Int J Adv Manuf Technol (2017) 91:1689–1695
DOI 10.1007/s00170-016-9886-4

ORIGINAL ARTICLE

A cost-effective approach for rapid manufacturing wax injection molds with complex geometrical shapes of cooling channels

Chil-Chyuan Kuo[1] · **Wei-Hua Chen**[1] · **Wei-Cong Xu**[1]

Received: 3 October 2016 / Accepted: 12 December 2016 / Published online: 17 December 2016

Abstract Rapid tooling techniques can reduce the time to market compared to conventional machining approaches. The aluminum-filled epoxy resin mold is a promising choice for short production runs because it can be a useful alternative of conventional steel mold and employed in wax injection mold or plastic injection mold. However, the cycle time is significantly longer because of the poorer thermal conductivity of the material compared to conventional mold steels. In this study, a new technique to produce wax injection molds with complex geometrical shapes of cooling channels was presented. The main advantages of this technique include low production cost, simple manufacturing processes, and short processing time.

Keywords Aluminum-filled epoxy resin · Cooling channels · Wax injection mold

1 Introduction

In general, metal parts with complex geometrical shapes were fabricated by investment casting process [1]. It is well known that the low-pressure wax injection molding is a promising approach to produce wax patterns for investment casting. The wax injection molding parts must be solidified before opening the mold because the quality of the molded wax patterns was affected significantly by the cooling stage. Cooling of the wax injection mold is crucial to the performance of the wax injection mold. To achieve efficient cooling for enhancing the productivity in the wax injection molding process, the cooling channels are widely incorporated into the mold to remove heat from wax patterns. The straight-line channels formed by traditional machining processes are widely used in the conventional injection molds. Unfortunately, the cooling effectiveness of the straight-line channels is inferior to the conformal cooling channels [2] because conformal cooling channels have uniform distance between the mold surfaces and the center of conformal cooling channels. The copper ducts [3, 4] are widely used as the conformal cooling channels. However, only conformal cooling channels with simple geometrical shapes can be used due to the limitation of bending process of copper pipes. Selective laser sintering or selective laser melting [5–8] is then developed to overcome this issue since the conformal cooling channel with complex geometrical shapes can be introduced to the mold using layer-by-layer modeling. However, the production cost is inexpensive because it requires precision beam delivery and focusing optical systems as well as long lead time. In order to solve this problem, a cost-effective, fast, and simple method was proposed to produce wax injection molds with complex geometrical shapes of cooling channels for wax injection molding in this study [9, 10]. The cross-sections of the fabricated wax injection mold were also investigated.

✉ Chil-Chyuan Kuo
jacksonk@mail.mcut.edu.tw

1 Department of Mechanical Engineering, Ming Chi University of Technology, No. 84, Gungjuan Road, New Taipei City 243, Taiwan

2 Experiment

The wax injection molds were built through transfer rapid tooling. A manufacturing process for fabricating wax injection molds with cooling channels was developed.

Figure 1 shows the process layouts for fabricating a wax injection mold with conformal cooling channels. The materials for positioning fixture and the spacer are the same as mold materials. There is no need to remove the positioning fixture and the spacer. The thickness of the spacer can control the distance between the mold surfaces and the center of conformal cooling channels to ensure the positioning accuracy of the conformal cooling channels inside the wax injection mold. Al-filled epoxy resins (70-3810R, Epoxies Inc.) were used to produce wax injection molds. A vacuum machine (F-600, Feiling) was used to eliminate air bubbles from the resulting mixture. The fabricated wax injection molds were then cured using a convection oven (DH400, Deng Yag) for obtaining the mechanical properties needed. This typically takes about 6–8 h. The cooling channels with complex geometrical shapes were designed by using the Pro/ENGINEER software according to the geometries of the master model. The hollow cooling channels were fabricated by using a three-dimensional printing machine (uPrint, Stratasys). The applied layer thickness was 0.254 mm. The material used for manufacturing the cooling channels was acrylonitrile butadiene styrene (ABS) [11, 12]. 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 order to evaluate the results after the removal process, silicone rubber (KE-1310ST, Shin Etsu) was used as the mold material because it is transparent. Three different approaches were proposed to remove the cooling channels from the silicone rubber mold. The first approach for removing the cooling channels is the use of an ultrasonic machine (LEO-1502, Guang Hua) with acetone liquid. The second approach for removing the cooling channels is the use of the flushing with acetone liquid. The third approach for removing the cooling channels is the use of the vapors of acetone [13]. The best approach was investigated based on the results after the removal process, which will be employed to remove cooling channels from wax injection molds fabricated by using Al-filled epoxy resins [14–17]. The cross-sections of the fabricated wax injection molds were prepared using a precision milling machine. The locations of cooling channels in the wax injection mold were inspected using a vision measuring system (Quick Vision Series 359, Mitutoyo).

