A NOVEL STRATEGY TO FABRICATE LOW-MELTING-POINT ALLOY AND ITS COMPOSITE PARTS USING EXTRUSION ADDITIVE MANUFACTURING

JINGCHAO JIANG[1], LIUCHAO JIN[1], XIAOYA ZHAI[1,2], KANG ZHANG[1], JUN CHEN[3,4], WEI-HSIN LIAO[1,5,*]

[1]Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Shatin, Hong Kong, China
[2]School of Mathematical Sciences, University of Science and Technology of China, China
[3]Zhejiang Provincial Key Laboratory of Advanced Chemical Engineering Manufacture Technology, College of Chemical and Biological Engineering, Zhejiang University, Hangzhou, China
[4]Institute of Zhejiang University-Quzhou, Quzhou, China
[5]Institute of Intelligent Design and Manufacturing, The Chinese University of Hong Kong, Shatin, Hong Kong, China
whliao@cuhk.edu.hk

ABSTRACT

Additive manufacturing (AM) has been continuously developed for more than 30 years. Different novel AM techniques, including electric-assisted, magnetic-assisted, robot-assisted, and UAV-assisted AM technologies have been created with various objectives. In this paper, we propose a new strategy for fabricating complex and/or multifunctional components of low-melting-point alloys (LMPA) using extrusion additive manufacturing (EAM). The main idea is using two nozzles in EAM, one for extruding polymers (e.g., PLA, PVA) while another for extruding LMPA. By using the proposed EAM system, there are three novel aspects of this study. First, the proposed system can achieve composite parts (polymer & LMPA) fabrication with improved mechanical properties. Second, the proposed system can be used to fabricate 3D products with LMPA wire inside acting as electrical wire. This achieves electrical wire inside a product without assembly, unlike conventional method which needs further step to insert the wires. Third, complex pure LMPA parts can be fabricated by dissolving the polymer after manufacturing, achieving complex LMPA parts fabrication using EAM (a low-cost AM technique, compared with traditional metal AM).

Keywords: Additive manufacturing, Low-melting-point alloys, Extrusion additive manufacturing

1 INTRODUCTION

Additive Manufacturing, also known as 3D Printing or AM, is a revolutionary manufacturing technique that builds parts in a layer-by-layer and point-by-point fashion solely based on 3D model data [1–3]. The ISO/ASTM has classified AM into seven different groups, including vat photopolymerization, binder jetting, material jetting, powder bed fusion, directed energy deposition, sheet lamination, and material extrusion [4].

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[*] Corresponding Author

Since its inception in the 1980s, AM technology has continued to evolve rapidly, with many new techniques emerging in the last two decades that focus on specific objectives such as electric-assisted [5], magnetic-assisted [6], robot-assisted [7,8], and UAV-assisted AM technologies [9]. For instance, Kokkinis et al. [6] developed a magnetically assisted 3D printing system that fabricates functional heterogeneous materials with intricate microstructural features. Zhang et al. [9] also recently proposed the concept of Aerial Additive Manufacturing (Aerial-AM), which utilizes a multi-robot framework for autonomous 3D printing. This innovative technology can print parts while flying, enabling manufacturers to create objects in previously inaccessible locations, such as high altitude or hard-to-reach areas. The versatility and adaptability of AM make it a promising technology for a wide range of industries, including aerospace, automotive, healthcare, robotics, and consumer goods. As AM technology continues to evolve, we can expect even more exciting advancements in the near future, further driving the growth and potential of this transformative technology.

