations: LMPA: Low-melting-point alloy; TPU: Thermoplastic polyurethane

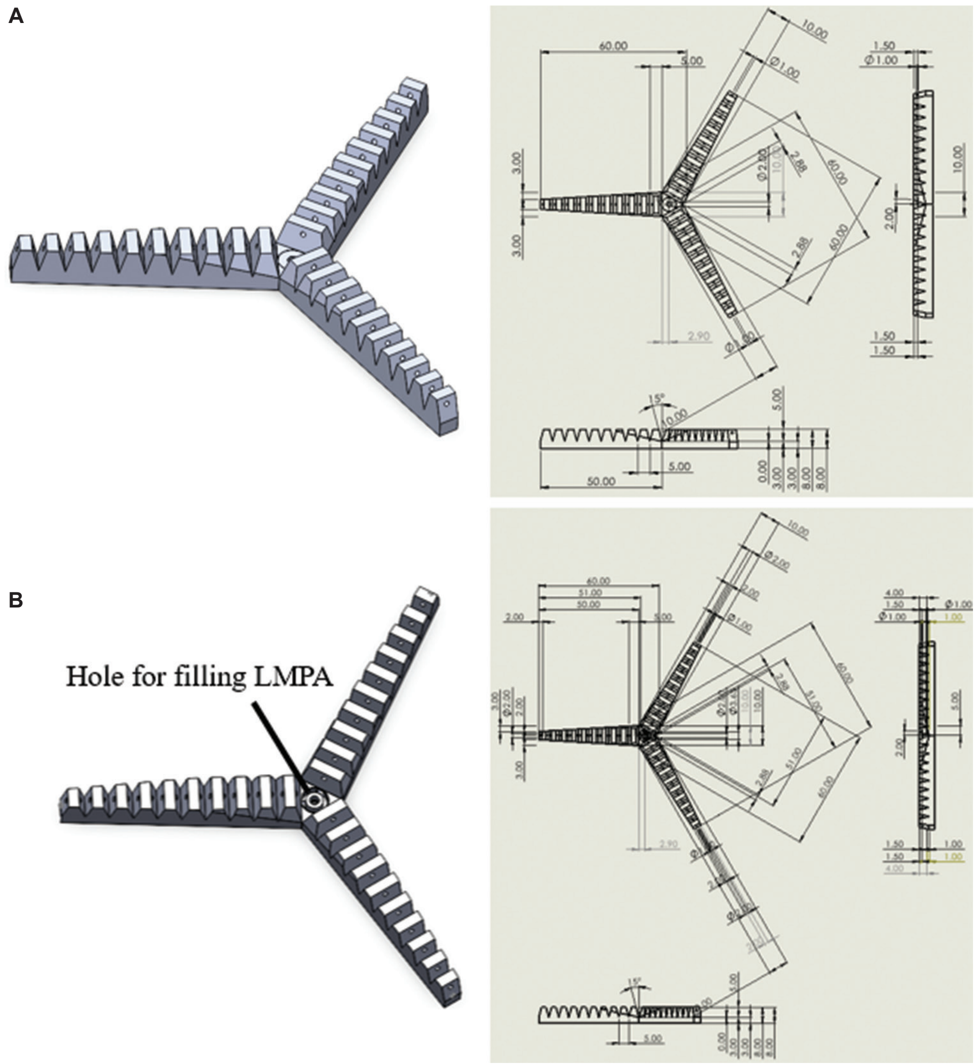

Figure 2. Design for pure soft gripper and LMPA-integrated soft gripper (A) Designed soft gripper of pure TPU (dimension unit: mm); (B) designed soft gripper of LMPA-integrated TPU (dimension unit: mm)
Abbreviations: LMPA: Low-melting-point alloy; TPU: Thermoplastic polyurethane

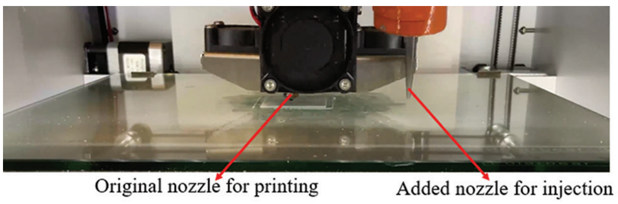

Figure 3. Customized 3D printer with two nozzles (one for printing TPU and another for injecting LMPA)
Abbreviations: LMPA: Low-melting-point alloy; TPU: Thermoplastic polyurethane

integrity. The print temperature was set at 205°C, with a print speed of 20 mm/s, a layer height of 0.15 mm, and an infill density of 30%. The bed temperature was maintained at 45°C to promote proper adhesion and reduce warping.