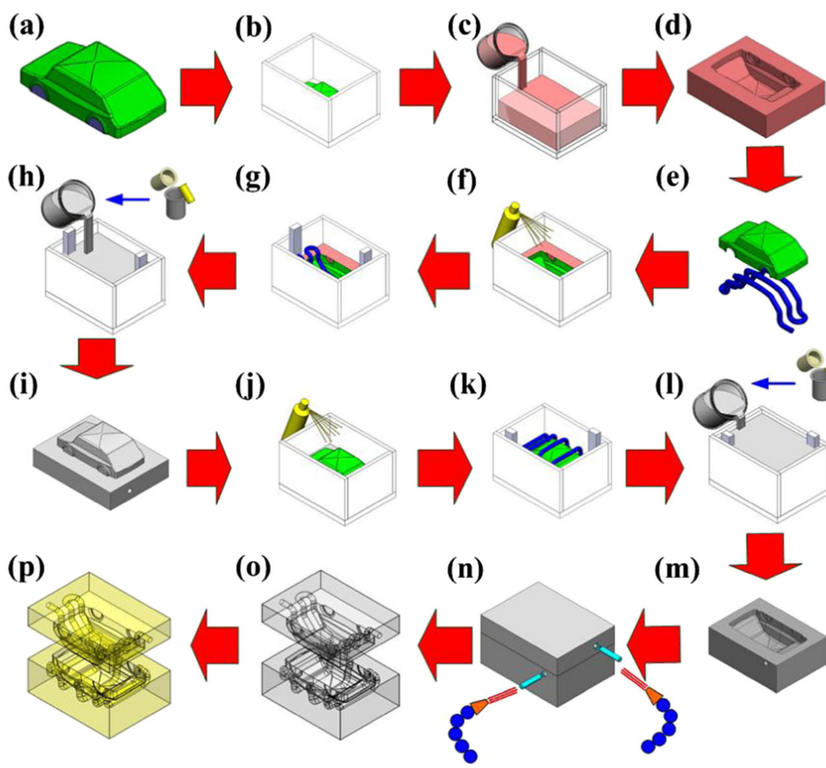


Fig. 1 Process layouts for fabricating a wax injection mold with conformal cooling channels. **a** Preparation of a master model. **b** Placing the master model into the mold frame. **c** Preparation of intermediate mold materials and casting. **d** Intermediate mold. **e** Designing a conformal cooling channel of core insert. **f** Placing the intermediate mold and master model into the mold frame. **g** Placing the positioning fixture and the conformal cooling channel for core insert into the mold frame. **h** Preparation of Al-filled epoxy resins. **i** Green part of core insert. **j** Placing the core and master model into the mold frame. **k** Placing positioning fixture and the conformal cooling channel for cavity insert into the mold frame. **l** preparation of Al-filled epoxy resins. **m** Green part of cavity insert. **n** Removing conformal cooling for core and cavity inserts. **o** Al-filled epoxy resin mold with conformal cooling channels. **p** Post heat treatment for Al-filled epoxy resin mold with conformal cooling channels

