A Cost-Effective Method for Rapid Manufacturing a Precision Mold With Microstructures Using Hybrid Manufacturing Technologies

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Research Article

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Abstract

Injection molding is a cost-effective to manufacture molded products by injection molding machine. A precision part with microstructures can be fabricated effectively through a precision mold. In this study, a cost-effective method for rapid manufacturing a precision component and a precision injection mold with microstructures by integrating additive manufacturing, rapid tooling, and computer numerical control milling. It was found that of the dimensional accuracy of a precision component in the length, width, and height can be controlled at approximately 30 μm. Injection molding was performed using an injection mold with microstructures with a microstructure of 950 μm and the dimensional accuracy of a molded part in the length, width, and microstructure can be controlled at approximately 60 μm, 50 μm, and 10 μm, respectively. The remarkable findings of this study can be used for the fabrication of molds or dies efficiently and economically for trial production in the mold industry since the quality of the precision component and the precision mold can meet the standards of the general industry.

1. Introduction

In order to maintain company competitiveness, reducing time to the market was considered as one of the important factors. To solve this problem, additive manufacturing (AM) [1] and rapid tooling (RT) technologies were proposed to reduce the production time and production cost. AM can produce prototype with complex geometries. Injection mold can be manufactured in a short time and at low cost by RT because RT can shorten the time to the market compared to conventional machining approaches [2–7]. It is widely known that computer numerical control (CNC) machining is the most effective method to manufacture components or molds with excellent surface quality, good dimensional accuracy, and microstructures [8]. Leal et al. [9] used AM to fabricate the stamping tools for the automotive industry. The mold surface quality is very important for a precision mold. The surface quality of the molds fabricated by AM can be improved by CNC machining [10], mathematic model [11], hot cutter machining [12], chemical finishing [13], or build orientation optimization [14]. In general, the injection mold can be fabricated by metal AM technologies such as direct metal laser sintering (DMLS) [15], electron beam melting (EBM) [16], selective laser melting (SLM) [17], selective laser sintering (SLS) [18], diffusion bonding (DB) [19], or direct metal deposition (DMD) [20].The advantage of the injection mold fabricated by metal AM technology is its excellent mechanical properties. Single trace deposition of Ti-6Al-4V wire over homologous substrate using DMD was investigated [21]. However, the surface quality of the injection mold fabricated by metal AM technology is not acceptable. In order to solve this drawback, hybrid manufacturing technology was proposed. Basinger et al. [22] developed a modular computer-aided process planning system for additive-subtractive hybrid manufacturing of pockets, holes, and flat surfaces. The injection mold can also be fabricated directly by AM using polymer materials such as acrylonitrile butadiene styrene [23–25]. However, the injection mold with microstructures can not be fabricated directly.

According to the literature reviews discussed above, it can be found that developing a low-cost method to rapid manufacture a precision mold with microstructures is an important research issue. In this study, a

simple approach to rapid manufacture a precision injection mold with microstructures was proposed by integrating AM, RT, and CNC milling.

2. Experimental Details

The test part, precision component, molds, and research object were designed with the Pro/ENGINEER computer-aided design (CAD) software. The CAD models were exported as stereolithograpgy files to AM manufacturing system. The CAD models were then horizontally sliced into a set of thin layers using the CURA software (Ultimaker Inc.) for fabricating three-dimensional (3D) physical models. The polylactic acid (PLA) filament with a diameter of 1.5 mm was used as modeling materials to fabricate 3D physical models. The liquid silicone rubber (KE-1310ST, Shin Etsu Inc.) and hardener (CAT-1310, Shin Etsu Inc.) were used to make silicone rubber molds. The silicone rubber and hardener were mixed in a weight ratio of 10:1. A vacuum machine (F-600, Feiling, Inc.) was used to extract the air-bubbles resulting from the mixing process under vacuum conditions. The wax (K512, President Inc.) was selected as a molding material in the injection molding. Injection molding was carried out using a low-pressure wax injection molding machine (0660, W&W Inc.). The process parameters for injection molding are injection pressure of 0.7 kgf/cm^2, degassing time of 7 s, injection temperature of 85°C, and injection time of 5 s. The dimensional changes in the process were measured using a vision measuring system (Quick Vision APEX 404 Pro, Mitutoyo). The recycled aluminum (Al)-filled epoxy resins (TE-365, Jasdi Chemicals Inc.) were then mixed with new epoxy resins (174 AB, Jasdi Chemicals Inc.) as a mixture to fabricate injection molds because this material is suitable for short production runs. The suspension ratio of the specimen was analyzed to determine the optimal mixing ratios of recycled powders and new epoxy resins using an optical microscopy. The fabricated rapid injection mold was then cured using a convection oven (DH400, Deng Yag) for achieving the required mechanical properties. A ball end mills with a radius of 0.5 mm was used to machine microstructures. A ball end mills with a radius of 1 mm was used for plane and surface machining. An end mill with a diameter of 6 mm was used for plane machining. A ball end mill with a diameter of 6 mm and a 0.5 mm corner radius was used for surface tangent plane machining. Figure 1 shows the steps of a cost-effective method for rapid manufacturing a precision part with microstructures using hybrid manufacturing technologies. Figure 2 shows the steps of a cost-effective method for rapid manufacturing a precision mold for injection molding. A product with microstructures was designed firstly. The upper mold and the lower mold were then designed according to the product. A precision mold for injection molding can be fabricated using hybrid manufacturing technologies.

3. Results And Discussion

In order to understand the limits of the microstructure in the physical model fabricated by AM, a physical model with nine different holes was fabricated. Figure 3 shows the different holes in the physical model fabricated by AM. It was found that the fine feature with a diameter less than 1 mm cannot be printed directly. Therefore, a fine feature in the component or mold with a dimension less than 1 mm must be machined by computer numerical control machining. Figure 4 shows the surface quality of a test part

before and after CNC milling. Two important phenomena were observed. One is the surface quality of the physical model can be improved significantly with amount of finish of 0.4 mm in the vertical direction. The other is no more amount of finish in the horizontal direction because the physical model has a dimensional error of about 0.2–0.3 mm in one side of the horizontal direction which can be mainly attributed to the drive motor positioning error. In order to maintain both dimensional accuracy and surface quality of the part after CNC milling, the height of the CAD model needs to add 0.4 mm as the amount of finish. Figure 5 shows the process flows for maintaining both dimensional accuracy and surface quality of the part using CNC machining. Figure 6 shows the result of a test part with microstructures. This result shows the part with excellent surface quality, good dimensional accuracy as well as a microstructure of 950 μm can be fabricated swiftly and economically thought AM, RT, and computer numerical control milling technologies.

