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Design for reversed additive manufacturing low-melting-point alloys

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ABSTRACT

Additive manufacturing (AM) technologies have been widely used in construction, medical, military, aerospace, fashion, etc. As AM advances, increasing new AM-based manufacturing methods have been developed (e.g. CNC machining and AM hybrid manufacturing). Recently, a new manufacturing method 'reversed additive manufacturing (RAM)' was proposed by the authors. First, the designed objective part needs to be reversed using a bounding box, obtaining the reversed outside part. Then fabricate the reversed outside part using AM with dissolvable material (e.g. PLA). After that, fill the reversed outside part using aimed material (e.g. low-melting-point alloys) of the objective part. Lastly, soak the whole part into the dissolvent to dissolve the outside part, obtaining the final objective part. In this paper, design for RAM is proposed. Print orientation, print parameter settings, injection parameter settings, shrinkage, cost and post-processing are discussed. Experiments with several lattice structures are carried out and case studies are demonstrated. The findings of this paper can benefit the design process for RAM, improving the design efficiency for RAM.

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KEYWORDS
Additive manufacturing; 3D Printing; reversed additive manufacturing; injection; design

1. Introduction

Additive manufacturing (AM), also known as 3D Printing, is a manufacturing technique fabricating parts in a point-by-point and then layer-by-layer manner, making parts from 3D model data (Gibson et al. 2021; Jiang 2023; Zhai, Jin, and Jiang 2022). Based on ISO/ASTM, AM can be divided into seven groups: vat photopolymerisation, material jetting, binder jetting, powder bed fusion, material extrusion, directed energy deposition and sheet lamination (ISO/ASTM52900 2021). Since the first AM technique was realised in the 1980s (Wohlers and Gornet 2014), different AM technologies have been developed thereafter in

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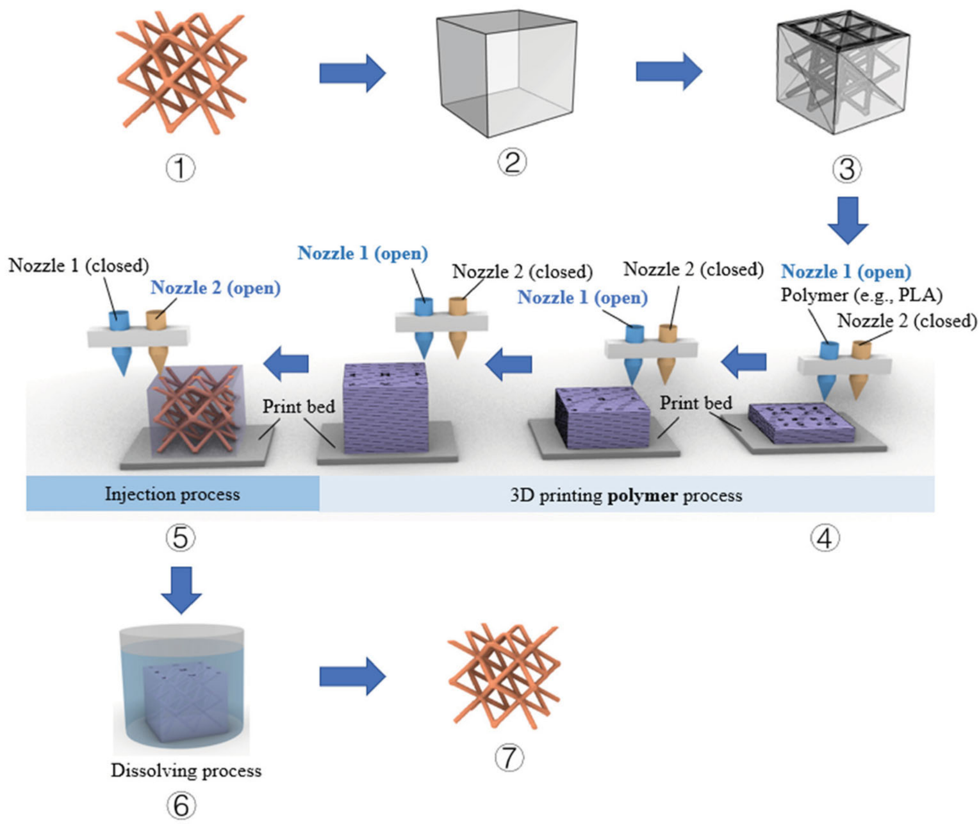

Figure 1. RAM process illustration.

