PERFORMANCE EVALUATION OF CONFORMAL AND STRAIGHT COOLING CHANNELS ON INJECTION MOULDED PART

SHAYFULL ZAMREE BIN ABD RAHIM

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

DECEMBER 2015

In the name of Allah, Most Gracious, Most Merciful

To my beloved wife Azzurawaty Binti Yusuf, who is praying for me and who provided me with support, help and encouragement that greatly contributed to the successful completion of my studies.

To my daughter Nur Allya Syaffiyah, and to my sons Muhammad Amirun Azzwar and Muhammad Amirun Amzar who have brought wonderful fun, great motivation and bright inspiration into my life.

ACKNOWLEDGEMENT

Alhamdulillah, all praise is due to Allah S.W.T, the Most Beneficent and the Most Merciful, who has taught me what I knew not.

First and foremost, I wish to express special thanks, appreciation and deep gratitude to my main supervisor, Prof. Dr. Safian Sharif, who has provided continuous guidance, advice, encouragement, support and generous amount of time in helping me to complete this research. His remarkable unique ways and professionalism of handling my weaknesses has turned my simplistic mind to see and think in more rational and critical view. Special thanks also to Assoc. Prof. Dr. Azlan Mohd. Zain, my honourable co-supervisor, for his continuous guidance, committed support and invaluable advice throughout my study.

Sincere appreciation of course goes to my friends who gave me unselfish support and my family, especially my wife Azzurawaty Yusuf for her support and encouragement throughout the completion of this research. Without their endless sacrifices, constant love and steadfast support, I would never have reached this level. To my daughter Nur Allya Syaffiyah and my sons Muhammad Amirun Azzwar and Muhammad Amirun Amzar, it is to all of you I dedicate this effort.

Above all, I would like to offer my deepest appreciation and thanksgiving to Allah SWT. There is no way to measure what You’ve bestowed. You are The One who has made things possible. You deserve all glory and honour.

ABSTRACT

In injection moulding process, warpage is one of the main quality aspects measured for moulded parts while cycle time to produce a part indicates the efficiency of the process. Efficient cooling is a huge challenge to many mould designers for achieving a uniform thermal distribution in an injection mould where it affects both quality and productivity. The use of conformal cooling design has been reported as very effective to distribute thermal uniformly, thus able to improve part quality as well as reducing moulding cycle time. However, most of previous researchers only focused on simulation studies and they hardly performed experimental works to verify the simulation results. In this study, a Milled Groove Square Shape (MGSS) conformal cooling channel has been designed, simulated, fabricated and tested using a front panel housing as the case study. Performance evaluations on the MGSS conformal cooling channel and straight cooling channel were conducted using simulation and experimental works in terms of quality (warpage) and productivity (cycle time) of the moulded part. Mould and coolant input temperatures were varied in both evaluations, i.e. mould temperature (40 ^{o}C to 80 ^{o}C) and coolant temperature (25 ^{o}C to 65 ^{o}C). Results showed that the MGSS conformal cooling was superior with improved cycle time from 37.57% to 48.66% (simulation) and confirmed by experimental trials (27.89% to 36.15%). Simulated results showed that there is no warpage on the front panel housing in x direction for both types of cooling channels. However, experimental results indicated that warpage occurs in x direction in both cooling channel designs, but MGSS conformal cooling type demonstrates more reduction from 36.36% to 76%. Similarly, warpage in y direction recorded a remarkable improvement within the range of 34.3% to 41.5% and 16.7% to 35.48% respectively from the simulated and experimental results when employing the MGSS conformal cooling channel. The fabrication cost of the MGSS conformal cooling channel is approximately 3 % to 5 % higher which depends on the complexity of part shape as compared to the straight cooling channel. The finding shows that the MGSS conformal cooling channel design offers very encouraging results which is able to improve part quality as well as productivity at an acceptable manufacturing cost.

ABSTRAK

Dalam proses pengacuan suntikan, ledingan adalah salah satu aspek utama kualiti yang diukur pada bahagian yang dibentuk manakala kitaran masa untuk menghasilkannya menunjukkan kecekapan proses. Penyejukan yang cekap adalah satu cabaran yang besar kepada kebanyakan pereka bentuk acuan untuk mencapai agihan haba yang seragam dalam acuan suntikan di mana ia memberi kesan kepada kualiti dan produktiviti. Penggunaan reka bentuk penyejukan konformal telah dilaporkan sangat berkesan untuk mengagihkan haba secara seragam, dengan itu dapat meningkatkan kualiti bahagian dan juga mengurangkan masa kitaran pembentukan. Walau bagaimanapun, kebanyakan penyelidik terdahulu hanya memberi tumpuan kepada kajian simulasi dan mereka jarang melakukan kerja-kerja eksperimen untuk mengesahkan keputusan simulasi. Dalam kajian ini, saluran penyejukan konformal berbentuk segiempat alur terkisar (MGSS) telah direkabentuk, disimulasi, difabrikasi dan diuji menggunakan panel perumah hadapan sebagai kajian kes. Penilaian prestasi saluran penyejukan konformal MGSS dan saluran penyejukan lurus telah dibuat menggunakan simulasi dan kerja-kerja eksperimen dari segi kualiti (ledingan) dan produktiviti (masa kitaran) bahagian yang dibentuk. Suhu masukan acuan dan penyejuk telah diubah dalam kedua-dua penilaian, iaitu suhu acuan (40 ^{o}C hingga 80 ^{o}C) dan suhu penyejuk (25 ^{o}C hingga 65 ^{o}C). Keputusan menunjukkan bahawa penyejukan konformal MGSS adalah lebih baik dengan penurunan masa kitaran daripada 37.57% hingga 48.66% (simulasi) dan disahkan oleh ujian percubaan (27.89% hingga 36.15%). Keputusan simulasi menunjukkan tidak ada ledingan pada panel perumah hadapan dalam arah x untuk kedua-dua jenis saluran penyejukan. Walau bagaimanapun, keputusan dari eksperimen menunjukkan ledingan berlaku dalam arah x bagi kedua-kedua reka bentuk saluran penyejukan, tetapi penyejukan jenis konformal MGSS menunjukkan lebih pengurangan daripada 36.36% sehingga 76%. Begitu juga, ledingan dalam arah y telah merekodkan penambahbaikan yang memberangsangkan dalam julat 34.3% hingga 41.5% dan 16.7% hingga 35.48% masing-masing daripada keputusan simulasi dan eksperimen apabila menggunakan saluran penyejukan konformal MGSS. Kos anggaran fabrikasi saluran penyejukan konformal MGSS adalah diantara 3% sehingga 5% lebih tinggi, bergantung kepada kerumitan bentuk bahagian berbanding dengan saluran penyejukan lurus. Dapatan kajian menunjukkan bahawa reka bentuk saluran penyejukan konformal MGSS menawarkan hasil yang sangat memberangsangkan yang mampu untuk meningkatkan kualiti bahagian dan juga produktiviti dengan kos pembuatan yang boleh diterima.

