

# EVALUATION ANALYSIS OF METAL EPOXY COMPOSITE (MEC) MOLD INSERTS IN RAPID TOOLING FOR INJECTION MOLDING

Radhwan Hussin<sup>a\*</sup>, Mohd Azlan Suhaimi<sup>b</sup>, Safian Sharif<sup>b</sup>, Shayfull Zamree Abd Rahim<sup>a</sup>, Mohd Nasir Mat Saad<sup>a</sup>, Mohd Tanwyn Mohd Khushairi<sup>c</sup>, Narzrezal Abdul Razak<sup>a</sup>

<sup>a</sup>Faculty of Mechanical Engineering and Technology, Universiti Malaysia Perlis, Main Campus Pauh Putra, 02600 Arau, Perlis, Malaysia

<sup>b</sup>Advanced Manufacturing Research Group (AMRG) Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

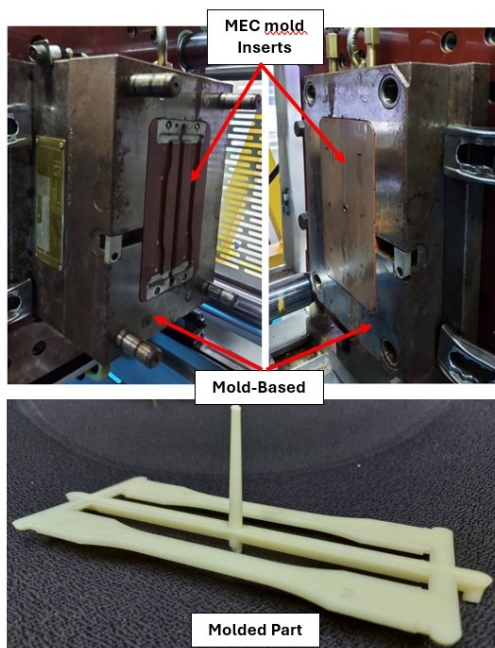
<sup>c</sup>Exzellent Profis Institute, 57000 Kuala Lumpur, Malaysia

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\*Corresponding author  
radhwan@unimap.edu.my

## Graphical abstract



## Abstract

Developing mold inserts for Rapid Tooling (RT) using Metal Epoxy Composite (MEC) material offers a commercially viable alternative for injection molding applications. However, existing research on actual MEC mold performance and the quality of the molded parts produced is limited. This study aims to analyze the performance of MEC mold inserts for injection molding applications, focusing on their cooling efficiency and the quality of molded parts produced. An indirect RT method was employed to fabricate MEC mold inserts, with a filler composition of 60% wt. Core and cavity inserts were designed with integrated cooling channels and tested using an injection molding machine. Cooling time was measured experimentally and compared to simulation results obtained via Moldflow software. The experimental findings revealed an average cooling time of 23.3s for the MEC mold inserts, compared to 21.9s in the simulation. Molded Parts with MEC inserts demonstrated improved tensile modules and reduced elongation compared to those molded parts with P20 steel mold inserts. However, the value difference is insignificant and still lies within the acceptable limits. This research contributes to the body of knowledge by providing practical insights into the fabrication and performance of MEC mold inserts using RT techniques, demonstrating that MEC is a promising material for RT applications in injection molding, with competitive performance characteristics.

Keywords: Rapid Tooling (RT), Hybrid Mold Inserts, Metal Epoxy Composite (MEC), Injection Molding; Cycle Time

