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ORIGINAL ARTICLE

Development of a low-cost wax injection mold with high cooling efficiency

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Abstract Reduction of the time and cost during the research and development stage of a new product is an important issue. Rapid tooling techniques can reduce the time to market compared to conventional machining approaches. In general, reduction in cooling time plays an important role on cycle time in manufacturing time. Wax injection mold fabricated from aluminum-filled epoxy resin can be employed for small-batch productions of wax patterns. However, the cooling time is much longer compared to metallic wax injection molds due to poorer thermal conductivity. In this study, three kinds of cooling-channel layouts were employed to fabricate wax injection molds for low-pressure wax injection molding using rapid prototyping and rapid tooling techniques. The effects of three kinds of wax injection molds on the cooling time during the low-pressure wax injection molding were investigated. It was found that the reduction in cooling time about 87% can be obtained when a wax injection mold with conformal cooling channels is compared to a conventional wax injection mold fabricated by Al-filled epoxy resin. The manufacturing cost reduction for a wax injection mold with high cooling efficiency about 63% can be obtained using the method proposed in this work.

Keywords Wax injection mold · Low-pressure wax injection molding · Cooling time · Cooling channels

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1 Introduction

The metal parts with complex geometries can be fabricated by wax patterns through investment casting process [1]. In general, the wax patterns were fabricated by wax injection molding. The aluminum-filled epoxy mold was a promising choice for short production runs of wax patterns. Unfortunately, the wax injection cycle time is significantly longer because of the poorer thermal conductivity of the material compared to the conventional metallic mold. To achieve efficient cooling for enhancing the productivity of the wax injection molding process, the cooling channels are widely incorporated into the mold to remove heat from parts. The straight-line channels formed by conventional machining processes are widely used in the conventional injection mold. The cooling effect of the straight-line channel is inferior to the conformal cooling channels [2] because conformal cooling channels have uniform distance between mold surfaces and the center of cooling channels. The copper ducts [3–5] are widely used to make cooling channels because of simplicity of processing. However, only cooling channels with simple geometries can be fabricated due to the limitation of bending process. Technologies such as selective laser sintering, selective laser melting, and diffusion bonding [6–9] were then developed to overcome this issue since the conformal cooling channel with complex shapes can be easily introduced to the mold using layer-by-layer modeling. However, the production cost is very costly and time-consuming because it requires precision beam delivery and focusing optical systems as well as long lead time. Rapid tooling seems to be a cost-effective solution due to shorter development time in its early design stage. In this study, a cost-effective, fast, and simple method was proposed for fabricating wax injection molds with three kinds of cooling channels [10]. The performances of the wax injection molds with three kinds of cooling channels were investigated. The cooling time for the wax injection molds with three kinds of cooling channels in the wax injection molding was also examined.

2 Experimental details

In order to evaluate the difference in the performance of the wax injection molds, three kinds of wax injection molds were fabricated in this study. A curved lens with the dimensions of 78 mm in diameter, 10.73 mm in height, and 1.8 mm in thickness was used as a master model in this study. The cooling channels were designed by using Pro/ENGINEER software according to the geometries of the master model. The diameter of the cooling channel is 10 mm. The cooling line pitch distance is 10 mm. The conformal cooling channels were then fabricated by using a three-dimensional printing machine (uPrint, Stratasys). The solution prepared by alkaline detergent (1310-73-2, sodium hydroxide) was used for removing the support materials of the cooling channels fabricated. The pH meter (pH 600) was used to monitor the variability of solution pH value. In this study, wax was used as materials for fabricating cooling channels because it can be removed from the wax injection molds easily by water vapor. A bridge silicone rubber mold for fabricating wax cooling channels was fabricated using a room temperature vulcanization silicone rubber (KE-1310ST, Shin Etsu). The curing agent and silicone rubber in a weight ratio of 10:1 were mixed for at least 30 min with a stirrer. The detailed manufacturing processes for a silicone rubber mold are

Fig. 2 Placement of positioning fixtures and conformal cooling channel in the mold frame