TABLES OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
AMI	Autodesk Moldflow Insight
ANSYS	Analysis System
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
CSCC	Conventional Straight Cooling Channels
DMD	Direct Metal Deposition
DMLS	Direct Metal Laser Sintering
DMT	Direct Metal Tooling
EBM	Electron Beam Melting
FEA	Finite Element Analysis
LCD TV	Liquid - crystal display television
MGSS	Milled Grooved Square Shape
PA	Polyamide
PC	Polycarbonate
PMMA	Poly(methyl methacrylate)
POM	Polyoxymethylene
PP	Polypropylene
RHCM	Rapid Heat Cycle Moulding
RP	Rapid Prototyping
RT	Rapid Tooling
R&D	Research and Development
SLS	Selective Laser Sintering
SM	Shot Material
SSCCC	Square Section Conformal Cooling Channel

3DP	-	Three Dimensional Printing

LIST OF SYMBOLS

D - Gate diameter

α - Thermal diffusivity

T_{melt} - Melt temperature

$T_{coolant}$ - Coolant temperature

T_{no_flow} - No flow melt temperature

$\dot{Q}_m$ - Heat flux from the molten plastic

$\dot{Q}_c$ - Heat flux exchange with coolant

$\dot{Q}_e$ - Heat flux exchange with environment

T_M - Melt temperature

T_E - Ejection temperature

c_p - Specific heat

ρ_m - Melt density

s - Part thickness

x - Pitch of the cooling channels

α - Heat transfer coefficient of coolant

k_{st} - Thermal conductivity of the mould steel

T_w - Mould temperature

T_C - Coolant temperature

S_e - Shape factor

y - Distance from centre of the cooling channels to the mould surface

R_e - Reynolds number

u - Velocity of the coolant

v - Kinematic viscosity of the coolant

t_{cp} - Cooling time of the moulded part in the form of plate

a - Thermal diffusivity

k_m - Thermal conductivity of the plastic material

P_i - Pressure drop for feeding segment

L_i - Length of the segment

L_{Total} - Total length of the feeding system

ΔP_{max} - Maximum pressure drop

R - Radius of runner

K - Reference viscosity of the polymer melts at the melt temperature

L - Length of runner

n - Reference viscosity of the polymer melts at the melt temperature

$\dot{V}_{melt}$ - Volumetric flow rate

P - Pressure

t_c - Cooling time

D - Diameter of the runner

T_{eject} - Ejection temperature

h - Thickness of the part

$\dot{\gamma}$ - Shear rate

W - Width of the gate

h - Thickness of the gate

R - Radius of the gate

t_s - Gate freezing time

D - Diameter of the gate

$Q_{molding}$ - Total amount of heat needs to be removed by the cooling system

$m_{molding}$ - Weight of the moulded part to be moulded

$\dot{Q}_{cooling}$ - Amount of energy that must be removed per second of cooling time

$\dot{Q}_{line}$ - Heat transfer rate per cooling line

n_{lines} - Numbers of cooling lines

$\dot{V}_{coolant}$ - Coolant flow rate

$\Delta T_{coolant}$ - The differences of the temperatures between the inlet and outlet of the coolant

$\rho_{coolant}$	-	Density of the coolant
$C_{p,coolant}$	-	Specific heat of the coolant
D	-	Diameter of the cooling channels
$\mu_{coolant}$	-	Viscosity of the coolant
ΔP	-	Half of the maximum pressure supplied from the coolant controller
L_{line}	-	Length of the cooling channels
$h_{conduction}$	-	Effective heat conduction coefficient
K_{mold}	-	Thermal conductivity of the mould material
H_{line}	-	Maximum depth of cooling channels

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Injection moulding process has been widely used in the manufacturing of plastic products with various types of shapes due to its high productivity and low cost for high volume production (Cho *et al.*, 2009; Lin, 2002; Spina, 2004). The important stages in injection moulding process are injection (filling), packing, cooling and ejection (Lin, 2002; Saifullah *et al.*, 2009; Tang *et al.*, 2006). During the injection stage, molten plastics are injected into the cavities. In the packing stage the molten plastics are continuously injected into the cavities until the gate freezes to fill in the leaving space due to plastic shrinkage during solidification. After the molten plastics solidify and are rigid enough at the cooling stage, the mould opens allowing the moulded parts to be ejected out of the mould. The mould then closes and the process continues for the next cycle (Bozdana and Eyercioglu, 2002). Among all the stages, cooling is the most significant phase that affects the productivity and the quality of the moulded parts (Hassan *et al.*, 2010b; Tang *et al.*, 2006). It contributes approximately 70% to 80% of the cycle time in injection moulding process (Saifullah and Masood, 2007b; Subramanian *et al.*, 2005).