Low-Melting-Point alloys (LMPA) are a category of metals that possess the unique ability to transform into a liquid or semi-liquid state at low temperatures, typically below 300℃ when exposed to atmospheric pressure [10]. This distinctive feature provides several benefits over conventional metals, including good thermal conductivity, easy handling, reusability, excellent mechanical strength, and electrical conductivity. Normally, LMPA is made up of low melting point elements such as indium (In), gallium (Ga), tin (Sn), and bismuth (Bi) [11]. Over time, LMPA has gained significant attention in various fields, including bionics [12,13], thermal management [14,15], clean energy [16], electromagnetic shielding [17], and biomedical [18] applications. However, there have been limited attempts to utilize 3D printing techniques with LMPA materials. For example, Liu et al. investigated the use of LMPA and polymer composite wires for fused deposition modeling (FDM) techniques, where they demonstrated a tensile modulus three times higher than pure PLA [19]. Huang et al. [20] used Electric Field Assisted Direct Writing for 3D printing LMPA, leading to successful fabrication of LMPA parts with low surface quality and weak bonding between layers. Similarly, Warrier and Kate [21] attempted to produce pure LMPA parts using FDM techniques, but the results showed low quality and an inability to create complex part structures. Hsieh et al. [22] also used FDM to fabricate LMPA, although only three single layers were printed. The literature illustrates that LMPA has tremendous potential for future multi-functional applications. However, current 3D printing technologies face challenges in producing pure complex LMPA parts with high quality. As a result, further research is necessary to improve 3D printing techniques for LMPA materials, unlocking possibilities for new and exciting applications of this exciting category of metals.

This paper presents a novel approach to producing complex parts with multi-functional applications using Low-Melting-Point alloys (LMPA) through Extrusion Additive Manufacturing (EAM). The central concept of our approach is to leverage two nozzles in EAM, with one nozzle being utilized for extruding polymers such as PLA or PVA, while the second nozzle is employed for extruding LMPA. Fig. 1 provides an illustration of our proposed system and its operation. As shown step by step in the figure from (a) to (d), nozzle 1 is used to fabricate the polymer section of the component while nozzle 2 is opened once the polymer segment is complete to fill the melted LMPA. Subsequently, following cooling down to room temperature, the melted LMPA hardens, and the final component is ready for use.

This paper presents a unique approach that has three distinct aspects of fabricating LMPA and its composite parts. The first aspect involves using the proposed system to print standard dog-bone parts to test the tensile strength of the composite part with improved mechanical properties. Second, 3D products with LMPA wire inside can be fabricated, which act as electrical wires without the need for any further assembly steps. This avoids the conventional method of inserting wires, and the "CUHK" light part with LMPA printed inside is used as an example in this study. Third, the strategy can be used for fabricating complex pure LMPA parts using Extrusion Additive Manufacturing (EAM). Following manufacturing, the polymer is dissolved to achieve complex LMPA parts fabrication using EAM, which is a low-cost AM technique compared with traditional metal AM. Examples of the complex “SCIEN” structures are demonstrated.