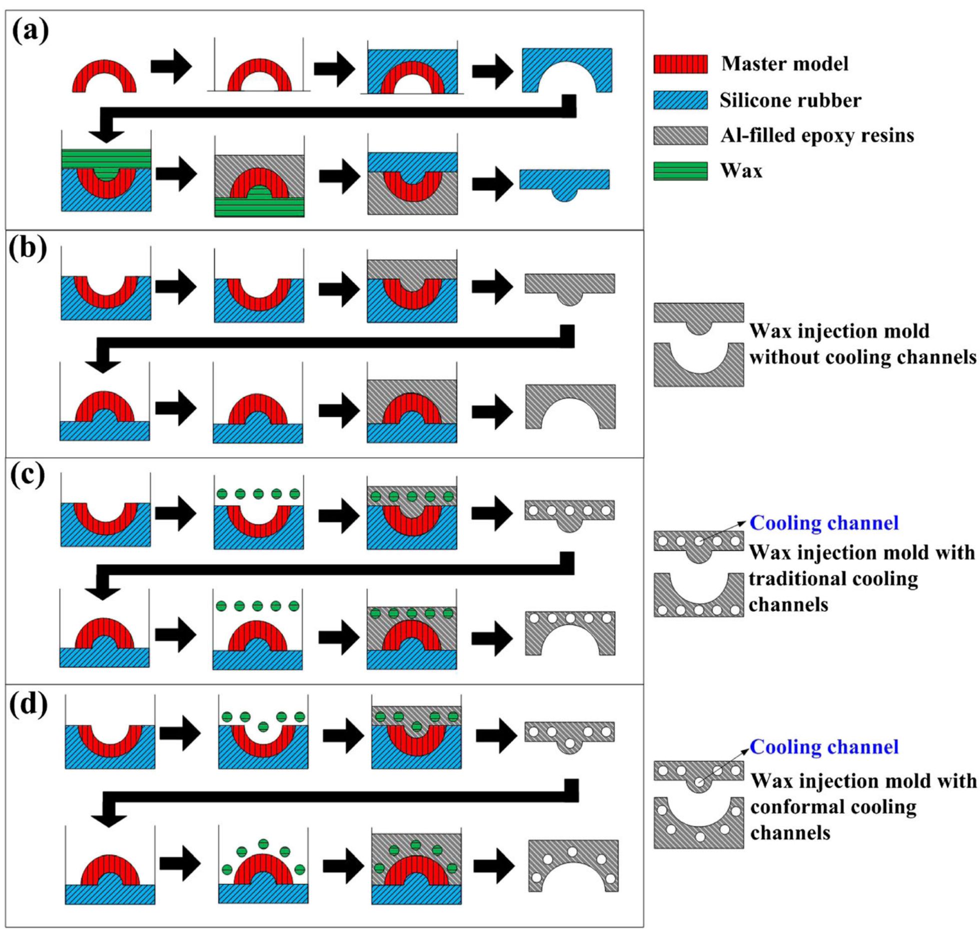


Fig. 1 Process layouts for fabricating **a** bridge tooling, **b** wax injection molds without cooling channels, **c** wax injection molds with conventional cooling channels, and **d** wax injection molds with conformal cooling channels