As such, in order to improve the cycle time in the injection moulding process, it is essential that the cooling time is reduced (Hassan *et al.*, 2010b).

1.2 Background of Study

The cost-effectiveness of the injection moulding process mainly depends on the moulding cycle time whereby the cooling stage is the primary stage influencing the cycle time and the production rate of the moulded parts (Hassan *et al.*, 2010b; Saifullah *et al.*, 2009). In addition, the design of cooling channels in the injection moulds affects the quality of moulded plastic part (Dimla *et al.*, 2005; Hassan *et al.*, 2010b; Li, 2007). The undesirable defects that commonly affect the quality of the moulded parts include hot spots, sink marks, differential shrinkage, thermal residual stress and warpage. All these defects can be minimized with an efficient cooling channel system which results in a uniform temperature distribution in the inserts of the injection mould (Chen *et al.*, 2000; Wang and Young, 2005).

Traditionally, simple cooling channels are designed with straight holes in the core and cavity inserts of the mould. It is simple to design and easy to fabricate using a conventional machining process such as drilling. Nowadays, many researchers and mould designers are trying to improve the efficiency of cooling channels by focusing on how to optimize the layout of the cooling channels system in terms of shape, size and location (Dang and Park, 2011; Hassan *et al.*, 2010a; Lam *et al.*, 2004; Shoemaker, 2006; Zhou *et al.*, 2009). On the other hand, some researchers studied on how to design and fabricate conformal cooling channels in order to ensure uniform thermal distribution and to increase the cooling efficiency (Ahn *et al.*, 2010; Altaf *et al.*, 2011; Dimla *et al.*, 2005; Park and Pham, 2009; Park and Dang, 2010; Saifullah *et al.*, 2009). Over the years, conformal cooling channels have proven more efficient as compared to conventional cooling channels in terms of production rate and parts quality (Saifullah and Masood, 2007b; Xu *et al.*, 2001). Several investigations on conformal cooling channels have been conducted which involved fabricating the channels as close as possible to the surface of the mould cavities in order to increase the efficiency of heat absorption from molten plastic thus ensuring the moulded parts to be cooled uniformly (Saifullah and Masood, 2007a; Saifullah *et al.*, 2009). The application of conformal cooling channels began when rapid tooling was first introduced because of its simple fabrication process with various technologies as compared to the conventional drilling and milling on hard tooling materials of the injection moulds.

In recent years, the high efficiency of conformal cooling channels in rapid tooling over conventional cooling channels has triggered many researchers to investigate its effectiveness on hard tooling for injection moulding process. Designing such cooling channels is always a big challenge because of its limitation in the fabrication process which involves free-form machining of the cooling channels that follows exactly the profile of the injected plastic parts.

1.3 Problems Statement

Warpage defect is a common issue in an injection moulding process due to non-uniform temperature variation causing differential shrinkage on the moulded parts (Fischer, 2003; Kazmer, 2007; Malloy, 2010). In designing plastic injection moulds, it is difficult to achieve efficient cooling with uniform thermal distribution by using traditional design of simple cooling channels with straight holes. To overcome these issues, the use of conformal cooling channels with uniform distance between the centre of the cooling channels and the mould surfaces was introduced which offers a better thermal distribution and reduction in cooling time.

Many researchers have studied the designing of conformal cooling channels on hard tooling for injection moulding process (Dang and Park, 2011; Park and Pham, 2009; Park and Dang, 2010; Saifullah and Masood, 2007a; Saifullah and Masood, 2007b; Saifullah *et al.*, 2009; Sun *et al.*, 2004). Similar to the findings on conformal cooling channels in rapid tooling, its efficiency and performance are proven superior in terms of the uniformity of thermal distribution, improvement on parts deflection, cooling time reduction and unquestionably the reduction in an injection moulding cycle time. However, most of the researches were focused on the simulation works or computer modelling which lack supports and verifications of real experimental data (Dang and Park, 2011; Park and Pham, 2009; Park and Dang, 2010; Saifullah and Masood, 2007a; Saifullah and Masood, 2007b; Sun *et al.*, 2004). Simulation results could not provide a full and accurate solutions to the actual problems in real production. Only Saifullah *et al.* (2009) had performed experimental works and compared to the simulation results. However, the experimental work only consider a circular part which is too simple. Besides that, most researchers only proposed the cooling channels in simulation without any consideration on mould fabrication. In addition, most of them used coolant temperature of 25°C and 35°C in their study which did not fulfilled the recommended temperature suggested by the material manufacturer. Therefore the results are questionable and less beneficial to the injection moulding society.

Hence, in this study extensive investigation involving experimental works were conducted in order to assist the moulding industries, particularly in small and medium enterprise, in improving the quality of plastic parts produced. A Milled Grooved Square Shape (MGSS) conformal cooling channels which are easy to design, fabricate and assemble is developed taking into the consideration on the fabrication of the conformal cooling channels, especially in hard tooling. The performance of the MGSS conformal cooling channels in term of productivity (cycle time) and quality (warpage) was compared to the conventional straight cooling channels with a same layout and cross sectional area through simulation and experimental works. Thus, the efficiency of the MGSS conformal cooling channels as compared to the conventional straight cooling channels was validated clearly. This study is able to address the following questions:

1. Can the MGSS conformal cooling channels be fabricated and used in real injection moulding processes?
2. How much a MGSS conformal cooling channels can improve the productivity of the injection moulding process as compared to the conventional straight cooling channels?
3. How much improvement on the quality of the moulded parts of a MGSS conformal cooling channels as compared to the conventional straight cooling channels?
4. What are the variation of the experimental results against the simulation results in terms of productivity and quality of the moulded parts?