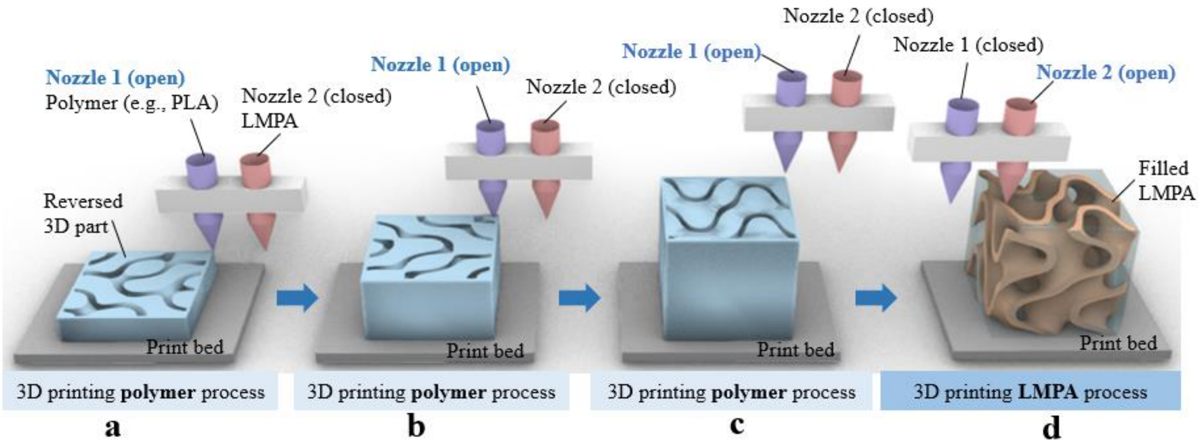

Fig. 1 Schematic showing the proposed printing system [23].

2 METHODOLOGY

The basic steps of the proposed method are illustrated in Fig. 2. Step 1: design the objective structure; Step 2: reverse the objective structure using a bounding box; Step 3: 3D Printing the outside reversed part; Step 4: filling the LMPA in the 3D Printed reversed part; Step 5: dissolve the outside reversed part; Step 6: obtain the final objective structure. These five steps are used for fabricating the pure LMPA structures. If the objective is the composite structure or electrical product, only step 1 to step 4 are necessary.

In this study, the reversed outside parts were 3D printed using PLA filament with a diameter of 1.75 mm from Polymaker Ltd. The LMPA used was obtained from Wude Alloys Ltd, China and consisted of Sn 12.5%, Bi 50%, Pb 25%, and Cd 12.5%, with a melting point of 70°C. Dichloromethane from RCI Labscan Ltd, Thailand (batch number 22020141) was used to dissolve the PLA. The key PLA printing parameters include print temperature of 205°C, print speed of 60 mm/s, layer height of 0.15 mm, infill density of 20%, and bed temperature of 45°C. For printing with LMPA, the print temperature was set at 100°C, and the print bed and chamber temperatures were set at 70°C. Tensile and three-point bending tests were carried out using a CMT5105 universal electromechanical testing machine from MTS Systems Co., Ltd, China with 2 kN load cell, with standard test pieces designed for the tests. Tensile tests were conducted at various speeds of 1, 50, and 100 mm/min, while the bending load velocities applied in the three-point bending tests were 1, 50, and 100 mm/min. Three tests were performed for each design. A direct current system, MS-305D from MAISHENG, was used to supply power to the printed CUHK and spring lights at 3 V.

3 RESULTS AND DISCUSSION

3.1 3D printing composite parts

The mechanical properties of LMPA/polymer composite parts fabricated using 3D printing are superior to those of traditional pure polymer 3D printed parts. Standard parts were designed for both tensile and three-point bending tests (Fig. 3). Each condition was tested three times.

The 3D printed pure PLA and PLA/LMPA standard parts used in the tensile tests are illustrated in Fig. 4(a). The Young's modulus and tensile strength values are presented in Fig. 4(b, c), which shows that both the Young's modulus and tensile strength of the PLA/LMPA composite part were significantly higher than those of the pure PLA part under various testing conditions. The tensile strength of the PLA/LMPA part was over twice that of the pure PLA part when tested at a speed of 50 mm/min. The 3D printed pure PLA and PLA/LMPA standard parts used in the three-point bending tests are shown in Fig. 4(d). The flexural modulus and flexural strength values are presented in Fig. 4(e, f), which shows that both were much higher for the PLA/LMPA composite part than for the pure PLA part under various testing conditions. The flexural strength of the PLA/LMPA part was over twice that of the pure PLA part when tested at a speed of 100 mm/min.

