TSINGHUA SCIENCE AND TECHNOLOGY
ISSN 1007-0214 18/38 pp108-115
Volume 14, Number S1, June 2009

Design and Manufacture of a Wax Injection Tool for Investment Casting Using Rapid Tooling

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Abstract: A rapid wax injection tool of a gearbox shift fork was designed, simulated, and manufactured using rapid prototyping and rapid tooling technology to save time and cost of producing wax models used for the investment casting process. CAE simulation softwares, in particular, MoldFlow, are used to get wax injection moulding parameters such as filling parameters, temperature profiles, freeze time, speed, and pressure. The results of this research were compared with conventional wax model production methods. The criteria of such comparison were based upon parameters such as time, cost, and other related characteristics, which resulted in saving of 50% in time and 60% in cost. In this research, design, assembly, and wax injection operation of the wax tool took 10 days. Considering the fact that wax melting temperature is as low as 70℃ and injection pressure of 0.5 MPa, the tool suffers no damage due to the thermal and pressure stresses, leading to the mass production of wax models.

Key words: rapid prototyping; stereolithography; rapid tooling; wax injection moulding; simulation; investment casting

Introduction

Nowadays, companies are experiencing increasing pressure to produce complex and diverse products in shorter product development cycles, aiming to achieve less overall cost with improved quality[1]. As delivery time and cost of products are on a downward trend, the modern mould manufacturers are increasingly more under pressure to produce moulds quickly, accurately, and at lower cost[2]. As manufacturing industry encounters a growing demand for rapid tooling, rapid prototyping (RP) technology, in particular, stereolithography tooling, has shown to have significant potential in product and tool development. Compared to still higher resolving techniques, stereolithography (SL) bears the advantages of short processing times and good surface finish. Tool makers and manufacturers usually describe the performance of their devices in terms of accuracy or minimal layer thickness, and minimal surface roughness achieved.

Due to the fact that stereolithography has obtained a resolution as high as 60 μm, this significant advance in resolution enables stereolithography to build insert components with improved performance. High performance stereolithography resin with minimum layer thickness of 60 μm, minimum surface roughness of 4 μm, and nearly zero shrinkage, is an ideal candidate for rapid tooling purposes[3]. Consequently, stereolithography tooling techniques are improving and are becoming increasingly popular among manufacturers[4-6]. Previous work at Nottingham University has shown that SL injection mould tooling can be used successfully in low to medium shot numbers of

Received: 2008-11-09; revised: 2009-03-03
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engineering plastics such as PP and ABS[7].

During the last few years, significant research and developments are achieved by different research groups which have worked on rapid tooling issues. Weissman has demonstrated that a rapid prototype model can be used as a master to get a shell of metal and with a supporting material such as epoxy resin, it can be used for injection moulding, metal forming, and electrical discharge machining (EDM) electrode[8]. Jacobs has discussed the non-homogeneous mechanical property of SL models. He showed that the mechanical property of SL models is a function of laser exposure and prior knowledge about it can help to reduce the shrinkage generated distortion during part building process and post curing operation[9]. Gargiulo carried out an experiment with various hatch styles to improve part accuracy of stereolithography[10]. Richard et al. discussed the effects of parameters on the accuracy of parts built by SL process[11]. Rahmati and Dickens developed a series of experiments to demonstrate the performance of SL rapid tooling to utilize them as injection moulding tools[12].

However, investment casting process is considered as an economic approach in mass production of metal parts with complex shapes using different material alloys. In order to produce wax models for investment casting process, usually conventional tools manufactured via machining process are being used. On the other hand, using conventional tooling for wax model production may lead to extra time and cost, resulting in reduction of overall throughput and reducing the benefit of using such approach particularly for batch production. Rapid prototyping technology and its down stream applications in rapid tooling can lead to significant reduction in time and cost of design and production[13]. One of such applications is direct or indirect production of wax models needed in investment casting industry[14]. Applications in wax models demand a kind of processes which are able to produce the final shape and geometry of the part's critical features in near to the net shape with minimum post processing requirements. In this research stereolithography technique is used to fabricate the shell for tool master model of a shift fork of Peugeot engine gearbox (Fig. 1), then using this shell is used to make the tool for producing wax model of shift fork using epoxy tooling and direct ACES injection moulding tooling.

