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ORIGINAL ARTICLE

Development and application of a large injection mold with conformal cooling channels

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Abstract
Reduction of time and production cost is an important issue in a new product development phase, especially for a large die or mold. In this study, a cost-effective approach was proposed to manufacture a large injection mold with conformal cooling channels. This large injection mold (470 mm × 270 mm × 180 mm) is not easy to fabricate using well-known metal additive manufacturing technology, especially for a new product in the research and development phase. The production cost savings up to 83.4% and the cooling time reduction up to 94.7% were obtained. In addition, a new method for producing wax conformal cooling channels was proposed in this study. Characterizations of a large injection mold with built-in three-dimensional cooling channels were also investigated. It was found that the surface roughness of a large injection mold is superior to that of the injection mold fabricated by direct metal printing (DMP) technology. The surface quality of the cooling channel wall inside the large injection mold is superior to that of the injection mold fabricated by DMP technology.

Keywords Large · Injection mold · Direct metal printing · Surface roughness · Surface quality

1 Introduction

Plastic injection molding is one of the common processes for manufacturing parts by injecting material into a mold [1]. The production rate was not good enough for the molds or dies with the conventional cooling channels machined in straight lines. The molded part's quality and production rate can be improved by the mold with conformal cooling channels. Conformal cooling donates the cooling channels that conform to the surface of the mold's cavity. The molds or dies with complex conformal cooling channels can be fabricated successfully by selective laser melting (SLM) [2], selective laser sintering (SLS) [3], vacuum diffusion bonding (VDB) [4], or direct metal printing. Kitayama et al. [5] examined the cooling efficiency of conformal cooling channel in plastic injection molding (PIM) numerically and experimentally. Holker and Tekkaya [6] developed extrusion dies with conformal cooling channels for increasing the productivity in hot aluminum (Al) extrusion. Lim et al. [7] proposed a method for designing the cooling channel by means of the energy balance principle and arrangement method. Wang et al. [8] employed optimization of mold with spherical spiral conformal cooling system and product structure to reduce service stress of the molded parts. Brooks and Brigden [9] proposed a concept for designing the conformal cooling layers with self-supporting lattices. Vojnová [10] introduced the benefits of molds with conformal cooling systems in the injection molding process. The rapid tooling technology (RTT) provides an alternative approach to quickly manufacture dies or molds for the required products because it could reduce the time to market compared to conventional machining approaches. A wax injection mold with different cross-sectional cooling channels has been developed [11]. However, the removing process of the acrylonitrile butadiene styrene (ABS) conformal cooling channels is not environment-friendly. A low-cost wax injection mold with high cooling efficiency has been developed [12]. A hot embossing stamp with conformal cooling channels for microreplication has been developed [13]. The removing process of the wax conformal cooling

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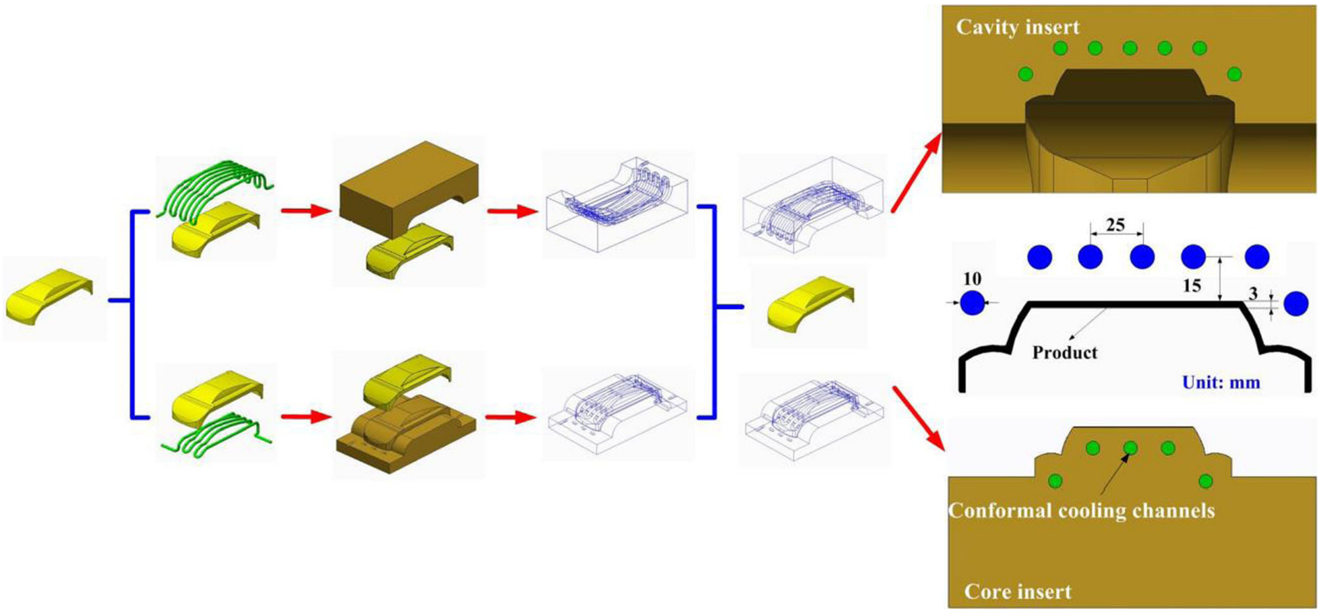
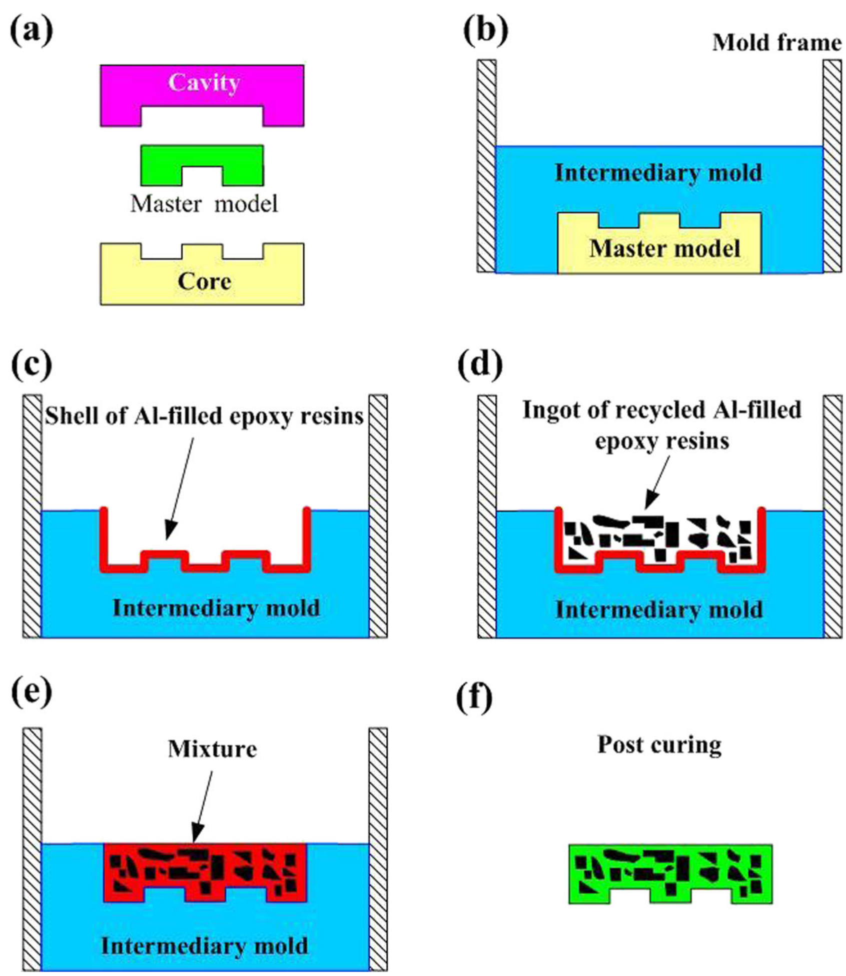