The length, width, and height of a precision component are 118 mm, 60 mm and 34.5 mm, respectively. According to the experience of the test part, the length, width, and height are then changed to 118 mm, 60 mm, and 34.9 mm, respectively. The shrinkage of the silicone rubber and Al-filled epoxy resins are almost negligible because the shrinkage of the silicone rubber and Al-filled epoxy resins were approximately 0.5% and 0.8%, respectively. Figure 7 shows the variations in dimension of the precision component manufacturing process for length, width, and height. The average length, width, and height of a precision component after NC machining were 117.97 mm, 60.03 mm, and 34.53 mm, respectively. This result means that the dimensional accuracy of a precision component in the length, width, and height approximately 30 μm can be obtained. In is noteworthy that the quality of this precision component can meet the standards of the general industry because the dimensional accuracy of the precision component in the industry is about 50 μm. Figure 8 shows a precision component before and after CNC milling. As can be seen, this precision component has excellent surface quality and good dimensional accuracy.

The length, width, and microstructures of the injection molded product designed are 57 mm, 36 mm, and 0.95 mm, respectively. The average length, width, and microstructure of the injection molded product are 56.94 mm, 35.95 mm, and 0.94 mm, respectively. Figure 9 shows the variations in dimension of the precision mold manufacturing process for length, width, and microstructures. The shrinkage of the wax is about 1.5%. The dimensional accuracy of a molded part in the length, width, and microstructure approximately 60 μm, 50 μm, and 10 μm can be obtained. This result means a precision mold for injection molding can be fabricated in a short time and at low cost. Figure 10 shows a precision injection mold with microstructure. In order to evaluate the effectiveness of the fabricated precision mold, low-pressure wax injection molding was carried out. Figure 11 shows a wax pattern with microstructures fabricated by a precision injection mold through injection molding. This result shows the fabricated precision mold has excellent mechanical properties[26]for low-volume production of precision wax patterns to manufacture a variety of metallic components using investment casting technology [27–29]. Figure 12 shows a precision injection mold fabricated by only AM technology and hybrid manufacturing technology. This result clearly revealed that it is impossible to fabricate a precision injection mold with microstructures only by the use of AM. A distinct advantage of a precision injection mold fabricated by

the proposed method is no residual thermal stress inside the mold compared to that fabricated by DMLS [30].

Generally, the production costs of a precision injection mold with microstructures fabricated by DMLS, EBM, SLM [31, 32], SLS [33], DB [34], DMD, or laser metal deposition (LMD) is expensive. However, the costs of materials used in this study, such as PLA filaments, silicone rubber, and Al-filled epoxy resins were inexpressive. The 3D physical models were fabricated with PLA filament using fused deposition modeling [35]. The intermediary silicone rubber mold was fabricated by liquid silicone rubber. The component and injection mold were fabricated by Al-filled epoxy resins. The surface quality of the component and injection mold was improved without losing the dimensional accuracy by CNC milling. The microstructures [36, 37] in the component or injection mold were also machined by CNC milling. Therefore, a precision mold with a microstructure can be fabricated swiftly and economically. According to the results discussed above, it can be concluded that a simple and cost-effective method to manufacture a precision mold with microstructures was demonstrated by integrating AM, RT, and CNC milling [38]. The findings of this work are very useful and provide the greatest application potential in both the precision machinery and investment casting industries since this technology can be employed to fabricate a precision mold for most general engineering purposes in the research and development stage. In this study, the material of the final precision injection mold is Al-filled epoxy resins. Ordinarily, the main disadvantage of the precision injection mold is that the mold service life was limited by the characteristics of injection mold materials. Therefore, some reinforcing additives, such as wollastonite, molybdenum disulfide [39–41], silica sand, glass sphere, zirconia [42–44], silicon nitride [45–47], or silica sand were recommended for adding to the injection mold. In this study, the injection mold was employed in wax injection molding for manufacturing precision wax patterns. Note that the proposed method can also be employed in plastic injection molds [48–50,], blow molding dies [51], metal injection molding molds [52], powder metallurgy molds [53], die casting dies [54], hot extrusion dies [55, 56], injection-compression molding molds [57], rotational molding dies, thermoforming molds, transfer molding dies, or hot stamping dies [58]. Finally, it is worth noting that two further studies are required for enhancing the surface quality of a precision mold machined and dimensional accuracy of a precision mold machined. One is accurate tool condition monitoring [59] is required during CNC milling. The other is that the surface quality monitoring [60] of a precision mold is also required during CNC milling. These issues are currently being investigated and the results will be presented in a later study.

4. Conclusions

The aim of this study is to develop a cost-effective approach for rapid manufacturing a precision product with microstructures using a precision mold fabricated by integrating AM, RT, and CNC milling. The proposed method is very effective to fabricate a precision mold, especially for the molded part with complex geometries. Based on the results discussed in this study, the following conclusions can be drawn:

1. The findings of this study are very practical and provide the greatest application potential in the both investment casting and precision machinery industries.
2. A precision mold with a microstructure of 950 μm can be fabricated in a short time and at low cost.
3. The quality of the fabricated precision mold can meet the standards of the general industry and has excellent mechanical properties for injection molding.
4. The dimensional accuracy of a molded part in the length, width, and microstructure approximately 60 μm, 50 μm, and 10 μm can be obtained.

Declarations

Ethical Approval

YES .The manuscript should not be submitted to more than one journal for simultaneous consideration.

YES The submitted work should be original and should not have been published elsewhere in any form or language (partially or in full), unless the new work concerns an expansion of previous work. (Please provide transparency on the re-use of material to avoid the concerns about text-recycling ('self-plagiarism').

YES A single study should not be split up into several parts to increase the quantity of submissions and submitted to various journals or to one journal over time (i.e. 'salami-slicing/publishing').

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Consent to Participate

I understand that all information I provide for this study will be treated confidentially.

Consent to Publish

All authors agreed to the consent to publish.

Author(s): ____

Author's signature: ____________________

Date: ____________________________

Chil-Chyuan Kuo/ 

Authors Contributions

All authors have read and agreed to the consent to the published version of the manuscript.