For the LMPA injection, the temperature was set at 100°C to ensure the alloy remained in a liquid state for smooth injection and even distribution within the gripper's structure. After the TPU gripper was printed, the LMPA was injected into the designed cavities of the gripper, ensuring a uniform fill and proper integration of the alloy within the TPU matrix.

2.4. Mechanical testing

To evaluate the mechanical performance of the soft grippers, tensile tests were conducted using a servohydraulic test system from MTS Landmark (MTS Systems Corporation, Canada). The test setup is illustrated in Figure 4A. The robotic arms of the grippers were subjected to tensile testing at a constant speed of 10 mm/min to assess their tensile strength and elongation characteristics.

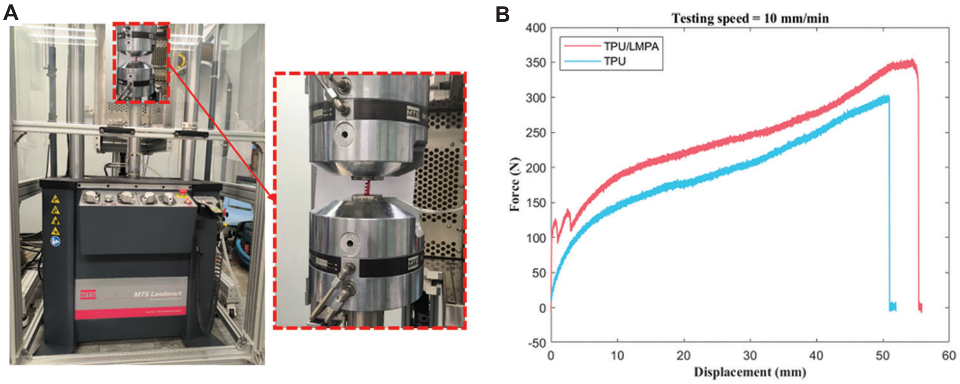

Figure 4. Experiment setup and results (A) Servohydraulic test system for tensile tests; (B) tensile test results of pure TPU and LMPA-integrated TPU robotic arms

Abbreviations: LMPA: Low-melting-point alloy; TPU: Thermoplastic polyurethane

The tensile tests were conducted to quantify the mechanical properties of the pure TPU and LMPA-integrated TPU grippers, providing insights into their respective strengths and durability. The outcomes of these tests are crucial for understanding the impact of LMPA integration on the mechanical performance of the soft grippers.

3. Results and discussion

3.1. Fabrication process

The fabrication process of the soft grippers involved distinct steps for the pure TPU and the LMPA-integrated TPU samples. Both types of grippers were initially printed using the same TPU parameters, including a print temperature of 205°C, a print speed of 20 mm/s, a layer height of 0.15 mm, an infill density of 30%, and a bed temperature of 45°C. This ensured that the foundational structure of each gripper was consistent and comparable.

For the LMPA-integrated TPU grippers, additional steps were required post-printing. A customized 3D printer equipped with a dual nozzle system was used, where one nozzle injected the LMPA at a controlled temperature of 100°C. This method ensured that the LMPA was evenly distributed within the gripper's internal structure. Maintaining precise control over the injection temperature and flow rate was critical to avoid air pockets and ensure uniform LMPA filling.