Fig. 1 Process layouts for fabricating a large injection mold tooling with conformal cooling channels

Fig. 2 A cost-effective method for fabricating a large injection mold. (**a**) Designing core insert and cavity insert for the master model; (**b**) fabrication of intermediary mold using liquid silicone rubber; (**c**) fabrication of shell of a large injection mold using aluminum-filled epoxy resin; (**d**) placing the ingot of recycled aluminum-filled epoxy resin into the mold frame; (**e**) pouring the mixture into the mold frame; and (**f**) post-curing of a large injection mold



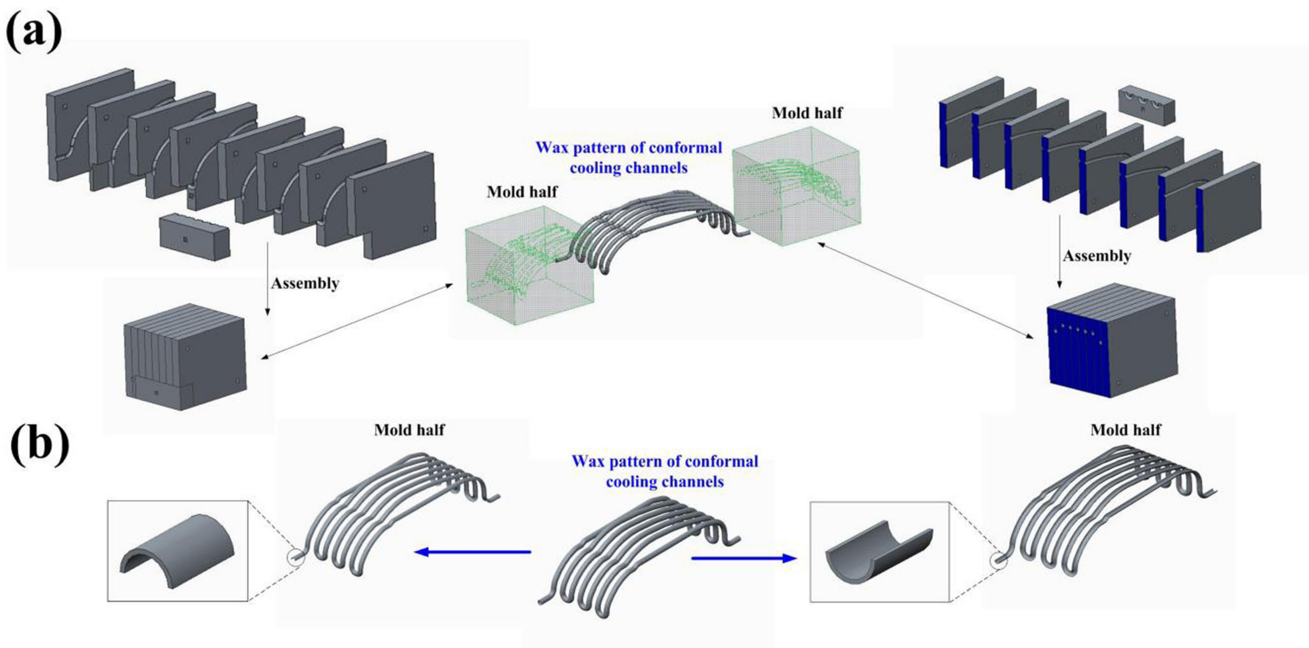


Fig. 3 Two methods for producing wax conformal cooling channels: (**a**) multi-segment method and (**b**) bisection method

channels is easy and environment-friendly. However, the production cost for a large injection mold with complex conformal cooling channels is costly. Thus, developing a cost-effective method for fabricating a large injection mold is an important research issue. In this study, a low-cost and environment-friendly approach for fabricating a large injection mold with built-in three-dimensional (3D) cooling channels was proposed. The qualities of both mold surface and geometries of conformal cooling channels were compared to those fabricated by direct metal printing (DMP) technology.

2 Experimental details

A manufacturing process for fabricating a large injection mold with complex geometric conformal cooling channels was developed. A large injection mold was built through transfer RTT. Figure 1 shows the process layouts for fabricating a large injection mold with conformal cooling channels. A car's shell was selected as a master model. The dimensions of a master mode are 310 mm in length, 150 mm in width, and 90 mm in height. The cooling channels for core and cavity inserts were

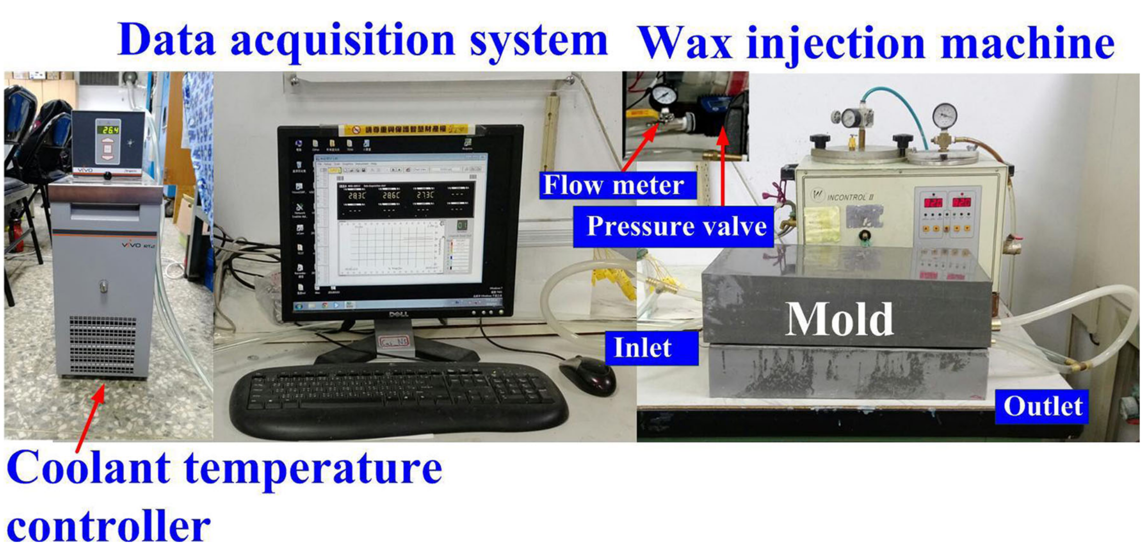


Fig. 4 Experimental setup for investigating the cooling efficiency of fabricated injection molds