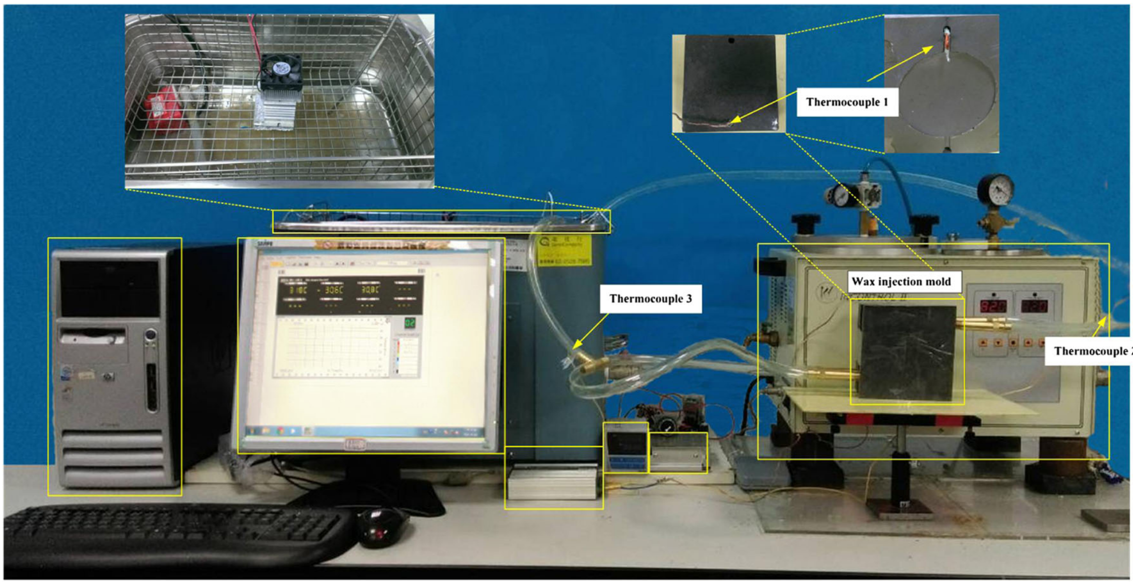


Fig. 3 A data acquisition system for recording the temperature histories

described in the previous study [11–14]. Figure 1 shows the process layouts for fabricating bridge tooling, wax injection molds without cooling channels, wax injection molds with conventional cooling channels, and wax injection molds with conformal cooling channels. The first wax injection mold was fabricated without cooling channels. The second wax injection mold was fabricated with conventional cooling channels, implying that the distance between the mold surface and cooling channel is not constant. The third wax injection mold was fabricated with conformal cooling channels, implying that the distance between the mold surface and cooling channel wall is constant. In order to prevent the use of release agents during the manufacturing processes of wax injection molds,

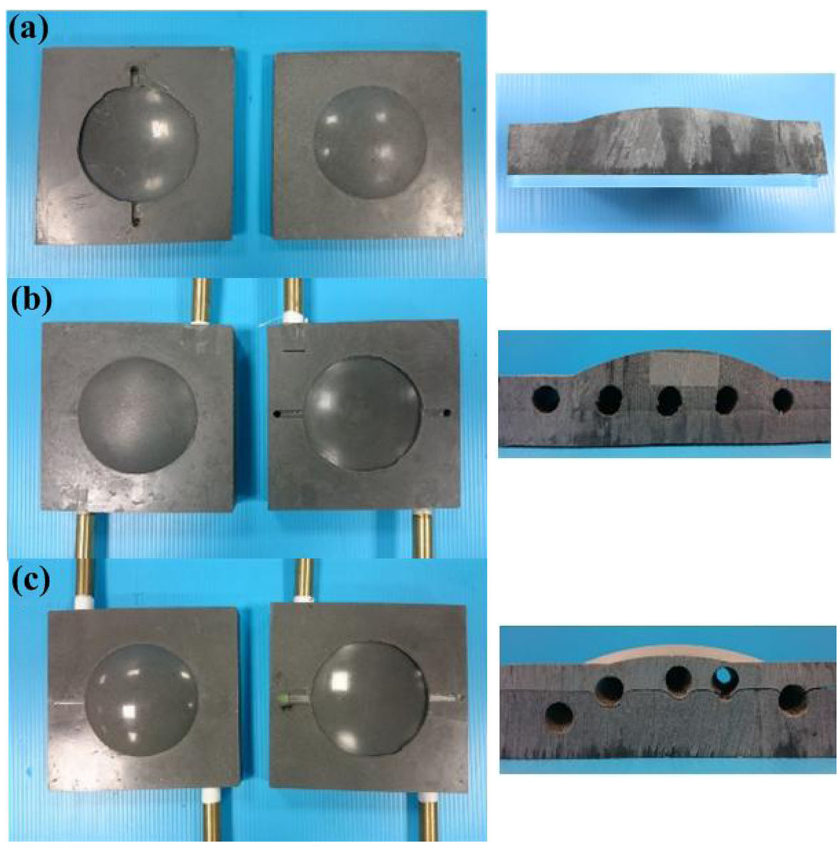


Fig. 4 Wax injection molds **a** without cooling channels, **b** with conventional cooling channels, and **c** with conformal cooling channels. *Inserts* show the cross section of the wax injection molds