## Abstrak

Membangunkan sisipan acuan untuk Rapid Tooling (RT) menggunakan bahan Metal Epoxy Composite (MEC) menawarkan alternatif yang berdaya maju secara komersial untuk aplikasi pengacuan suntikan. Walau bagaimanapun, penyelidikan sedia ada mengenai prestasi acuan MEC sebenar dan kualiti bahagian acuan yang dihasilkan adalah terhad. Kajian ini bertujuan untuk menganalisis prestasi sisipan acuan MEC untuk

aplikasi panacean suntikan, memberi tumpuan kepada kecekapan penyjukan dan kualiti bahagian acuan yang dihasilkan. Kaedah RT tidak langsung telah digunakan untuk membuat sisipan acuan MEC, dengan komposisi pengisi sebanyak 60% berat. Sisipan teras dan rongga direkabentuk dengan saluran penyjukan bersepadu dan diuji menggunakan mesin pengacuan suntikan. Masa penyjukan diukur secara eksperimen dan dibandingkan dengan keputusan simulasi yang diperoleh melalui perisian Moldflow. Penemuan eksperimen mendedahkan purata masa penyjukan 23.3s untuk sisipan acuan MEC, berbanding 21.9s dalam simulasi. Bahagian acuan yang dibentuk dengan sisipan MEC menunjukkan modulus tegangan yang lebih baik dan pemanjangan yang berkurangan berbanding dengan bahagian acuan yang dibentuk dengan sisipan acuan keluli P20. Walau bagaimanapun, perbezaan nilai ini adalah tidak ketara dan masih terletak dalam had penerimaan. Penyelidikan ini menyumbang kepada badan pengetahuan dengan memberikan pandangan praktikal ke dalam fabrikasi dan prestasi sisipan acuan MEC menggunakan teknik RT, menunjukkan bahawa MEC ialah bahan yang menjanjikan untuk aplikasi RT dalam pengacuan suntikan, dengan ciri prestasi yang kompetitif.

**Kata kunci:** Perkakas Pantas (RT), Sisipan Acuan Hibrid, Logam Epoksi Komposit (MEC), Pengacuan Suntikan, Masa Kitaran

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## 1.0 INTRODUCTION

The injection molding process has been one of the most widely used processes for the manufacture of plastic products in various types and applications, from technical parts to consumer products due to its high productivity, stability and good performance [1-2]. Most plastic parts are manufactured via injection molding for various applications under pressure and heat conditions to form the product in the mold cavities to the desired size and shape [2-3]. Fabrication of molds is normally made of tool steel and machined using a Computer Numerical Control (CNC) precision machine [4-6]. The tooling fabrication process's precision is defined by the final product's specifications, which require high precision for complex geometry and fine surface finishing [7-8]. Therefore, to achieve high production flexibility and high-quality parts, mold manufacturers are required to make significant investments in expensive equipment such as CNC machine tools, Electro-Discharge Machines, drilling machines, and metrology equipment. However, due to the labor-intensive nature of mold fabrication, these machines typically come with long lead times and high costs [9-12].

In today's global market, Rapid Tooling (RT) technologies are advancing swiftly in response to the need for rapid product development. This demand stems from the desire to replace conventional methods with faster fabrication processes, particularly in mold making [13-17]. RT is a method of involving Additive Manufacturing (AM) technique and applied to the fabrication mold insert [1, 13 -14, 18]. Typically, AM models as master patterns are used to build mold inserts indirectly or made directly from the AM process for a limited number of prototypes [13, 16, 19-21].

Furthermore, there is a growing market need for products that are more affordable, undergo shorter product development cycles, maintain higher quality standards, and meet sustainability criteria in terms of environmental impact [14, 22]. The manufacturer is pursuing the development and commercialization of RT due to its market potential. Manufacturers industry benefited from RT process for tooling fabrication and explored alternative materials with reduced tooling fabrication time, product quality and compatible with global trends [20]. To keep pace with the requirements of modern product manufacturing cycles, it's crucial to embrace advancements in both tooling methods and materials [20, 23].

The answer to this scenario in the last few decades has been to combine RT and AM techniques with conventional metal mold manufacturing techniques to produce hybrid molds [17, 20, 24-26]. Hybrid molds is an innovative approach to injection molding that combines conventional machining for the mold-based and RT techniques for the mold insert (core and cavity) [17, 20]. The conventional method of fabrication mold uses core and cavity, which takes more fabrication time to be ready for delivery [13, 27-28]. To enhance competitiveness, integrating Metal Epoxy Composite (MEC) mold inserts in RT applications has the potential to reduce tooling costs and fabrication times by up to 50% [20, 29]. MEC material is a combination of metallic or non-metallic filler particles mixed with epoxy resin. This trend, especially when materials softer than tool steel are used as mold inserts, results in a hybrid mold concept that is particularly suitable for low/custom production [30]. However, the life and performance of mold inserts are dependent on the quantity and conditions of the plastic injection molding process [31].