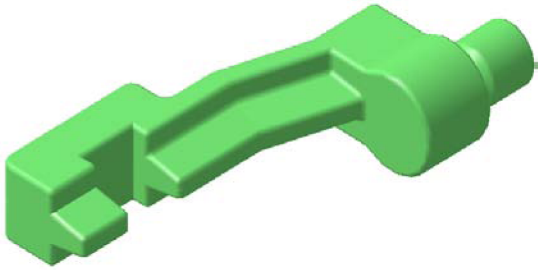

Fig. 1 Shift fork of Peugeot engine gearbox

1 Methodology

In this research, first the 3-D model of the part was created in Catia software. Then, the CAD model of the shift fork was analyzed using MoldFlow to investigate the ideal and optimum conditions of tool operation during wax injection moulding process. In order to construct wax injection moulding tool, epoxy insert shells were fabricated directly from CAD data on an SL machine. These inserts were then fitted into steel mould bases through steel frames accompanied by cooling pipes and were back-filled with aluminium powder/aluminium chip/epoxy resin mixture (Fig. 2). The back-filled mixture added strength to the inserts and allowed heat to be conducted away from the mould. The modular steel mould bases were two standard base plates machined with a pocket to fit the steel frames and the inserts (Fig. 3)[15]. Next, vacuum casting machine (MCP 006) was used for creating wax patterns. Experiments were focused on optimization of casting parameters such as wax temperature, vacuum pressure, and mould temperature to achieve better dimensional accuracy of the wax models.

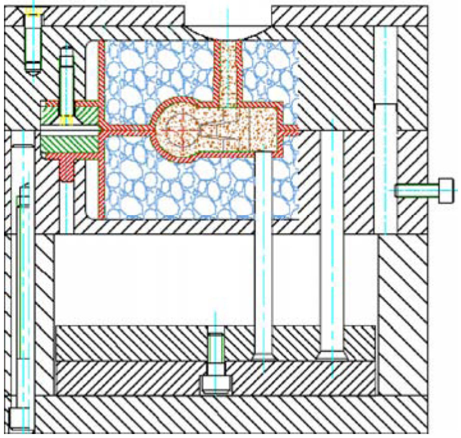

Fig. 2 Shift fork of Peugeot engine gearbox

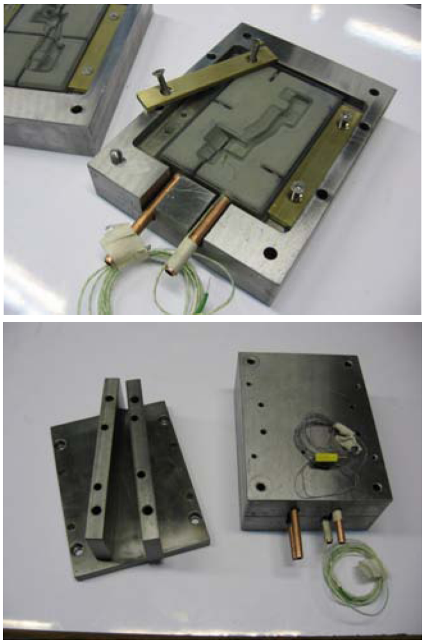

Fig. 3 Tool assembly components and the steel frames

1.1 Design of wax model

The first step was creating the specific shape of the product. Therefore, the 3-D model of the part, based on the nominal dimensions, was created in Catia software (Fig. 4). The ideal dimensions are the nominal dimensions plus the shrinkage factors due to the wax material and final casting metal. Therefore, the actual dimensions of the model are the dimensions of the actual casting wax.

1.2 Determination of shrinkages

In traditional moulding, the shrinkages of casting metal and wax material must be considered while creating the mould cavity[16]. Thus, the mould cavity dimensions should be bigger than the nominal data to compensate the shrinkages of wax and casting metal. The wax shrinkage depends on the thermal conductivity of the mould and the wax solidification rate. Linear shrinkage of the wax could be estimated as follows:

$$S_{\mathrm{L}} = \frac{L_{\mathrm{W}} - L_{\mathrm{F}}}{L_{\mathrm{W}}} \times 100 \tag{1}$$

where S_{L} is the linear shrinkage, L_{W} is the tool dimension, and L_{F} is the wax model dimension.