Arthur 1: Chil-Chyuan Kuo—Wrote the paper/ Conceived and designed the analysis/ Performed the analysis/Conceptualization

Arthur 2/ 3: Bo-Han Lin, Zheng-Ting Luo —Simulation/Experiment/Collected the data/Contributed data or analysis tools

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Conflicts of Interest / Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and materials

Data openly available in a public repository that issues datasets with DOIs

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Figures

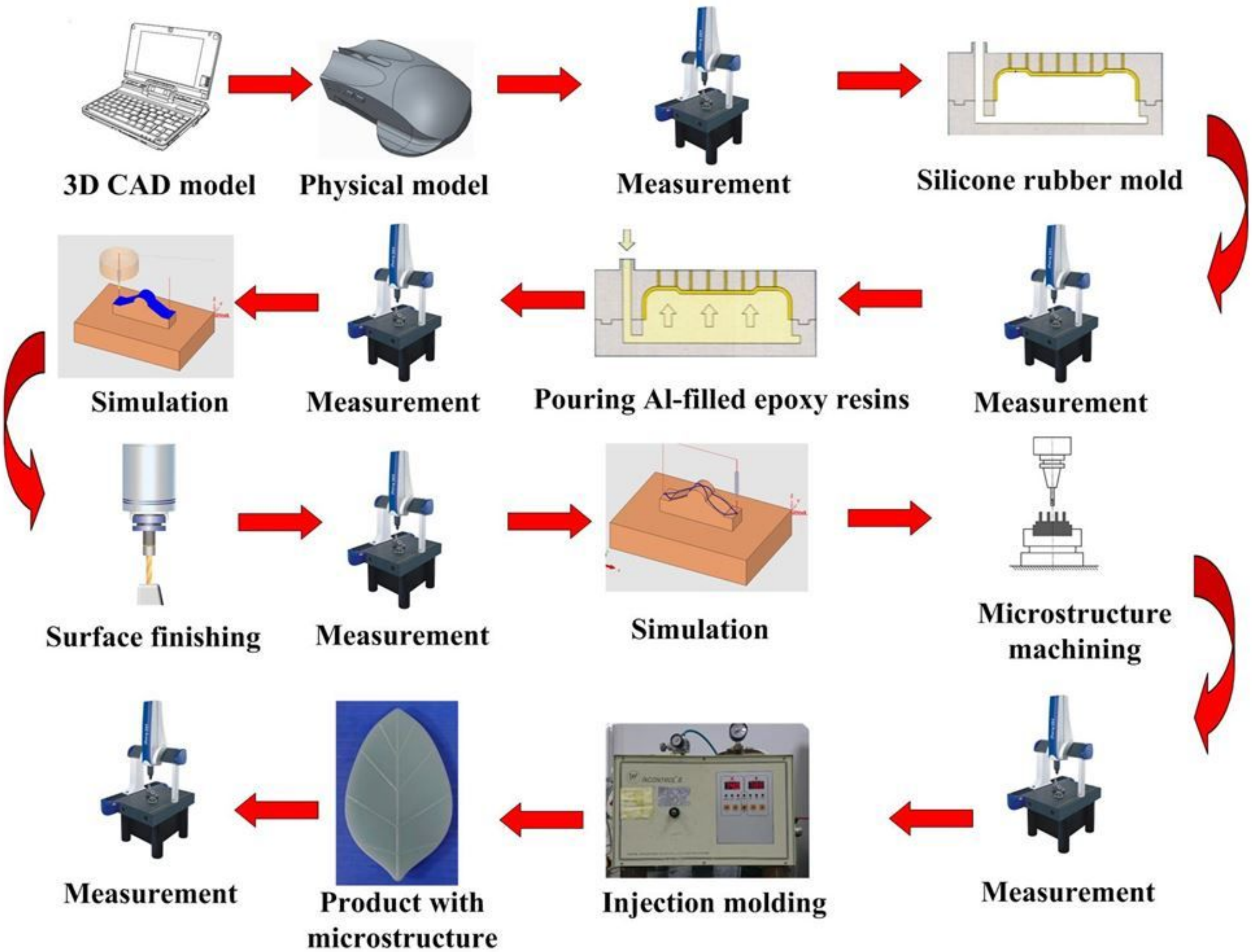

Figure 1

Steps of a cost-effective method for rapid manufacturing a precision part with microstructures using hybrid manufacturing technologies