Despite these precautions, minor deviations in the manufactured samples were noted. The LMPA integration process occasionally led to slight variations in the internal structure (shrinkage[50,51] and porosity[52]), which could affect the uniformity and mechanical properties of the grippers. Shrinkage defects occur due to the contraction of the material as it cools and solidifies, leading to dimensional inaccuracies and potential weaknesses in the printed components. The porosity in LMPAs can arise from several factors, including improper material flow, incomplete fusion of layers, or trapped gases during the printing process. These variations were minimized through meticulous control of the injection process and temperature settings, but they highlight the need for further optimization in the manufacturing process to ensure consistent quality.

The quality of 3D-printed parts is significantly influenced by the nozzle size used during the AM process. Nozzle size affects the resolution, surface finish, and mechanical properties of the printed components.[53] In our integrated extrusion-based AM process, the influence of nozzle size was primarily observed in the printing of TPU. Larger nozzle sizes tended to produce parts with lower resolution and rougher surface finishes, while smaller nozzles could achieve higher precision and finer details. However, the trade-off includes potential issues with clogging and slower printing speeds when using smaller nozzles. In contrast, the impact of nozzle size on LMPAs was minimal. The LMPAs were introduced into the TPU matrix through an injection-like process, which ensures uniform distribution and solidification. This method mitigates the potential adverse effects of nozzle size variations on the quality of LMPA components.

Our manufacturing process for LMPAs, however, presents a distinctive advantage in this regard. Unlike layer-by-layer AM processes,[54] our method involves the continuous deposition and solidification of LMPAs as a single, cohesive unit. This continuous solidification reduces the thermal gradients and the associated residual stresses that typically arise in layer-by-layer approaches. The reduced residual stress in our LMPA parts can be attributed to the following factors. First, the entire LMPA part solidifies together as a whole, rather than in discrete layers. This uniform solidification minimizes thermal gradients, which are the primary source of residual stress in layer-by-layer methods. Second, LMPAs melt and solidify at relatively low temperatures compared to traditional metal powders used in processes like selective laser melting. The lower processing temperatures further reduce thermal stresses.

3.2. State-changing effect and recovery rates

The state-changing effect of the LMPA-integrated TPU gripper was a pivotal aspect of this study. When heated above 70°C, the LMPA transitioned from a solid to a liquid state, allowing the gripper to alter its shape and grasp objects effectively. This state change enabled the gripper to conform to various shapes and sizes, enhancing its versatility and functionality.

Upon cooling to room temperature, the LMPA solidified, enabling the gripper to maintain its hold on objects without external power. This passive holding capability is particularly advantageous for applications requiring prolonged gripping, as it reduces energy consumption. The recovery rate, or the time required for the LMPA to solidify and secure the grip, was found to be dependent on ambient conditions and the specific heat capacity of the LMPA. Experimental observations indicated that the LMPA could solidify within 30 s to 1 min under typical laboratory conditions. This relatively quick transition supports practical applications, ensuring that the gripper can rapidly secure objects without significant delays.

3.3. Mechanical strength and energy efficiency

The mechanical performance and energy efficiency of the soft grippers were evaluated through a series of tests. Figure 1 illustrates the final 3D-printed soft grippers. As depicted in Figure 1B and C, a clear distinction is observed between the pure TPU soft gripper and the LMPA-integrated soft gripper. The pure TPU gripper requires continuous external force to maintain its grip on components. In contrast, the LMPA-integrated gripper can maintain its grasp without external force due to the solidification of the LMPA, particularly during the motion of components.

This behavior stems from the unique properties of LMPA. When the gripper is heated beyond 70°C, the LMPA transitions into a liquid state, without compromising the gripper's functionality. Upon cooling to temperatures below 70°C, the LMPA solidifies, enabling the gripper to hold onto the components securely. This transition obviates the need for continuous external energy or force, thus conserving energy during prolonged gripping or transportation tasks.

The pure TPU gripper is fully dense, as shown in Figure 2. In contrast, the LMPA-integrated soft gripper contains cavities filled with LMPA. When the gripper is actuated by a cable, the LMPA is in its melted state, thus exerting minimal resistance to the cable-driven motion. This results in a reduced force requirement for actuating the LMPA-integrated gripper compared to the fully dense TPU gripper. In addition, the presence of cavities and the softened state of TPU at elevated temperatures contribute to easier deformation.