However, if α is defined as tool expansion coefficient and β as wax expansion coefficient, C can be defined as the tool actual dimension as follows:

$$L_{\mathrm{F}} = L_{\mathrm{W}}(1+\alpha),$$
$$C = L_{\mathrm{F}}(1+\beta) \Rightarrow C = L_{\mathrm{W}}(1+\alpha)(1+\beta) \tag{2}$$

However, in this research the shrinkage of casting metal was determined from casting design handbook and POULADIR Investment Casting Company[17].

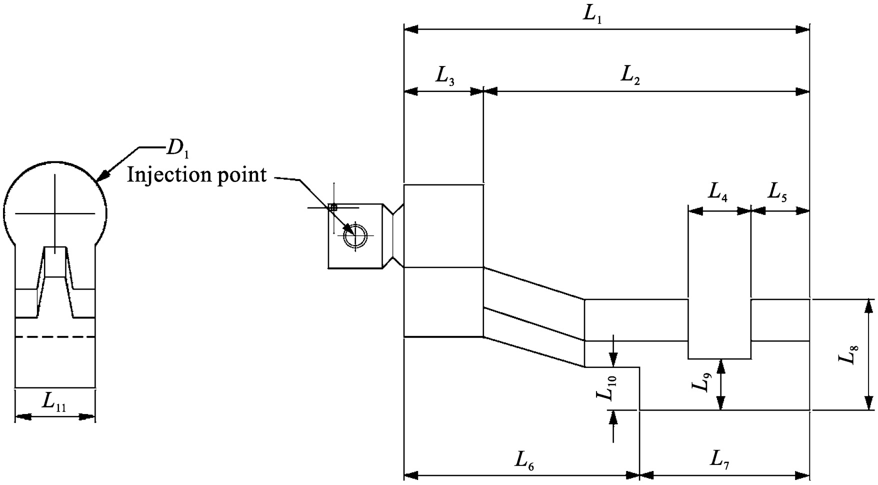

Fig. 4 Wax model parameters

2 Tool Simulation and Analysis

Computer CAE simulation can reveal tool/model design problems, injection parameters, and difficulties encountered during operation, well before commencing the real operation. In this research, all tool design stages are simulated repeatedly to achieve optimum wax tool performance.

2.1 Wax injection process simulation

MoldFlow package was applied to simulate and predict different scenarios and investigate the optimum tool design and injection parameters according to *the MoldFlow User Manual*. Parameters investigated include filling patterns, temperature profiles, residual stresses, tool clamping force centre of gravity, the pressure at different time intervals, tool temperature at any time, and freeze time. Providing correct data input results in appropriate analysis. While providing wax model and tool data to the MoldFlow, the proposed wax data did not exist at the MoldFlow database. Therefore, by consulting MoldFlow Company, a similar wax data from Argueso Company was provided to the MoldFlow database.

Among injection setting parameters, injection time was set at 10 s and freeze time at 30 s. Running different simulations resulted in the most favourable setting appropriate to produce 100 wax models per hour, whereas in conventional tooling these two parameters are 5 s and 10 s, which results in 300 shots per hour. Regarding tool surface temperature determination in MoldFlow, thermal analysis of ANSYS at permanent phase and MoldFlow at the transient phase was conducted according to *the ANSYS User Manual*, *Version 6.1*.

2.2 Simulation results analysis

Problems encountered during actual wax injection process such as weld lines and blush, are determined and corrected by the proper mould design, gate location, and gate design. Figure 5 indicates air trap spots locations which may occur during wax injection. Figure 6 indicates weld lines on the wax model where by choosing appropriate gate location, it avoids any weld lines.