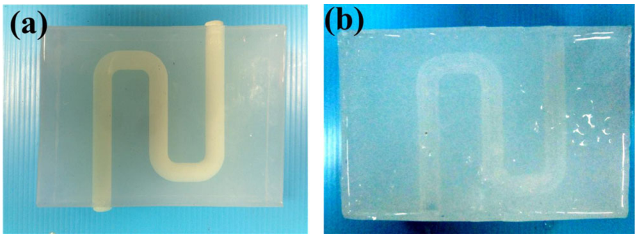


Fig. 2 Silicone rubber molds **a** before and **b** after removing a cooling channel by using the ultrasonic vibrations with acetone liquid

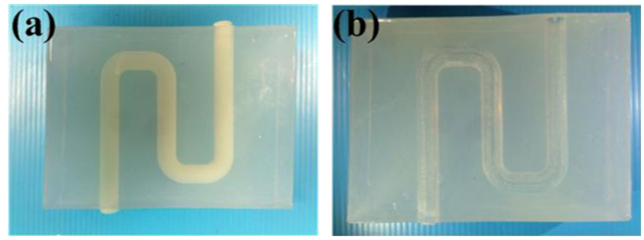


Fig. 4 Silicone rubber molds **a** before and **b** after removing a cooling channel by using the flushing with acetone liquid

3 Results and discussion

In order to determine the best approach for removing the cooling channels from wax injection mold, silicone rubber was first used for making rapid tooling. Figure 2 shows the silicone rubber molds before and after removing a cooling channel by using the ultrasonic vibrations with acetone liquid. Figure 3 shows the schematic illustrations of silicone rubber molds in the process of removing a cooling channel by using the ultrasonic vibrations with acetone liquid after 0 to 65 min. As can be seen, a cooling channel was removed from the inside or the outside. In addition, the removing speed of the linear portions of a cooling channel is faster than the corners of a cooling channel. The cooling channel removal time is about 65 min, and the wall thickness of the cooling channel is 1 mm. As a result, the cooling channel removal rate is about 0.0154 mm/min. This indicates that a cooling channel can be removed completely by using the ultrasonic vibrations with acetone liquid. However, the silicone mold surface is foggy due to temperature effects caused by ultrasonic vibrations.