the last three decades, with different objectives, including electric-assisted (Zhang et al. 2020, 2021; Zhu et al. 2019, 2021), magnetic-assisted (Kokkinis, Schaffner, and Studart 2015; Li et al. 2021; Liu et al. 2022), robot-assisted (Ishak and Larochelle 2019; Wang et al. 2016; Xu et al. 2022; Zhao et al. 2018), and hybrid AM technologies (e.g. CNC machining and AM) (Dilberoglu et al. 2021). For example, Kokkinis et al. proposed a magnetically assisted 3D printing system for manufacturing functional heterogeneous materials with exquisite microstructural features (Kokkinis, Schaffner, and Studart 2015). Zhang et al. proposed aerial additive manufacturing (Aerial-AM) that uses a multi-robot framework for autonomous 3D printing (2022). Amanullah et al. developed a hybrid additive and subtractive manufacturing system, where CNC milling was added to AM process (Amanullah, Murshiduzzaman, and Khan 2017). Recently, the authors proposed a new AM-based manufacturing technology 'Reversed additive manufacturing (RAM)' (Jiang et al. 2023). The proposed RAM process is shown in Figure 1. Step 1: design the aimed 3D part; Step 2: reverse the aimed 3D part using a bounding box; Step 3: obtain the reversed 3D part for fabrication; Step 4: 3D printing the reversed part; Step 5: injection process for filling the aimed material of final part; Step 6: dissolve the outside 3D printed bounding part; Step 7: obtain the final aimed part. The main advantage of RAM is that it can fabricate complex 3D parts with materials (e.g. wax and low-melting-point alloys (LMPA)) that are not able to be 3D printed using traditional fused deposition modelling (FDM).

For traditional manufacturing, the concept 'Design for Manufacturing and Assembly (DfMA)' was proposed and investigated for efficient design and manufacturing (Da Silva et al. 2014). DfMA is an engineering methodology to optimise the manufacturing and assembling process of products, which originated from the Second Word War that Ford and Chrysler applied as a principle for the weapon production process (Lu et al. 2020). This methodology includes two parts: Design for Manufacturing (DfM) and Design for Assembly (DfA). DfM is an engineering practice to save costs of manufacturing by selecting the cost-effective raw materials and minimise the complexity of manufacturing operations during the product design stage (definition of dimensional and geometric tolerances, definition of roughness, etc.) (Favi, Germani, and Mandolini 2016). DfA is a process to reduce the time of assembling through minimising the number of individual parts and assembly steps (Boothroyd 1987). Above all parts are all carried out in the early design phase of the product life cycle. DfMA provides a way to evaluate and improve product design by considering downstream processes of manufacturing and assembly, marking a shift from traditional sequential design thinking to a nonlinear approach (Geoffrey Boothroyd 2005); it enables efficient design and manufacturing of products. Then the concept 'Design for Additive Manufacturing (DfAM)' was proposed when AM became mature (Jiang et al. 2022; Rosen 2007, 2014). DfAM is a generic type of design process or tool that optimises functional performance, mechanical qualities and other critical product life cycle aspects such as manufacturability, dependability and cost while assuring production capability in AM systems (Tang and Zhao 2016). To be more specific, it includes three levels of abstraction of DfMA: (1) provide tools, strategies and recommendations for adapting the design to a specific set of final production restrictions; (2) quantify and comprehend the influence of the design process on the production system to increase product quality; (3) determine the link between design and manufacturing, as well as the effect it has on designers and practice. The above objectives and goals of DfMA are applicable to AM, but the DfAM's expertise of design, tools, regulations, procedures and techniques will differ greatly (Thompson et al. 2016). Therefore, for designers to better understand the use of DfAM in AMs, Alfaify et al. systematically summarised approaches of DfAM: cellular structures, consolidation and assembly of parts, materials, support structures, build orientation, part complexity and product sustainability (2020). Relying on the concept of DfMA, the advantages of AM can be fully exploited. It can manage to fabricate complex external shapes without a significant increase in cost and time; it allows the fabrication of complex internal shapes at different scales (macroscopic, mesoscopic and microscopic); thus, the process is more direct between design and manufacture, reducing the number of subsequent assembling steps and manual intervention (Taborda et al. 2021).

The proposed RAM in this paper is a comparatively new manufacturing technique. Therefore, this paper proposes the concept of design for RAM. Figure 2 shows the development of design for manufacturing, the proposed design for RAM is a new concept and method. DfMA is an engineering method for simplifying the design of products to improve manufacturing and assembly efficiency. DfAM is the strategy for improving the efficiency of additive manufacturing. Based on the development of DfMA and DfAM, this paper proposes the rules of design for reversed additive manufacturing (DfRAM). Print orientation, print parameter settings, injection parameter settings, shrinkage, cost and post-processing will be discussed in detail to make RAM efficient. The remaining of this paper is organised as

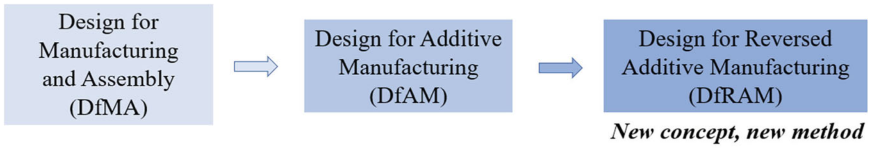

Figure 2. The development of design for manufacturing.

