EFFECTS OF HEAT TRANSFER IN JIG MOLDS IN INJECTION CASTING

HUSSAM ABDULLA MOUSSA MOUHANNA

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2019

EFFECTS OF HEAT TRANSFER IN JIG MOLDS IN INJECTION CASTING

HUSSAM ABDULLA MOUSSA MOUHANNA

RESEARCH REPORT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF MANUFACTURING ENGINEERING

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2019

UNIVERSITY OF MALAYA

ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: Hussam Abdulla Moussa Mouhanna

Matric No: KQG160017

Name of Degree: Master of Manufacturing Engineering

Title of Project Paper/Research Report/Dissertation/Thesis ("this Work"): Effects of Heat Transfer in Jig Molds in Injection Casting

Field of Study: Advanced Manufacturing

I do solemnly and sincerely declare that:

(1) I am the sole author/writer of this Work;
(2) This Work is original;
(3) Any use of any work in which copyright exists was done by way of fair dealing and for permitted purposes and any excerpt or extract from, or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the Work and its authorship have been acknowledged in this Work;
(4) I do not have any actual knowledge nor do I ought reasonably to know that the making of this work constitutes an infringement of any copyright work;
(5) I hereby assign all and every rights in the copyright to this Work to the University of Malaya ("UM"), who henceforth shall be owner of the copyright in this Work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained;
(6) I am fully aware that if in the course of making this Work I have infringed any copyright whether intentionally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

Candidate's Signature Date:

Subscribed and solemnly declared before,

Witness's Signature Date:

Name:

Designation:

EFFECTS OF HEAT TRANSFER IN JIG MOLDS IN INJECTION CASTING

ABSTRACT

Injection Molding is a widely used process in the manufacturing industry. One of its limitations is the design of cooling channels in molds. Traditionally, only straight channels could be drilled in molds thereby providing non-uniform cooling. Additive manufacturing provides a means to create conformal channels that fit the needs of specific designs previously implausible to create. This study seeks to study the effect of conformal cooling channels in the injection molding of Tin jigs and optimize the parameters of the channels to minimize the cooling time and expedite the cooling process. This is done by exploring the effect of different design parameters of the channels using simulations. The thermal transient model is used in ANSYS 19.1 R1 to run the simulations and obtain results. These would then be analyzed using the Taguchi method to see their effects. The results showed a 28.8% decrease in cooling time with the conforming channels. Additionally, the diameter was found to be the most important factor followed by the pitch while the length was found to have a minor effect. The Taguchi method was then used to optimize and select the best parameters. Comparisons between straight and conformal channels were carried out and showed that conformal channels provide better cooling and more uniform temperature distribution.

Keywords: Injection molding, Cooling channels, Conformal cooling channels, Finite element analysis

[TAJUK LAPORAN PENYELIDIKAN/DISERTASI/TESIS]

ABSTRAK

Injection Molding adalah proses yang digunakan secara meluas dalam industri pembuatan. Namun, terdapat satu halangan reka bentuk saluran penyejuk di dalam acuan. Secara tradisinya, saluran lurus hanya boleh digerudi dalam acuan untuk menyediakan penyejukan yang tidak eragam. *Additive manufacturing* menyediakan cara untuk mewujudkan saluran *conformal* yang sesuai dengan keperluan reka bentuk tertentu yang mana sebelum ini tidak dapat dilaksanakan. Penyelidikan ini bertujuan untuk mengkaji kesan saluran penyejukan *conformal cooling channels* dalam acuan suntikan *Tin jigs* dan mengoptimumkan parameter saluran untuk meminimumkan masa dan mempercepatkan proses penyejukan. Ini dapat dilakukan dengan mengkaji kesan parameter reka bentuk yang berbeza dari saluran menggunakan simulasi. Model *Thermal Transient* digunakan dalam ANSYS 19.1 R1 untuk menjalankan simulasi serta mendapatkan hasil kajian. Kajian ini seterusnya dianalisa menggunakan kaedah *Taguchi method* untuk melihat kesannya. Keputusan menunjukkan penurunan sebanyak 28.8% dalam masa penyejukan dengan saluran yang sesuai. Di samping itu, diameter itu dikenalpasti sebagai faktor paling penting diikuti oleh *pitch* manakala panjang saluran didapati mempunyai kesan yang lebih kecil. *Taguchi method* kemudian digunakan untuk mengoptimumkan dan memilih parameter terbaik. Perbandingan antara saluran lurus dan *conformal cooling channels* telah dijalankan dan menunjukkan bahawa saluran *conformal cooling channels* memberikan penyejukan yang lebih baik dan pengagihan suhu yang lebih seragam.

Kata kunci: Injection molding, Cooling channels, Conformal cooling channels, Finite element analysis

ACKNOWLEDGEMENTS

I would like to acknowledge the University of Malaya for providing the support and guidance to carry out this research. Any opinions, findings, conclusions, and recommendations expressed in this investigation are those of the writers and do not necessarily reflect the views of the university.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

PET	:	polyethylene terephthalate
D	:	Diameter
P	:	Pitch
L	:	Length
HTC	:	Heat transfer coefficient
NC	:	No Channel
SC	:	Straight Channel
CC	:	Conformal Channel

CHAPTER 1: INTRODUCTION

1.1 Injection Molding

The injection molding process is used to produce parts of varying sizes and complexities from a plethora of materials including metals, plastics and glasses. The operation involves molten material forced into mold with a cavity of the desired shape, which then solidifies after enough time of cooling. Then the mold is opened, the part is ejected from the mold after which it is closed again and the cycle repeats. It involves various process filling, cooling and ejection. Figure1.1 shows a typical injection molding machine. The machine in this example could be used to make parts from plastics, metals and other materials.

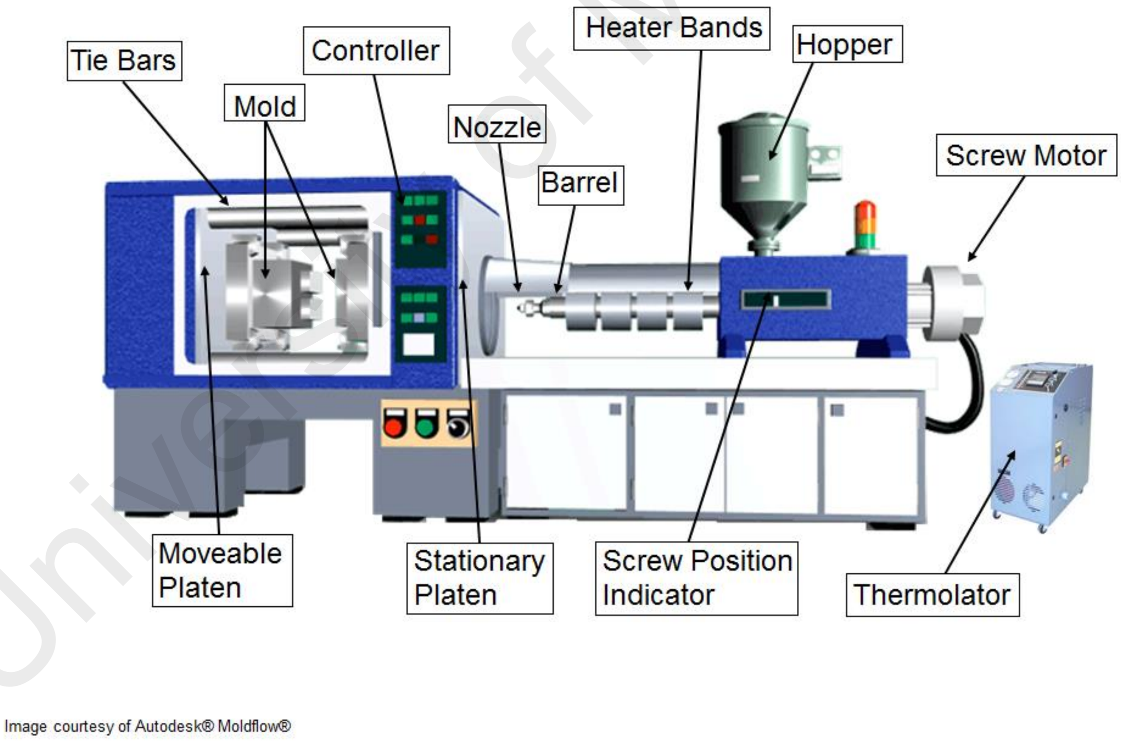

Figure 1.1: Injection Molding Machine[1]

[1] Injection Molding Machine. (2019). Retrieved July 22, 2019, from http://www.beaumontinc.com/injection-molding-glossary/injection-molding-machine/

1.2 Cooling Cycle and Channels

In injection molding the cooling phase is critical to obtain quality parts (Venkatesh & Ravi Kumar, 2017). The cooling of injection molding tooling plays a very important role in the total production cycle time of the injection molding process. Time is significant in the entire process, as it constitutes about half of the time in the overall production cycle(Jahan et al., 2017). Figure 1.1 shows a generic distribution of time in the total injection molding process.