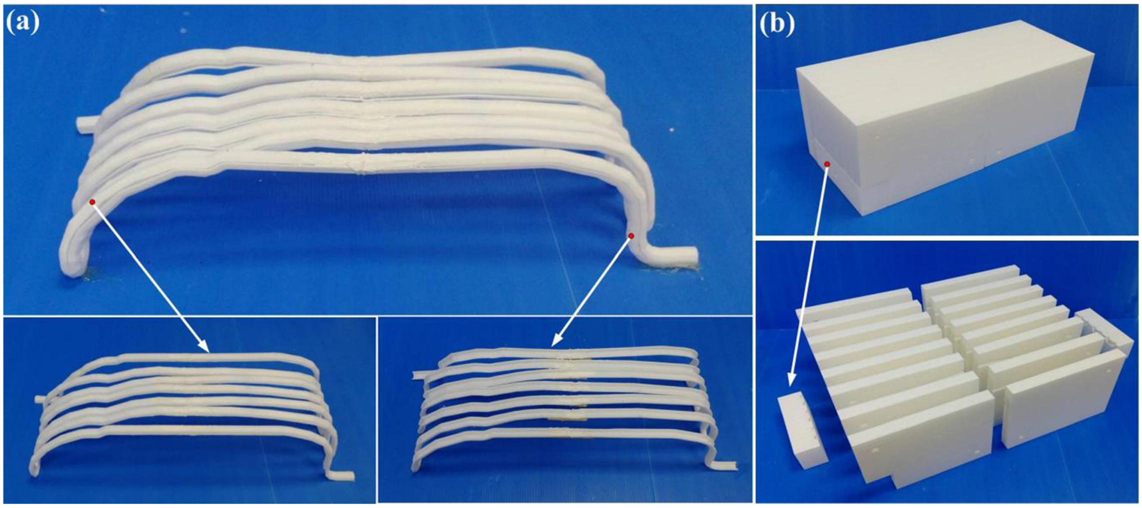


Fig. 5 Molds fabricated by the (**a**) bisection method and the (**b**) multi-segment method for producing wax conformal cooling channels

designed by using Pro/ENGINEER software according to the geometries of the master model. According to the conformal cooling channel design guideline [14–16], the cooling channel diameter, center distance between cooling channels, and center distance with respect to mold cavity is 10, 15, and 25 mm, respectively, because the wall thickness of the molded part is 3 mm. The material used for manufacturing the master model was ABS due to its excellent mechanical properties [17, 18]. The wax conformal cooling channels were manufactured by a wax injection machine (0660, W&W Inc.). An intermediary mold, which is complementary in shape to the injection mold, was fabricated by both liquid silicone rubber (KE-1310ST, Shin Etsu Inc.) and polyurethane foam. The liquid silicone rubber was used as a surface material of the intermediary mold. In order to reduce the production cost, the polyurethane foam was, then, added to the back of the silicone rubber shell to give the support of the silicone rubber shell. The backside of the intermediary mold was sealed with liquid silicone rubber. In order to reduce the production cost of a large injection mold, the recycled pieces of Al-filled epoxy resins (TE 375, Jasdi Chemicals Inc.) were machined into fine powders using a milling machine [19]. Figure 2 shows a cost-effective method for fabricating a large injection mold. The measurement of average particle sizes of powders was carried out using scanning electron microscopy (SEM) (MH-12C07AA8, Sumitomo Inc.). The recycled powders were, then, mixed with

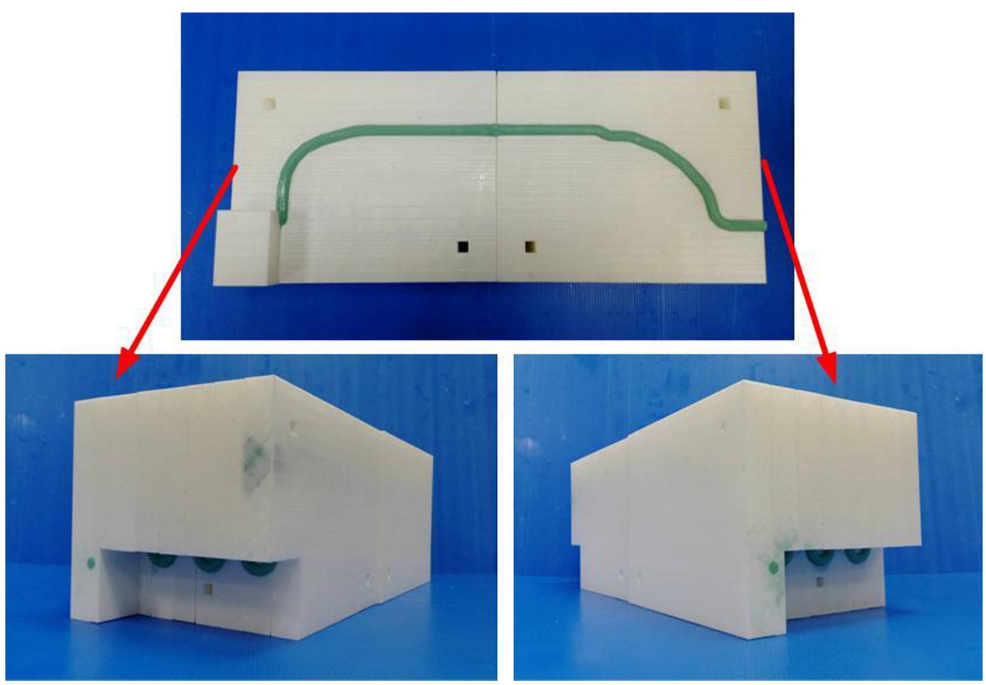


Fig. 6 A typical wax conformal cooling channel inside the mold fabricated by the multi-segment method