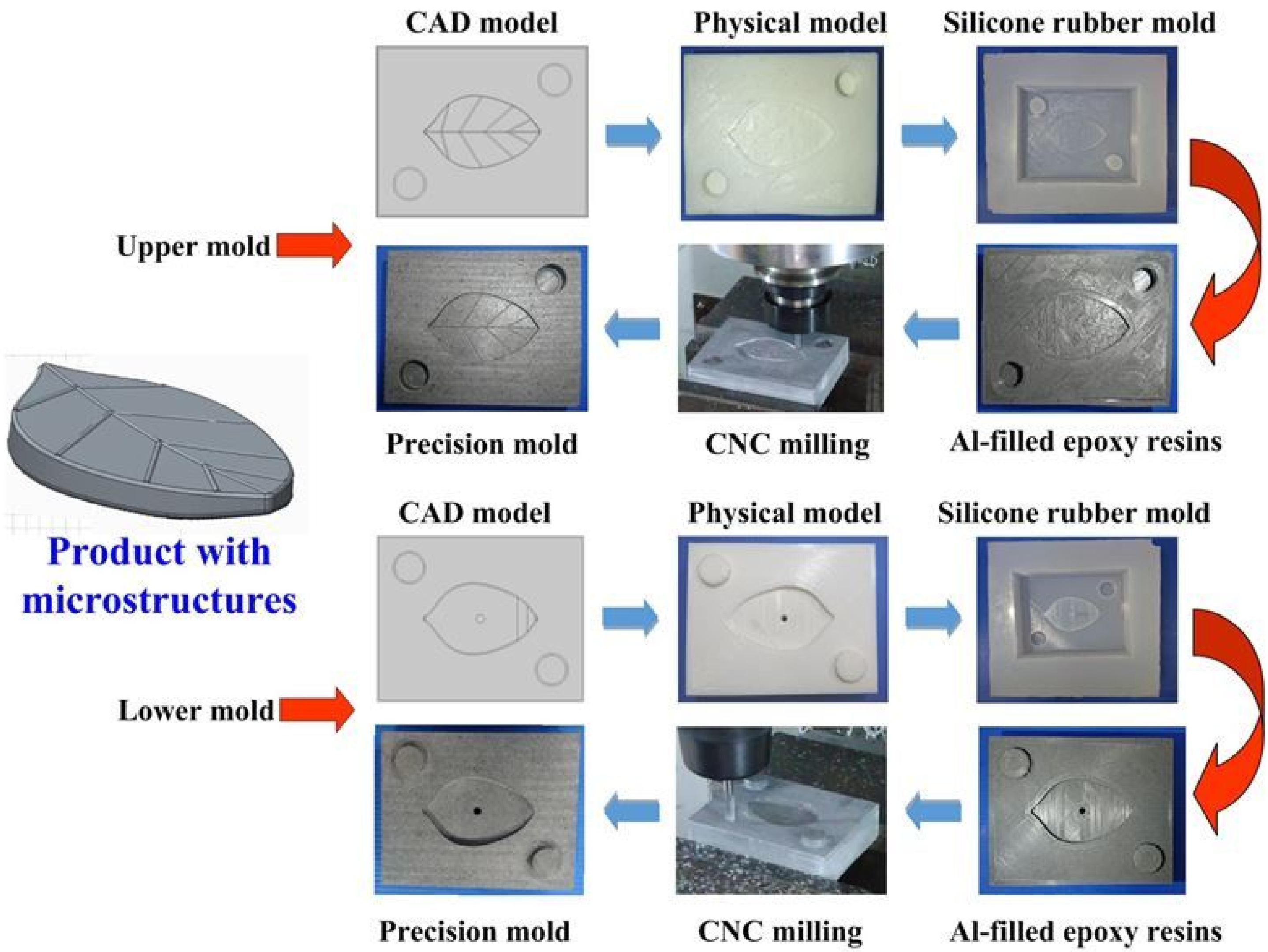

Figure 2

Steps of a cost-effective method for rapid manufacturing a precision mold for injection molding