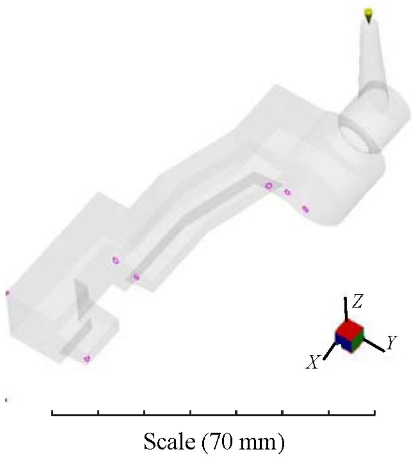

Fig. 5 Air trap spots locations

Filling process is clearly a complicated process. Figure 7 indicates the mould filling time of 10.21 s and Fig. 8 indicates the complete melt temperature after the cavity being completely filled to analyze the consistency of uniform temperature distribution of the wax model. Figure 9 indicates that the freeze time needed for the wax model is 30 s. The injection pressure of the mould cavity is 0.5 MPa.

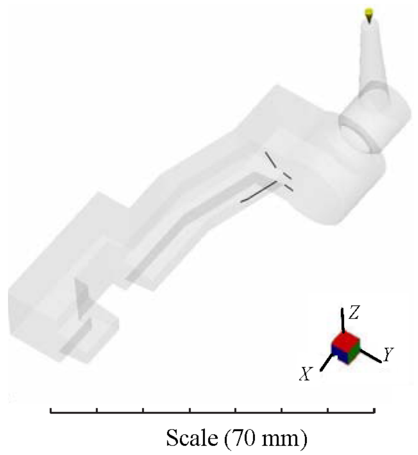

Fig. 6 Wax model weld lines

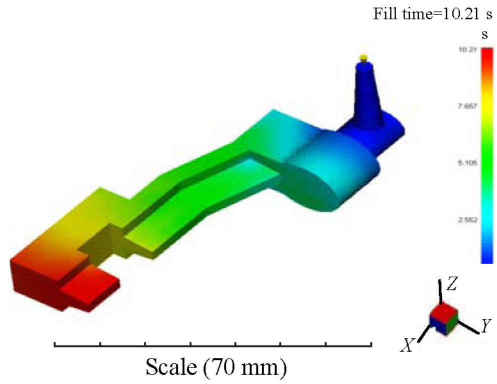

Fig. 7 Wax model filling time

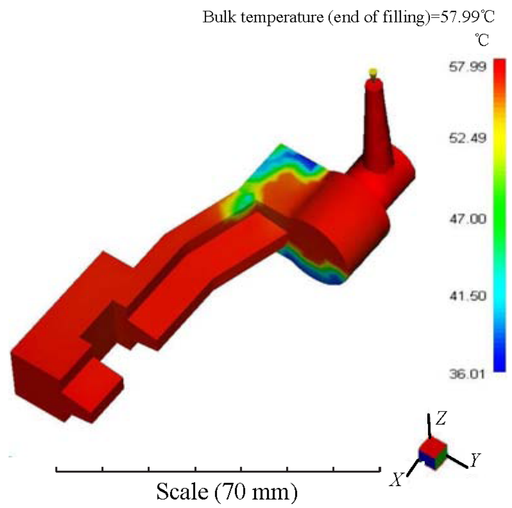

Fig. 8 Wax model temperature distribution

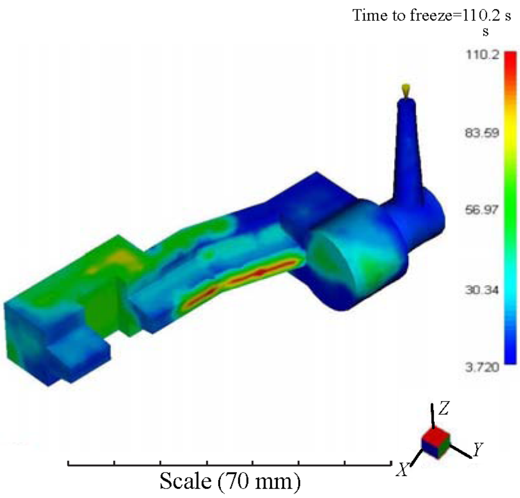

Fig. 9 Wax model freeze time

3 Wax Tool Fabrication

For fabrication of the insert cavity by stereolithography, the 3-D CAD model from Catia software was corrected by applying the shrinkage values of wax and metal casting to the nominal dimensions. Then, the final wax CAD model was converted into STL format by 3-D Lightyear software. STL is a standard format in RP industries which approximates 3-D-model surfaces with several triangle facets. After implementation of some complementary actions on the STL model, like model review, defining supports, and build orientation, the final CAD file was sent to rapid prototyping apparatus. In this project, insert cavity was fabricated by photo-curable WaterShed 11120 resin with a 3-D SLA-5000^{TM} machine (Fig. 10). Part layer thickness used in this process was 0.1 mm. After producing SLA inserts, post-processing operations such as washing excessive resin and removing supports were carried out, and finally core and cavity inserts were post cured in a UV oven. The final stage of post-processing operation was delicately finishing using a very fine sand paper.

Fig. 10 Fabricated inserts of Peugeot engine gearbox shift fork using stereolithography