1.4 Objectives

The main objectives of this study are:

1. To design and fabricate of conformal cooling channels for moulds used in the injection moulding process of a plastic part.
2. To evaluate the performance of MGSS conformal cooling channels in injection moulding process on the productivity and quality of the moulded parts by simulation.
3. To experimentally compare the quality and productivity of the moulded parts produced using a MGSS conformal cooling channels mould against the simulation results in term of shrinkage, warpage, cooling time and cycle time.

1.5 Scopes of Study

The scope of this study involves designing, fabrication and testing of the plastic injection moulds with a MGSS conformal cooling channels in the injection moulding of a front panel housing made from Acrylonitrile Butadiene Styrene (ABS) material. Comparative study was conducted between the MGSS conformal cooling channels and the straight cooling channels for the coolant temperature of 25 ^{o}C to 65 ^{o}C in order to obtain the mould temperature of 40 ^{o}C to 80 ^{o}C as per recommended by the plastic material manufacturer. Performance evaluations were conducted by simulation and validated experimentally with regards to productivity (cycle time) and quality (warpage) of the moulded parts. In this study, the values of the melt temperature, injection rate, packing pressure and part thickness were kept constant. The parameters that were varied are mould temperature, filling time and packing time. The mould temperature depends on the coolant temperature while the filling and packing time depend on the mould temperature from the Fill + Pack analysis form simulation. Therefore, in order to control the mould temperature, filling and packing time, the coolant temperature needs to be controlled. A commercial Computer Aided Engineering (CAE) software, Autodesk Moldflow Insight 2013 was used for the analysis and simulation works in this study. Meanwhile a 80 Tonne

Nissei NEX1000 injection moulding machine at the production laboratory, School of Manufacturing Engineering, Universiti Malaysia Perlis was used to perform the experimental works.

1.6 Significance of the Study

This study provides useful scientific knowledge and solution to plastic manufacturing industries pertaining to plastic injection moulding in improving the quality (warpage) and productivity (cycle time) of the moulded parts through the MGSS conformal cooling channels of an injection mould. MGSS conformal cooling channels has been developed and proven to be used in the real injection moulding process. Slight difference exists between the results from simulation and experimental because of the few assumptions used in Autodesk Moldflow Insight 2013. However, the experimental results are in line with the simulation results whereby the MGSS conformal cooling channels is able to improve the quality and productivity of the moulded parts produced. The fabrication cost of MGSS conformal cooling channels for the front panel housing is approximately to be within 3 % to 5 % higher as compared to the straight cooling channels. However, the fabrication cost of MGSS conformal cooling channels depends mainly on the shape complexity of the moulded parts.

1.7 Organisation of the Thesis

This thesis begins with an introductory chapter that describes the general information of conventional injection moulding, problems statement, objectives, scopes and significance of this study. In Chapter 2, a thorough discussion of the literature on the performance of conformal cooling channels in rapid and hard tooling for injection moulding with different approaches to improve the quality and productivity of moulded parts are highlighted. In Chapter 3, detailed methodologies from part design, design of gating system, analysis using Autodesk Moldflow 2013 and experimental are presented. The simulation and experimental results are discussed in Chapter 4 whereas Chapter 5 concludes all of the findings of the study.

REFERENCES

Ahn, D. G., Park, S. H. and Kim, H. S. (2010). Manufacture of an injection mould with rapid and uniform cooling characteristics for the fan parts using a DMT process. *International Journal of Precision Engineering and Manufacturing*, 11 (6): 915-924.

Akay, M., Ozden, S. and Tansey, T. (1996). Prediction of process-induced warpage in injection molded thermoplastics. *Polymer Engineering & Science*, 36 (13): 1839-1846.

Alam, M. M. and Kumar, D. (2013). Reducing shrinkage in plastic injection moulding using taguchi method in tata magic head light. *International Journal of Science and Research*, 2 (2): 107-110.

Al-Kaabneh, F. A.-K., Barghash, M. and Mishael, I. (2013). A combined analytical hierarchical process (AHP) and taguchi experimental design (TED) for plastic injection molding process settings. *The International Journal of Advanced Manufacturing Technology*, 66 (5-8): 679-694.

Altaf, K., Raghavan, V. R. and Rani, A. M. A. (2011). Comparative thermal analysis of circular and profiled cooling channels for injection mold tools. *Journal of Applied Sciences*, 11 (11): 2068-2071.

Altan, M. (2010). Reducing shrinkage in injection moldings via the taguchi, ANOVA and neural network methods. *Materials & Design*, 31 (1): 599-604.

Annicchiarico, D. and Alcock, J. R. (2014). Review of factors that affect shrinkage of molded part in injection molding. *Materials and Manufacturing Processes*, 29 (6): 662-682.

Azdast, T. and Behravesh, A. H. (2008). An analytical study of constrained shrinkage of injection molded semi-crystalline plastic parts. *Polymer-Plastics Technology and Engineering*, 47 (12): 1265-1272.

Bozdana, A. T. and Eyercioglu, O. (2002). Development of an expert system for the determination of injection moulding parameters of thermoplastic materials: EX-PIMM. *Journal of Materials Processing Technology*, 128 (1-3): 113-122.

British Standards Institution, (2008). Plastics standard atmospheres for conditioning and testing, BS EN ISO 291. London: British Standards Institution.

Chen, C. C., Su, P. L. and Lin, Y. C. (2009). Analysis and modeling of effective parameters for dimension shrinkage variation of injection molded part with thin shell feature using response surface methodology. *The International Journal of Advanced Manufacturing Technology*, 45 (11-12): 1087-1095.

Chen, C. C. A. and Chang, S. W. (2008). Shrinkage analysis on convex shell by injection molding. *International Polymer Processing*, 23 (1): 65-71.

Chen, C. P., Chuang, M. T., Hsiao, Y. H., Yang, Y. K. and Tsai, C. H. (2009). Simulation and experimental study in determining injection molding process parameters for thin-shell plastic parts via design of experiments analysis. *Expert Systems with Applications*, 36 (7): 10752-10759.