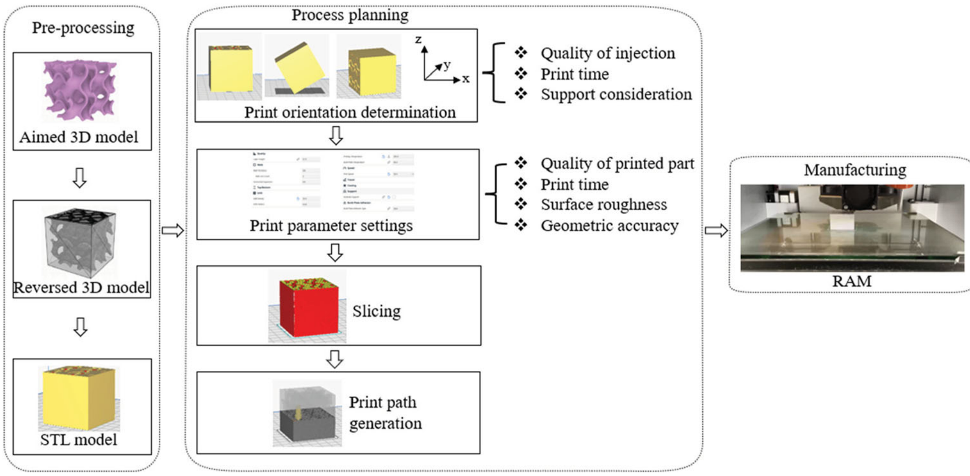

Figure 3. Workflow for RAM manufacturing.

follows. Section 2 discusses the design rules for RAM. The experimental settings and results are given in Section 3. Finally, Section 4 concludes this paper with some remarks.

2. Design for reversed additive manufacturing

This section gives the details of design for reversed additive manufacturing (DfRAM). Figure 3 shows the process from pre-processing (including design the 3D model, reverse the 3D model and generate STL model), process planning (including print orientation determination, print parameters setting, slicing and print path generation), to manufacturing. The following aspects regarding DfRAM will be discussed in this section: print orientation, print parameter settings, injection parameter settings, considering shrinkage and considering post-processing.

2.1. Printable threshold reversed overhang

In traditional additive manufacturing, especially fused deposition modelling (FDM), support structures are needed for overhang features with angle sizes less than a threshold value. The printable threshold overhang angle size needs to be tested and then integrated into the support generation process. Figure 4(a) shows an example 3D overhang model for testing the printable threshold overhang angle in traditional FDM. As seen in Figure 4(b), once the overhang angle size is less than 20°, the overhang cannot be printed successfully, leading to collapsed materials; while for the overhang angle sizes between 20° and 40°, the