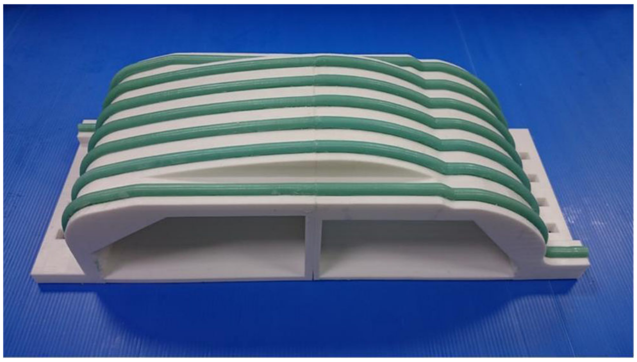


Fig. 7 A typical wax conformal cooling channel inside the mold fabricated by the modified bisection method

new epoxy resins (174 AB, Jasdi Chemicals Inc.) as a mixture to manufacture a large injection mold with conformal cooling channels. In order to study the optimal mixing ratios of recycled powders and new epoxy resins, 11 different weight ratios (2.4:1, 2.3:1, 2.2:1, 2.1:1, 2:1, 1.9:1, 1.8:1, 1.7:1, 1.6:1, 1.5:1, 1.4:1) were employed to fabricate specimens. The dimensions of a mold for fabricating the specimen are 50 mm in length, 35 mm in width, and 20 mm in height. The suspension ratio of the specimen was analyzed to determine the optimal mixing ratios of recycled powders and new epoxy resins using an optical microscope (OM) (M835, Microtech Inc.). A vacuum machine (F-600, Feiling) was used to eliminate air bubbles from the resulting mixture. The fabricated injection mold was, then, cured using a convection oven (DH400, Deng Yag) for achieving the required mechanical properties.

In this study, 3D printing technology was used to make the molds for fabricating wax conformal cooling channels. The material used to manufacture molds for fabricating wax conformal cooling channels was polylactic acid (PLA). According to the parting line of the cooling channels, two methods are proposed to make molds for producing wax conformal cooling channels, in this study. One is a multi-segment method, in which the mold is composed of a number of multiple segments. The other is a bisection method, in which the mold is composed of two half-sections. Figure 3 shows the two methods for producing wax conformal cooling channels. The shape and size of the conformal cooling channels were investigated using OM. The characteristics of the fabricated injection mold was investigated and compared to the injection mold fabricated by DMP technology (ProX 100, 3D System, Inc.) using white light interferometry (WLI) (7502, Chroma Inc.). The centerline average surface roughness (Ra) value was used to evaluate the changes in the surface roughness. The measurement area is 350 μm × 350 μm.

In order to evaluate the cooling efficiency of a large injection mold with complex conformal cooling channels, the molding process was carried out by a low-pressure wax injection machine (0660, W&W Inc.). Figure 4 shows the experimental setup for investigating the cooling efficiency of fabricated injection molds. This system comprises hoses, temperature controlling unit, thermocouples (C071009-079, Cheng Tay Inc.), and data acquisition system (MRD-8002L, IDEA System Inc.). The water was used as the coolant in the cooling system. One water reservoir with a thermo-electric cooler (TEC12706AJ, Caijia Inc.) and a temperature controller (JCM-33A, Shinko Inc.) was used to maintain the coolant temperature. The inlet coolant temperature was kept at room temperature. A wax injection machine was used to fabricate wax conformal cooling channels. Three k-type thermocouples were placed in the wax injection molds for online measuring temperatures of the molded

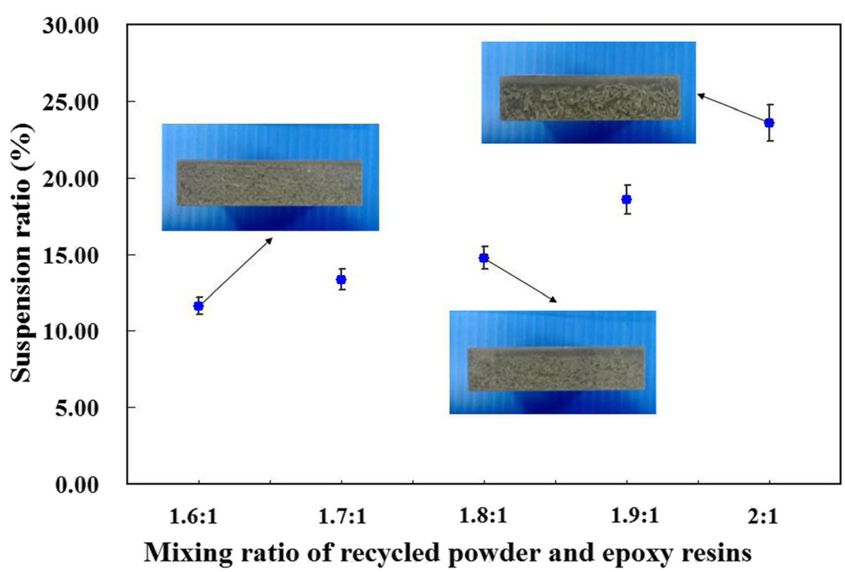


Fig. 8 Suspension ratios of the epoxy resins as a function of mixing ratio of recycled powder and epoxy resins

part, inlet coolant temperature, and outlet coolant temperature. Temperature histories were recorded by a data acquisition system. The thermocouple was placed at a fixed location in the cavity. This location is the final solidification of the molded part. The heat transfer is highly efficient when the flow in the cooling channels is turbulent. The performance of the wax injection mold with different kinds of cooling channels was investigated. The ejection temperature of the molded parts was determined at 30 °C through a series of test runs. The cooling time of the molded parts for an injection mold with and without cooling channels after the wax injection molding was measured and analyzed.

3 Results and discussion

Figure 5 shows the molds fabricated by the bisection and the multi-segment methods for producing wax conformal cooling channels. The advantage of the bisection method is that few materials were used for fabricating the mold. However, the wax conformal cooling channels cannot be easily produced by a mold fabricated by a bisection method because the wall thickness of a mold is too thin. Conversely, the wax conformal cooling channels can be easily produced by a mold fabricated by the multi-segment method, as shown in Fig. 6. The disadvantage of the multi-segment method is that more materials were used for fabricating the mold. In order to overcome the drawbacks of both the bisection and the multi-segment methods, a modified bisection method was proposed. Figure 7 shows a typical wax conformal cooling channel inside the mold fabricated by the modified bisection method. This method was characterized by less material used for fabricating the mold. In addition, wax conformal cooling channels were easy to produce. This result reveals that the modified bisection method can be recommended to produce wax conformal cooling channels with complex geometric shapes.