Chen, S. C., Jong, W. R. and Chang, J. A. (2006). Dynamic mold surface temperature control using induction heating and its effects on the surface appearance of weld line. *Journal of Applied Polymer Science*, 101 (2): 1174-1180.

Chen, S. C., Lin, Y. W., Chien, R. D. and Li, H. M. (2008). Variable mold temperature to improve surface quality of microcellular injection molded parts using induction heating technology. *Advances in Polymer Technology*, 27 (4): 224-232.

Chen, W. C., Tai, P. H., Wang, M. W., Deng, W. J. and Chen, C. T. (2008). A neural network-based approach for dynamic quality prediction in a plastic injection molding process. *Expert Systems with Applications*, 35 (3): 843-849.

Chen, X., Lam, Y. C. and Li, D. Q. (2000). Analysis of thermal residual stress in plastic injection molding. *Journal of Materials Processing Technology*, 101 (1-3): 275-280.

Chiang, K. T. and Chang, F. P. (2006). Application of grey-fuzzy logic on the optimal process design of an injection-molded part with a thin shell feature. *International Communications in Heat and Mass Transfer*, 33 (1): 94-101.

Chiang, K. T. and Chang, F. P. (2007). Analysis of shrinkage and warpage in an injection-molded part with a thin shell feature using the response surface methodology. *The International Journal of Advanced Manufacturing Technology*, 35 (5-6): 468-479.

Cho, K. J., Koh, J. S., Kim, S., Chu, W. S., Hong, Y. and Ahn, S. H. (2009). Review of manufacturing processes for soft biomimetic robots. *International Journal of Precision Engineering and Manufacturing*, 10 (3): 171-181.

Crawford, R. J. (1989). Plastic engineering. 2nd ed. Oxford: Pergamond.

Dang, X. P. and Park, H. S. (2011). Design of U-shape milled groove conformal cooling channels for plastic injection mold. *International Journal of Precision Engineering and Manufacturing*, 12 (1): 73-84.

Dangayach, G. S. and Kumar, D. (2012). Reduction in defect rate by taguchi method in plastic injection molded components. *Advanced Materials Research*, 488-489: 269-273.

Dimla, D. E., Camilotto, M. and Miani, F. (2005). Design and optimisation of conformal cooling channels in injection moulding tools. *Journal of Materials Processing Technology*, 164-165: 1294-1300.

Elleithy, R., Ali, I., Al-Haj Ali, M. and Al-Zahrani, S. M. (2011). Different factors affecting the mechanical and thermo-mechanical properties of HDPE reinforced with micro-CaCO3. *Journal of Reinforced Plastics and Composites*, 30 (9): 769-780.

Erzurumlu, T. and Ozcelik, B. (2006). Minimization of warpage and sink index in injection-molded thermoplastic parts using taguchi optimization method. *Materials & Design*, 27 (10): 853-861.

Fernandes, C., Pontes, A. J., Viana, J. C. and Gaspar Cunha, A. (2010). Using multiobjective evolutionary algorithms in the optimization of operating conditions of polymer injection molding. *Polymer Engineering & Science*, 50 (8): 1667-1678.

Ferreira, J. C. and Mateus, A. (2003). Studies of rapid soft tooling with conformal cooling channels for plastic injection moulding. *Journal of Materials Processing Technology*, 142 (2): 508-516.

Fischer, J. (2003). Handbook of molded part shrinkage and warpage. United States of America: Plastics Design Library / William Andrew, Inc.

Geddes, C. (2011). 3D-forming process: plastics injection moulding. Edinburgh, Scotland: Scottish Plastics And Rubber Association.

Guan, W. and Huang, H. (2011). Effect of backward melt flow on injection-compression molded part thickness distribution. *In Annual Technical Conference (ANTEC)*. 1523.

Harris, R. A., Newlyn, H. A., Hague, R. J. M. and Dickens, P. M. (2003). Part shrinkage anomalies from stereolitography injection mould tooling. *International Journal of Machine Tools and Manufacture*, 43 (9): 879-887.

Hassan, H., Regnier, N., Le Bot, C. and Defaye, G. (2010a). 3D study of cooling system effect on the heat transfer during polymer injection molding. *International Journal of Thermal Sciences*, 49 (1): 161-169.

Hassan, H., Regnier, N., Pujos, C., Arquis, E. and Defaye, G. (2010b). Modeling the effect of cooling system on the shrinkage and temperature of the polymer by injection molding. *Applied Thermal Engineering*, 30 (13): 1547-1557.

Huang, M. C. and Tai, C. C. (2001). The effective factors in the warpage problem of an injection-molded part with a thin shell feature. *Journal of Materials Processing Technology*, 110 (1): 1-9.

Huang, M. S. and Tai, N. S. (2009). Experimental rapid surface heating by induction for micro-injection molding of light-guided plates. *Journal of Applied Polymer Science*, 113 (2): 1345-1354.

Jacques, M. S. (1982). An analysis of thermal warpage in injection molded flat parts due to unbalanced cooling. *Polymer Engineering & Science*, 22 (4): 241-247.

Jansen, K. M. B., Pantani, R. and Titomanlio, G. (1998a). As-molded shrinkage measurements on polystyrene injection molded products. *Polymer Engineering & Science*, 38 (2): 254-264.

Jansen, K. M. B., Van Dijk, D. J. and Husselman, M. H. (1998b). Effect of processing conditions on shrinkage in injection molding. *Polymer Engineering & Science*, 38 (5): 838-846.

Jin, J., Yu, H. Y. and Lv, S. (2009). Optimization of plastic injection molding process parameters for thin-wall plastics injection molding. *Advanced Materials Research*, 69-70: 525-529.

Kazmer, D. (2007). Injection mold design engineering. Munich: Hanser.

Kikuchi, H. and Koyama, K. (1996). Generalized warpage parameter. *Polymer Engineering & Science*, 36 (10): 1309-1316.