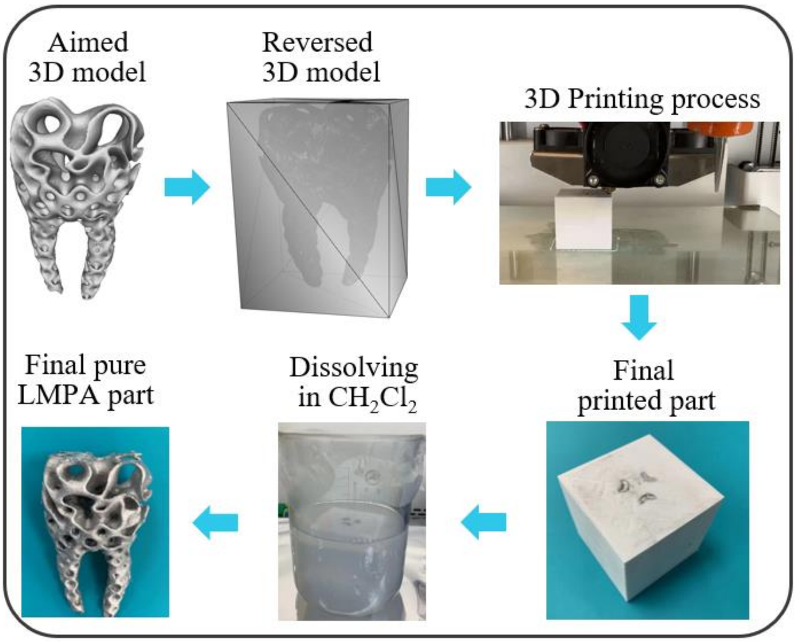

Fig. 2 Steps of the proposed method.

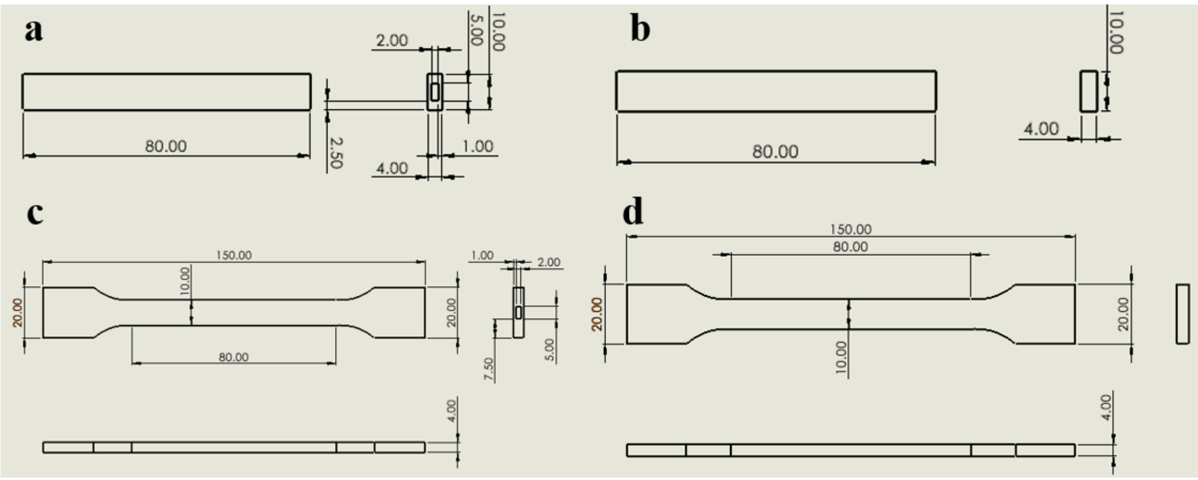

Fig. 3 Test pieces designed for the three-point bending tests: (a) pure PLA and (b) LMPA/PLA composite; and test pieces designed for the tensile tests: (c) pure PLA and (d) LMPA/PLA composite (unit: mm).