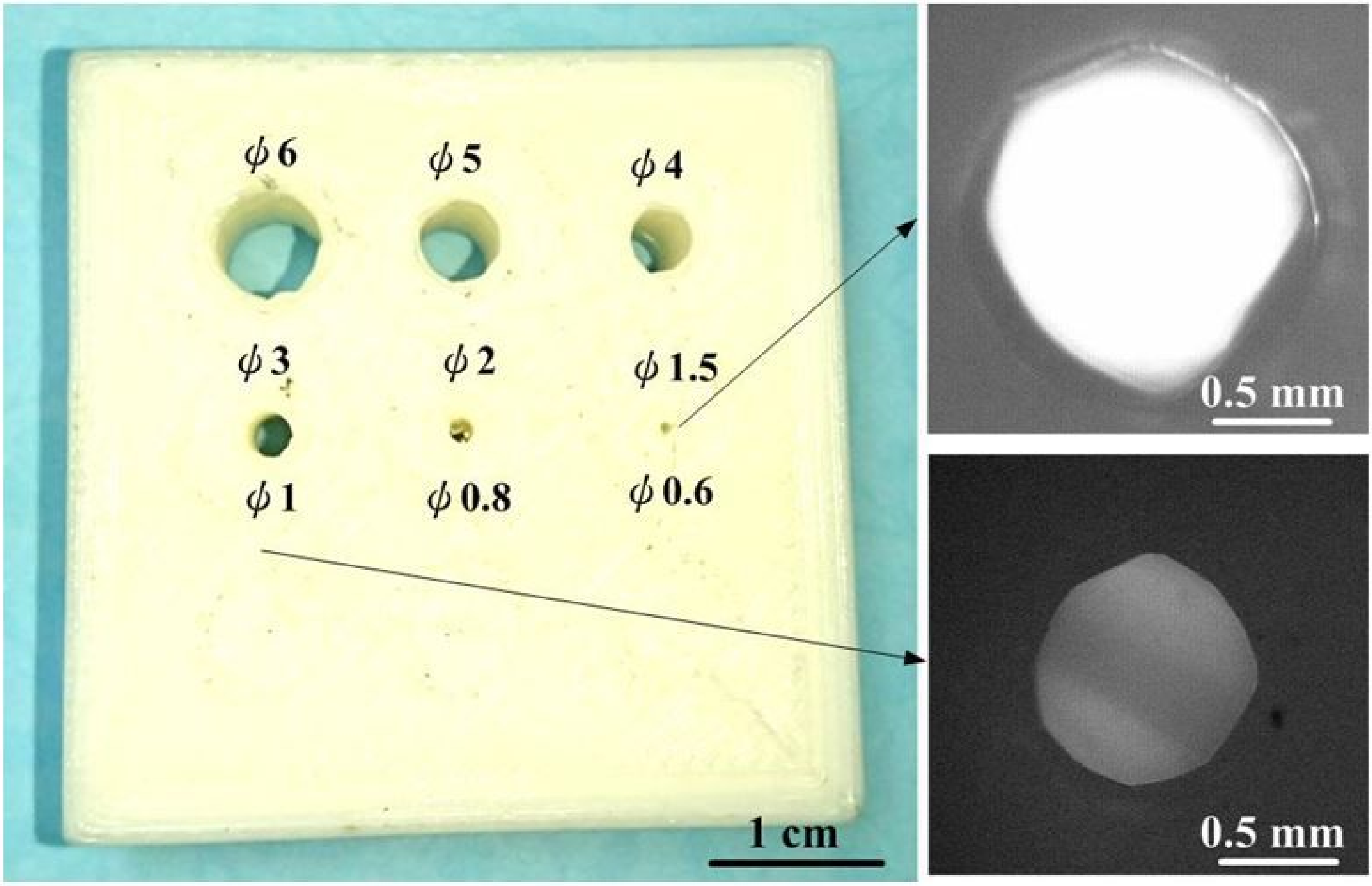

Figure 3

Different holes in the physical model fabricated by AM

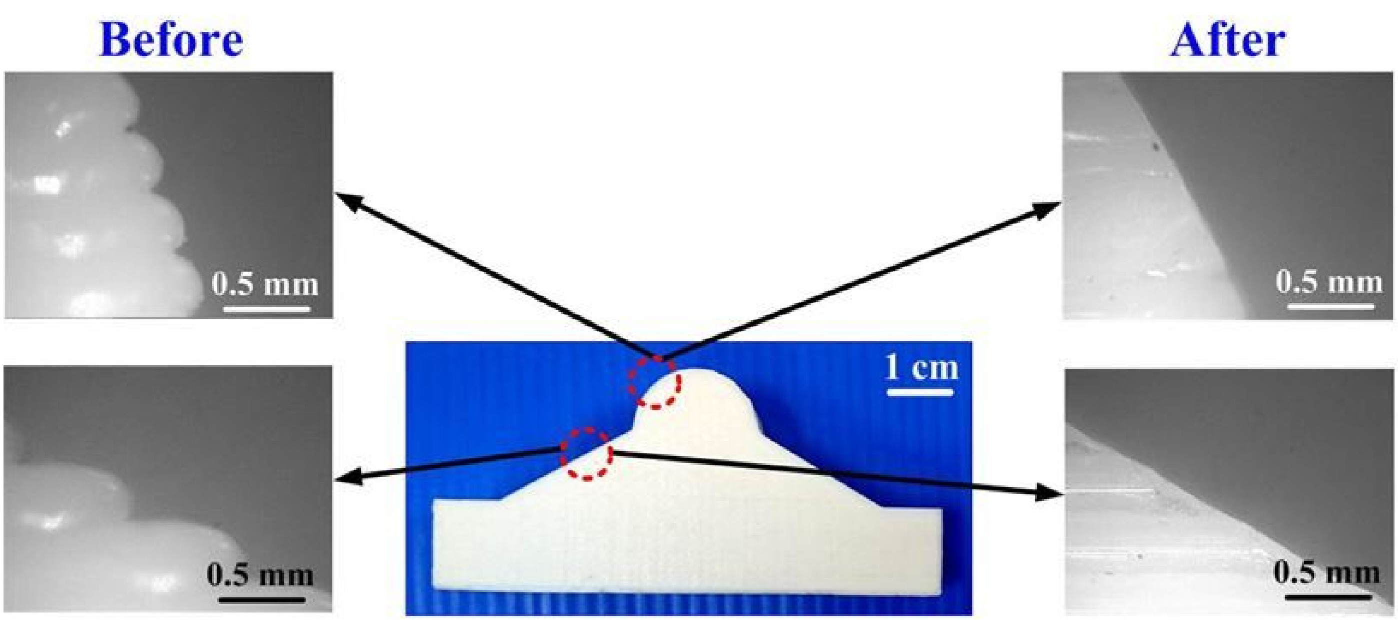

Figure 4

Surface quality of a test part (a) before and (b) after CNC milling

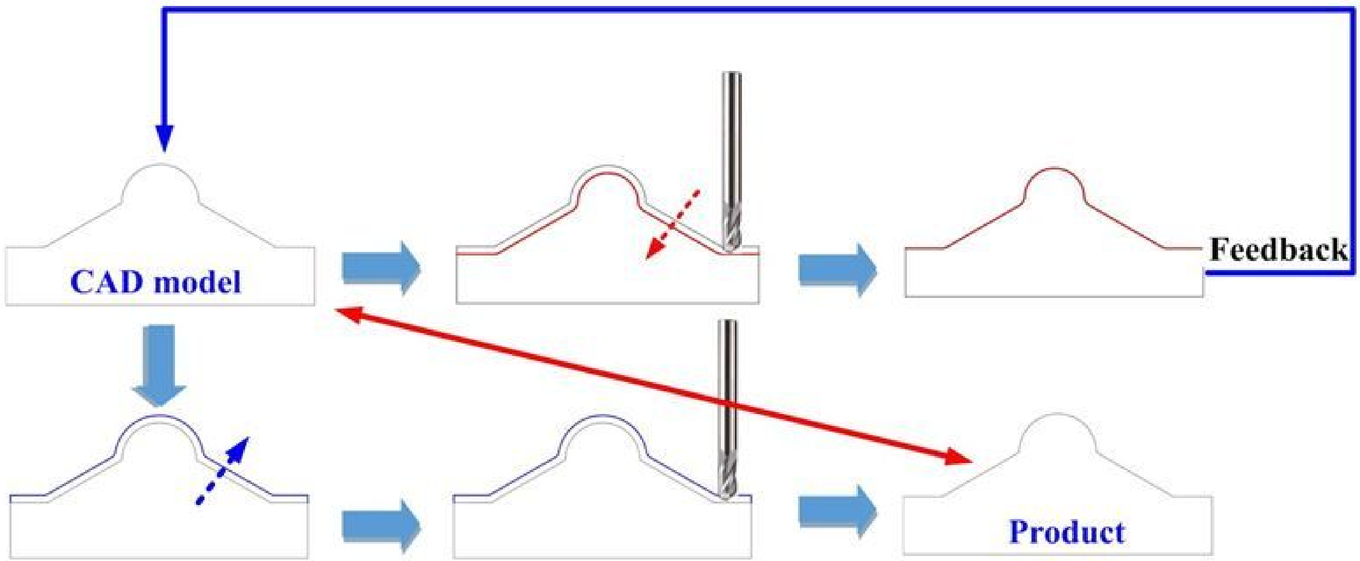

Figure 5

Process flows for maintaining both dimensional accuracy and surface quality of the part using CNC machining