To increase the tool mechanical stiffness, hardness, and precise tool alignment, and to minimize epoxy material consumption, a modular steel mould base was designed. Two standard base plates were machined into rectangular pocket to fit the inserts (Fig. 11). Base plates were machined using high speed milling machine to satisfy the required assembly tolerances. The inserts were then fitted into steel mould bases through steel frames, and back-filled with aluminium powder/aluminium chip/epoxy resin (Vantico5052) mixture (Fig. 12).

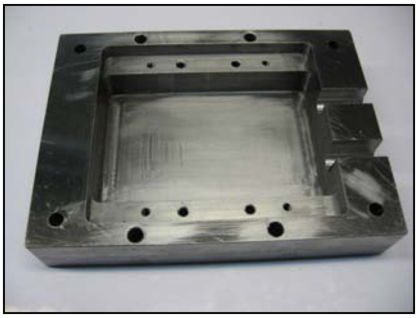

Fig. 11 Base plate machined into a rectangular pocket

(a)

(b)

Fig. 12 Back-filling inserts along with copper cooling pipes

The vacuum casting machine (MCP 006) was used to vacuum the back-filled material to the desired pressure for an hour to ensure no bubbles would remain during back-filling process. In the mean time, to conduct away heat from the tool during wax injection, copper pipes were applied as shown in Fig. 12. The back-filled mixture added strength to the inserts and allowed heat to be conducted away through copper pipes and the mould. After the back-filled solidification occurred in ambient condition, the back-filled surface which is going to be in contact with the base plate was machined and grinded.

4 Wax Tool Injection Process

During the initial moulding process, the wax injection test was carried out at SAPCO Co. manually, in such a way that two mould halves were held against each other using different holders and clamps. Then five shots of wax were injected at 80℃ and at two bars pressure. Next, for the actual moulding process, the tool was taken to the POLADIR Investment Casting Company to produce final wax patterns. MV30 wax injection machine was used at vertical orientation and parameter settings were applied using the simulation analysis results.

During the moulding process, the temperature and pressure of the cavity were monitored, and the melt temperature was controlled using different thermocouples to ensure that the conditions within the cavity remained as consistent as possible. Finally, 100 shots of shift fork of Peugeot engine gearbox were made with wax melt temperature at 65℃ and 5 bars pressure (Fig. 13).