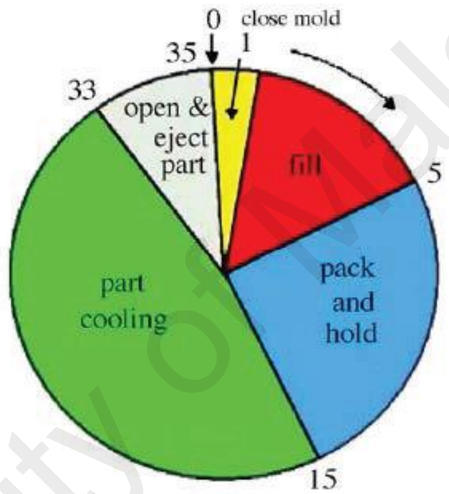

Figure 1.2: Typical cycle time in injection molding (Dimla, Camilotto, & Miani, 2005)

Previously the limiting factor in many cases for better design was the manufacturing methods available to fabricate injection tooling and allow for more innovative and efficient designs. The introduction of rapid tooling and additive manufacturing however provided a means to achieve more efficient designs with lower cooldown times and lower costs.

An example of such design is conforming cooling channels. Traditionally straight holes are drilled into the solid dies to cool the hot molten material inside the cavity. While traditional channels helped reduce the cooling time as compared to without channels, they had their limitations. Firstly, straight channels did not provide uniform cooling as they were mostly drilled on the sides of the mold. Secondly, due to their nature they could not properly reach and cool parts with more complex geometries. In order to improve the cooling process and with the help of AM, it became possible and more feasible to create conformal cooling channels. These “conform” to the shape of the internal cavity wall, thus can reach much closer to the molten material, compared to the cases of traditional molds. Additionally, with the use of advanced additive manufacturing technology, the shape and size of the channels are no longer limited to larger circular cross-section, rather it is up to the requirement of the optimal channel configuration(Jahan et al., 2017). That being said, star or hexagonal shaped cross-sections are still difficult to design as they are more susceptible to damage, fracture and design failure inside the channels(Jahan & El-Mounayri, 2016).

1.3 Objectives

There are two objectives in this research:

1. To investigate the heat transfer in the jig mold during the casting process using simulation technique
2. To determine the optimum parameters in casting process for jig productions.

The focus of this study is the effect of adding conformal cooling channels to the mold compared to not having any. Secondly, it aims to find the optimal cooling channel design parameters for use in the injection molding of metallic fishing jigs. Three main parameters will be investigated using simulations after which the results will be analyzed using the Taguchi method to identify the optimal configuration to be used. Experimental runs were not performed in this study due to time and money constraints.

CHAPTER 2: LITERATURE REVIEW

Additive Manufacturing has been studied to improve the molding process in the manufacturing industry. One aspect of it was cooling channels. Research on the effect of cooling channels in general and molds with conformal cooling channels in specific has been carried out before. This is because the cost-efficiency of the process is dependent on the time spent in the molding cycle. Correspondingly, the cooling phase is the most significant step amongst the three, it determines the rate at which the parts are produced (Dimla et al., 2005). Later a different study also showed the use of conforming cooling in the forms for injection molding of plastic has a positive effect on shortening the production cycle and improving dimensional stability of the product (Vojnová, 2016).

A framework for optimizing additive manufacturing of plastic injection molds was presented in 2015, experimenting on simpler shapes for validation before applying it to dies with conforming cooling channels in the future (Wu et al., 2015). The same group used Design of experiments technique is used to study the effect of critical design parameters of conformal channels. This included studying the effect of the diameter of a circular cross-section, the pitch of channels and the distance between the mold walls and the channel centerline. Moreover, they compared the cooling time of 5 different cross-section shapes of the channels. In addition, a trade-off technique is utilized to obtain optimum design configurations of conformal cooling channels for “best” thermo-mechanical performance of a mold. The mechanical aspect was done by taking the von-mises stresses on the mold as one of the parameters to optimize (Jahan et al., 2017).

Park & Dang conducted a study to create local conformal cooling channels in the injection molding of a complex automotive part. The part contained traditional cooling channels as well as spiral conforming channels in areas with thicker walls. The research results show that conformal cooling channels reduce the cycle time approximately 30% compared to conventional cooling channels (Park & Dang, 2017).

Additionally in 2017, a study was released were various cooling channel designs were made to optimization of cooling effect and to minimize the cooling defects in injection molding process (Venkatesh & Ravi Kumar, 2017). The variables they studied were the cross-sectional profile of the channels (circular, trapezoid and rectangle), the cooling passage way (spiral, spiral square and straight line) and the channel centerline to part surface. Finite element analysis was used to analyze thermal stresses in the mold surface geometry generated around the mold using ANSYS Thermal analysis. After that design of experiments was conducted by the Taguchi orthogonal method to optimize the results and find the optimum parameters.

The same group also released a study that made a direct comparison between conventional and straight channels and conforming channels (Venkatesh, Y, & Raghavendra, 2017). This paper focused on studying the effect of conformal cooling channels on common problems faced in traditional cooling systems, such as warpage cycle time and part quality. Their results show that the proposed optimum conformal channels design improved cycle time and allowed for more uniform heat transfer compared to straight channels.

Most recently in 2018, Liew et al. released a study that focuses on optimizing the design of PET bottle blow mold. This is to avoid bottle stress cracking or breaking to non-uniform cooling or unsatisfactory cooling. Conformal cooling channels were used to resolve these issues and for cooling efficiency comparison, the shape and size of the conformal cooling channels, fluid temperature and flow rate were varied for both experiments and simulations. The capability and accuracy of simulation on conformal cooling channel design and analysis were verified via experiments. Their results show a decrease in cooling time from 2.9 seconds to 1 second as well as a more uniform temperature distribution and less temperature difference of 4°C (Liew, Peng, Jou, & Wang, 2018)

Also in 2018, Babenko et al. performed a study on the heat transfer coefficient (HTC) in microinjection molding. HTC determines the heat flux across the interface of the polymer melt and the mold wall. It is a dominant parameter in cooling simulations especially for microinjection molding, where the high surface to volume ratio of the part results in very rapid cooling. The simulation results have shown that the heat transfer coefficient is a significant parameter in the computer simulation of the microinjection molding. This work suggests that the default values of heat transfer coefficients are unsuitable for microinjection molding and values in the range 7000–8000 W/m2 C for both the filling and packing phases will provide more accurate results. (Babenko et al., 2018).

It can be seen that while there have been studies on conformal cooling channels, research that looks into the effect of different parameters that concern different parts is very limited. Additionally, most research concerning these parameters uses plastic injection molding as the base, while our study is concerned with metal injection molding.

CHAPTER 3: METHODOLOGY

This study will be conducted using software simulations. A 3D model will be needed after which simulations will be run in software to observe the cooling effects of the conformal channels with different design parameters.

3.1 3D Mold Model

A 3D model of the mold was created using Solidworks 2018. The mold has the basic dimensions of 155mm length, 100mm width and 61mm depth. It consists of a top and bottom part as shown in figure 3.1 below. The top and bottom parts are made of Steel.

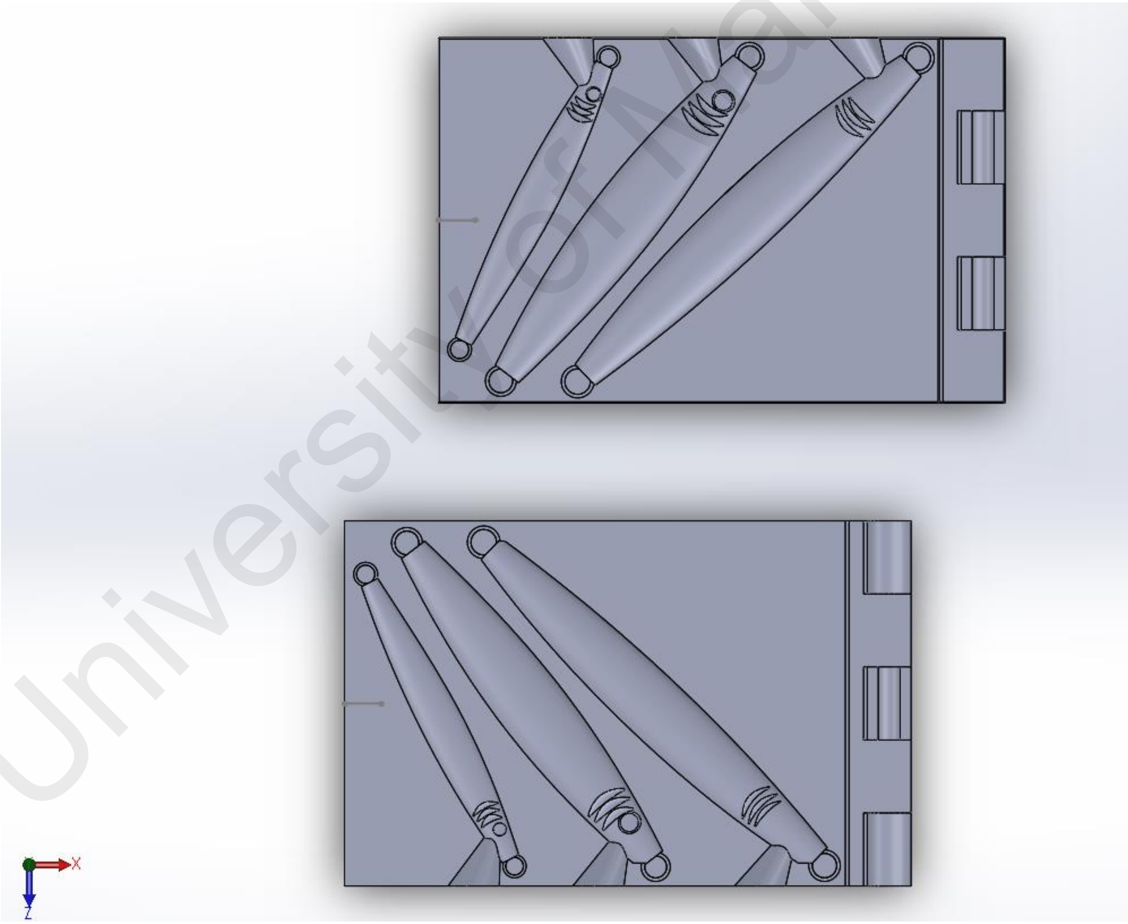

Figure 3.1: Mold Parts

The two parts are held together by joints and can be opened and closed with ease

The jigs are made of tin and come in three varying sizes as shown in figure 3.2 below.