Figure 6

Result of a test part with microstructures

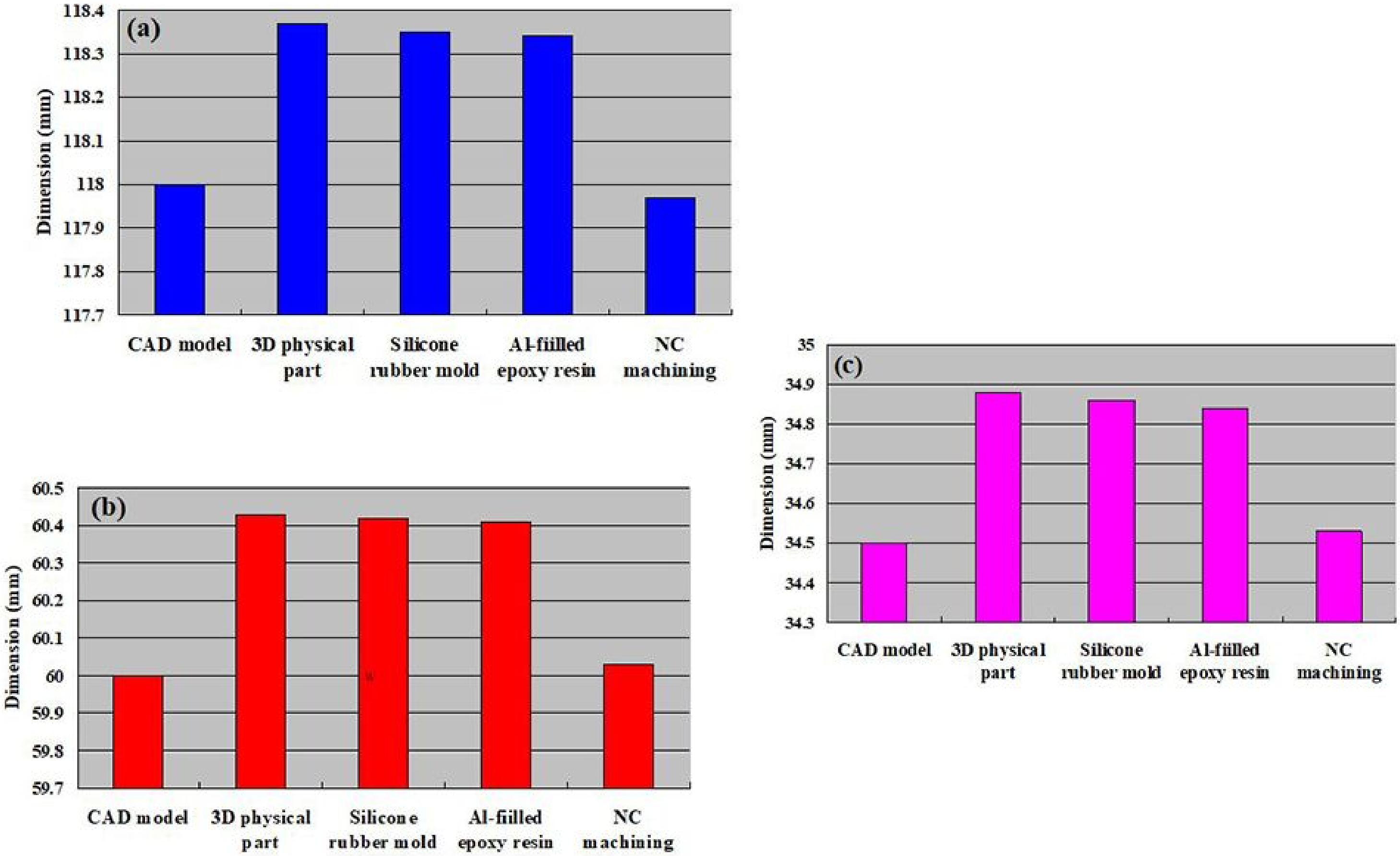

Figure 7

Variations in dimension of the precision component manufacturing process for (a) length, (b) width, and (c) height