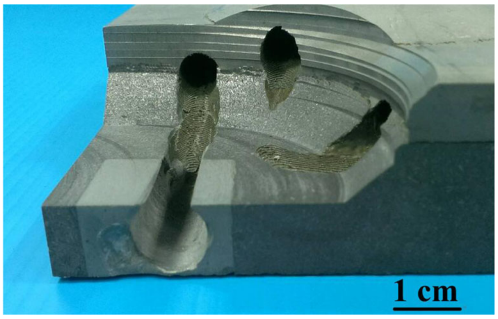


Fig. 5 Cut away section of a wax injection mold

bridge tooling was fabricated using silicone rubber. In this study, Al-filled epoxy resins (TE-375, Jasdi Chemicals) were used to produce wax injection molds via a bridge tooling. Release agent must be used to prevent sticking between the bridge tooling and wax injection molds fabricated. A vacuum machine (F-600, Feiling) was used to eliminate air bubbles from the resulting mixture. A key technology is that a thin first layer ensures minimal micro-bubble entrapment in the surface of the wax injection molds. The fabricated wax injection molds were then cured using a convection oven (DH400, Deng Yag) for obtaining the mechanical properties needed. The positioning fixtures were designed and fabricated for conformal cooling channel. Figure 2 shows the placement of positioning fixtures and conformal cooling channel in the mold frame. The distance between the mold surface and cooling channel wall was kept at 3 mm.

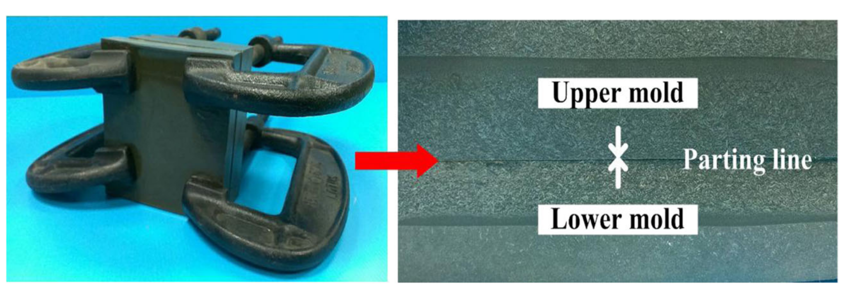
The wax injection machine (0660, W&W) was employed to fabricate wax patterns via wax injection molds. A cooling system was developed in this study, providing heat extraction during the low-pressure wax injection molding process. Water was used as the coolant in the cooling system. Three k-type thermocouples (C071009-079, Cheng Tay) were used in this study. Thermocouple 1 was embedded in a wax injection mold for online measuring of the temperature history of the wax patterns. Thermocouple 2 and thermocouple 3 were used to record the coolant inlet and outlet temperature histories during the low-pressure wax injection molding process. The inlet coolant temperature was kept at room temperature (27 °C) using a thermo-electric cooler (TEC12706AJ, Caijia) and a temperature controller (JCM-33A, Shinko). The temperature histories were recorded using a data acquisition system (MRD-8002L, Acqview), as shown in Fig. 3. In order to increase the cooling efficiency, the flow of water with Reynolds number of 10,000 was performed by the water pump. The ejection temperature was set at room temperature through a series of test runs. The cooling time during the wax injection molding process was measured. The performance of the wax injection mold with three kinds of cooling channels was investigated.

3 Results and discussion

In order to enhance the heat extraction capacity, cooling channels were embedded in the wax injection molds fabricated. Figure 4 shows the wax injection molds without cooling channels, with conventional cooling channel, and with conformal cooling channels. The corresponding cut away section is shown in Fig. 5. As can be seen, the cross-sectional shapes of the conventional cooling channels in wax injection molds are circular. The locations of cooling channels in the wax injection mold can be fabricated accurately to meet the industrial application requirement. In addition, the wax injection mold is rigid enough for wax injection molding using low-pressure injection molding machine. In order to prevent a wax pattern with flash after wax injection molding, a flat mold surface is required. A C-clamp was used to ensure the same deformation between upper mold and lower mold during post curing of a wax injection mold in a convection oven. Figure 6 shows a wax injection mold with a flat mold surface after post curing.

The cooling time is the key factor affecting the process cycle time. In order to evaluate the cooling performance, three kinds of wax injection molds were performed using a wax injection molding machine. Figure 7 shows the temperature as a function of the cooling time during low-pressure wax injection molding process. The cooling time can be determined when the temperature of molded parts reached the demolding temperature. In order to ensure the embossed part was solidified, the embossed parts must be cooled below the demolding temperature of 27 °C before opening the wax injection mold. It was found that the cooling time for wax