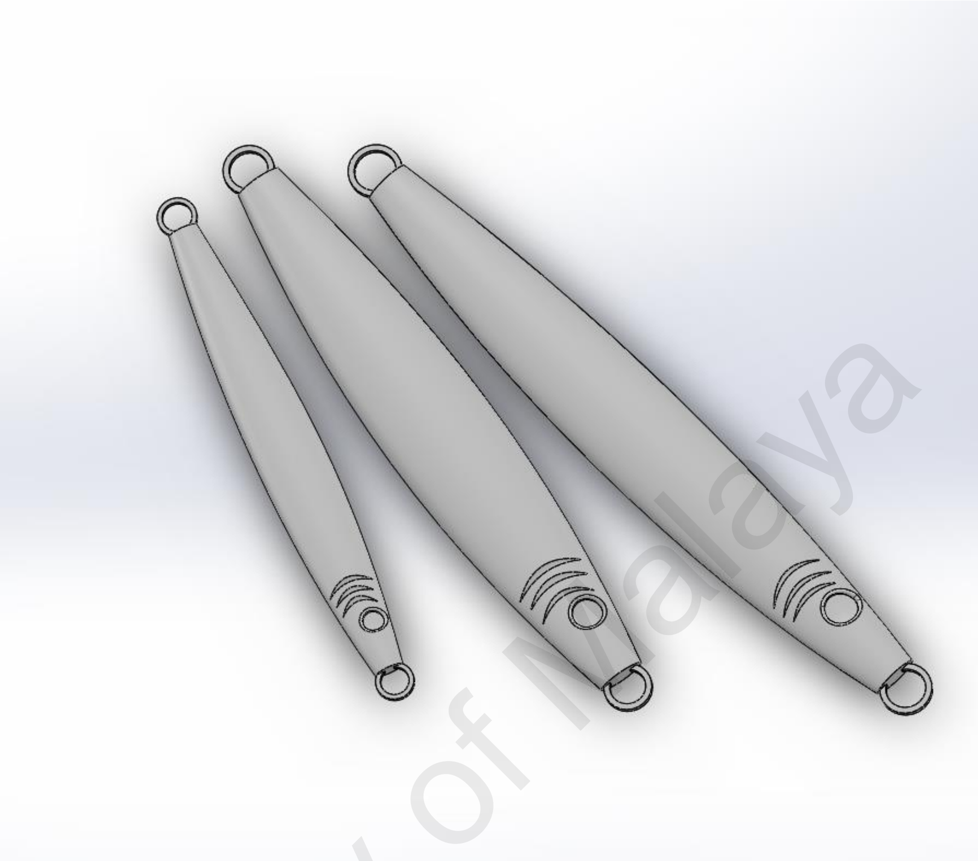

Figure 3.2: Jigs

Figure 3.3 shows the assembly of the mold and molded jigs.

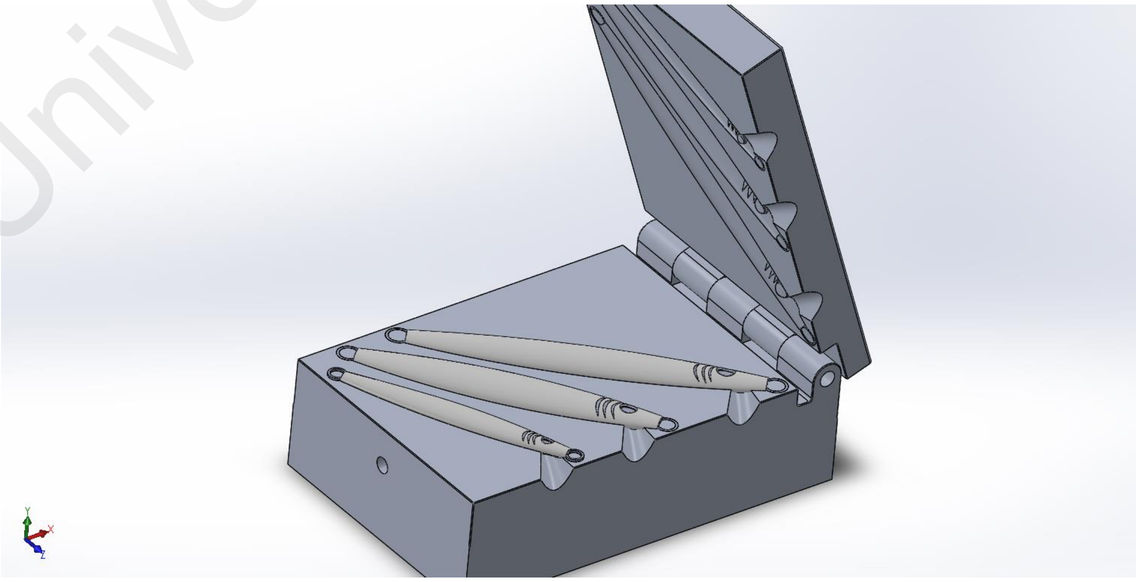

Figure 3.3: Mold and jigs assembly

The main parameters in this study are the diameter of the cooling channel (D), the pitch (P) and the length between molded part and centerline of the cooling channel (L). Different mold designs are studied by changing the parameters of the conformal cooling channels. Figure 3.4 illustrates and defines the parameters. The upper and lower bounds of the parameters were chosen according to table 3.1, which provides a general reference for the relationship between the parameters.

Table 3.1: A rule of thumb for conformal cooling channel designs in 3D printed molds (Mayer, 2007)

Wall thickness of molded part (mm)	Channel diameter, D (mm)	Pitch distance, P (mm)	Channel centerline to mold wall distance, L (mm)
0-2	4-8	2D - 3D	1.5D – 2D
2-4	8-12	2D - 3D	1.5D – 2D
4-8	12-14	2D - 3D	1.5D – 2D

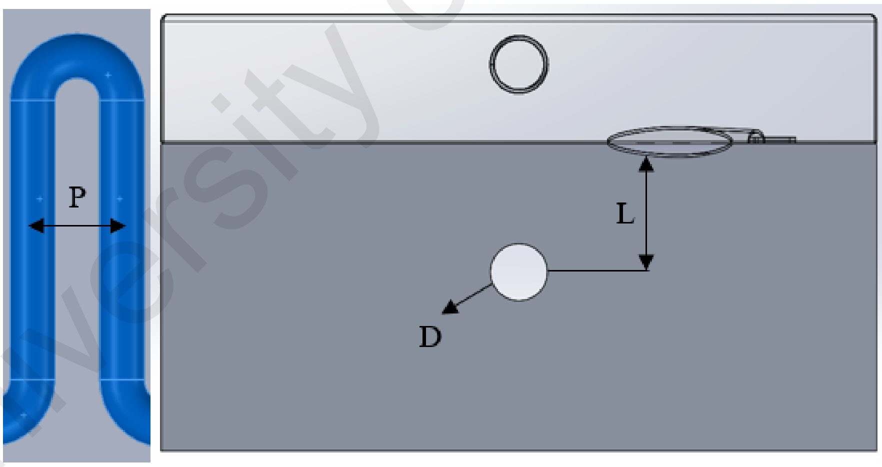

Figure 3.4: Parameter illustration and definition

3.2 Thermal Model

The finite element analysis and simulations were run on the ANSYS 19.1 R1 software. The steady state model was first used, and its results were then used as an input to the transient thermal analysis module.

The molten Tin is inserted into the mold, after which the mold is cooled using water passing through the channels. The water also warms up the mold to reduce shrinkage in the jigs(Jahan et al., 2017). Hence the water temperature is set to 25℃. As the study is concerned about the cooling process and the phenomena happening after the molten Tin is inside the cavity, it's considered to be already inside the mold cavity. Therefore, at time t=0, the Tin is already inside and water starts running inside the cooling channel.

The material properties used for Tin and Steel (mold) are shown in table 3.2. The mesh size was set to default and smoothing to medium. On average the various mold designs had 67600 nodes and 38500 elements.

Table 3.2: Material Properties

Material	Tin	Structural Steel
Density (kg/m3)	7280	7850
Thermal conductivity (W/m-K)	68.2	60.5
Specific heat (J/kg-K)	228	1900

The initial settings of the steady state thermal analysis were an initial mold temperature of 22℃, the water temperature at 25℃, and the temperature of the molten Tin set at 250℃. The results of this are then entered to the transient thermal analysis. Convection is added to the walls of the channels with a HTC of 400 W/m^2-K. In this study the HTC is taken to be constant through all designs so that only the 3 design parameters of D, P and L have any effect on the data. The simulation runtime is set to 150 seconds. Figure 3.5 shows the overall module of the simulation.