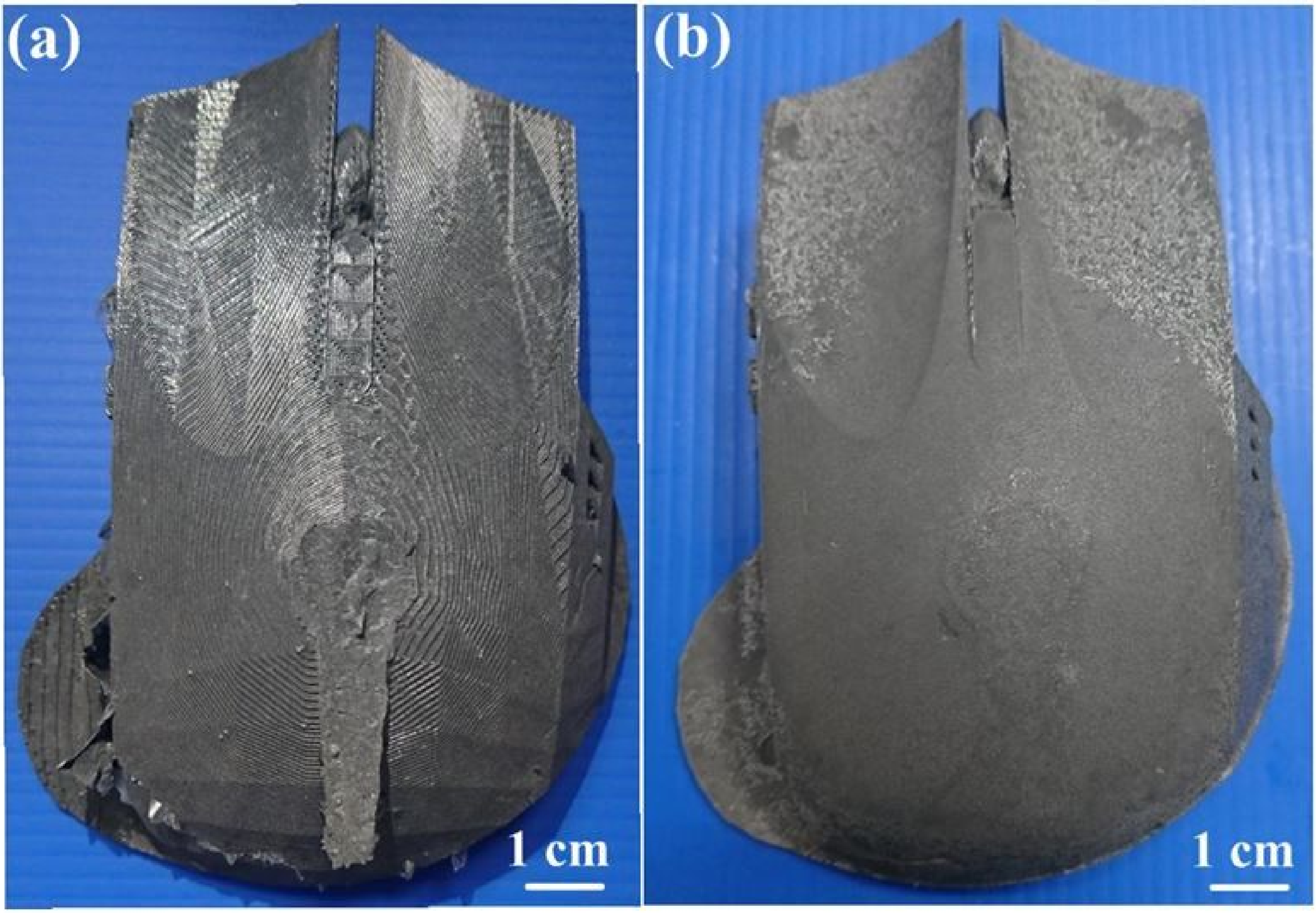

Figure 8

A precision component (a) before and (b) after CNC milling

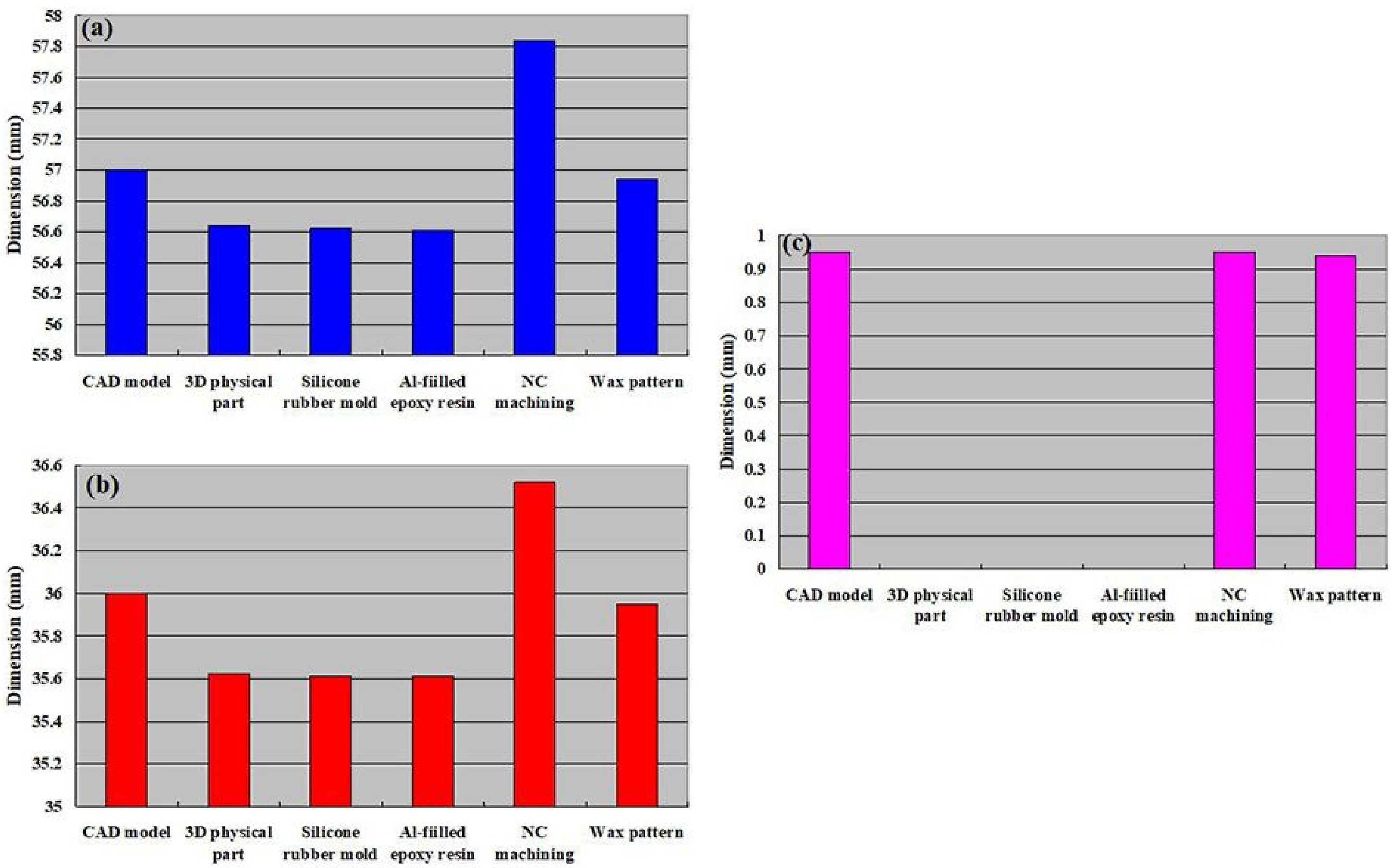

Figure 9

Variations in dimension of the precision mold manufacturing process for (a) length, (b) width, and (c) microstructures