## 2.0 METHODOLOGY

### 2.1 Resin and Filler Particle

Epoxy resin Miracast 1516 A/B manufactured by Miracon (M) Sdn. Bhd, Selangor, Malaysia, was selected for the tooling application and copper filler in the form of powder were selected as the metal fillers supplied by Chengdu Huarui Industrial Co., Ltd, Chengdu, China, employed in this research. The properties of particle size and shapes are given in Figure 1.

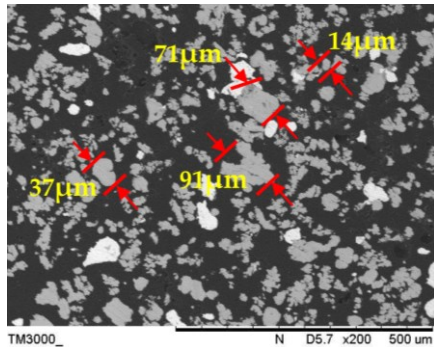


Figure 1 Copper irregular shape (10 – 100 microns)

### 2.2 Mold Insert Design

The 3D model for the thick flat part in this research was design using Computer-aided design (CAD) software (Solidworks 2014, Dassault Systèmes, S. A., Suresnes, France), adhering to the guidelines outlined in the international standard ISO 3167 for multipurpose plastics injection test specimens [32]. The profile of the specimen is illustrated in Figure 2.

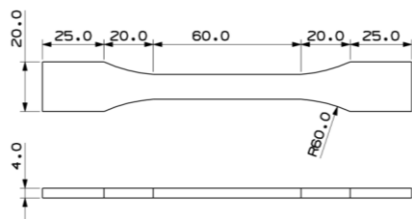


Figure 2 Detail of the thick flat part (all dimensions in mm)

Figure 3 shows the mold insert design for the thick flat part used for this research. The mold design phase emphasizes several critical characteristics, including the shape of the part, the mold type, the cooling channels, the gating system, the mold dimensions, the material for mold inserts, and the mold base, all of which must be properly selected [12, 26, 33]. The specimens were molded using Acrylonitrile Butadiene Styrene (ABS), specifically Polylac PA-777B grade manufactured by Chi Mei Corporation. The properties of ABS are detailed in Table 1.

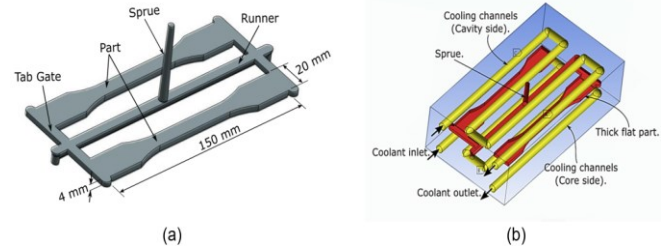


Figure 3 Mold inserts designed for the thick flat part; (a) Part design; (b) Cavities insert design

Table 1 Properties of ABS material (Rahim, 2016)

Property	Unit	Value
Thermal conductivity	WmK-1	0.178
Melt density	kg/m <sup>3</sup>	956.17
Specific heat	J/kg.C	1464.7
Elastic modulus	MPa	2.24×103

The assembly mold as a hybrid mold design is illustrated in Figure 4. The thick flat part is used as the set of specimens formed in two plates using inserts with straight cooling channels. Mold inserts (core and cavity) were made from MEC material and inserted into the P20 mold base. Data acquisition (DAQ) model TcDAQ-9188 from National Instruments was used with a K-Type Thermocouple to monitor and record the temperature profile of the coolant at the entry and exit, ambient temperature, and temperature of the mold insert (core and cavity).