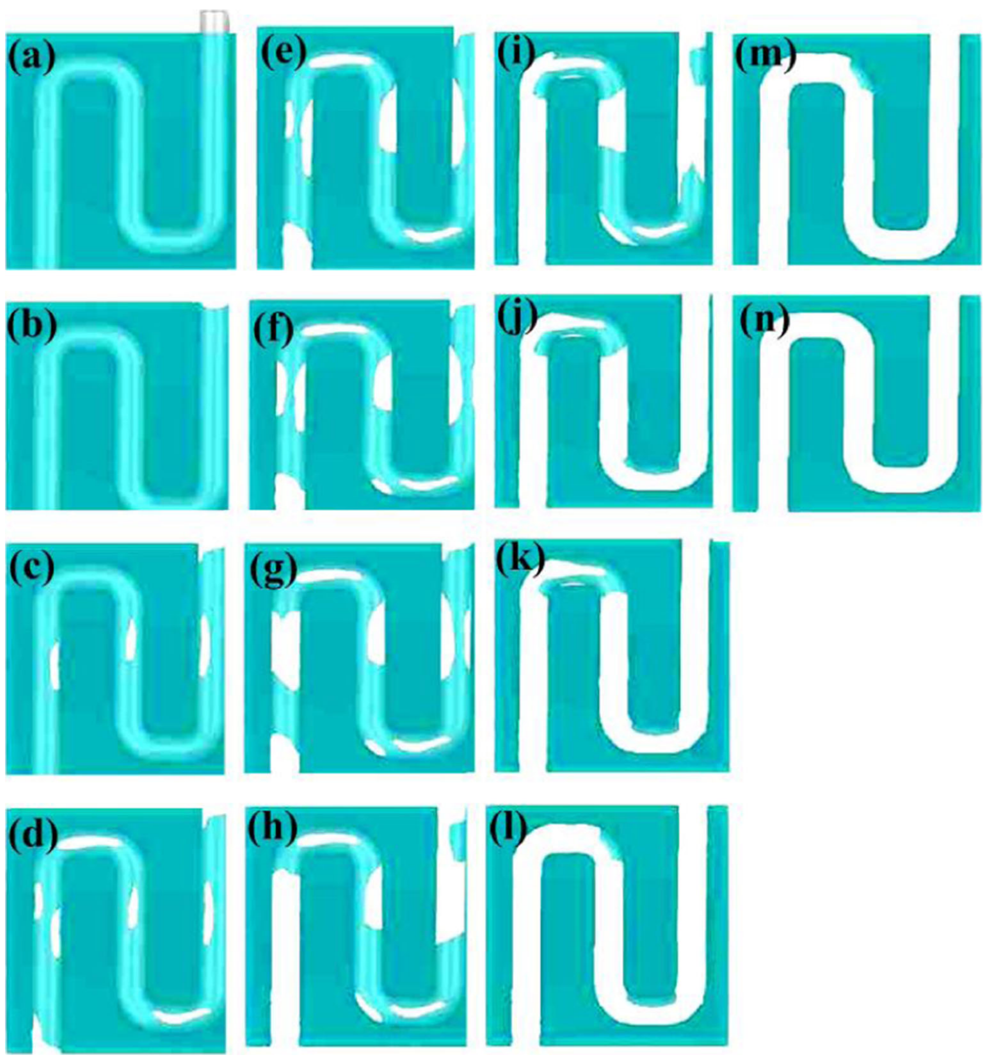


Fig. 3 Schematic illustrations of silicone rubber molds in the process of removing a cooling channel by using the ultrasonic vibrations with acetone liquid after **a** 0, **b** 5, **c** 10, **d** 15, **e** 20, **f** 25, **g** 30, **h** 35, **i** 40, **j** 45, **k** 50, **l** 55, **m** 60, and **n** 65 min

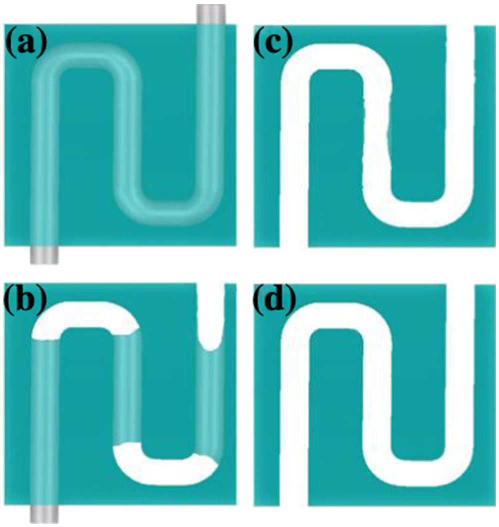


Fig. 5 Schematic illustrations of silicone rubber molds in the process of removing a cooling channel by using the flushing with acetone liquid after **a** 0, **b** 5, **c** 10, and **d** 15 min

Figure 4 shows the silicone rubber molds before and after removing a cooling channel by using the flushing with acetone liquid. Figure 5 shows the schematic illustrations of silicone rubber molds in the process of removing a cooling channel by using the flushing with acetone liquid after 0 to 15 min. As can be seen, a cooling channel was removed from the inside or the outside. However, the removing speed on the corners of a cooling channel is faster than the linear portions of a cooling channel due to turn effect. This result is a significant difference compared to that removed by the ultrasonic vibrations with acetone liquid. The cooling channel removal time is about 15 min, and the wall thickness of the cooling channel is 1 mm. As a result, the cooling channel removal rate is about 0.067 mm/min, which is 4.3 times of that by using the ultrasonic vibrations with acetone liquid. This indicates that a cooling channel can be removed completely by using the ultrasonic vibrations with acetone liquid. In addition, it clearly shows that the silicone mold surface is still clear.

Figure 6 shows the silicone rubber molds before and after removing a cooling channel by using the acetone vapor. It was observed that the cooling channel begins to soften when the cooling channel interacts with acetone vapor. As a result, the cooling channel cannot be removed completely due to increase in viscosity coefficient of a cooling channel.