The tensile test outcomes of robotic arms with pure TPU and LMPA-integrated TPU are presented in Figure 4B. The LMPA-integrated robotic arm exhibited enhanced mechanical strength, withstanding a tensile force of approximately 350 N, compared to the pure TPU robotic arm's endurance of around 270 N. This significant improvement in mechanical strength can be attributed to the reinforcing effect of the solidified LMPA within the gripper structure.

It is important to emphasize that the showcased soft gripper serves as an illustrative instance. The benefits of energy utilization and mechanical strength enhancement can also be extended to other soft grippers employing diverse energy sources (e.g., pneumatic). The integration of LMPA offers a versatile approach to improving the performance of soft robotic systems, making them more efficient and capable of handling a wider range of tasks with minimal energy consumption.

4. Conclusion

This paper introduces the utilization of material extrusion for the fabrication of soft grippers incorporating LMPA. The primary concept revolves around harnessing the favorable property of LMPA's low melting temperature, enabling the soft gripper to transition between a pliable state and a solid one. Upon heating the LMPA within the soft gripper beyond its melting point, the gripper operates conventionally providing the necessary flexibility and adaptability to grasp various objects. In contrast, as the LMPA temperature decreases to ambient levels, the soft gripper transforms into a solid state, becoming capable of securing objects without the need for external power or force.

This innovation effectively curtails energy consumption during the motion process, particularly during long-distance transportation, by eliminating the need for continuous external power to maintain grip. The integration of LMPA not only contributes to energy efficiency but also enhances the mechanical performance of the soft robots. The tensile tests demonstrated that the LMPA-integrated TPU grippers exhibit superior mechanical strength compared to their pure TPU counterparts, withstanding greater tensile forces and providing more robust and reliable operation.

Furthermore, the ability of the LMPA to transition between states opens up new possibilities for the design and application of soft robots. This state-changing capability can be leveraged to create more versatile and adaptable robotic systems that can perform a wider range of tasks with improved efficiency and performance. The use of material extrusion and 3D printing technologies also allows for the precise and customizable fabrication of these soft grippers, enabling the creation of intricate designs that are tailored to specific applications.

However, it is important to acknowledge the limitations of this method. The thermal processes involved in heating and cooling the LMPA require time, which can lead to extended durations in the process of transporting objects. This time factor may pose a challenge in applications where rapid response and quick operations are critical. Future research could focus on optimizing the thermal management and control systems to reduce the transition times and enhance the overall efficiency of the LMPA-integrated soft grippers.

The integration of LMPA into soft grippers through material extrusion presents a promising approach to address the energy consumption challenges in soft robotics. This innovation not only enhances the energy efficiency and mechanical performance of the soft grippers but also paves the way for more versatile and adaptable robotic systems. Despite the current limitations, the potential benefits and applications of this technology are significant, warranting further exploration and development in the field of soft robotics.

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Conflicts of interest

Jingchao Jiang serves as the Editorial Board Member of the journal but was not in any way involved in the editorial and peer-review process conducted for this paper, directly or indirectly. Other authors declare that they have no competing interests.

Author contributions

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Writing – original draft: Liuchao Jin and Jingchao Jiang
Writing – review and editing: Jingchao Jiang and Wei–Hsin Liao

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

The data supporting the findings of this study are available within the article.

References

1. Gibson I, Rosen DW, Stucker B, *et al*. *Additive Manufacturing Technologies*. Vol. 17. Germany. Springer; 2021.

   doi: 10.1007/978-1-4939-2113-3

2. Zhai X, Jin L, Jiang J. A survey of additive manufacturing reviews. *Mater Sci Addit Manuf*. 2022;1(4):21.

   doi: 10.18063/msam.v1i4.21

3. Jiang J. A survey of machine learning in additive manufacturing technologies. *Int J Comput Integr Manuf*. 2023;36(9):1258-1280.

   doi: 10.1080/0951192X.2023.2177740

4. Jin L, Zhai X, Wang K, *et al*. Big data, machine learning, and digital twin assisted additive manufacturing: A review. *Mater Des*. 2024;244:113086.