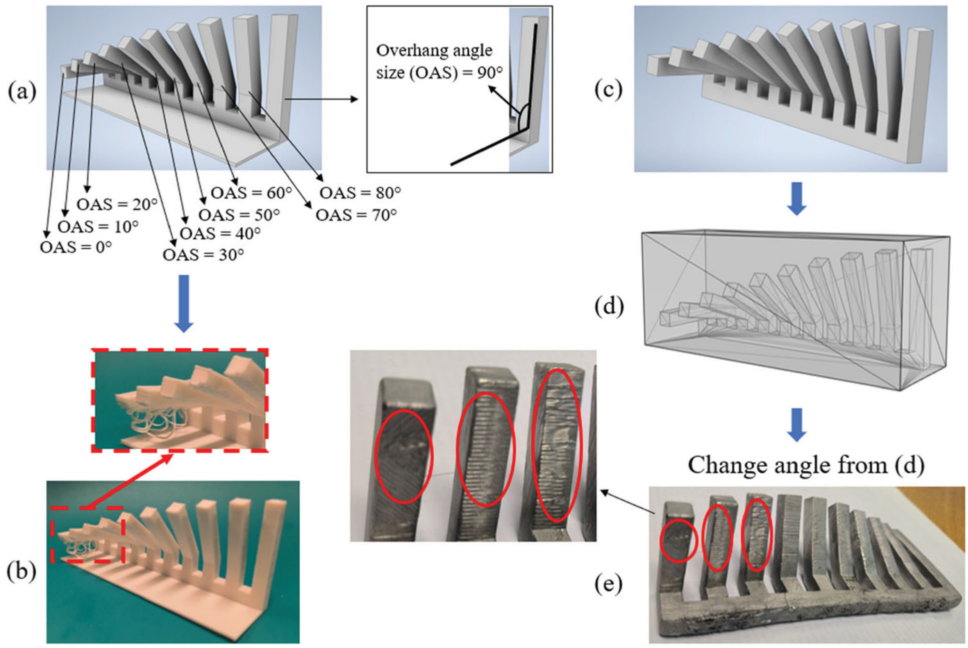

Figure 4. (a) Designed overhang structures for testing in traditional FDM; (b) Reversed overhang structures testing in RAM; (c) Fabricated final overhang structures using RAM.

surface qualities on the bottom surfaces are not satisfied. Therefore, in the design process, all the designed structures with overhang angle sizes less than 40° need to be considered carefully. More details regarding printable threshold overhang angle can be found (Jiang et al. 2018). In RAM, similarly, printable threshold reversed overhang size also needs to be tested. Figure 4(c) shows the designed part for testing the printable overhang angle size, Figure 4(d) shows the reversed 3D part of the overhang structures, and Figure 4(e) demonstrates the finally fabricated overhang structures using RAM. As seen, totally speaking, the surface quality is acceptable when the overhang angle size is larger than 30°.

2.2. Print orientation

Print orientation will influence the print time, support generation and final printed quality. RAM is a manufacturing technique encompassing the processes of additive manufacturing and injection, this subsection discusses the print orientation considering from two different aspects (additive manufacturing and injection).

2.2.1. Considering additive manufacturing

Considering the additive manufacturing process of RAM, the main concern is the support generation that will influence the success of injection. As discussed previously regarding the printable threshold reversed overhang, the print orientation should be determined with all the overhang features that have larger overhang angle size than the threshold. Figure 5(a) illustrates the printable threshold reversed overhang angle size (PTROAS). Figure 5(b) shows an example of the reversed T part with PTROAS = 0, which cannot be successfully fabricated as the PTROAS is less than the threshold value. Figure 5(c) shows an

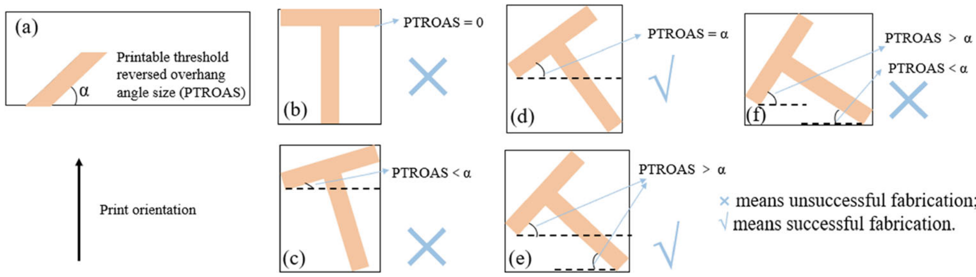

Figure 5. (a) Illustration of printable threshold reversed overhang angle size (PTROAS); (b) Example of the reversed T part with PTROAS = 0; (c) Example of the reversed T part with PTROAS $= \alpha$; (d) Example of the reversed T part with PTROAS $= \alpha$; (e) Example of the reversed T part with PTROAS $= \alpha$; (f) Example of the reversed T part with one PTROAS $= \alpha$and the other PTROAS $= \alpha$.

example of the reversed T part with PTROAS $= \alpha$, which cannot be successfully fabricated either as the PTROAS is still less than the threshold value. Figure 5(d,e) shows the examples of the reversed T part with PTROAS $= \alpha$and PTROAS $= \alpha$, which can be successfully fabricated. Figure 5(f) demonstrates an example of the reversed T part with one PTROAS $= \alpha$ and another PTROAS $= \alpha$, which cannot be successful for fabrication.

2.2.2. Considering injection

Print orientation will influence the injection process, some print orientation may lead to unsuccessful injection and sometimes may increase the final quality if using a better orientation. The main concerns of print orientation in the injection process are illustrated in Figure 6. Figure 6(a) shows an example of a reversed part with closed corner. In this case, the injection process may not be successful due to the closed corner where materials cannot get to the end as the air inside the corner cannot be pushed out. Figure 6(b) demonstrates the reversed part after changing to a better orientation where the closed corner is brought up to the top surface, thus the part can be injected successfully. Figure 6(c) shows an example of a reversed part with inclination walls with the small end upwards, this can be fabricated, but with worse geometrical accuracy due to the shrinkage. Figure 6(d) demonstrates the reversed part with inclination walls after changing to a better orientation with the large end upwards. In this case, the geometrical accuracy can be improved after shrinkage.