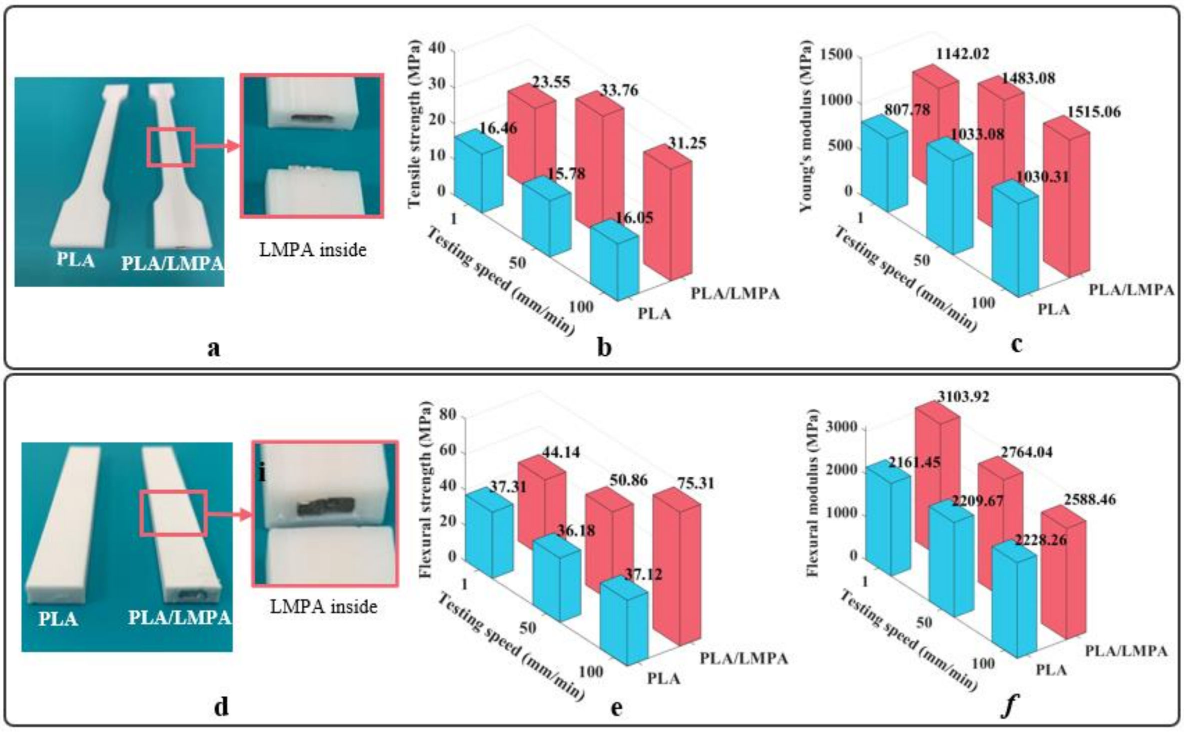

Fig. 4 Tensile and three-point bending tests, and the corresponding results. (a) 3D printed PLA and PLA/LMPA standard parts for the tensile tests; (b) Results of the tensile strength and (c) Young's modulus tests; (d) 3D printed PLA and PLA/LMPA standard parts for the three-point bending tests; (e,f) Flexural strength and flexural modulus values during the three-point bending tests.

3.2 3D printing electrical products

We created a CUHK light part, which features LMPAs acting as internal electrical wires, to demonstrate the fabrication of 3D electrical products. The CUHK light part was designed using Autodesk Inventor Professional 2020 software. Fig. 5 (a, b) shows the designed structures. Fig. 5(c) shows the final part and Fig. 5(d) shows the part with lights on. During 3D printing, each hole or through-hole with a diameter of 1.5 mm was filled with LMPA while the outside parts were printed with PLA. The dimensions of the CUHK piece were 196 × 66 × 35 mm, and as shown in the figure, the piece was successfully fabricated with internal electrical wires comprising the LMPA, without requiring an assembly step. Although we have highlighted the CUHK piece as an example, our proposed method enables other 3D applications/products that need internal electrical wires to be designed and produced, thereby reducing post-processing costs. Additionally, this technique can construct intricate 3D electrical components that would be impossible to manufacture using traditional methods.