   doi: 10.1016/j.matdes.2024.113086

5. Uriondo A, Esperon-Miguez M, Perinpanayagam S. The present and future of additive manufacturing in the aerospace sector: A review of important aspects. *Proc Inst Mech Eng G J Aerosp Eng*. 2015;229(11):2132-2147.

   doi: 10.1177/0954410014568797

6. Lu Z, San SLL, Tan MJ, An J, Zhang Y, Chua CK. Preliminary investigation on tensile and fatigue properties of ti6al4v manufactured by selected laser melting. *Mater Sci Addit Manuf*. 2023;2(2):0912.

doi: 10.36922/msam.0912

7. Marchal V, Zhang Y, Labed N, Lachat R, Peyraut F. Fast layer fiber orientation optimization method for continuous fiber-reinforced material extrusion process. *Mater Sci Addit Manuf*. 2023;2(1):49.
doi: 10.36922/msam.49

8. Menon V, Aranas C Jr., Saha G. Cold spray additive manufacturing of copper-based materials: Review and future directions. *Mater Sci Addit Manuf*. 2022;1(2):12. doi: 10.18063/msam.v1i2.12

9. Salmi M. Additive manufacturing processes in medical applications. *Materials* (*Basel*). 2021;14(1):191.
doi: 10.3390/ma14010191

10. Fayyazbakhsh F, Tusar MH, Huang YW, Leu MC. Effect of bioactive borate glass on printability and physical properties of hydrogels. *Mater Sci Addit Manuf*. 2024;3(1):2845.
doi: 10.36922/msam.2845

11. Rouf S, Malik A, Raina A, *et al*. Functionally graded additive manufacturing for orthopedic applications. *J Orthop*. 2022;33:70-80.
doi: 10.1016/j.jor.2022.06.013

12. Kouhi M, de Souza Araújo IJ, Asa'ad F, *et al*. Recent advances in additive manufacturing of patient-specific devices for dental and maxillofacial rehabilitation. *Dent Mater*. 2024;40:700-715.
doi: 10.1016/j.dental.2024.02.006

13. Lu W, He W, Wu J, Zhang Y. A critical review of additive manufacturing technology in rehabilitation medicine via the use of visual knowledge graph. *Virtual Phys Prototyp*. 2023;18(1):e2132265.
doi: 10.1080/17452759.2023.2248464

14. Huang Y, Zhu Q, Liu H, Ren, Zhang L, Gou M. Current materials for 3D-printed flexible medical electrodes. *Mater Sci Addit Manuf*. 2023;2(4):2084.
doi: 10.36922/msam.2084

15. Kuzmanić I, Vujović I, Terzić V, Petković M, Šoda J. Additive manufacturing in marine engineering education. *Prog Addit Manuf*. 2022;7(3):521-530.

16. Jia Y, Abdelrahman S, Hauser CA. Developing a sustainable resin for 3D printing in coral restoration. *Mater Sci Addit Manuf*. 2024;3(2):3125.
doi: 10.36922/msam.3125

17. Wang Z, Zhang B, He Q, *et al*. Multimaterial embedded 3D printing of composite reinforced soft actuators. *Research* (*Wash D C*). 2023;6:0122.
doi: 10.34133/research.0122

18. Rouway M, Tarfaoui M, Chakhchaoui N, Omari LEH, Fraija F, Cherkaoui O. Additive manufacturing and composite materials for marine energy: Case of tidal turbine. *3D Print Addit Manuf*. 2023;10(6):1309-1319.
doi: 10.1089/3dp.2021.0194

19. Garbatov Y, Marchese SS, Epasto G, Crupi V. Flexural response of additive-manufactured honeycomb sandwiches for marine structural applications. *Ocean Eng*. 2024;302:117732.
doi: 10.1016/j.oceaneng.2024.117732

20. Wang M, Li D, Zang Z, *et al*. 3D food printing: Applications of plant-based materials in extrusion-based food printing. *Crit Rev Food Sci Nutr*. 2022;62(26):7184-7198.
doi: 10.1080/10408398.2021.1911929