2.3. Print parameter settings

Different print parameters also influence the final fabricated quality and time. Table 1 lists the main effects of different parameters.

2.4. Injection parameter settings

During the injection process after additive manufacturing, the injection parameters will also influence the final qualities and time used. Figure 7(a) shows the injection process with parameters of temperature and injection speed. If the injection speed is too fast, defects such as blowholes will occur, as shown in Figure 7(b). While if the temperature is too high and the cooling speed is too fast, defects such as crack will occur, as shown in Figure 7(c).

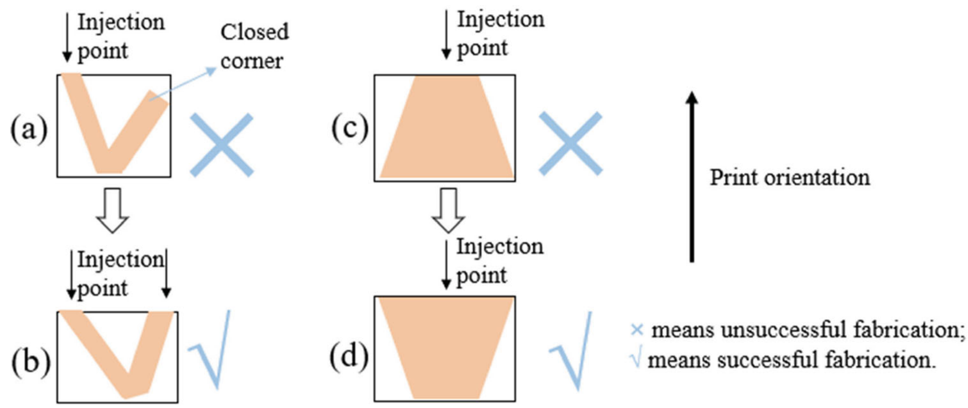

Figure 6. (a) Example of reversed part with closed corner; (b) Example of reversed part after changing to a better orientation; (c) Example of reversed part with inclination walls with the small end upwards; (d) Example of reversed part with inclination walls after changing to a better orientation with the large end upwards.

Table 1. Effects of different parameters on final printed qualities and time.

Main parameters	Effects
Print speed	Higher print speed means less print time used, but if the speed is too high, the quality may be reduced.
Layer thickness	Lower layer thickness means better surface quality after fabrication but may lead to more time consumed for printing.
Print temperature	Higher print temperature may lead to worse surface quality while if the temperature is too low, the material may not be able to be extruded, leading to failure of printing. The best print temperature needs to be investigated.
Infill density	Higher infill density means more material will be used and wasted, also print time will be longer. However, if the infill density is too low, it may not be strong enough to support the injected material in the next step. The suitable infill density should be investigated.

2.5. *Considering shrinkage*

After injection, the injected material will need to be cooled down. After cooling down, the injected part will shrink, leading to smaller geometry of the final part. Therefore, in the design process, shrinkage needs to be considered and the objective part needs to be redesigned for compensation. Figure 8(a) illustrates the shrinkage phenomenon and Figure 8(b) shows the example of redesigning the objective part considering compensation.

2.6. *Considering post-processing*

After additive manufacturing and injection, the top open surfaces of the part need to be polished. For example, as shown in Figure 9 in the red circles, all these surfaces are top open surfaces which need to be polished after fabrication. Polishing wastes labour and post-processing time. Therefore, the less top surfaces the better. The design of Figure 9(a) is better than that in Figure 9(b) as Figure 9(a) has two open surfaces only. Note that, for

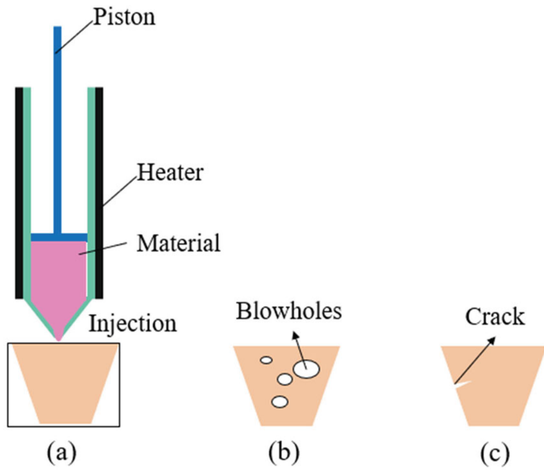

Figure 7. (a) Injection process; (b) Blowhole defect example; (c) Crack defect example.