According to the above findings, flushing with acetone liquid is a good candidate for removing the cooling channels. In order to demonstrate the feasibility of the proposed method, a wax injection mold was fabricated. Figure 7 shows the wax injection mold of car's shell on core side, cross-section of core side, cavity side, and cross-section of cavity side. The wax injection mold is rigid enough for wax injection molding using low-pressure injection molding machine. As can be seen, cooling channels have been incorporated both into the

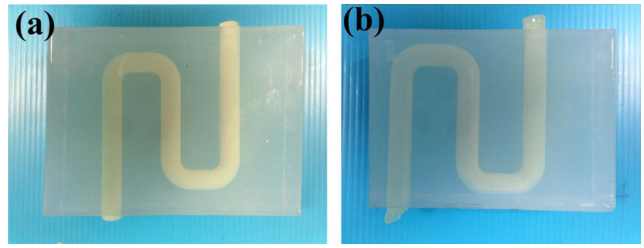


Fig. 6 Silicone rubber molds **a** before and **b** after removing a cooling channel by using the vapors of acetone

core and cavity halves of the wax injection mold. The locations of cooling channels in the wax injection mold can be fabricated accurately to meet the industrial application requirement. The cross sectional shapes of the conventional cooling channels in wax injection molds are circular. This kind of cooling channel was usually machined through computer-aided numerical machining. It should be noted that the cross sectional shapes of cooling channels are semi-circle and rectangle. Especially, the cross sectional shape of semi-circle means that the cooling channels are conformal to the shape of the products. This kind of cooling channel can solve the disadvantage of conventional circular cooling channel because it has better cooling efficiency than a conventional circular cooling channel. In addition, the cooling channel layout can be revised easily directly from a CAD model. According to the results from the case study, this indicates that the wax injection molds [18] with complex geometrical shapes of cooling channels can be fabricated using rapid tooling and three-dimensional printing techniques [11, 19, 20]. It is worth noting that the production cost of a wax injection mold with complex geometry of cooling channels is cheaper compared to those fabricated by conventional approaches such as selective laser melting [21], selective laser sintering [22], or diffusion bonding [23–25]. In the high-variety low-volume manufacturing systems, the wax injection molds can be fabricated in less time compared to that fabricated by conventional method. Thus, this technique not only reduce the development time but also reduce the production cost in the research and development stages of a new wax injection mold with complex geometrical shapes of cooling channels.