King, D. and Tansey, T. (2003). Rapid tooling: selective laser sintering injection tooling. *Journal of Materials Processing Technology*, 132 (1-3): 42-48.

Kramschuster, A., Cavitt, R., Ermer, D., Chen, Z. and Turng, L. S. (2005). Quantitative study of shrinkage and warpage behavior for microcellular and conventional injection molding. *Polymer Engineering & Science*, 45 (10): 1408-1418.

Kramschuster, A., Cavitt, R., Ermer, D., Chen, Z. and Turng, L. S. (2006). Effect of processing conditions on shrinkage and warpage and morphology of injection moulded parts using microcellular injection moulding. *Plastics, Rubber and Composites*, 35 (5): 198-209.

Kurtaran, H., Ozcelik, B. and Erzurumlu, T. (2005). Warpage optimization of a bus ceiling lamp base using neural network model and genetic algorithm. *Journal of Materials Processing Technology*, 169 (2): 314-319.

Lam, Y. C., Zhai, L. Y., Tai, K. and Fok, S. C. (2004). An evolutionary approach for cooling system optimization in plastic injection moulding. *International Journal of Production Research*, 42 (10): 2047-2061.

Lee, B. H. and Kim, B. H. (1995). Optimization of part wall thicknesses to reduce warpage of injection-molded parts based on the modified complex method. *Polymer-Plastics Technology and Engineering*, 34 (5): 793-811.

Leo, V. and Cuvelliez, C. (1996). The effect of the packing parameters, gate geometry, and mold elasticity on the final dimensions of a molded part. *Polymer Engineering & Science*, 36 (15): 1961-1971.

Li, C. L. (2007). Part segmentation by superquadric fitting-a new approach towards automatic design of cooling system for plastic injection mould. *The International Journal of Advanced Manufacturing Technology*, 35 (1-2): 102-114.

Li, X. and Gong, N. (2011). Fatigue source analysis of dynamic mold temperature injection mold for large plastic parts *Advanced Materials Research*, 305: 210-213.

Liao, S. J., Chang, D. Y., Chen, H. J., Tsou, L. S., Ho, J. R., Yau, H. T., Hsieh, W. H., Wang, J. T. and Su, Y. C. (2004). Optimal process conditions of shrinkage and warpage of thin-wall parts. *Polymer Engineering & Science*, 44 (5): 917-928.

Lin, J. C. (2002). Optimum cooling system design of a free-form injection mold using an abductive network. *Journal of Materials Processing Technology*, 120 (1-3): 226-236.

Lin, Z. C. and Chou, M. H. (2002). Design of the cooling channels in nonrectangular plastic flat injection mold. *Journal of Manufacturing Systems*, 21 (3): 167-186.

Liu, C. and Manzione, L. T. (1996). Process studies in precision injection molding. I: process parameters and precision. *Polymer Engineering & Science*, 36 (1): 1-9.

Liu, F., Zeng, S., Zhou, H. and Li, J. (2012). A study on the distinguishing responses of shrinkage and warpage to processing conditions in injection molding. *Journal of Applied Polymer Science*, 125 (1): 731-744.

Malloy, R. A. (2010). Plastic part design for injection moulding. 2nd ed. Munich: Hanser.

Mamat, A., Trochu, T. F. and Sanschagrin, B. (1995). Analysis of shrinkage by dual kriging for filled and unfilled polypropylene molded parts. *Polymer Engineering & Science*, 35 (19): 1511-1520.

Mathivanan, D. and Parthasarathy, N. S. (2009). Sink-mark minimization in injection molding through response surface regression modeling and genetic algorithm. *The International Journal of Advanced Manufacturing Technology*, 45 (9-10): 867-874.

Mazumder, J., Dutta, D., Kikuchi, N. and Ghosh, A. (2000). Closed loop direct metal deposition: art to part. *Optics and Lasers in Engineering*, 34 (4-6): 397-414.

Mehat, N. M., Kamaruddin, S. and Othman, A. R. (2012). A study of hybrid optimization of injection moulding process parameters for plastic gear. *Advanced Materials Research*, 591-593: 2135-2138.

Mulyana, R., Daniel, T., Min, Y., Castro, J. M. and Lee, L. J. (2010). The use of water containing TPO/activated carbon in injection molding. *In Annual Technical Conference (ANTEC)*, Orlando, FL, United States. 1339-1343.

Oktem, H., Erzurumlu, T. and Uzman, I. (2007). Application of taguchi optimization technique in determining plastic injection molding process parameters for a thin-shell part. *Materials & Design*, 28 (4): 1271-1278.

Othman, M. H., Shamsudin, S. and Hasan, S. (2012). The effects of parameter settings on shrinkage and warpage in injection molding through cadmould 3D-F simulation and taguchi method. *Applied Mechanics and Materials*, 229-231: 2536-2540.

Ozcelik, B. and Erzurumlu, T. (2006). Comparison of the warpage optimization in the plastic injection molding using ANOVA, neural network model and genetic algorithm. *Journal of Materials Processing Technology*, 171 (3): 437-445.

Pantani, R., Jansen, K. M. B. and Titomanlio, G. (1997). In-mould shrinkage measurements of PS samples with strain gages. *International Polymer Processing*, 12 (4): 396-402.

Park, H. S. and Pham, N. H. (2009). Design of conformal cooling channels for an automotive part. *International Journal of Automotive Technology*, 10 (1): 87-93.

Park, H. S. and Dang, X. P. (2010). Optimization of conformal cooling channels with array of baffles for plastic injection mold. *International Journal of Precision Engineering and Manufacturing*, 11 (6): 879-890.

Park, K., Sohn, D. H. and Cho, K. H. (2010). Eliminating weldlines of an injection-molded part with the aid of high-frequency induction heating. *Journal of Mechanical Science and Technology*, 24 (1): 149-152.