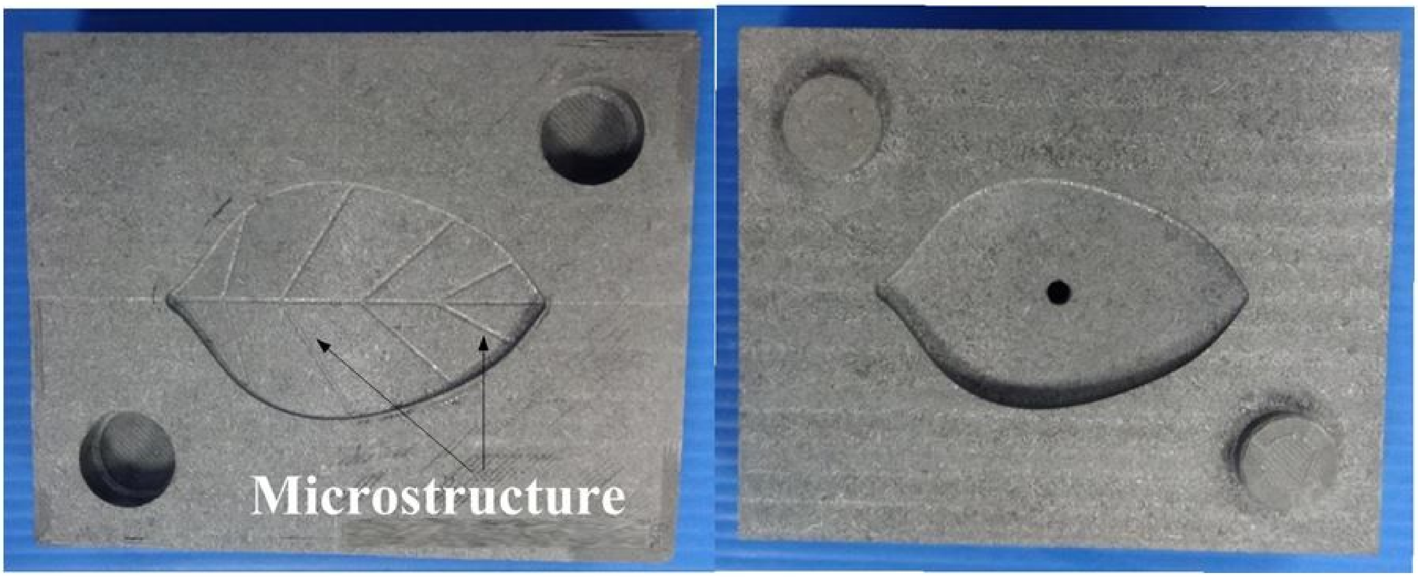

Figure 10

A precision injection mold with microstructure

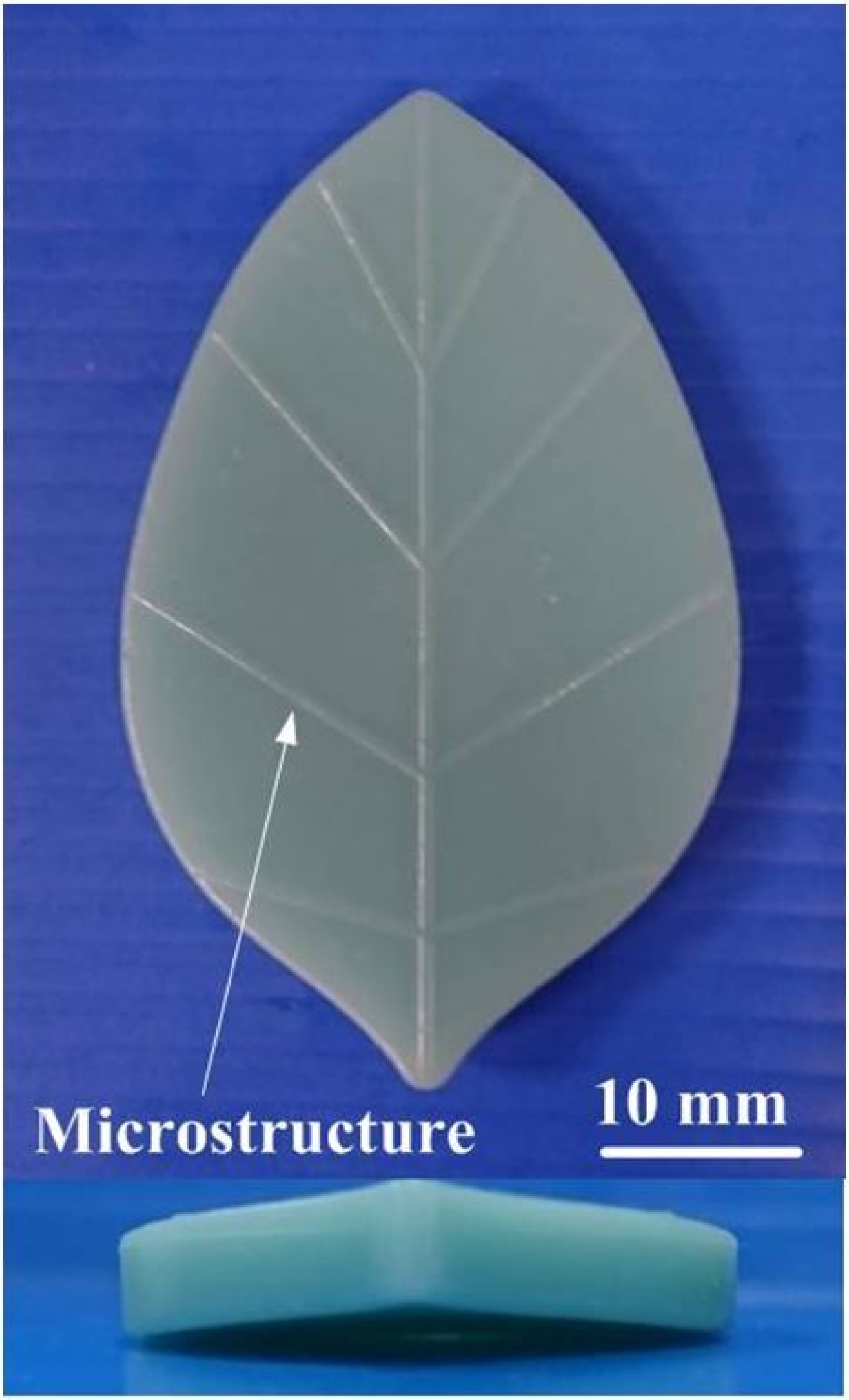

Figure 11

A wax pattern with microstructures fabricated by a precision injection mold through injection molding

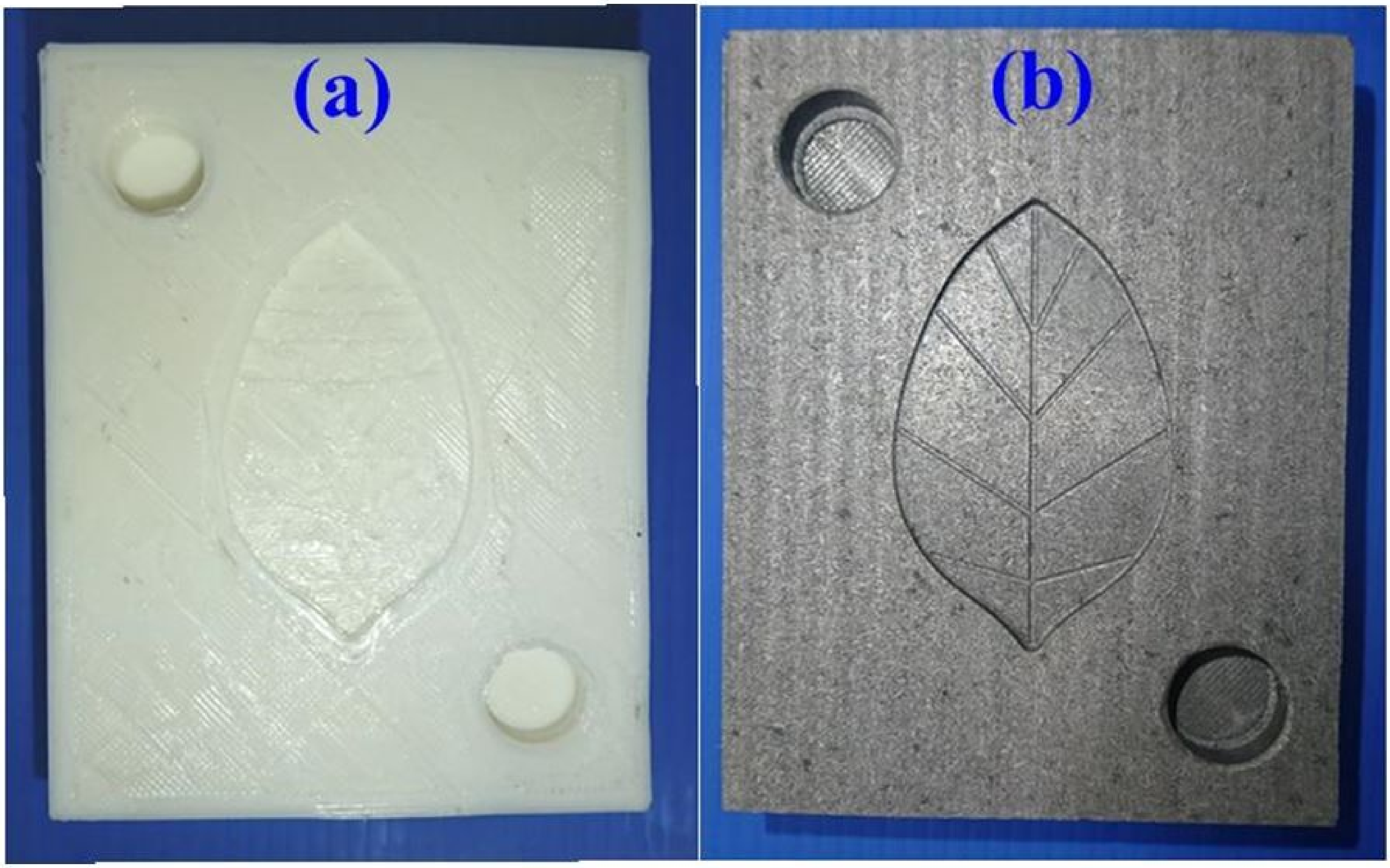

Figure 12

A precision injection mold fabricated by (a) AM technology and (b) hybrid manufacturing technology