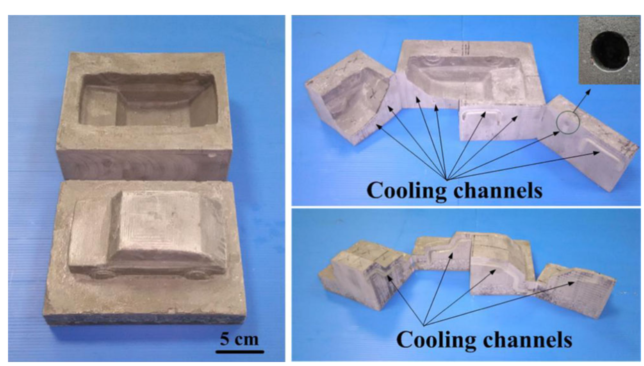


Fig. 7 Wax injection mold of car's shell

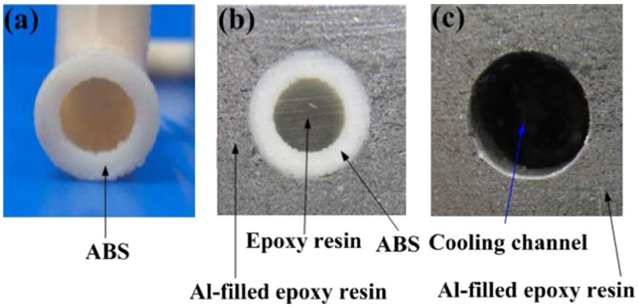


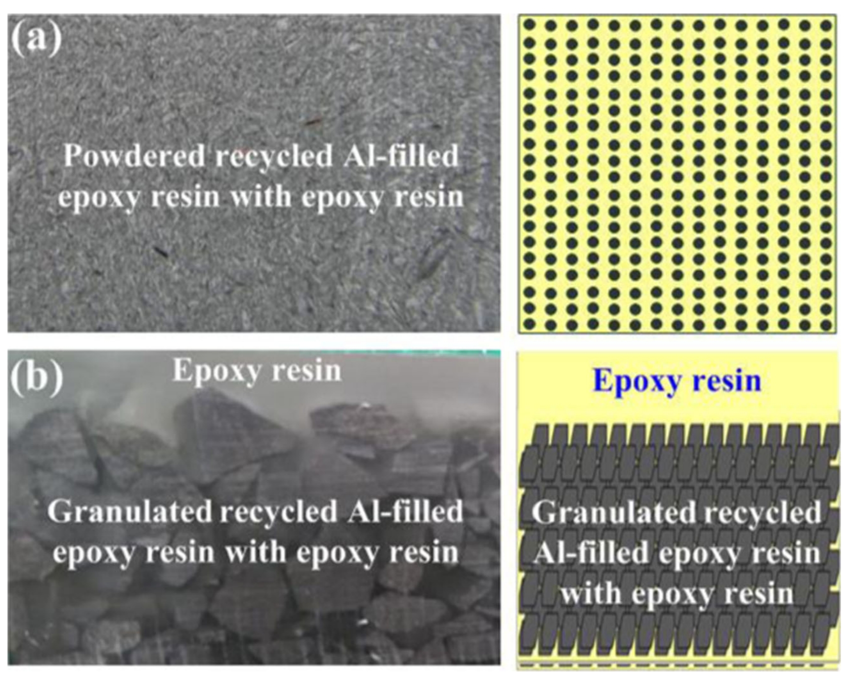
Fig. 8 Photos of **a** cross-section of the ABS cooling channel, **b** internal of the ABS cooling channel that was penetrated with epoxy resins, and **c** cross-section of wax injection mold

In the wax injection mold making process, this study found that internal of the ABS cooling channel was penetrated with epoxy resins. Figure 8 shows the photos of cross-section of the ABS cooling channel, internal of the ABS cooling channel that was infiltrated with epoxy resins, and cross-section of wax injection mold. In order to avoid penetration of epoxy resin into the interior of the ABS cooling channel, the external of the ABS cooling channel was coated with a thin layer of epoxy resin. It should be noted that it is not required to remove this thin layer of epoxy resin because it will eventually become part of the material of wax injection mold.

In order to reduce the production cost of wax injection mold, the recycled pieces of Al-filled epoxy resins were used in this study. Firstly, the recycled pieces of Al-filled epoxy resins were first milled into powder and granulation using a precision universal milling machine. Secondly, a mixture was prepared by mixing new epoxy resin and recycled Al-filled epoxy resins. Figure 9 shows the cross-section of wax injection molds fabricated from a mixture of powdered recycled Al-filled epoxy resin with epoxy resin and a mixture of granulated recycled Al-filled epoxy resin with epoxy resin. As can be seen, the dispersion of powder of recycled Al-filled epoxy resins is better than granulation of recycled Al-filled epoxy resins in the mixture. A portion of the epoxy resin floated on the surface of wax injection mold, causing poor mold surface quality after flushing with acetone liquid in the process of removal of ABS cooling channels. Conversely, the quality of mold surface is acceptable after flushing with acetone liquid when the wax injection molds fabricated from a mixture of powdered recycled Al-filled epoxy resin with epoxy resin. This means that the powdered recycled Al-filled epoxy resin was recommended for fabricating wax injection molds to meet the objective of green manufacturing. In addition, this method has a significant industrial value because cost reduction increases with increasing the volumes of the wax injection molds fabricated.