Park, S. J. and Kwon, T. H. (1998). Optimal cooling system design for the injection molding process. *Polymer Engineering & Science*, 38 (9): 1450-1462.

Plastics Today, Staff. (2014). Global injection molding plastics market expected to reach $277.78 billion by 2020. Plastics Today.

Rannar, L. E., Glad, A. and Gustafson, C. G. (2007). Efficient cooling with tool inserts manufactured by electron beam melting. *Rapid Prototyping Journal*, 13 (3): 128-135.

Rao, N. S., Schumacher, G., Schott, N. R. and O’brien, K. T. (2002). Optimization of cooling systems in injection molds by an easily applicable analytical model. *Journal of Reinforced Plastics and Composites*, 21 (5): 451-459.

Rao, N. S. and Schumacher, G. (2004). Design formulas for plastics engineers. 2 ed. Munich: Hanser.

Sachs, E., Wylonis, E., Allen, S., Cima, M. and Guo, H. (2000). Production of injection molding tooling with conformal cooling channels using the three dimensional printing process. *Polymer Engineering & Science*, 40 (5): 1232-1247.

Saifullah, A. B. M. and Masood, S. H. (2007a). Cycle time reduction in injection moulding with conformal cooling channels. *Proceedings of The International Conference on Mechanical Engineering*, Dhaka, Bangladesh. December 29-31, 2007. 1-4.

Saifullah, A. B. M. and Masood, S. H. (2007b). Finite element thermal analysis of conformal cooling channels in injection moulding. *Proceedings of the 5th Australasian Congress on Applied Mechanics*, Brisbane, Australia. December 10-12, 2007. 337-341.

Saifullah, A. B. M., Masood, S. H. and Sbarski, I. (2009). New cooling channel design for injection moulding. *Proceedings of the World Congress on Engineering*, London, U.K. July 1-3, 2009. 700-703.

Sanchez, R., Aisa, J., Martinez, A. and Mercado, D. (2012). On the relationship between cooling setup and warpage in injection molding. *Measurement*, 45 (5): 1051-1056.

Santis, F. D., Pantani, R., Speranza, V. and Titomanlio, G. (2010). Analysis of shrinkage development of a semicrystalline polymer during injection molding. *Industrial & Engineering Chemistry Research*, 49 (5): 2469-2476.

Sepe, M. (2013). Dimensional stability after molding: part 1. Plastics Technology

Shayfull, Z., Sharif, S., Zain, A. M., Ghazali, M. F. and Saad, R. M. (2014). Potential of conformal cooling channels in rapid heat cycle molding: a review. *Advances in Polymer Technology*, 33 (1): 1-24.

Shoemaker, J. (2006). Moldflow design guide: a resource for plastics engineers. 1st ed. Framingham, Massachusetts, USA: Hanser.

Spina, R. (2004). Injection moulding of automotive components: comparison between hot runner systems for a case study. *Journal of Materials Processing Technology*, 155-156: 1497-1504.

Subramanian, N. R., Tingyu, L. and Seng, Y. A. (2005). Optimizing warpage analysis for an optical housing. *Mechatronics*, 15 (1): 111-127.

Sun, B., Wu, Z., Gu, B. and Huang, X. (2010). Optimization of injection molding process parameters based on response surface methodology and genetic algorithm. *Proceedings of 2nd International Conference on Computer Engineering and Technology (IEEE)*, Chengdu, China. April 16-18, 2010. 397-400.

Sun, Y. F. (2003). *Finite Element Method in Cooling Analysis and Design of Plastic Injection Moulds*: National University of Singapore.

Sun, Y. F., Lee, K. S. and Nee, A. Y. C. (2004). Design and FEM analysis of the milled groove insert method for cooling of plastic injection moulds. *The International Journal of Advanced Manufacturing Technology*, 24 (9-10): 715-726.

Tang, S. H., Kong, Y. M., Sapuan, S. M., Samin, R. and Sulaiman, S. (2006). Design and thermal analysis of plastic injection mould. *Journal of Materials Processing Technology*, 171 (2): 259-267.

Tang, S. H., Tan, Y. J., Sapuan, S. M., Sulaiman, S., Ismail, N. and Samin, R. (2007). The use of taguchi method in the design of plastic injection mould for reducing warpage. *Journal of Materials Processing Technology*, 182 (1-3): 418-426.

Titomanlio, G. and Jansen, K. M. B. (1996). In-mold shrinkage and stress prediction in injection molding. *Polymer Engineering & Science*, 36 (15): 2041-2049.

Wang, T. H. and Young, W. B. (2005). Study on residual stresses of thin-walled injection molding. *European Polymer Journal*, 41 (10): 2511-2517.

Wu, C. H. and Huang, Y. J. (2007). The influence of cavity deformation on the shrinkage and warpage of an injection-molded part. *The International Journal of Advanced Manufacturing Technology*, 32 (11-12): 1144-1154.

Xu, X., Sachs, E. and Allen, S. (2001). The design of conformal cooling channels in injection molding tooling. *Polymer Engineering & Science*, 41 (7): 1265-1279.

Xu, Y. J., Yang, W., Xie, B. H., Liu, Z. Y. and Yang, M. B. (2009). Effect of injection parameters and addition of nanoscale materials on the shrinkage of polypropylene copolymer. *Journal of Macromolecular Science, Part B*, 48 (3): 573-586.

Yao, D. and Kim, B. (2002). Development of rapid heating and cooling systems for injection molding applications. *Polymer Engineering & Science*, 42 (12): 2471-2481.

Zhang, Z. and Jiang, B. (2007). Optimal process design of shrinkage and sink marks in injection molding. *Journal of Wuhan University of Technology-Mater. Sci. Ed.*, 22 (3): 404-407.

Zhou, H. and Li, D. (2005). Mold cooling simulation of the pressing process in TV panel production. *Simulation Modelling Practice and Theory*, 13 (3): 273-285.