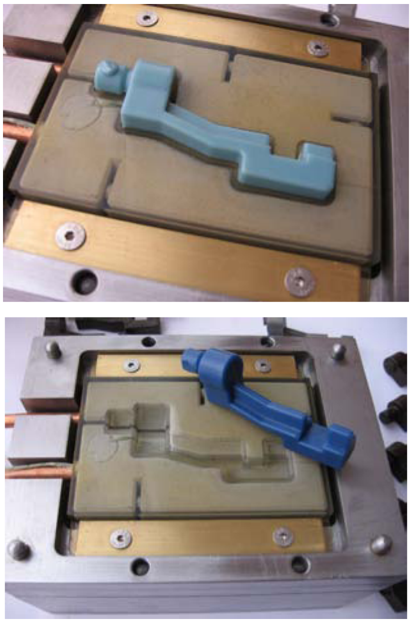

Fig. 13 Wax moulding of shift fork of Peugeot engine gearbox

5 Discussion

The rapid wax injection tool was successfully tested and the results revealed the success of the technique. Slim edges and sharp corners have been very well reflected on the wax model. This is specially highlighted when compared with traditional tooling which requires special attention while machining sharp corners. For example, during machining the traditional tools, the tool radius leads to undesirable fillets, which requires additional process such as EDM machining to trim such fillets into sharp corners. Any additional process means additional time and cost, probably sacrificing accuracy as well.

During wax model production, in spite of the abrupt difference in heat conductivity coefficient between epoxy and steel, heat of wax melt was conducted well to the tool base and the cycle time had no significant change compared with traditional tooling. Temperature data regarding barrel and nozzle during injection process is given in Table 1. The proper tool design, with copper cooling pipes and continuous tool temperature monitoring using different thermocouples, has resulted in uniform cycle profiles as shown in Fig. 14. According to the present production rate, the tool has produced 100 shots in an hour versus 300 shots in an hour in traditional tooling, which seems to be acceptable. It is possible to improve this rate using multi-cavity tool, which makes this technique further suitable and economical for fast part production.

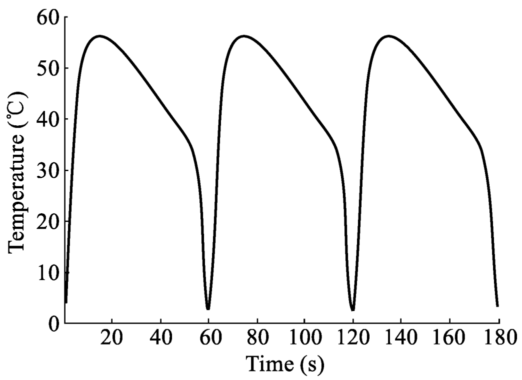

Fig. 14 Temperature changes at tool cavity surface versus time in consecutive cycles

Table 1 Temperature settings during wax injection process (℃)

Nozzle	Barrel	Upper plate	Lower plate	Wax model
65	60	13	14	45

In order to check the dimensional accuracy of the wax model, optical measuring system was applied to extract the interested dimensions. The standard deviation of the wax model was 0.08 mm (Fig. 4). The general tolerance of the wax model was found to be in the range of ±0.1 mm, which was acceptable by the manufacturer. The nominal dimensions of the wax model are given at Table 2, and the actual dimensions of the produced wax model are given at Table 3.

Table 2 Wax model nominal dimensions (mm)

L_1	L_2	L_3	L_4	L_5	L_6
77.8	62.42	15.38	11.99	11.33	45.1
L_7	L_8	L_9	L_{10}	L_{11}	D_1
32.7	21.12	9.74	8.2	15.38	19.47

Table 3 Wax model actual dimensions (mm)

L_1	L_2	L_3	L_4	L_5	L_6
77.5	62.1	15.17	11.8	11.25	45.3
L_7	L_8	L_9	L_{10}	L_{11}	D_1
32.53	20.82	9.55	8.15	15.1	19.25

Comparing the results of Tables 2 and 3, the largest difference belongs to L_1 and L_3, which is 0.3 mm. These two parameters are located where they can have free shrinkage while other parameters have constraint in shrinkage. With respect to the thickness, except L_4 which has 0.19 mm increase in thickness, the remaining parameters fit within the tolerance. Parameter L_{11} has shrinkage of 0.29 mm which is precisely equivalent to the forecasted value suggested by the simulation software (Fig. 15).