In addition, there are three different types of ABS channels that can be used for manufacturing wax injection molds. The first method is solid ABS channels. The advantage of this method is that the interior of the ABS cooling channel can be prevented from infiltrating of epoxy resin in the mold making process. However, the production cost of this method is the highest. The second method is hollow ABS channels. This kind of channels means that the internal support materials were removed completely. The advantage of this method is that the removal time of ABS channels can be reduced significantly because the removal direction of ABS channels can be changed from the axial direction to the radial direction. However, it needs higher running cost because a high-

Fig. 9 The cross-section of wax injection molds fabricated from **a** a mixture of powdered recycled Al-filled epoxy resin with epoxy resin and **b** a mixture of granulated recycled Al-filled epoxy resin with epoxy resin



pressure apparatus is required to meet this requirement. The third method is thin shell ABS channels with support materials. The production cost of this method can be lower. In addition, the preparation time of this kind of cooling channels is the lowest. This means that the thin shell ABS channels with support materials were recommended for fabricating wax injection molds.

The fabricated wax injection molds are capable of manufacturing wax patterns for customized metal components through investment casting technology. Generally, conduction is the major mechanism for transferring the heat energy of the molten wax to the surface of the channels through wax injection mold materials. Thus, the fabricated wax injection molds can enhance the cooling rate and reduce the process cycle time of the wax patterns during the wax injection molding process, resulting in cost savings in low-volume production of wax patterns for investment casting [26]. Investigation on the cooling time for different wax injection molds with complex geometrical shapes of cooling channels is in progress. The main limitation of the wax injection molds fabricated is the limited mold service life. In addition, further studies are needed to optimize the layout of cooling channels in the wax injection molds by using computer simulation software because a better design of conformal cooling channels is more efficient for reducing the cycle times [27].

4 Conclusions

The main purpose of this study is to develop a new technique to produce wax injection molds with complex geometrical shapes of cooling channels using rapid tooling and three-dimensional printing techniques. A cost-effective manufacturing process has demonstrated the potential to produce wax injection molds with intricate geometries. Based on the results discussed in this study, the conclusions are listed as follows:

1. The feasibility of the proposed approach in this study has been demonstrated to produce wax injection molds with conformal cooling channels.
2. The proposed approach provides a fast, simple, and cost-effective alternative to conventional approaches to produce molds or dies with conformal cooling channels. The cooling channels with any cross sectional shapes in the wax injection mold can be fabricated using rapid tooling and three-dimensional printing techniques.
3. The results presented in this study have important industrial applications because wax injection molds with complex geometrical shape cooling channels can be fabricated swiftly and effectively. In contrast to conventional methods regarding manufacture of wax injection mold with complex geometrical shape conformal cooling channels, the main advantages of this technique include short lead time, short processing time, simple manufacturing processes, and low production cost.
4. Flushing with acetone liquid is the best approach for removing the cooling channels in the wax injection mold.
5. The powdered recycled Al-filled epoxy resin was suggested for making wax injection molds to save production cost due to acceptable mold surface quality.
6. The thin shell ABS channels with support materials were recommended for fabricating wax injection molds due to low production cost and short preparation time.

Acknowledgements The authors gratefully acknowledge the financial support from the Ministry of Science and Technology of Taiwan under contract nos. MOST 104-2221-E-131-026 and MOST 105-2221-E-131-012.