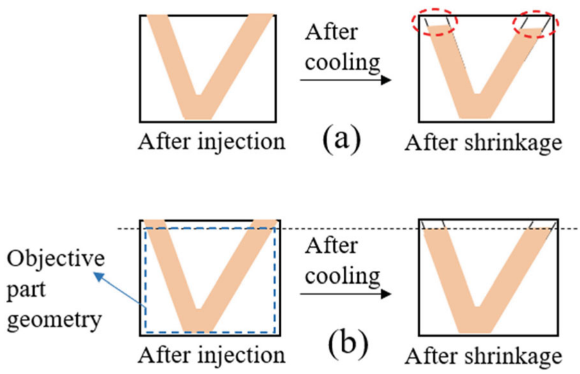

Figure 8. (a) Shrinkage phenomenon; (b) Redesigning the objective part considering compensation.

each design, at least two top open surfaces are necessary, where one for injecting material and another for pushing out the air inside.

2.7. Cost

Cost is another important aspect that needs to be considered during the production process. One simple method is making the bounding box as small as possible with less volume. Taking the part shown in Figure 10 as an example, the bounding box in Figure 10(a) is the best option which uses the least material for 3D printing the outside part, thus saving cost, print time and energy.

3. Experiments and results

3.1. Materials and experimental settings

In this study, PLA was used for additive manufacturing the outside bounding box part. PLA was from Polymaker LTD. The diameter of PLA was 1.75 mm. Low-melting-point alloys

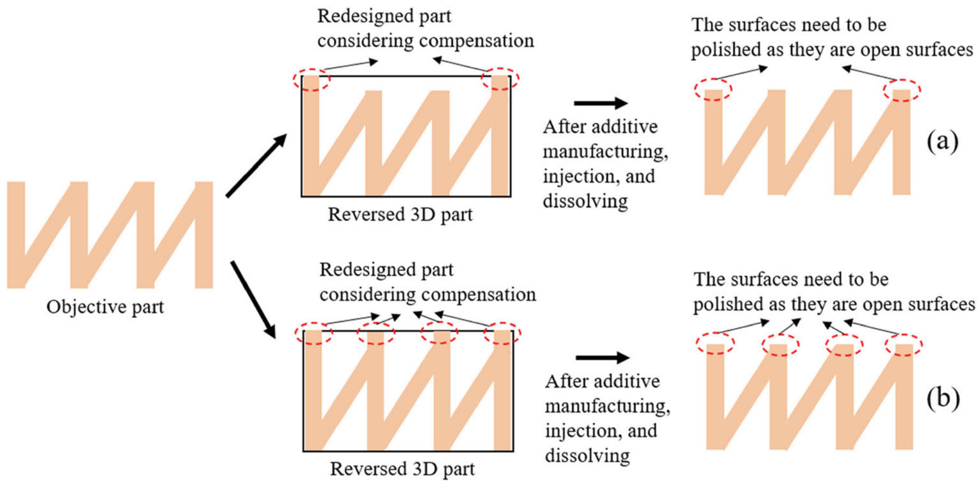

Figure 9. Two different cases of illustrating post-processing with (a) two top open surfaces and (b) four top open surfaces.

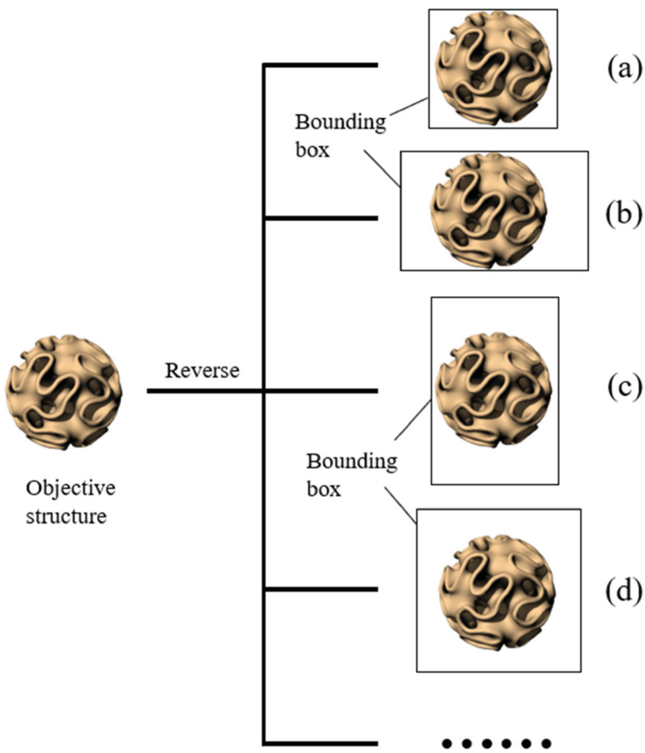

Figure 10. Examples of bounding box options.