Fig. 6 Wax injection mold with a flat mold surface after post curing



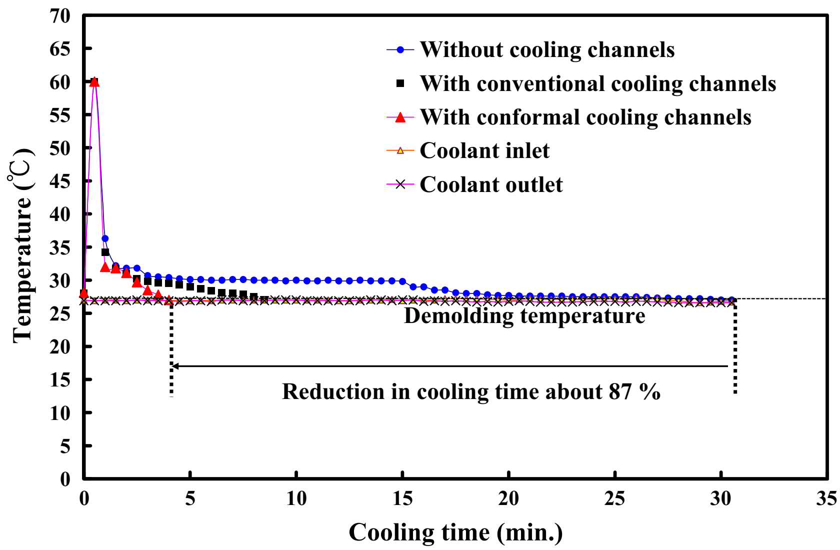


Fig. 7 Temperature as a function of the cooling time during the low-pressure wax injection molding process

injection mold without cooling channels, with conventional cooling channels, and with conformal cooling channels is 30.5, 8.5, and 4 min, respectively. Based on the results shown in this figure, it was clear that the cooling time for a wax injection mold with conventional cooling channels can be shortened by 72% compared to a wax injection mold without cooling channels. In addition, the cooling time for a wax injection mold with conformal cooling channels can be shortened by 87% compared to a wax injection mold without cooling channels. This means the cooling time in the low-pressure wax injection molding process can be further enhanced about 15%. Figure 8 shows a typical wax pattern fabricated by a low-pressure wax injection mold with conformal cooling channels.

To understand the experimental error of the cooling time, ten test runs were carried out in this study. Figure 9 shows the variations of cooling time in the low-pressure wax injection molding process. The average cooling time for wax injection molds without cooling channels, with conventional cooling channels, and with conformal cooling channels is 30.43, 8.44, and 3.98 min, respectively. The results show that the variations of the cooling time for ten test runs are small and the standard deviation of the cooling time for wax injection molds without cooling channels, with conventional cooling channels, and with conformal cooling channels is only about 7, 4, and 5 s, respectively. This reveals that a wax injection mold with conformal cooling channels can enhance the productivity in the low-pressure wax injection molding process because the cooling time in the low-pressure wax injection molding process can be reduced significantly.

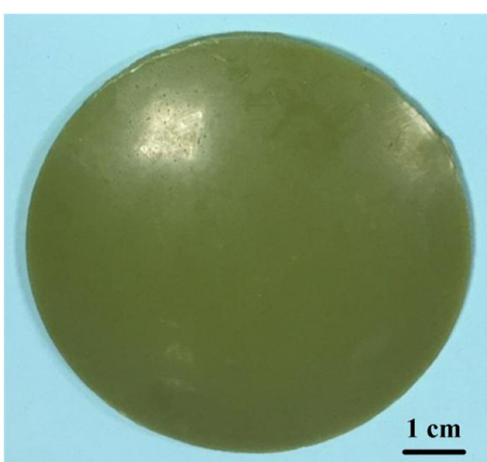


Fig. 8 A typical wax pattern fabricated by a low-pressure wax injection mold with conformal cooling channels

As can be seen, wax injection molds with conformal cooling channels have the advantage of much shorter cooling time in the wax injection molding. In addition, wax injection molds fabricated by Al-filled epoxy resins have advantages of lower production costs and shorter mold making times compared to conventional metallic wax injection mold. In addition, minimizing the production cost is one of the important issues in this study. In general, the main factor influencing the manufacturing cost is the quantity of new Al-filled epoxy resin used. In order to reduce the manufacturing cost, mixtures prepared by recycling Al-filled epoxy resin powders and new epoxy resin were used as backing materials for fabricating new wax injection molds. Figure 10 shows wax injection molds were fabricated using green manufacturing technology. As can be seen, a wax injection mold has a hybrid structure which was composed of new materials and recycling materials. The manufacturing cost for a wax injection mold with conformal cooling channels fabricated by recycling materials as backing materials is only NT1455, while that fabricated by all new materials is NT3930. It is apparent that the manufacturing cost savings about 63% can be obtained. Figure 11 shows the schematic illustration of the surface of conformal cooling channels inside the wax injection molds