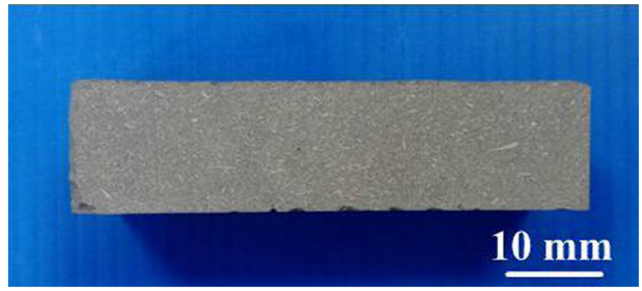


Fig. 10 Recycled powders dispersed into the mixture homogeneously

The manufacturing costs for mold or die with conformal cooling channels fabricated by DMP, SLM, SLS, or VDB are inexpensive, especially for a large injection mold. In order to reduce the production cost of a large injection mold, the recycled powders were used in this study. The idea of using recycled powders as base matrix materials for fabricating a large injection mold is that it is a green RTT due to reduction of accumulation of waste materials. The 11 different weight ratios were prepared for investigating the optimal mixing ratios of recycled powders and new epoxy resins. The average particle size of the recycled powders is about 123 μm. In order to prevent the agglomeration [20] of recycled powders in the mixture, an ultrasonic machine was employed in the mixing process. The suspension ratio is defined as the ratio of epoxy resin floats above the mixture. Figure 8 shows the suspension ratios of the epoxy resins as a function of mixing ratio of recycled powder and epoxy resins. The results clearly show that the suspension ratio of the epoxy resins for the mixing ratio of recycled powder and epoxy resins of 1.6:1 is the lowest. For the mixing ratio below 1.5:1, the

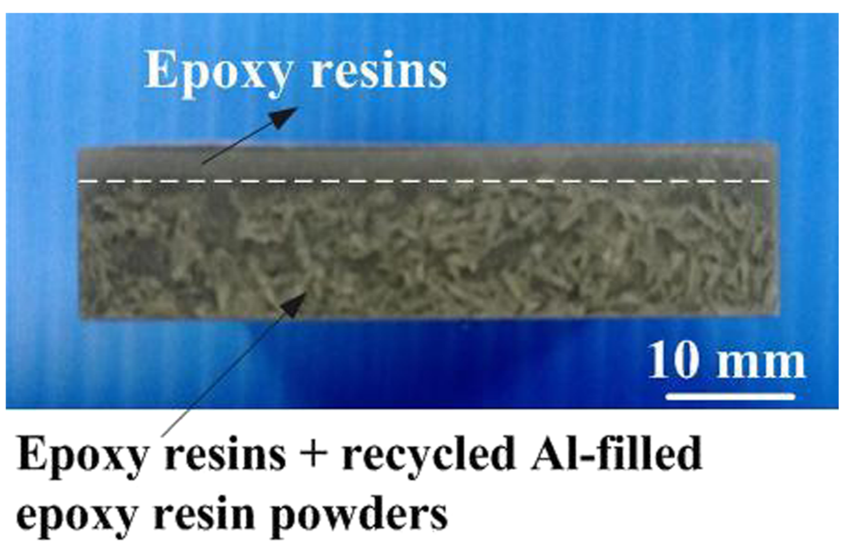


Fig. 9 Epoxy resin suspension results

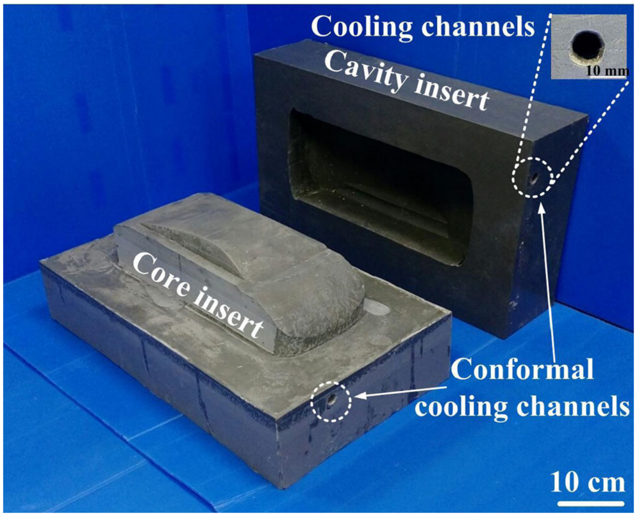
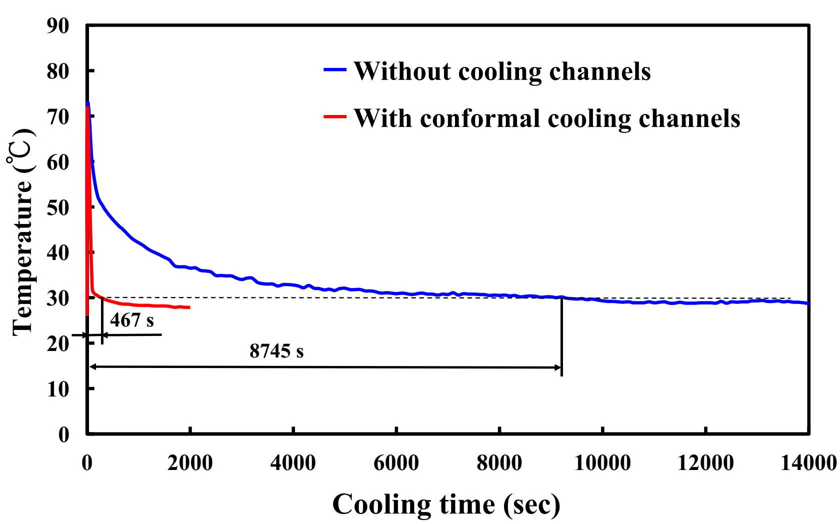


Fig. 11 A large injection mold with conformal cooling channels

viscosity of the mixture is too high; thus, it cannot be poured into the mold frame. For the mixing ratio higher than 2:1, the suspension ratio of the mixture is too high; thus, it cannot be employed for fabrication of the injection mold, as shown in Fig. 9. In order to reduce the suspension ratios of the epoxy resins to zero for the mixing ratio of 1.6:1, the dispersant [21] was added into to the mixture. In this study, 2, 3, 4, 5, 6, 7, and 8 wt% dispersants were added into the mixture. It was found that the suspension ratio of the epoxy resins is about 0% for all the specimens. This result means that the recycled powders were dispersed into the mixture homogeneously, as shown in Fig. 10. The function of the dispersant is to prevent the sedimentation of the denser Al particles in the mixture. In order to further study the effectiveness of dispersant, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 wt% dispersants were added into the mixture. The results show that the suspension ratio of the epoxy resins is also about 0% for all the specimens. According to the above-mentioned research results, it was found that the recycled powder can be dispersed uniformly into the mixture just by adding a small amount of dispersant into the mixture for the mixing ratio of 1.6:1. It is interesting to note that the approach proposed in this study meets the objectives of green manufacturing [22, 23] and provides the greatest application potential in the precision machinery because of the production cost reduction increases with the increase of the sizes of the injection mold.