References

1. Huang PH, Lin CJ (2015) Computer-aided modeling and experimental verification of optimal gating system design for investment casting of precision rotor. Int J Adv Manuf Technol 79(5):997–1006
2. Armillotta A, Baraggi R, Fasoli S (2014) SLM tooling for die casting with conformal cooling channels. Int J Adv Manuf Technol 71(1):573–583
3. Ferreira JC, Mateus A (2003) Studies of rapid soft tooling with conformal cooling channels for plastic injection moulding. J Mater Process Technol 142(2):508–516
4. Au KM, Yu KM, Chiu WK (2011) Visibility-based conformal cooling channel generation for rapid tooling. Comput Aided Des 43(4):356–373
5. Pupo Y, Monroy KP, Ciurana J (2015) Influence of process parameters on surface quality of CoCrMo produced by selective laser melting. Int J Adv Manuf Technol 80(5):985–995
6. Taha MA, Yousef AF, Gany KA, Sabour HA (2012) On selective laser melting of ultra high carbon steel: effect of scan speed and post heat treatment. Mater Werkst 43(11):913–923
7. Singh S, Sharma VS, Sachdeva A, Sinha SK (2013) Optimization and analysis of mechanical properties for selective laser sintered polyamide parts. Mater Manuf Process 28(2):163–172
8. Temmler A, Willenborg E, Wissenbach K (2015) Design surfaces by laser remelting. Mater Werkst 46(7):692–703
9. Wang D, He B, Li F, Wang F, Sun B (2013) Experimental and numerical analysis on core deflection during wax injection. Mater Manuf Process 28(11):1209–1214
10. Liu C, Jin S, Lai X, He B, Li F (2015) Influence of complex structure on the shrinkage of part in investment casting process. Int J Adv Manuf Technol 77(5):1191–1203
11. Dawoud M, Taha I, Ebeid SJ (2015) Effect of processing parameters and graphite content on the tribological behaviour of 3D printed acrylonitrile butadiene styrene. Mater Werkst 46(12):1185–1195
12. Kuo CC, Tsou YC (2016) A flexible and efficient system for removing support materials from rapid prototypes. Mater Werkst 47(7):635–645
13. Kuo CC, Mao RC (2016) Development of a precision surface polishing system for parts fabricated by fused deposition modeling. Mater Manuf Process 31(8):1113–1118
14. Kuo CC, Zhuang BC (2016) Manufacturing process development of a precision rapid tooling with high-aspect-ratio micro-sized features. Mater Werkst 47(1):29–36
15. Rajaguru J, Duke M, Au C (2015) Development of rapid tooling by rapid prototyping technology and electroless nickel

plating for low-volume production of plastic parts. Int J Adv Manuf Technol 78(1):31–40
16. Kuo CC, Li MR (2016) A cost-effective method for rapid manufacturing sheet metal forming dies. Int J Adv Manuf Technol 85(9):2651–2656
17. Kuo CC, Wang YJ, Liao HY, Hsu HJ, Chian TS (2016) The evolution of manufacturing processes for micro-featured epoxy resin mold. Mater Werkst 47(4):341–350
18. Kuo CC, Su SJ (2013) A cost-effective approach for rapid manufacturing a low pressure wax injection mold with high surface finish and high dimensional accuracy. Mater Werkst 44(4):330–339
19. Kuo CC (2013) Fabrication of modeling platform for fused deposition modeling using vacuum casting. Mater Werkst 44(11):922–926
20. Hölker R, Tekkaya AE (2016) Advancements in the manufacturing of dies for hot aluminum extrusion with conformal cooling channels. Int J Adv Manuf Technol 83(5):1209–1220
21. Song C, Yang Y, Liu Y, Luo Z, Yu JK (2015) Study on manufacturing of W-Cu alloy thin wall parts by selective laser melting. Int J Adv Manuf Technol 78(5):885–893
22. Song XH, Li W, Song PH, Su QY, Wei QS, Shi YS, Liu K, Liu WG (2015) Selective laser sintering of aliphatic-polycarbonate/hydroxyapatite composite scaffolds for medical applications. Int J Adv Manuf Technol 81(1):15–25
23. Xue Z, Yang Q, Gu L, Hao X, Ren Y, Geng Y (2015) Diffusion bonding of TiAl based alloy to Ti–6Al–4 V alloy using amorphous interlayer. Mater Werkst 46(1):40–46
24. Jahn S, Sändig S, Dahms S, Gemse F (2014) Diffusion bonding systems. Mater Werkst 45(9):807–814
25. Harhash M, Ataya S, Abd El Hady M, El Mahallawy N (2014) Microstructural characterization and kinetics of diffusion bonded AZ31/Al by hot press cladding. Mater Werkst 45(1):15–20
26. Li H, Chen J, Chandrashekhara K, Xu M, Lekakh SN, Richards VL (2015) Characterization and modeling of anisotropic SL pattern during investment casting process. Int J Adv Manuf Technol 80(9):1933–1943
27. Kim WW, Gang MG, Min BK, Kim WB (2014) Experimental and numerical investigations of cavity filling process in injection moulding for microcantilever structures. Int J Adv Manuf Technol 75(1):293–304