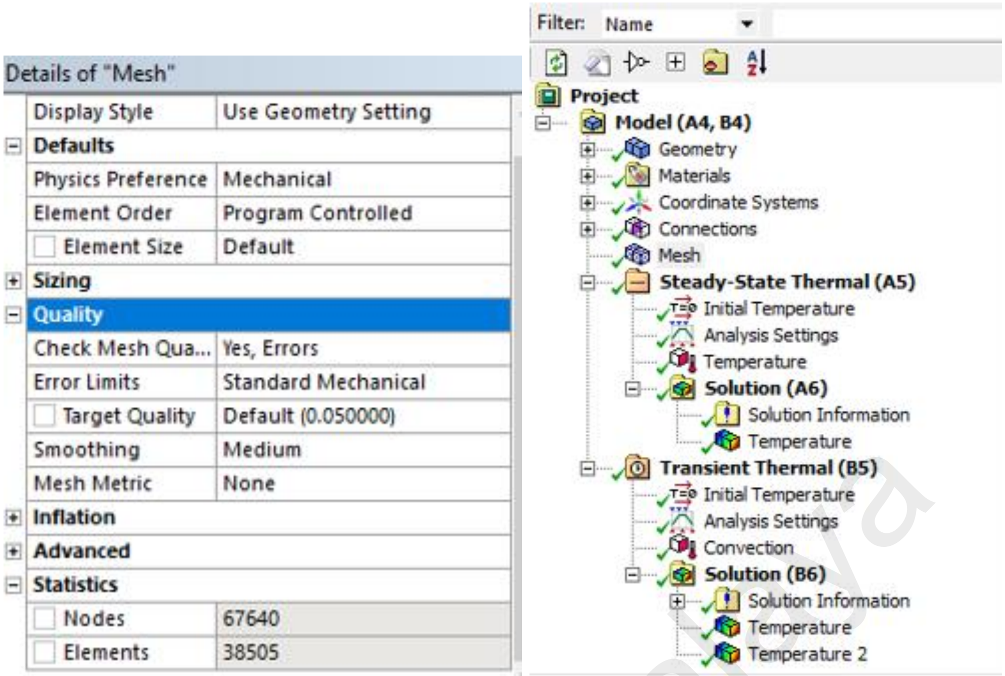

Figure 3.5: Simulation Breakdown

The part to be made has no walls as it is a solid part, hence the range for diameter used is 4mm to 8mm following the recommendation of table 3.1 previously mentioned. Correspondingly, with a diameter of 4mm the lowest pitch would be 8mm while the highest pitch would be 24mm at diameter 8mm. Likewise, the lowest value for L would 6 and the highest value would 16. During the modeling phase however the original design of the model proved to be limiting in that 6mm length was not plausible, and to allow the biggest range in the parameters, the upper limit of length was increased from 16mm to 18mm. the final range of values for the 3 parameters are shown in table 3.3 below.

Table 3.3: Parameter Range

Parameter	Range (mm)
Diameter	4-8
Pitch	8-24
Length	8-18

The Taguchi method was used to select the different combinations according to the L9 (3x3) array, with 3 factors and 3 levels per factor resulting in 9 runs.

CHAPTER 4: RESULTS AND DISCUSSION

Table 4.1 shows the results obtained from the simulations. All the simulations showed jig temperature results lower than 245.2℃ which is what was observed without channels. The lowest temperature was obtained using the parameters of 8-10-18 at 171.7℃ while the highest temperature was 4-20-18 at 224.43℃. This however does not indicate which parameter is the most impactful on the cooling process. In order to analyze the results, Minitab 19 to do statistical analysis. As the parameters were chosen with the Taguchi method, that will be used to identify the effect of D, P and L.

Table 4.1: Simulation Results

Case	Diameter(mm)	Pitch(mm)	Length(mm)	Jig Temp(℃)
1	4	10	12	203.39
2	4	15	15	217.50
3	4	20	18	224.43
4	6	10	15	185.42
5	6	15	18	204.98
6	6	20	12	212.13
7	8	10	18	171.70
8	8	15	12	188.32
9	8	20	15	199.76

The analysis was done with the ‘lesser is better’ option as the objective is to minimize the temperature of the jigs. Table 4.2 shows the response table and the ranking of the factors, with diameter being the most impactful parameter followed closely by the pitch. The length on the other hand shows very little impact in comparison.

Table 4.2: Response Table for Means

Level	Diameter	Pitch	Length
1	215.1	186.8	201.3
2	200.8	203.6	200.9
3	186.6	212.1	200.4
Delta	28.5	25.3	0.9
Rank	1	2	3

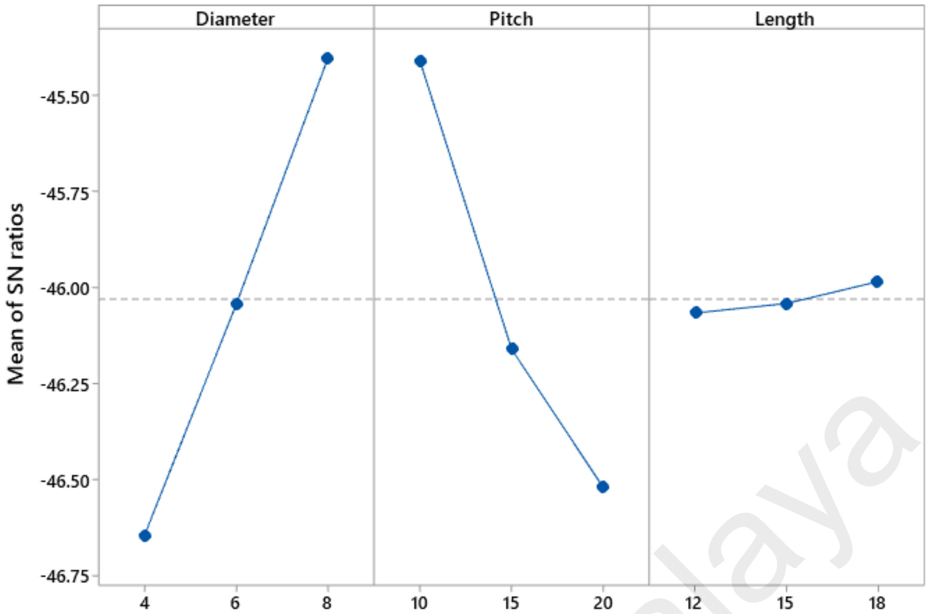

Figure 4.1: Main Effects Plot for S/N ratios

The optimum parameters are shown in the graph 4.1 as 8-10-18. From this we can conclude that increasing the diameter while keeping the pitch constant or decreasing the pitch while keeping the diameter constant will yield a lower temperature at the end of the simulation. This can be explained as an increase in diameter would increase the cooling surface area, so the rate of cooling would increase. The same logic applies to decreasing the pitch. As the Pitch decreases, the greater the total cooling surface area, hence the better the cooling rate.

As for the length, it was expected that a lower value would produce better cooling. This is due to a result by a research group which states that the minimum value of L will provide the minimum cooling time (Jahan & El-Mounayri, 2016). The results of this study on the other hand show the opposite. This could something specific to this study specifically. At L=18mm for instance, the channels are more centered in the mold, thus the temperature distribution is more uniform, and so more uniform cooling brought the temperature of the mold down faster. This in turn results in cooling the jigs faster. Further testing is required to verify this claim, however.

To accurately see the impact of the cooling channels on the casting process, a simulation was done without any channels and only air convection. The result is shown below, with figure 4.2 comparing the mold temperatures and figure 4.3 comparing jig temperatures. For the purposes of this simulation, the side resting on the ground was not subjected to air convection.

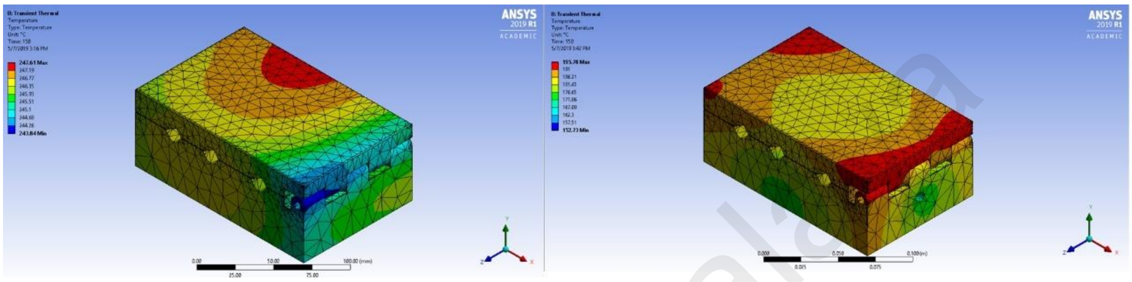

Figure 4.2: Mold Comparison - NC (left), case 7 (right)