In general, the process of fabricating an injection mold with conformal cooling channels using conventional machining is considered a highly skilled task that is time-consuming. RTT is a process utilizing additive technology directly or indirectly to manufacture molds or dies for short-run production. Thus, it is an effective way to make a large injection mold with or without cooling channels. Figure 11 shows a large injection mold with conformal cooling channels. It should be noted that the wax cooling channels were removed completely. The length, width, and height of a large injection mold are 470, 270, and 180 mm, respectively. It is noteworthy that it is difficult to fabricate such a large injection mold using the atom diffusion additive manufacturing (ADAM), electron beam melting (EBM) [24], SLM [25], SLS [26], direct metal deposition (DMD) [27], direct metal laser sintering (DMLS) [28], or DMP due to size restriction of print beds. In order to fabricate a large injection mold, 55.973 kg of material is required. The costs of new Al-filled epoxy resins, epoxy resin 174 A and B, are new Taiwan dollar (NTD) 3000 and 750 per kilogram, respectively. The production costs of a large injection mold with cooling channels are only NTD 27,845, while that of the large injection mold with cooling channels fabricated by all the new Al-filled epoxy resins is NTD 167,073. The production cost savings about 83.4% can be obtained using the method proposed in this work. It is interesting to note that the results obtained in this study are very practical and have

Fig. 12 Temperature of the molded part as a function of the cooling time for injection mold with and without conformal cooling channels. The coolant temperature and the coolant flow rate are 27 °C and 2.8 L/min, respectively



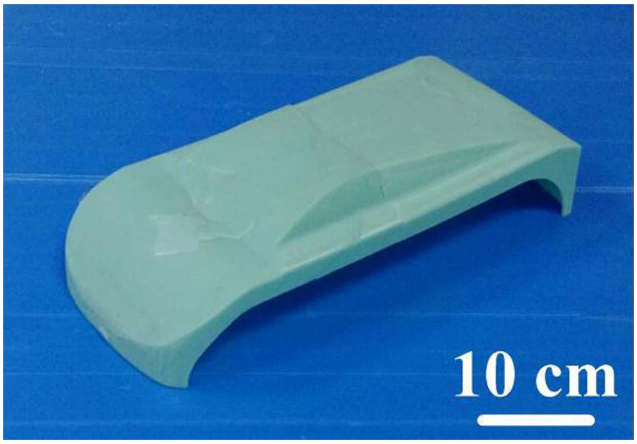


Fig. 13 A typical large molded part fabricated by an injection mold with conformal cooling channels

potential application for the precision mold industry because of the production cost reduction increases with the increase of the sizes of the injection mold. Thus, the approach proposed in this work is a cost-effective method to fabricate a large injection mold.

To understand the difference between the mold with and without conformal cooling channels, a series of tests was carried out. The process parameters for injection molding are an injection pressure of 0.06 MPa, injection temperature of 82 °C, and filling time of 40 s. Figure 12 shows the temperature of the molded part as a function of the cooling time for injection mold with and without conformal cooling channels. The complex conformal cooling channels follow with the molded part's contours to facilitate uniform and faster cooling. It is clear that there is a notable difference between cooling efficiency for wax injection molds with and without cooling channels. The cooling time of the injection mold without cooling channel is 8745 s, while that of the injection mold with a conformal cooling channel is only 467 s. This result means that the cooling efficiency for the injection mold with a series of conformal cooling channel about 94.7% can be enhanced. Figure 13 shows a typical large molded part fabricated by an injection mold with conformal cooling channels. The dimensions of the molded part are 310 mm in length, 150 mm in width, and 90 mm in height.

To understand the effect of coolant temperature on the cooling time, a series of tests was carried out. Figure 14 shows the temperature of the molded part as a function of the cooling time for four different coolant temperatures. As can be seen, the cooling time is 510, 380, 160, and 95 s when the coolant temperature is 27, 20, 15, and 13 °C, respectively. This result indicates that the cooling time will become shorter when the cooling system uses a lower temperature coolant. The coolant flow rate is an important issue on the cooling efficiency for injection mold with conformal cooling channels. In general, the turbulent flow (Reynolds number > 4000) provides three to five times as much heat transfer as laminar flow (Reynolds number < 2100) [29]. The coolant flow performs the complete turbulence when the Reynolds number exceeds 4000 [30]. In this study, four different coolant flow rates were used, 2.8, 3.9, 4.5, and 5.5 L/min. The Reynolds number for the four different coolant flow rates is about 5945, 8280, 9554, and 11,677, respectively. As can be seen, the four coolants reach turbulence completely.

To understand the effect of the coolant flow rate on the cooling time, a series of tests was carried out. Figure 15 shows the temperature of the molded part as a function of the cooling time for the different coolant flow rate. As can be seen, the cooling time of the molded part for the coolant flow rate of 2.8, 3.9, 4.5, and 5.5 L/min is 549, 880, 1026, and 1131 s, respectively. This result indicates that the cooling time of the

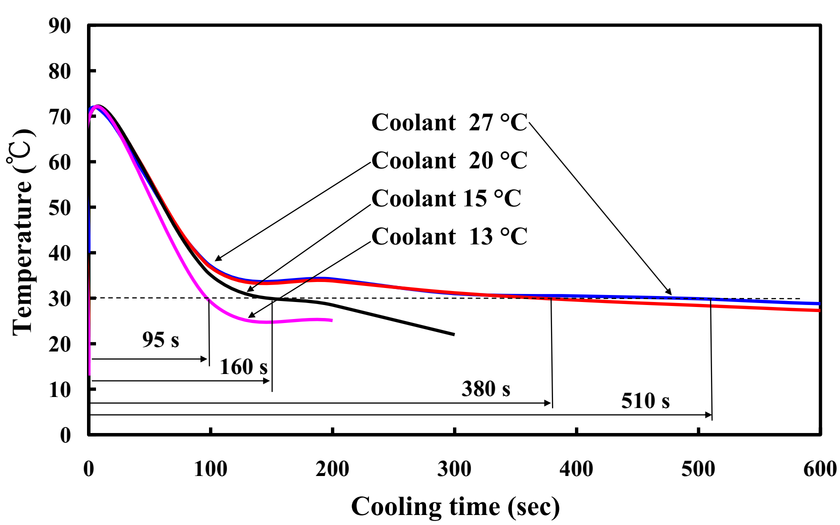


Fig. 14 Temperature of the molded part as a function of the cooling time for the four different coolant temperatures. The coolant flow rate is 2.8 L/min

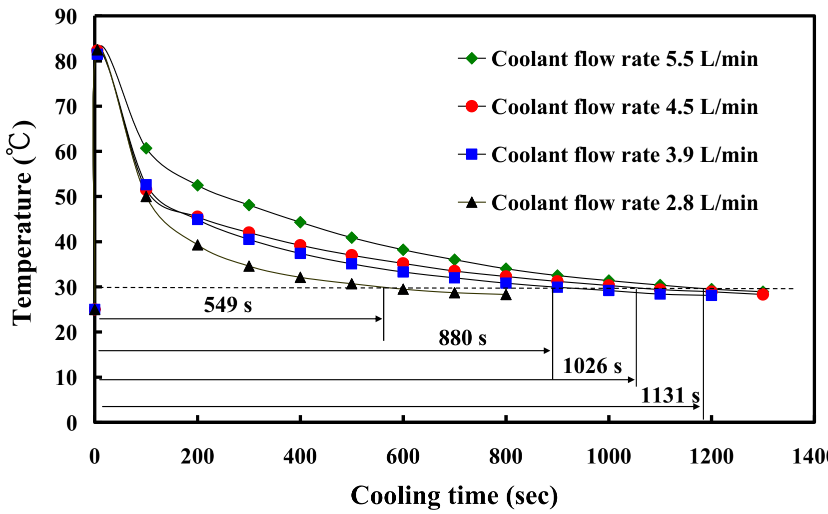


Fig. 15 Temperature of the molded part as a function of the cooling time for the different coolant flow rates. The coolant temperature is 27 °C

molded part is shorter when the coolant flow rate is smaller because the coolant has sufficient time to absorb the heat from the molded part inside the cavity.