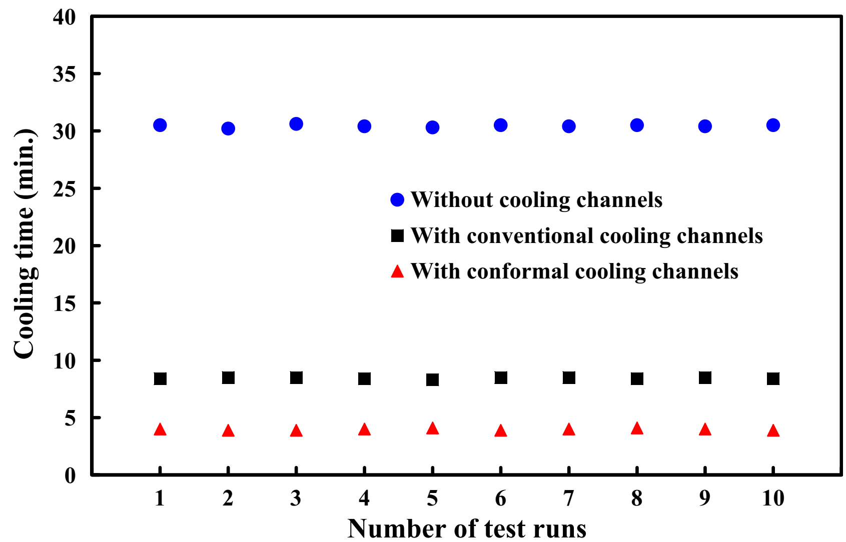


Fig. 9 The variations of cooling time in the low-pressure wax injection molding process

fabricated by selective laser sintering technology [15], selective laser melting technology [16], diffusion bonding technology [17, 18], and the method proposed in this study. The results clearly showed that the surface of conformal cooling channels inside the wax injection mold has better surface quality. This is because the surface quality of the wax conformal cooling channels can be improved by water vapor treatment to reduce the stair-steps of the conformal cooling channels built with fused deposition modeling technique. This would be beneficial to the better flow of coolant during the cooling stage after low-pressure wax injection molding. In addition, the water scale was not easy to accumulate.

The cooling time is dependent on the mold temperature, thermal conductivity of the mold material, size of the mold, and thickness and dimension of the molded parts. It is well-known that decreasing the cycle time is beneficial to the production rates for manufacturers. The optimization of conformal cooling channel layout is in progress because a better design of conformal cooling channels is more efficient for reducing cycle times. Wax patterns for investment casting [19, 20] can be fabricated using the wax injection mold. The advantages of this study include low production cost compared to the technologies proposed by Dong et al. [21] and simple manufacturing process compared to the technique proposed by Ahn et al. [22]. In order to gain more consumer markets for their products, manufacturing businesses will increasingly employ wax patterns for fabricating metal parts. The cycle-time reduction provides a significant impact on production cost. Thus, the results presented in this study have important industrial applications because the cooling-time reduction is the main advantage of this work and the developed low-pressure wax injection mold with conformal cooling channels is capable of fabricating wax patterns efficiently for aerospace, automotive, and aircraft applications. According to the above findings, the results of this study provide the greatest application potential in the industry because the wax