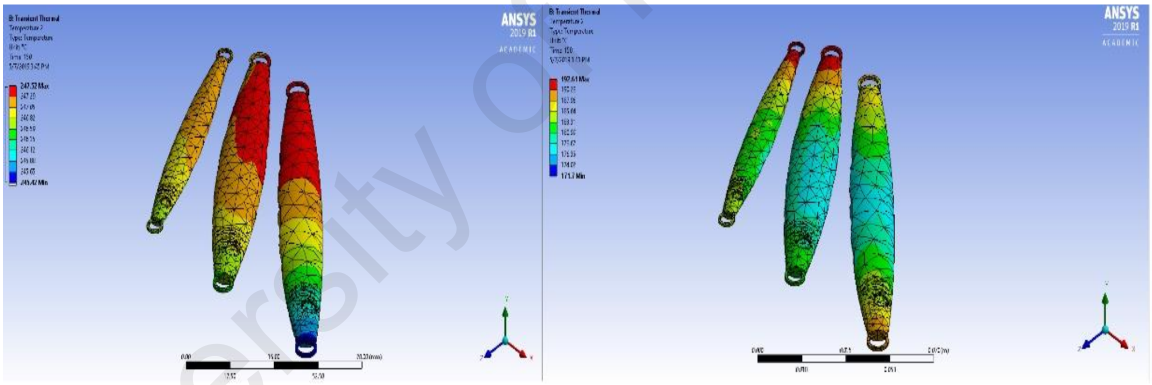

Figure 4.3: Jig comparison - NC (left), case 7 (right)

The final temperature with no channels was 243.84°C, which shows there was close to no cooling during simulation runtime. There was a 28.8% decrease in cooling time in case 7 (171.7°C) as compared to no channels, which shows a clear improvement in the cooling process. Moreover, even if the highest cooling time obtained in our results (case 3) is used in the comparison that is still a 7.6% decrease in cooling time. There is also a more uniform temperature distribution in the mold and jigs with cooling channels than without as can be seen in figures 4.4 and 4.5 below.

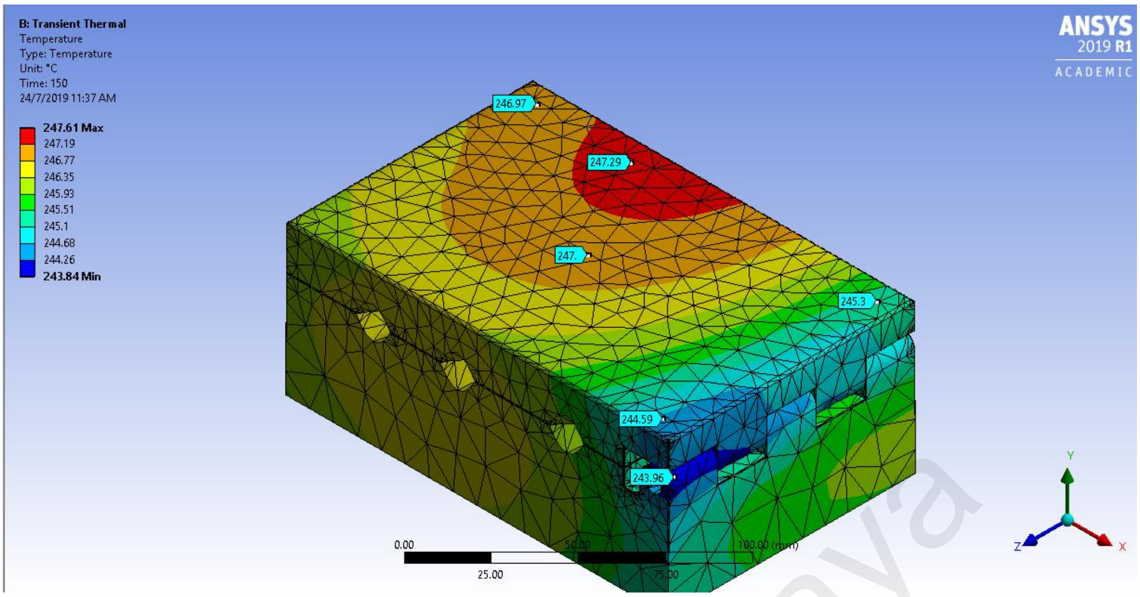

Figure 4.4: NC Mold

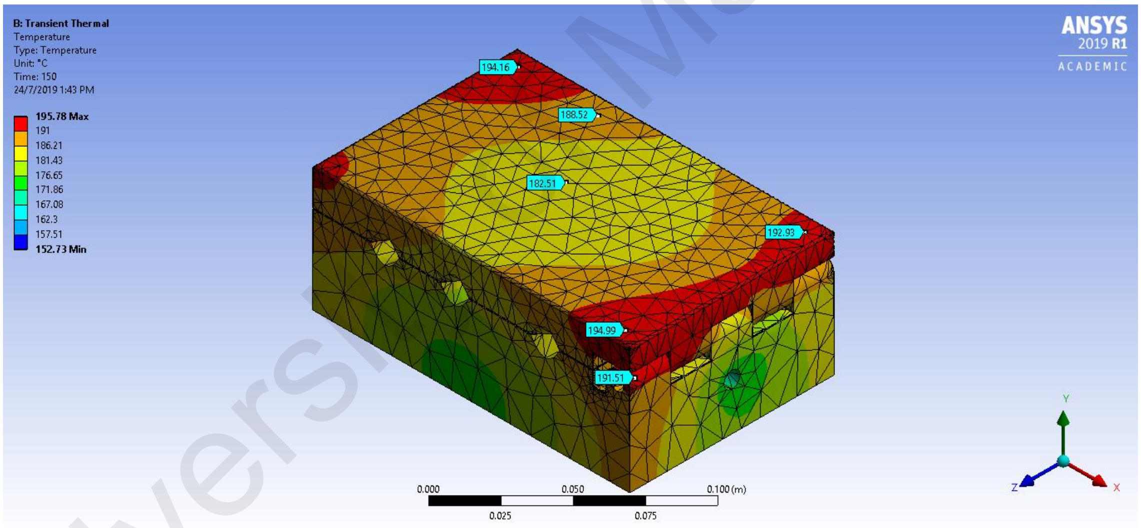

Figure 4.5: Case 7 Mold

We can see some point values of the temperature at the same positions in the mold

The temperature distribution on the jigs can be seen below in figures 4.6 and 4.7.

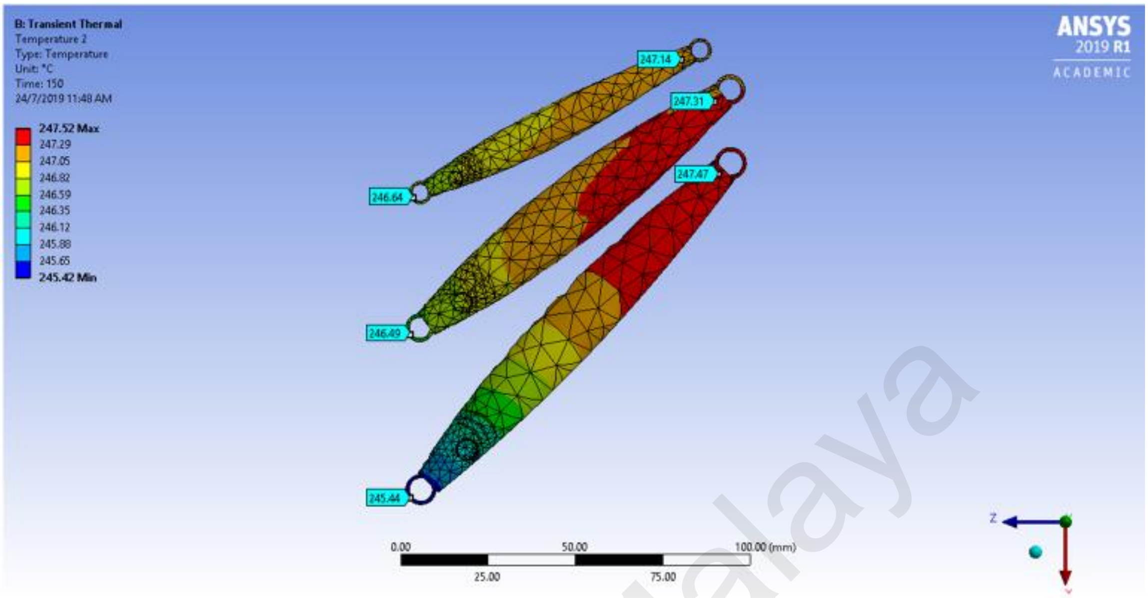

Figure 4.6: NC Jigs

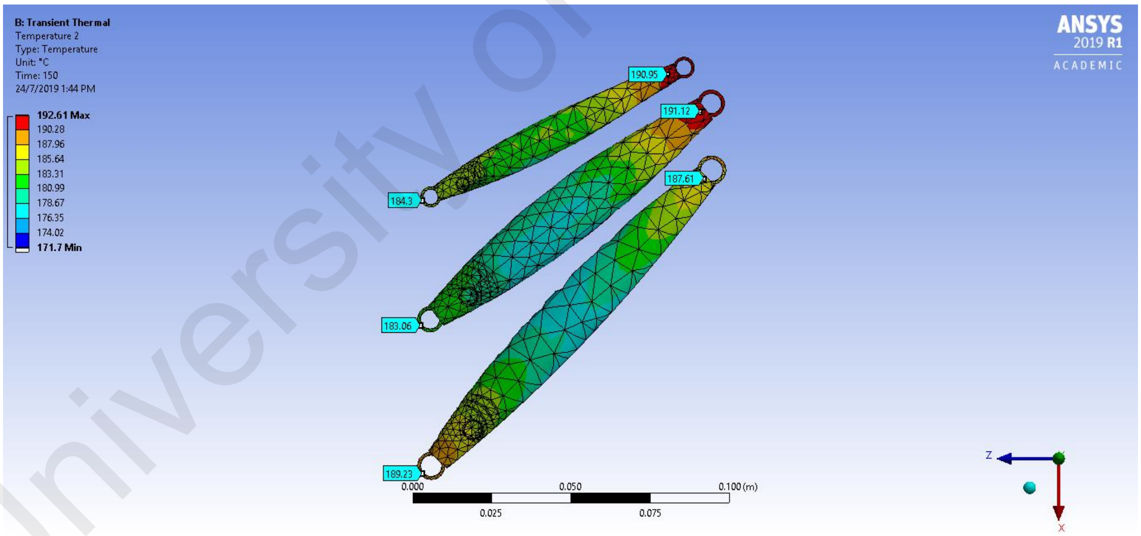

Figure 4.7: Case 7 Jigs

Almost the same distribution can be seen on the jigs. In both cases however the tail end of the jigs receives much less cooling that the center and head. This could be due to the channels not completely reaching the tails and the small surface area of the ends.