In order to evaluate the performance of the injection mold technology, two approaches were used to fabricate a mold with conformal cooling channels having a diameter of 1.75 mm. Figure 16 shows the molds fabricated by DMP with 18Ni-300 maraging steel powder and RTT. As can been seen, a mold with conformal cooling channel diameter of only 1.75 mm can be fabricated by both methods. Two important phenomena can be found. One is the mechanical properties of the molds fabricated by DMP were better than those fabricated by RTT. The other is that the roundness of the conformal cooling channel in the mold fabricated by RTT is obviously superior to that fabricated by SLS due to the wax filaments, used to make the conformal cooling channel, having high dimensional accuracy and smooth surface, as shown in Fig. 17.

In order to further confirm the quality of the mold fabricated by RTT and DMP technology, the mold surface and cooling channels were examined using OM and WLI. Figure 18 shows the surface roughness of the molds fabricated by DMP and RTT. The average surface roughness of the mold fabricated by DMP is 1350 nm, while that of

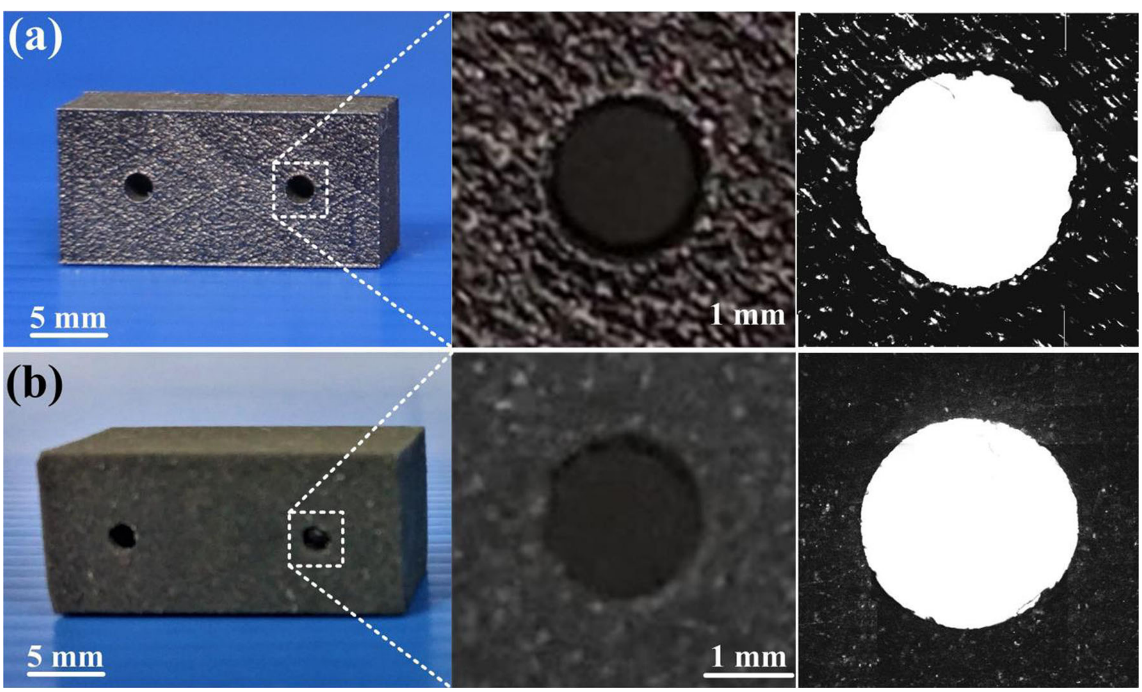


Fig. 16 Molds fabricated by (**a**) DMP and (**b**) RTT

Fig. 17 A wax filament for fabricating conformal cooling channel

the mold fabricated by RTT is only 769 nm. As can be seen, the mold surface quality fabricated by DMP technology is inferior to that fabricated by RTT because some voids were observed. This result means that the surface quality of an injection mold without post-processing is better than that fabricated by DMP technology. Figure 19 shows the surface roughness of the cooling channel wall of the molds fabricated by DMP technology and RTT. The average surface roughness of the cooling channel wall of the mold fabricated by DMP technology is 426 nm, while that of the cooling channel wall of the mold fabricated by RTT is only 318 nm. This result means that the surface quality of the cooling channel wall of the mold fabricated by RTT is superior to that for the mold fabricated by DMP technology. This is because the cooling channel walls of the mold fabricated by DMP technology have a small fraction of unmelted particles.

It is well-known that the DMLS is the most prominent additive manufacturing (AM) technique for manufacturing molds or dies with complex conformal cooling channels. In addition, there are two approaches outside of AM being employed, such as liquid interface diffusion and VDB. However, the production costs of a large injection mold fabricated by ADAM, EBM, SLM, SLS, VDB [31], DMD, DMP, or DMLS are costly. In order to reduce the production costs, the injection mold fabricated by ADAM, EBM, SLM, SLS, DB, DMD, DMP, or DMLS is made with a hybrid structure. The lower part of the injection mold was manufactured by conventional computer numerical control milling. The upper part, having conformal cooling channels, was, then, fabricated by AM. However, the injection mold fabricated by hybrid manufacturing method will result in coolant leakage from the connection locations of the mold since the bonding strength is inferior to other parts of a mold. A distinct advantage of the injection mold fabricated by the method proposed in this work is that the coolant will not result in leakage during injection molding since an injection mold can be manufactured by one-process manufacturing. Figure 20 shows the schematic illustration of the injection mold fabricated by hybrid manufacturing and RTT. This study focuses