Zhou, H., Zhang, Y., Wen, J. and Li, D. (2009). An acceleration method for the BEM-based cooling simulation of injection molding. *Engineering Analysis with Boundary Elements*, 33 (8–9): 1022-1030.

APPENDIX A

1. **Z. Shayfull**, **S. Sharif**, **Azlan Mohd Zain**, R. Mohd Saad and S.M. Nasir, Improving the Quality and Productivity of Molded Parts with a New Design of Conformal Cooling Channels for the Injection Molding Process, ***Advances in Polymer Technology***, DOI: 10.1002/adv.21524, **2015**. **Impact Factor: 1.045**.

2. **Z. Shayfull**, **S. Sharif**, **Azlan Mohd Zain**, M.F. Ghazali and R. Mohd Saad Potential of Conformal Cooling Channels in Rapid Heat Cycle Molding: A Review, ***Advances in Polymer Technology***, 33(1): 1-24, **2014**. **Impact Factor: 1.045**.

3. **Z. Shayfull**, **S. Sharif**, **Azlan Mohd Zain**, R. Mohd Saad and M.A. Fairuz, Warpage analysis with straight drilled and conformal cooling channels on front panel housing by using taguchi method, ***Key Engineering Materials*** 594, 593-603, **2014**. **(Scopus)**.

4. **Z. Shayfull**, **S. Sharif**, **Azlan Mohd Zain**, R. Mohd Saad, and M. A. Fairuz, Milled Groove Square Shape Conformal Cooling Channels in Injection Molding Process, ***Materials and Manufacturing Processes***, 28: 884–891, **2013**. **Impact Factor: 1.486**.

5. **Z. Shayfull**, M. Fathullah, **S. Sharif**, S.M. Nasir, N.A. Shuaib, Warpage analysis on ultra-thin shell by using taguchi method and analysis of variance (ANOVA) for three-plate mold. **International Review of Mechanical Engineering**, Vol. 5, No. 6, 1116-1124, September **2011**. **(Scopus)**.

6. M. Fathullah, **Z. Shayfull**, **S. Sharif**, N.A. Shuaib, S.M. Nasir, A study on two plate and three plate mold of ultra thin plates in minimizing warpage issue. **International Review of Mechanical Engineering**, Vol. 5, No. 7, 1189-1195, November **2011**. **(Scopus)**.

APPENDIX B

1. Special Award from Chinese Innovation & Invention Society - Taiwan (CIIS), New Design of Milled Groove Square Shape Conformal Cooling Channels in Injection Molding Process, International Warsaw Invention Show (IWIS) 2013, Warsaw, Poland.

2. Special Award from Korea Invention News, New Design of Milled Groove Square Shape Conformal Cooling Channels in Injection Molding Process, International Warsaw Invention Show (IWIS) 2013, Warsaw, Poland.

3. Award in Invention Academics & Education Order of Merit Category, World Inventor Award Festival (WIAF) 2013, New Design of Milled Groove Square Shape Conformal Cooling Channels in Injection Molding Process, Seol, Korea.

4. Award in Manufacturing Order of Merit Category, World Inventor Award Festival (WIAF) 2013, New Design of Milled Groove Square Shape Conformal Cooling Channels in Injection Molding Process, Seol, Korea.

5. Special Award, Honor of Invention from World Invention Intelectual Property Associations, A New Design of Milled Groove Square Shape Conformal Cooling Channels (Milled Grooved Square Shape Conformal Cooling Channels) in Injection Molding Process, Invention, Innovation & Technology Exhibition (ITEX) 2014, Kuala Lumpur Convention Centre (KLCC), Malaysia

6. Leading Innovation Award from International Intelectual Property Netwrok Forum, Improving Productivity and Quality In Conventional and Rapid Heat Cycle Molding With A New Design of Conformal Cooling Channels, International Exhibition on Invention Kunshan (IEIK) 2014, Kunshan, China.

7. Special Award from Korea University Invention Association, Improving Productivity and Quality In Conventional and Rapid Heat Cycle Molding With A New Design of Conformal Cooling Channels, International Exhibition on Invention Kunshan (IEIK) 2014, Kunshan, China.

8. Special Award from Crotian Inventors Association, Improving Productivity and Quality In Conventional and Rapid Heat Cycle Molding With A New Design of Conformal Cooling Channels, International Exhibition on Invention Kunshan (IEIK) 2014, Kunshan, China.

APPENDIX C

1. Gold Medal, New Design of Milled Groove Square Shape Conformal Cooling Channels in Injection Molding Process, International Warsaw Invention Show (IWIS) 2013, Warsaw, Poland.

2. Silver Medal, Improving Quality and Productivity in Rapid Heat Cycle Moulding with A New Design of Conformal Cooling Channels, European Exhibition of Creativity and Innovation (EUROINVENT) 2014, Iasi, Romania.

3. Gold Medal, A New Design of Milled Groove Square Shape Conformal Cooling Channels (Milled Grooved Square Shape Conformal Cooling Channels) in Injection Molding Process, Innovation & Technology Exhibition (ITEX) 2014, Kuala Lumpur Convention Centre (KLCC), Malaysia.

4. Gold Medal, Design of Milled Groove Square Shape (MGSS) Conformal Cooling Channels in Injection Molding Process, Ekspo Rekacipta dan Penyelidikan UniMAP 2014, University Malaysia Perlis, Malaysia.

5. Bronze Medal, Improving Productivity and Quality In Conventional and Rapid Heat Cycle Molding With A New Design of Conformal Cooling Channels, International Exhibition on Invention Kunshan (IEIK) 2014, Kunshan, China.

6. Silver Medal, Improving Productivity and Quality In Injection Molding Process with a New Design of Conformal Cooling Channels, Malaysia Technology Expo (MTE) 2014, Kuala Lumpur Convention Centre (KLCC), Malaysia.