21. Silva LRG, Stefano JS, Nocelli RCF, Janegitz BC. 3D electrochemical device obtained by additive manufacturing for sequential determination of paraquat and carbendazim in food samples. *Food Chem*. 2023;406:135038.
doi: 10.1016/j.foodchem.2022.135038

22. Oliveira SM, Martins AJ, Fucinos P, Cerqueira MA, Pastrana LM. Food additive manufacturing with lipid-based inks: Evaluation of phytosterol-lecithin oleogels. *J Food Eng*. 2023;341:111317.
doi: 10.1016/j.jfoodeng.2022.111317

23. Yu Q, Zhang M, Bhandari B, Li J. Future perspective of additive manufacturing of food for children. *Trends Food Sci Technol*. 2023;136:120-134.
doi: 10.1016/j.tifs.2023.04.009

24. Hu G, Damanpack A, Bodaghi M, Liao WH. Increasing dimension of structures by 4D printing shape memory polymers via fused deposition modeling. *Smart Mater Struct*. 2017;26(12):125023.
doi: 10.1088/1361-665X/aa95e

25. Zhang K, Gao Q, Jiang J, *et al*. High energy dissipation and self-healing auxetic foam by integrating shear thickening gel. *Compos Sci Technol.* 249 (2024) 110475.
doi: 10.1016/j.compscitech.2024.110475

26. Jin L, Yu S, Cheng J, *et al*. Machine learning-driven forward prediction and inverse design for 4d printed hierarchical architecture with arbitrary shapes. *Appl Mater Today.* 2024;40:102373.
doi: 10.1016/j.apmt.2024.102373

27. Li X, Wang X, Mei D, Xu C, Wang Y. Acoustic-assisted DLP 3D printing process for carbon nanofiber reinforced honeycomb structures. *J Manuf Processes*. 2024;121:374-381.
doi: 10.1016/j.jmapro.2024.05.047

28. Yu C, Jiang J. A perspective on using machine learning in 3D bioprinting. *Int J Bioprint.* 2020;6(1):253.

doi: 10.18063/ijb.v6i1.253

29. Kryou C, Leva V, Chatzipetrou M, Zergioti I. Bioprinting for liver transplantation. *Bioengineering*. 2019;6(4):95.

doi: 10.3390/bioengineering6040095

30. Jo HJ, Kang MS, Jang HJ, *et al*. Advanced approaches with combination of 2D nanomaterials and 3D printing for exquisite neural tissue engineering. *Mater Sci Addit Manuf*. 2023;2(2):0620.

doi: 10.36922/msam.0620

31. Liu C, Ling C, Chen C, *et al*. Laser additive manufacturing of magnesium alloys and its biomedical applications. *Mater Sci Addit Manuf*. 2022;1(4):24.

doi: 10.18063/msam.v1i4.24

32. Xu W, Nassehi A, Liu F. Metal additive manufacturing of orthopedic bone plates: An overview. *Mater Sci Addit Manuf*. 2023;2(4):2113.

doi: 10.36922/msam.2113

33. Stano G, Percoco G. Additive manufacturing aimed to soft robots fabrication: A review. *Extreme Mech Lett*. 2021;42:101079.

doi: 10.1016/j.eml.2020.101079

34. Sparrman B, Du Pasquier C, Thomsen C, *et al*. Printed silicone pneumatic actuators for soft robotics. *Addit Manuf*. 2021;40:101860.

doi: 10.1016/j.addma.2021.101860

35. Roels E, Terryn S, Brancart J, Verhelle R, Van Assche G, Vanderborght B. Additive manufacturing for self-healing soft robots. *Soft Robot*. 2020;7(6):711-723.

doi: 10.1089/soro.2019.0081

36. Jin L, Cui W. On technical issues for underwater charging of robotic fish schools using ocean renewable energy. *Ships Offshore Struct*. 2023:1-11.

doi: 10.1080/17445302.2023.2245164

37. El-Atab N, Mishra RB, Al-Modaf F, *et al*. Soft actuators for soft robotic applications: A review. *Adv Intell Syst*. 2020;2(10):2000128.