In addition to the NC vs case 7 comparison, another comparison was made between straight cooling channels and conformal cooling channels. Both channel designs use the same 8-10-18 (case 7) set of parameters. The straight channel results can be seen in figures 4.8 and 4.9 below. The figures also show the temperature point at the same positions as the previous cases.

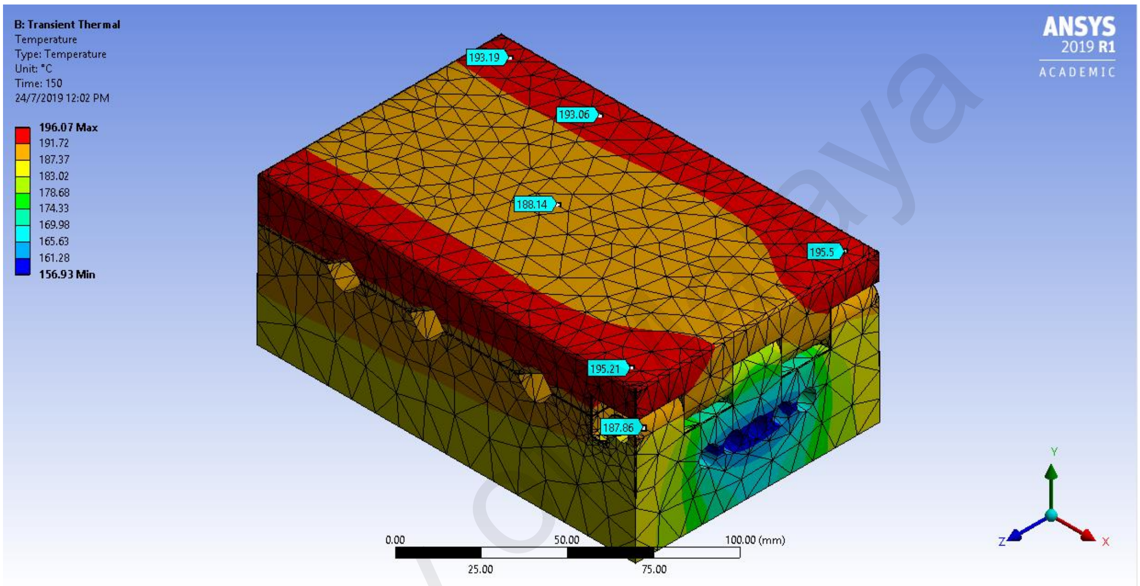

Figure 4.8: Straight channel Mold

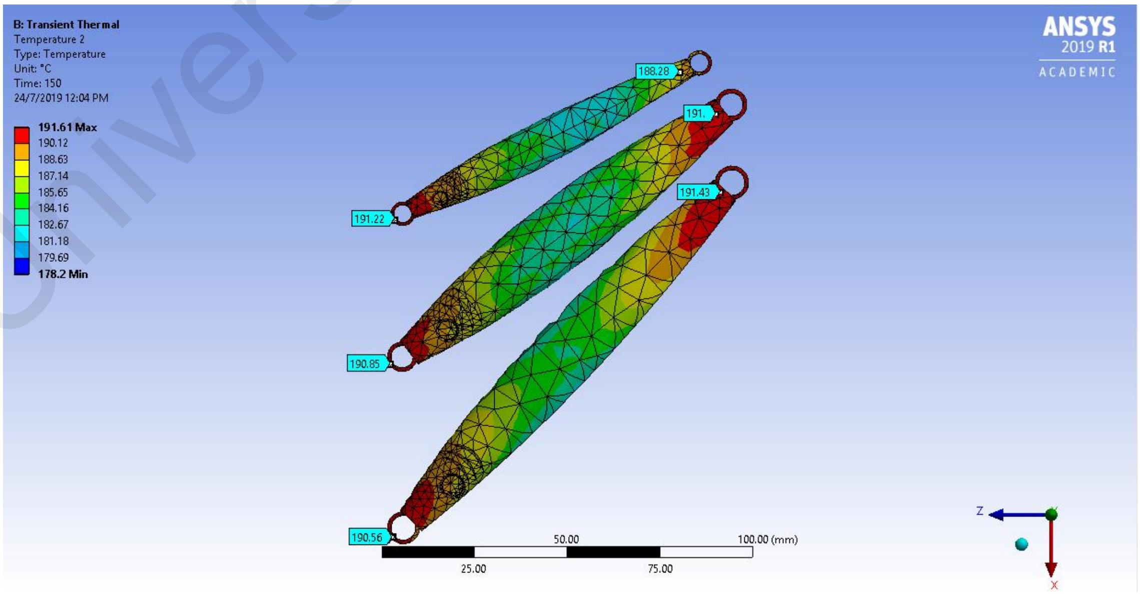

Figure 4.9: Straight channel jigs

The minimum jig temperature with straight channels was 178.2 °C, 6.5°C higher than the conformal channels result. Similarly, the minimum mold temperature was only 4.2 °C higher than the mold temperature of the conformal channels at 156.93 °C.

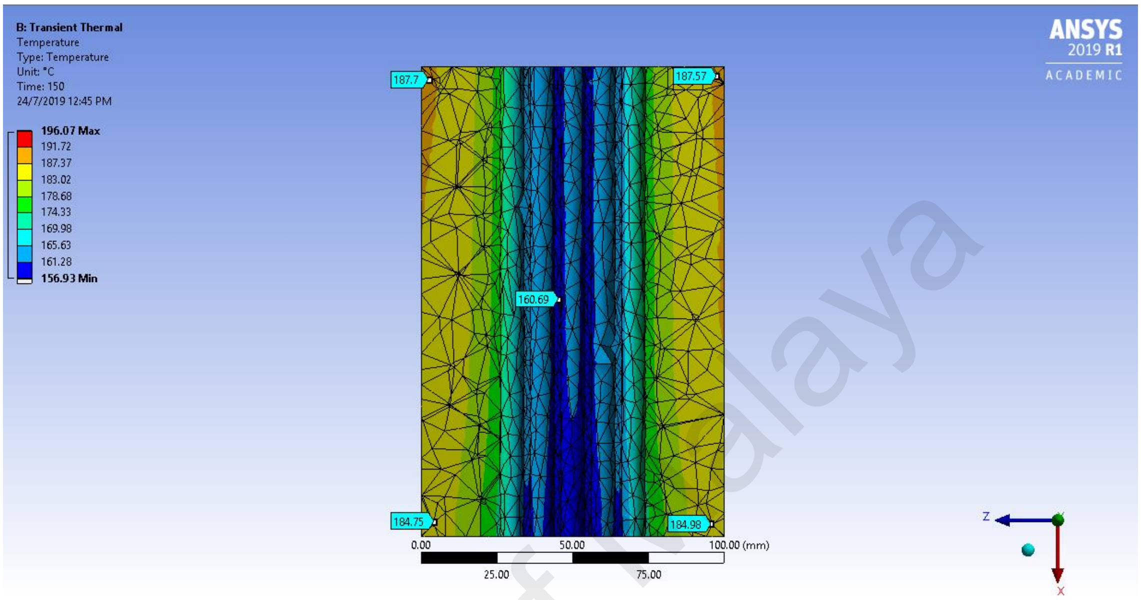

Figure 4.10: SC mold cross-section

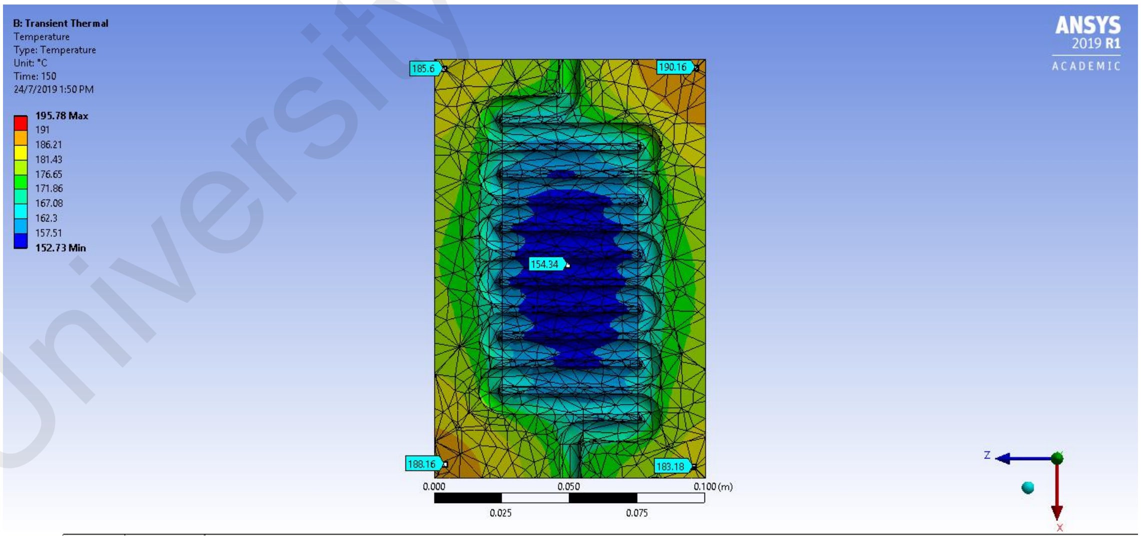

Figure 4.11: CC mold cross-section

The cross-section images in figures 4.10 and 4.11 the temperature distribution at the center of the channels for the SC and CC cases. The total contact surface area of both channel designs is approximately the same, CC have 20588mm^2 while the SC have 19477mm^2. This was as close as the surface areas could get without changing the basic designs or parameters, while also using approximately the same design area.