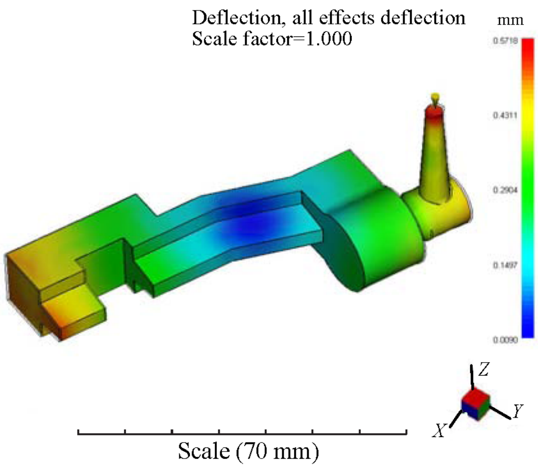

Fig. 15 Wax model warpage and shrinkage after ejection

Considering the difference between the nominal and actual dimensions, and with respect to the applied coefficient of shrinkage, it could be concluded that the tool cooling method has influence on the wax shrinkage[18]. Moreover, those parameters which reveal larger shrinkages have no constraint and can shrink freely. Therefore, the calculated shrinkage was found to be 1.5% in length and 2.5% in thickness, which is in accordance to the suggested values by the MoldFlow simulation software (Fig. 16).

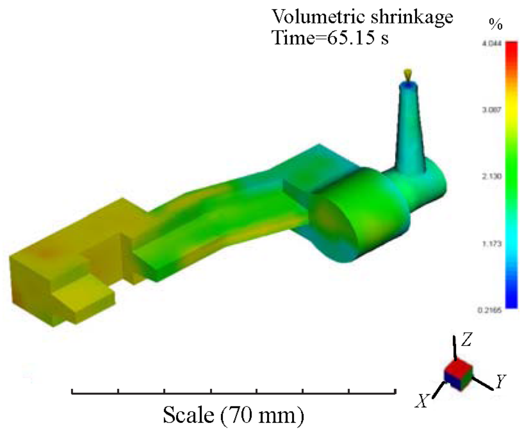

Fig. 16 Shrinkage at 10th second of wax injection

Comparing the theoretical results of the simulation softwares with the actual results confirms the reliability and correctness of the investigation. With respect to the time and cost saving in applying wax rapid tooling compared to the traditional tooling, the time saving was 50% and the cost saving was 60%. This comparison takes into consideration parameters affecting the time and cost of tool design, manufacturing, and issues such as material recruitment, other services for tool manufacturing in terms of instruments, human resources, and finishing operations.

6 Summary

This research aimed at investigating the feasibility of applying rapid prototyping and rapid tooling technology into the wax model production for investment casting process. The results not only confirm the success of such application, but also prove valuable benefits with respect to the common tooling techniques.

- Due to the fact that many moulding parameters inside the cavity such as pressure and melt temperature, are not easily possible to be measured; therefore, CAE simulation softwares are unique and inexpensive alternatives to analyze and evaluate such rapid tools.
- Obviously, CAE simulation softwares such as MoldFlow and ANSYS are significant aids in rapid tooling analysis, acquiring tooling parameters and melt behavior in the cavity; and today's rapid tooling analyses of different rapid

tooling techniques have been developed and are complementary for each other.

- The results of this paper indicate saving of 50% in time and 60% in cost. Design, assembly, and wax injection operation took 10 days, compared with the traditional techniques which may take at least two month.
- Considering the fact that wax melting temperature is as low as 70℃ and injection pressure of 0.5 MPa, the tool can suffer no damage due to the thermal and pressure stresses, leading to the mass production of wax models.
- Using simulation softwares prevents common moulding defects well in advance before being encountered during operation.
- Injection cycle time is found to be between 40-50 s which is longer than the common tooling techniques (5-15 s), due to the fact that the tool cavity is a nonconductive material; however, this may be improved by increasing the number of cavities (multi cavity).
- Due to the modular nature of tool plate and frame assembly, it is possible to reuse the material for similar tool dimensions, leading to more saving in time and cost for new tools.

According to the above findings, it could be concluded that the rapid wax injection tooling is an appropriate alternative for mass production via investment casting process. Therefore, rapid wax injection tooling technique could replace many expensive, time consuming, and complex machining techniques.

Acknowledgements

The authors would like to thank the Rapid Prototyping & Tooling Branch of SAPCO Part Supplier of Car Manufacturing Co. of Iran-Khodro and POULADIR Investment Casting Company for supporting this project.

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