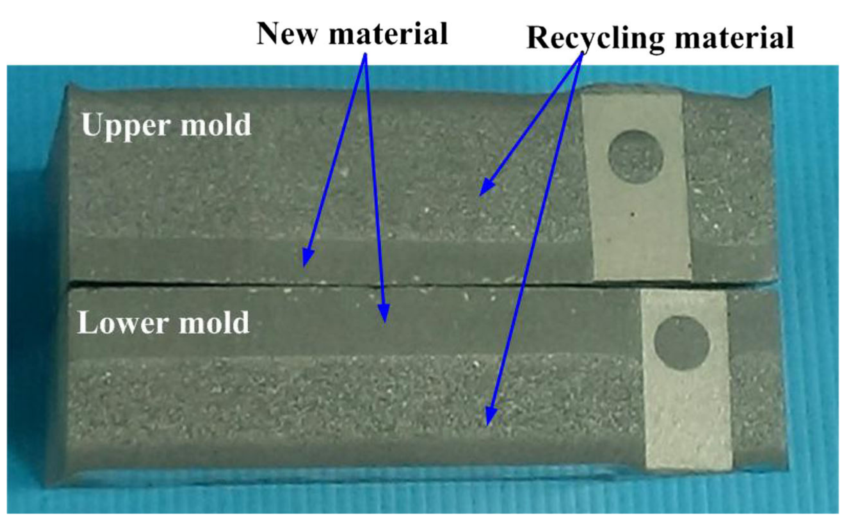


Fig. 10 Wax injection molds were fabricated using green manufacturing technology

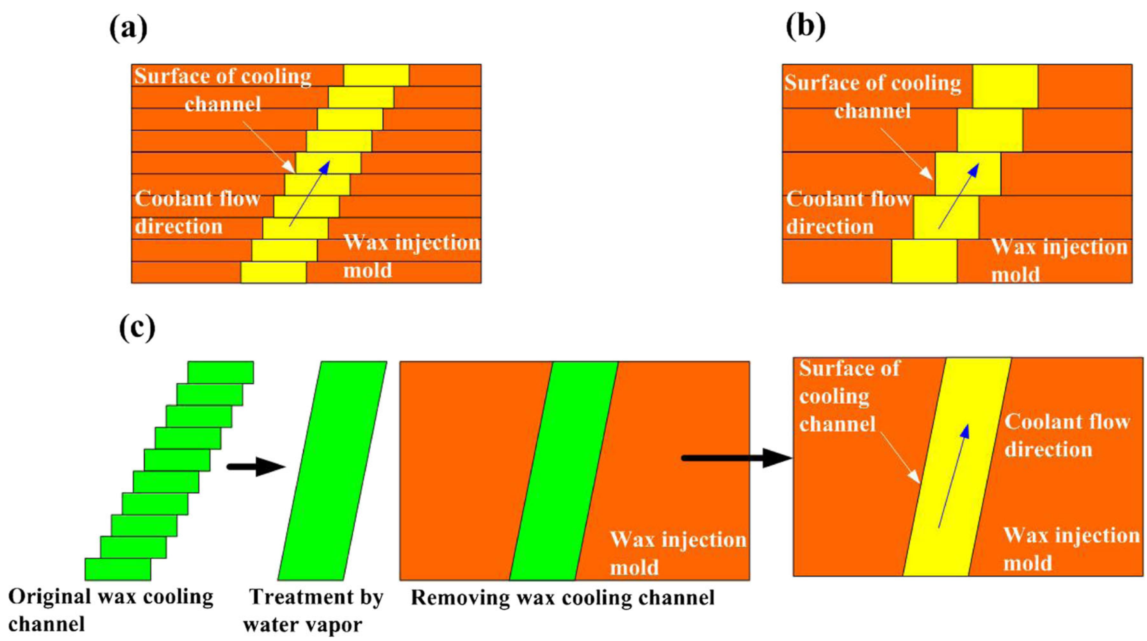


Fig. 11 Schematic illustration of the surface of conformal cooling channels inside the wax injection molds fabricated by **a** selective laser sintering or selective laser melting technologies, **b** diffusion bonding technology, and **c** the method proposed in this study

patterns can be fabricated efficiently by a rapid tooling with sophisticated geometries of cooling channels. The fabricated wax patterns can be used for fabricating metal elements inexpensively and swiftly in the precision investment casting industry.

4 Conclusions

The cooling time of a wax injection part is important when a large number of wax patterns need to be fabricated. An alternative technique of manufacturing wax injection molds with conformal cooling channels has been demonstrated. The performances of the wax injection molds with three kinds of cooling channels have been investigated. Based on the results discussed in this study, the following conclusions can be drawn:

1. The proposed method for fabricating low-pressure wax injection molds with conformal cooling channels requires no expensive apparatus compared to molds fabricated by the selective laser sintering, selective laser melting, or diffusion bonding. The main advantages of this technique include short lead time, short processing time, simple manufacturing processes, and low production cost. In addition, conformal cooling channels with intricate geometries can also be implemented by the method proposed in this work.
2. Effects of three kinds of wax injection molds on the cooling time have been successfully confirmed by experimental tests. The developed wax injection mold with conformal cooling channels has important industrial applications because the cooling efficiency can be enhanced by 87%.
3. The developed low-pressure wax injection mold with conformal cooling channels has a significant industrial application value because reduction in production costs about 63% can be obtained.

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