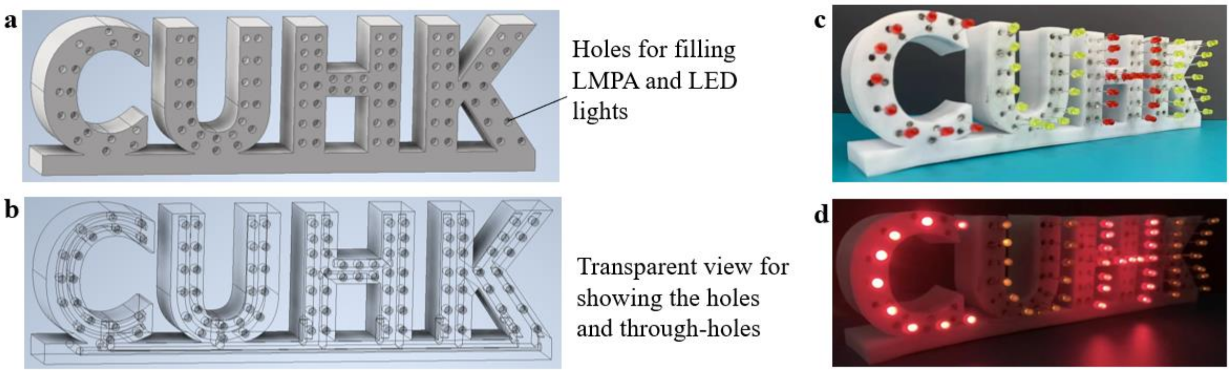

Fig. 5 (a, b) Designed CUHK piece and its transparent view; (c) Fabricated CUHK piece; (d) Fabricated CUHK piece with LED lights turned on.

3.3 3D printing complex pure LMPA parts

The proposed approach is capable of 3D printing intricate pure LMPA parts, as depicted in Fig. 6. Initially, the final complex 3D part is designed and then reversed using a bounding box to obtain the reversed 3D model. Then, 3D print the reversed 3D part and fill the LMPA inside the printed reversed 3D part to produce the PLA/LMPA composite part. Subsequently, the composite part is soaked in CH_2Cl_2 to dissolve the PLA, resulting in the production of complex pure LMPA parts. Fig. 6 showcases several designed and fabricated complex pure LMPA parts (SCIEN). As per the literature, LMPA shows immense potential for future multi-functional applications, such as smart structures, electromagnetic shielding, biomedicine, thermal management, and energy harvesting [24–26]. Our study is the first to demonstrate the generation of intricate LMPA structures using EAM which is a low-cost AM technique. This will facilitate the creation of LMPA structures that can be applied with enhanced efficiency across various fields.

Fig. 6 Demonstration of printed complex pure LMPA parts.

4 CONCLUSION

This paper proposes an innovative strategy for 3D printing LMPA parts, LMPA/polymer composite parts and complex pure LMPA parts. The strategy achieves the fabrication of integrated LMPA polymer parts with improved mechanical properties, intricate pure LMPA parts, and sophisticated parts incorporating electrical functions without the need for post-assembly. Standard parts were designed and 3D printed for tensile and three-point bending tests, finding that the integrated LMPA parts exhibited substantially better mechanical performance than those printed using pure PLA. Furthermore, the proposed strategy enabled the successful 3D printing of various complex pure LMPA parts. This study is the first to use EAM to fabricate such complex LMPA structures using EAM. The ability to print complex LMPA parts affords greater design freedom for LMPA structures, which hold promise across multiple fields including electromagnetic shielding, biomedicine, thermal management, and energy harvesting. We then demonstrated the capability of our strategy to 3D print whole products complete with electrical functions, eliminating the need for assembly. This not only reduces post-processing costs but also allows the creation of complex 3D electrical parts that would be impossible to fabricate using traditional manufacturing techniques.

5 ACKNOWLEDGEMENT

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