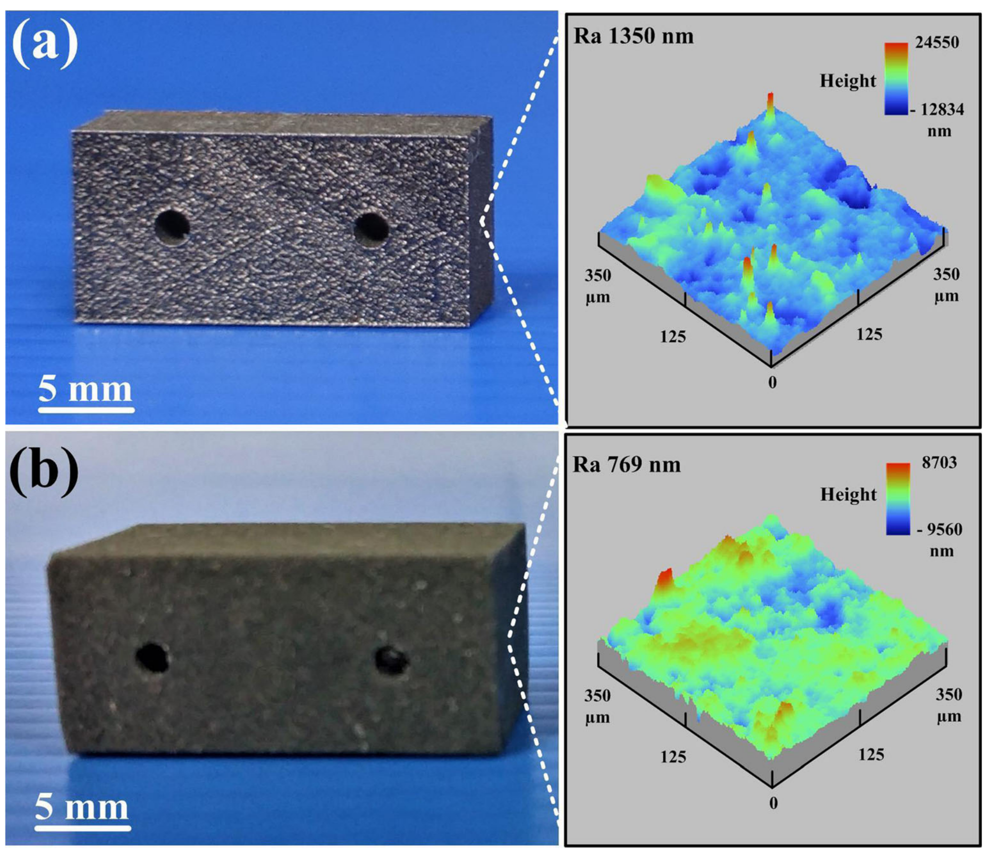


Fig. 18 Surface roughness of the molds fabricated by (a) DMP and (b) RTT

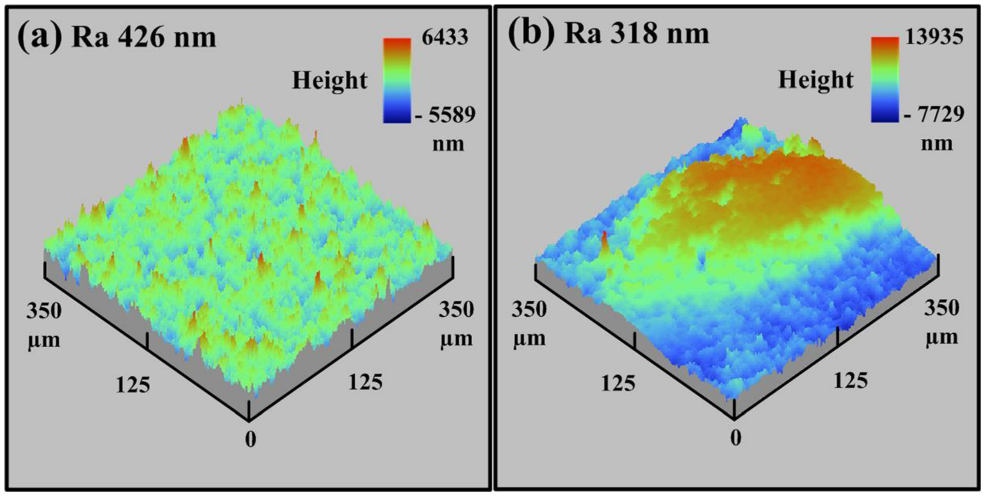


Fig. 19 Surface roughness of the cooling channel wall of the molds fabricated by (**a**) DMP and (**b**) RTT

on the implantation of a large injection mold with built-in 3D cooling channels. The quality of the molded part, such as warpage [32], shrinkage [33], or sink marks [34, 35], can also be improved by injection mold with 3D conformal cooling channels. Optimization of the conformal cooling channels using computer-aided engineering software [36–38] and topology optimization approach [39] is also an important research issue. These works are currently being investigated and will be presented in a later work.

4 Conclusions

The main factor affecting throughput in the company is the cycle time. The cycle time can be reduced by shortening the cooling time during the cooling stage because the cooling time takes most of the cycle time after injection molding. The cooling time can be shortened by the molds with conformal cooling channels. In this study, a cost-effective approach to manufacture a large injection mold with conformal cooling channels was proposed. Based on the results discussed in this study, the following conclusions can be drawn:

1. A large injection mold (470 mm × 270 mm × 180 mm) with conformal cooling channels can be fabricated swiftly and effectively through an intermediary mold, which is difficult to fabricate using the DMP, ADAM, EBM, SLM, SLS, DMD, or DMLS.
2. The modified bisection method is good for producing wax conformal cooling channels with complex geometric shapes due to less material used for fabricating the mold and wax conformal cooling channels that were easy to produce.
3. Recycled material was used to manufacture a large injection mold. The production cost savings up to 83.4% can be obtained.

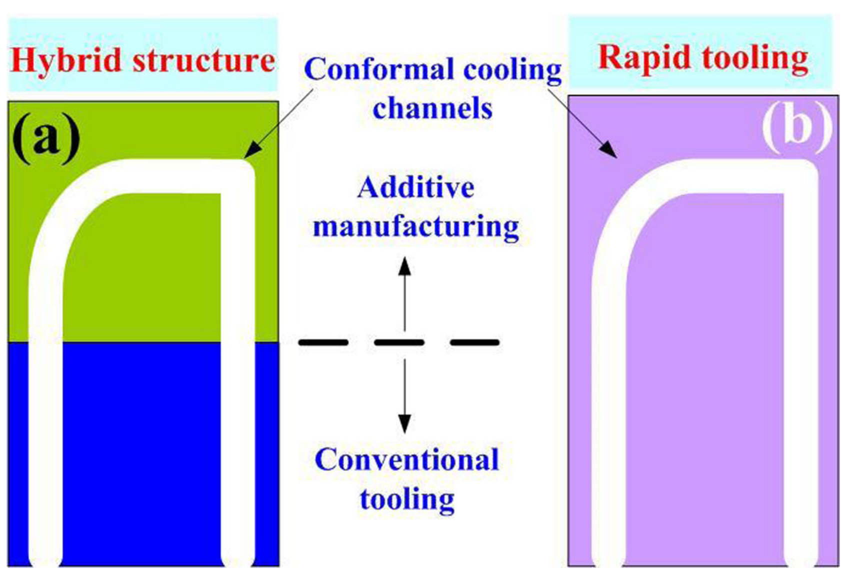


Fig. 20 Schematic illustration of injection mold fabricated by (**a**) hybrid manufacturing and (**b**) RTT

4. Cooling time reduction up to 94.7% was obtained with a wax injection mold with conformal cooling channels compared to that without cooling channels.

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