The temperature distribution for the SC is not as uniform as the conformal channels, as we can see that firstly the values at the 5 positions are lower in the CC mold and secondly the sides of the mold received better cooling than their SC counterparts. This applies to both the mold and jigs. Therefore, even with the same parameters conformal channels provide better cooling and uniformity. In figures 4.12-14 below are the three temperature vs time graphs for the min, max and average jig temperatures for all three (NC, SC, CC) cases.

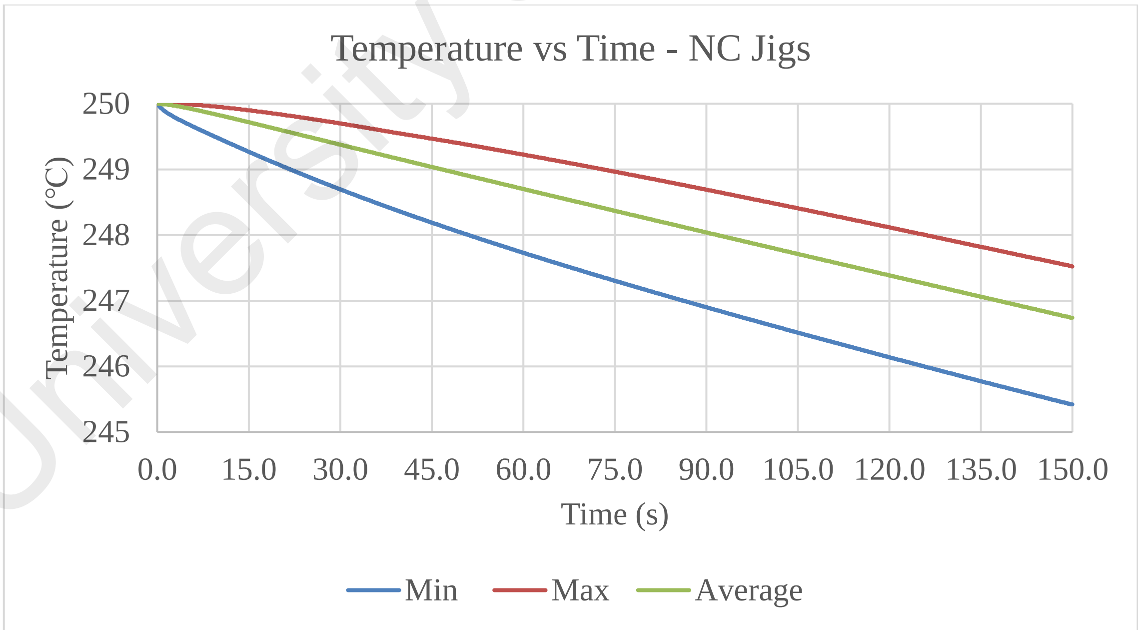

Figure 4.12: Temperature vs Time NC

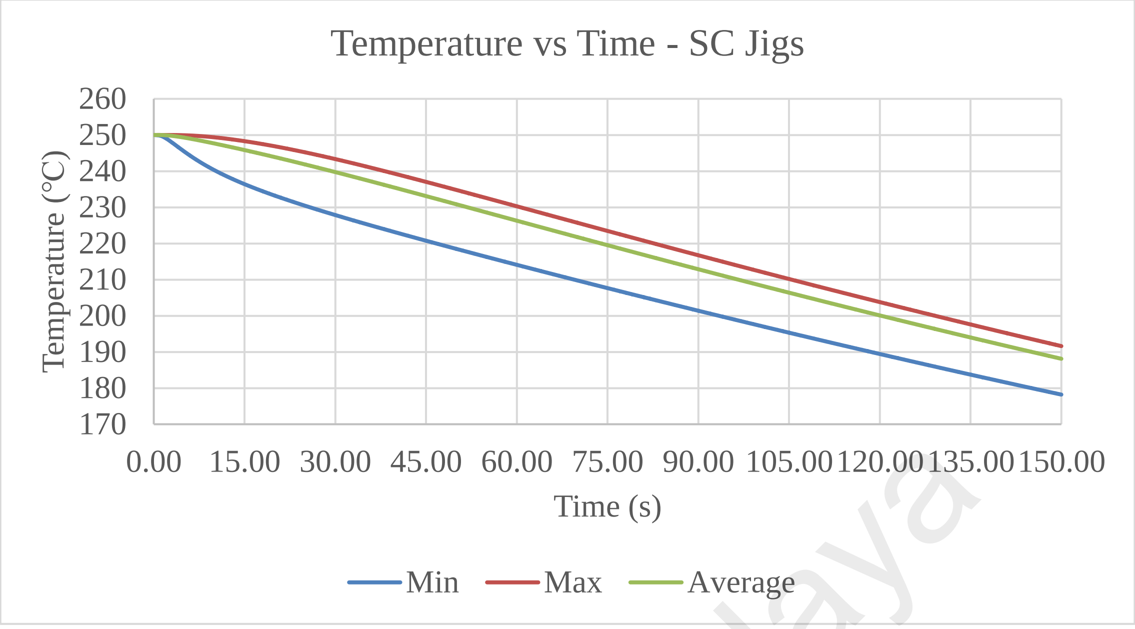

Figure 4.13: Temperature vs Time SC

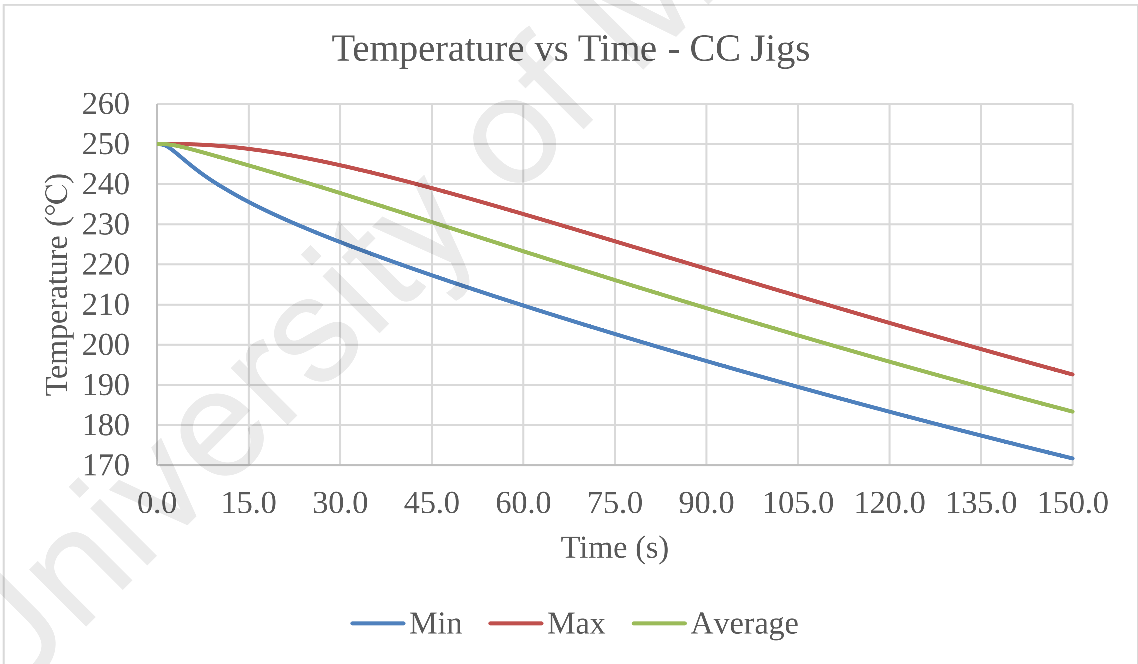

Figure 4.14: Temperature vs Time CC

These results also show that cooling channels drastically improves the cooling process under the same conditions. The final mold temperature is lower than the jig temperature as the water is directly passing through it as opposed to through a medium like the jigs. This was the case observed in all the simulations run.

It should be noted that the average temperature for the jigs with CC is almost the midpoint between the minimum and maximum temperatures, while the average temperature for the SC jigs is more skewed towards the upper/maximum end. This further shows that conformal channels provide more uniform cooling in our case.