doi: 10.1002/aisy.202000128

38. Usevitch NS, Hammond ZM, Schwager M, Okamura AM, Hawkes EW, Follmer S. An untethered isoperimetric soft robot. *Sci Robot*. 2020;5(40):eaaz0492.

doi: 10.1126/scirobotics.aaz0492

39. Tang Y, Chi Y, Sun J, *et al*. Leveraging elastic instabilities for amplified performance: Spine-inspired high-speed and high-force soft robots. *Sci Adv*. 2020;6(19):eaaz6912.

doi: 10.1126/sciadv.aaz6912

40. Wang Y, Yang Z, Zhou H, *et al*. Inflatable particle-jammed robotic gripper based on integration of positive pressure and partial filling. *Soft Robot*. 2022;9(2):309-323.

doi: 10.1089/soro.2020.0139

41. Li S, Stampfli JJ, Xu HJ, *et al*. A vacuum-driven origami magic-ball soft gripper. In: 2019 International Conference on Robotics and Automation (ICRA). United States: IEEE; 2019. p. 7401-7408.

doi: 10.1109/ICRA.2019.8794068

42. Faber JA, Arrieta AF, Studart AR. Bioinspired spring origami. *Science*. 2018;359(6382):1386-1391.

doi: 10.1126/science.aap7753

43. Liu Y, Tu K. Low melting point solders based on Sn, Bi, and In elements. *Mater Today Adv*. 2020;8:100115.

doi: 10.1016/j.mtadv.2020.100115

44. Daeneke T, Khoshmanesh K, Mahmood N, *et al*. Liquid metals: Fundamentals and applications in chemistry. *Chem Soc Rev*. 2018;47(11):4073-4111.

doi: 10.1039/c7cs00043j

45. Wang X, Guo R, Liu J. Liquid metal based soft robotics: Materials, designs, and applications. *Adv Mater Technol*. 2019;4(2):1800549.

doi: 10.1002/admt.201800549

46. Xu S, Yang XH, Tang SS, Liu J. Liquid metal activated hydrogen production from waste aluminum for power supply and its life cycle assessment. *Int J Hydrogen Energy*. 2019;44(33):17505-17514.

doi: 10.1016/j.ijhydene.2019.05.176

47. Zhang XD, Yang XH, Zhou YX, *et al*. Experimental investigation of Galinstan based Minichannel cooling for high heat flux and large heat power thermal management. *Energy Convers Manag*. 2019;185:248-258.

doi: 10.1016/j.enconman.2019.02.010

48. Yan J, Lu Y, Chen G, Yang M, Gu Z. Advances in liquid metals for biomedical applications. *Chem Soc Rev*. 2018;47:2518-2533.

doi: 10.1039/C7CS00309A

49. Zhang M, Zhang P, Zhang C, Wang Y, Chang H, Rao W. Porous and anisotropic liquid metal composites with tunable reflection ratio for low-temperature electromagnetic interference shielding. *Appl Mater Today*. 2020;19:100612.

doi: 10.1016/j.apmt.2020.100612

50. Jiang J, Zhai X, Zhang K, *et al*. Low-melting-point alloys integrated extrusion additive manufacturing. *Addit Manuf*. 2023;72:103633.

doi: 10.1016/j.addma.2023.103633

51. Jiang J, Zhai X, Jin L, *et al*. Design for reversed additive manufacturing low-melting-point alloys. *J Eng Des*. 2023:1-14.

doi: 10.1080/09544828.2023.2261096

52. Bartlett JL, Heim FM, Murty YV, Li X. *In situ* defect detection in selective laser melting via full-field infrared thermography. *Addit Manuf.* 2018;24:595-605.

    doi: 10.1016/j.addma.2018.10.045

53. Sushchenko A, Scherschel A, Love-Baker C, *et al*. Evaluating consumer 3D printing nozzles as a low-cost alternative for mesophase pitch-derived carbon fiber production. *Carbon*. 2024;225:119088.

    doi: 10.1016/j.carbon.2024.119088

54. Bartlett JL, Li X. An overview of residual stresses in metal powder bed fusion. *Addit Manuf.* 2019;27:131-149.

    doi: 10.1016/j.addma.2019.02.020