(LMPA) were used as the injection material, from Dongguan Houjie Dingtai metal materials LTD, China (consisting of Sn 12.5%, Bi 50%, Pb 25% and Cd 12.5%). The melting point of this LMPA was 70°C. The printed parts were cooled down naturally at room temperature

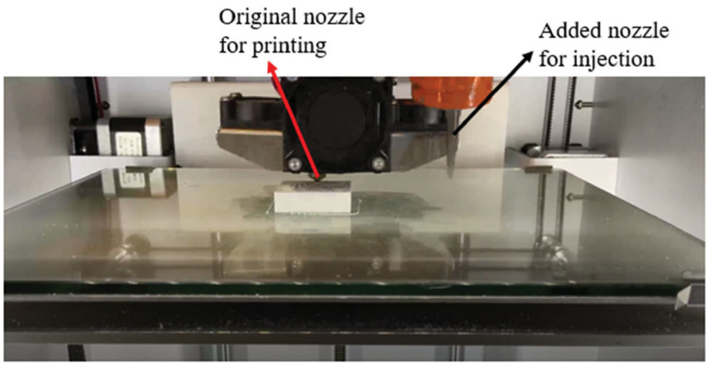

Figure 11. Additive manufacturing machine used for 3D printing.

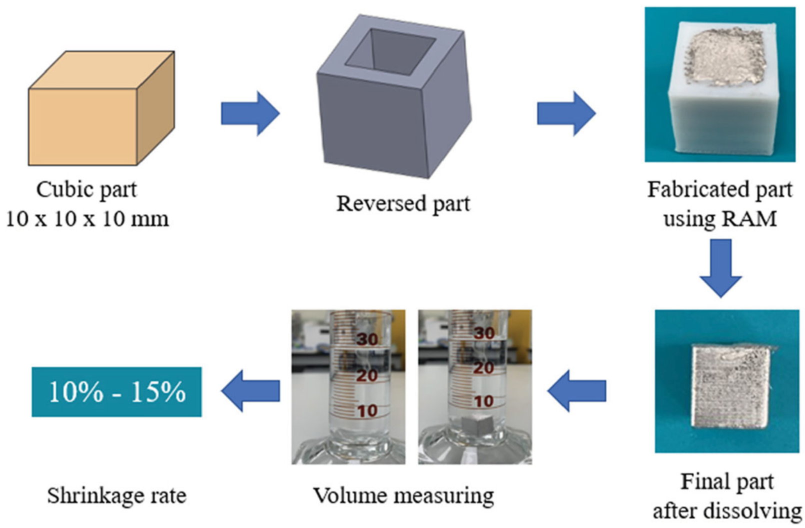

Figure 12. Shrinkage rate testing process.

of 25°C. Dichloromethane (Batch No. 22020141) was used for dissolving PLA, from RCI Labscan Limited, Thailand. The additive manufacturing machine used for 3D printing was from Polarbear 3D, and was customised by the authors. Figure 11 shows the 3D printer with the added second nozzle for injection. The shrinkage rate of LMPA has been tested using the method shown in Figure 12. A cubic part (10 × 10 × 10 mm) was designed and reversed for fabrication using reversed additive manufacturing. After fabrication, the volume of LMPA part was measured and compared with the designed value 1000 mm^3. The shrinkage rate of LMPA is around 10–15% after testing.

In this study, several lattice structures (tesseract, x, vintiles, honeycomb and star) were fabricated using the design rules stated in this paper. The designed lattices, determined print orientations and reversed parts are shown in Figure 13. Table 2 lists the parameters used for fabricating these parts.