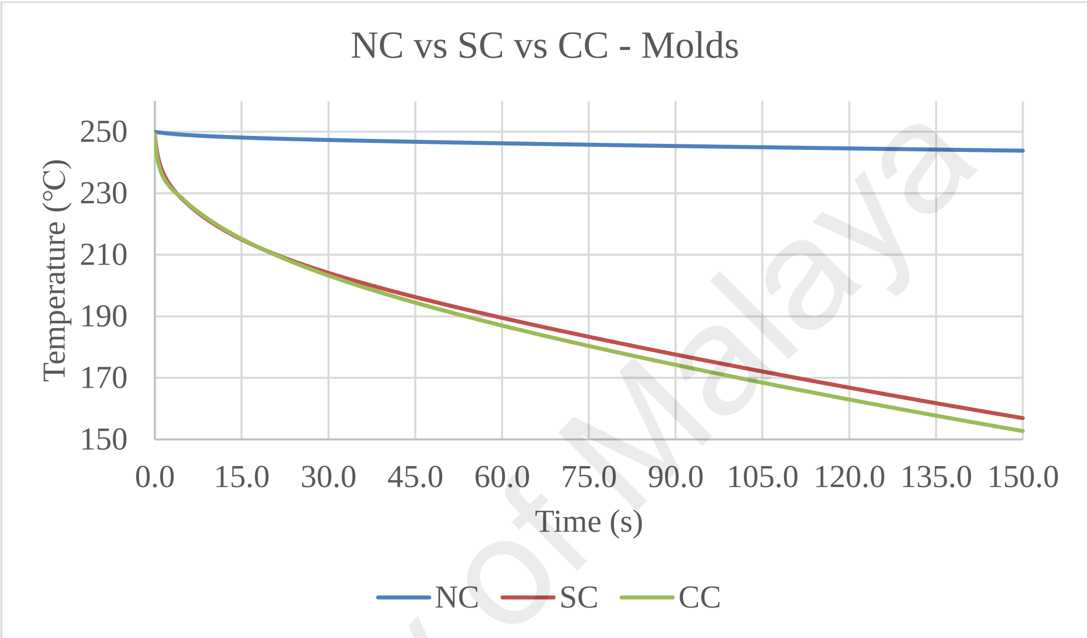

Figure 4.15: Mold temperatures

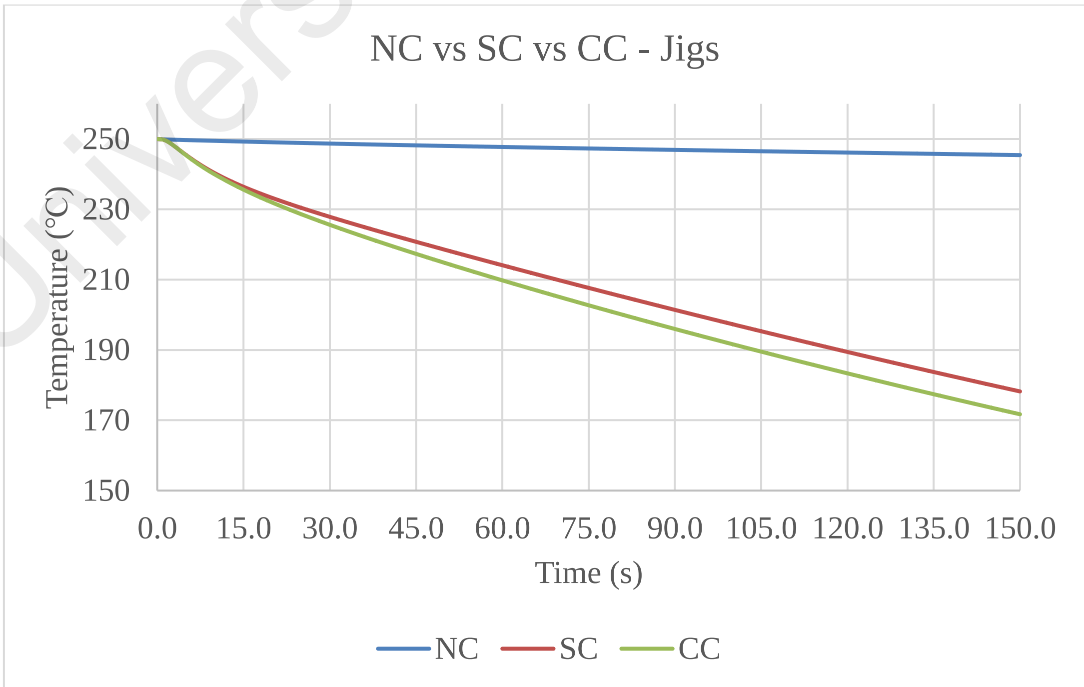

Figure 4.16: Jig temperatures

Finally, figures 4.15 and 4.16 are direct comparisons between the minimum mold and jig temperature throughout the simulations for each of the 3 cases. The graphs show that while the straight channels provide a similar rate of cooling at the start of the simulation, it gradually becomes slower as time goes by. This could be attributed to the less uniform cooling distribution in the straight channel case. Provided there is constant cooling happening, as the temperature of the mold goes down so does the jigs. Therefore, since the overall mold temperature with conformal channels is lower than with SC, the jigs cooldown at a higher rate.

CHAPTER 5: CONCLUSION

In this research we studied the effect of conforming cooling channels in the injection molding process of jigs. Simulations were used to study the effect of the different parameters of the cooling channel and they were analyzed using the Taguchi method. The results show that the diameter and pitch have a significant effect on the cooling time while length has a much smaller effect in comparison. Increasing the surface area of cooling by increasing the pitch or diameter decreases the overall cooling time. Length has a minimal effect on the cooling time, but the results have shown that the higher length in our mold produced a better cooling effect. There was a 28.8% decrease in cooling time using optimal channels compared to no channels. Comparisons were carried out between no channels, straight channel (using case 7 parameters) and case 7. It was observed that the temperature distribution is more uniform with conformal channels than the other two cases, with straight channels provided better cooling than no channels.

CHAPTER 6: RECOMMENDATIONS

Due to time and financial constraints, the scope of this research was limited. Future works could focus on studying different cross section profiles of the conformal channels or different channel configurations. If there is financial support, then the designed molds can be made and tested experimentally.

REFERENCES

Babenko, M., Sweeney, J., Petkov, P., Lacan, F., Bigot, S., & Whiteside, B. (2018). Evaluation of heat transfer at the cavity-polymer interface in microinjection moulding based on experimental and simulation study. *Applied Thermal Engineering*, *130*, 865–876. https://doi.org/10.1016/j.applthermaleng.2017.11.022

Dimla, D. E., Camilotto, M., & Miani, F. (2005). *Design and optimisation of conformal cooling channels in injection moulding tools*. *165*, 1294–1300. https://doi.org/10.1016/j.jmatprotec.2005.02.162

Jahan, S. A., & El-Mounayri, H. (2016). Optimal Conformal Cooling Channels in 3D Printed Dies for Plastic Injection Molding. *Procedia Manufacturing*, *5*, 888–900. https://doi.org/10.1016/j.promfg.2016.08.076

Jahan, S. A., Wu, T., Zhang, Y., Zhang, J., Tovar, A., & Elmounayri, H. (2017). Thermo-mechanical Design Optimization of Conformal Cooling Channels using Design of Experiments Approach. *Procedia Manufacturing*, *10*, 898–911. https://doi.org/10.1016/j.promfg.2017.07.078

Liew, K., Peng, H., Jou, T., & Wang, C. (2018). Investigation on the Establishment and Analyses of Conformal Cooling Channel Design for Blow Mold. *2018 IEEE International Conference on Applied System Invention (ICASI)*, *4*(1), 1236–1239. https://doi.org/10.1109/ICASI.2018.8394514

Mayer, S. (2007). *EOS Optimized Mould Temperature Control Procedure Using DMLs.pdf* (pp. 1–10). pp. 1–10. EOS Whitepaper, EOS GmbH LtD.

Park, H., & Dang, X. (2017). Development of a smart plastic injection mold with conformal cooling channels. *Procedia Manufacturing*, *10*, 48–59. https://doi.org/10.1016/j.promfg.2017.07.020

Venkatesh, G., & Ravi Kumar, Y. (2017). Thermal Analysis for Conformal Cooling Channel. *Materials Today: Proceedings*, *4*(2), 2592–2598. https://doi.org/10.1016/j.matpr.2017.02.113

Venkatesh, G., Y, R. K., & Raghavendra, G. (2017). ScienceDirect Comparison of Straight Line to Conformal Cooling Channel in Injection Molding. *Materials Today: Proceedings*, *4*(2), 1167–1173. https://doi.org/10.1016/j.matpr.2017.01.133

Vojnová, E. (2016). The benefits of a conforming cooling systems the molds in injection moulding process. *Procedia Engineering*, *149*(June), 535–543. https://doi.org/10.1016/j.proeng.2016.06.702

Wu, T., Jahan, S. A., Kumaar, P., Tovar, A., El-Mounayri, H., Zhang, Y., … Nalim, R. (2015). A Framework for Optimizing the Design of Injection Molds with Conformal Cooling for Additive Manufacturing. *Procedia Manufacturing*, *1*, 404–415. https://doi.org/10.1016/j.promfg.2015.09.049