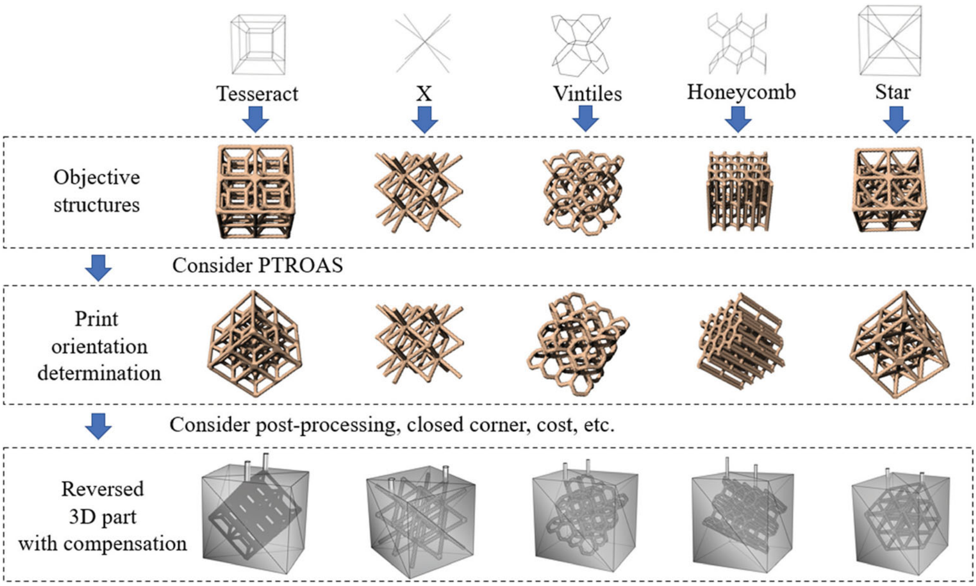

Figure 13. Designed lattice structures, determined print orientations, and reversed parts for testing.

Table 2. Parameters used for fabricating lattice parts.

Parameter	Value	Parameter	Value
Print temperature	210°C	Infill density	20%
Print speed	30 mm/s	Injection temperature	100°C
Layer thickness	0.2 mm	Injection speed	0.5 mm/s

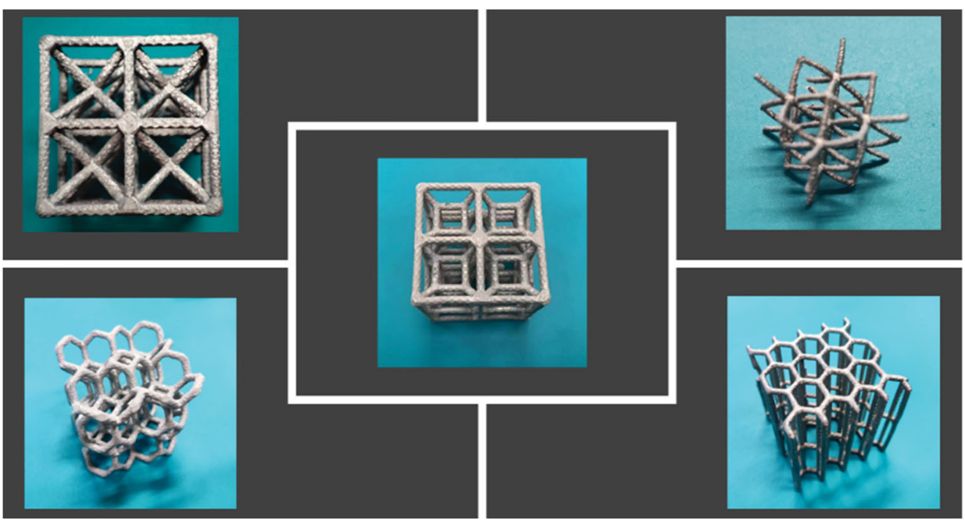

Figure 14. Final fabricated lattice parts.

3.2. Results

The fabrication process of the reversed parts involved soaking them in dichloromethane to dissolve the PLA material and obtain pure LMPA structures. Figure 14 shows the final fabricated lattice parts in good quality. The successful fabrication of these parts can be attributed to the careful adherence to the design rules of PTROAS, print orientation and other parameters as stated above. The absence of any failures, blowholes, cracks, or volume loss of shrinkage attests to the design rules for reversed additive manufacturing, providing more potential applications of LMPA in a variety of areas, from engineering to medicine.

4. Conclusions

From traditional ‘Design for Manufacturing and Assembly’ and ‘Design for Additive Manufacturing’, this paper proposes the concept of design for RAM that is a new hybrid manufacturing technique recently proposed by the authors. The aim of design for RAM is to improve the design and manufacturing efficiency for RAM manufacturing. PTROAS, print orientation, print parameters, injection parameters, shrinkage, post-processing and cost are discussed. Totally speaking, print orientation should be optimised to increase the quality of final manufactured parts considering PTROAS and the shrinkage phenomenon. Print parameter settings need to be considered to balance the fabrication time used and final printed qualities. Labour and time can also be reduced in the post-processing process by reducing the top open surface area. Several case studies (lattice structures) are designed and fabricated using the design method proposed in this paper. However, this paper only focuses on the design for RAM of LMPA. Other materials (e.g. wax) should be investigated in the future. The findings of this paper can be used as a reference for other materials.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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