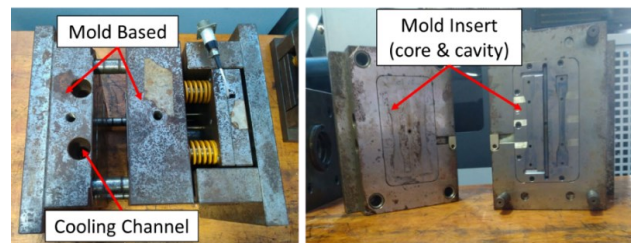


Figure 4 Mold assembly (mold based and mold insert)

### 2.3 Simulation of MEC Mold insert design

Moldflow Plastics Insight software (Autodesk Moldflow Insight 2012) was used for simulation. Some of the parameters are set as input variables, while others are fixed at the recommended value. Input variables were chosen based on previous research relevant to this research [32], [33]. At this point, the ranges of the input variables are also determined. The simulation process begins with the importation of a 3D model for the thick flat part and analyzed based on the process settings that had been configured in the software. Flow chart of these processes is shown in Figure 5. Four analyzes were conducted, which were molding window analysis, fill analysis, fill + pack

analysis, and cool analysis. Recommended injection molding parameters obtained from the related results of the simulation analysis. The simulation value of packing pressure in cavity mold inserts is an important value to be considered to ensure that the compressive strength of the new material MEC is sufficient for the tooling insert of core and cavity mold. The recommended processing parameter values were obtained at the end of the analysis.

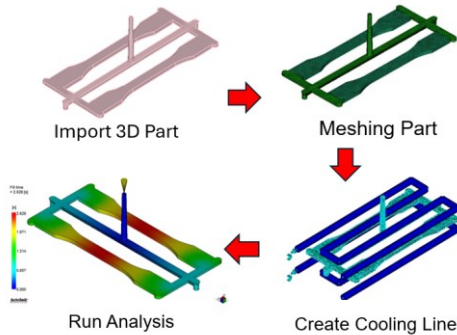


Figure 5 Flow diagram of the simulation process

Equation 1 used to calculate the ram speed (mm/s) at the beginning and final stages were, and Equation 2 was used to determine the shot material (SM) required to mold the selected part. Where  $V_{part}$  is the volume of the molded parts ( $\text{mm}^3$ ),  $V_{gs}$  is the volume of the gating system ( $\text{mm}^3$ ), and  $A_{screw}$  is the cross-sectional area of reciprocating screw ( $\text{mm}^2$ ). About 25% of material was added because plastic has a large volumetric change from melt to solid during packing process. Then, to prevent the reciprocating screw from hitting the valve in the barrel, 5 mm was added as a cushion. Diameter of reciprocating screw in the injection molding machine is 28 mm. SM was calculated by referring to the volume obtained from the NX software for the volume of part and gating system [32].

$$\text{Ram Speed} = \text{Flow rate}/A_{screw} \quad (1)$$

$$\text{SM} = ((V_{part}+V_{gs})/A_{screw}) + 25\% ((V_{part}+V_{gs})/A_{screw})+5 \quad (2)$$

The results of the fill+pack analysis obtained from simulation are utilized to assess the recommended maximum packing pressure in the mold cavities necessary to achieve complete filling in accordance with the variations in the mass of the molded parts. Based on this recommended maximum packing pressure, the MEC material compressive strength test results shall be higher to avoid MEC mold insert failure during the injection molding process. Table 2 summarises the results of experiments used in the Moldflow simulation, such as specific heat, density, and thermal conductivity tests. Additional data such as Poisson ratio, Elastic modulus and the coefficient of thermal expansion were obtained from a similar

study conducted by previous researchers [17], [27], [32].

Table 2 Parameter for plastic flow analysis

Property	Unit	MEC
Mold Density	g/cm <sup>3</sup>	2.24
Mold Specific Heat	J/kg.C	1300
Mold Thermal Conductivity	WmK <sup>-1</sup>	2.66
Elastic Modulus, E	GPa	9.8 GPa
Poisson Ratio	-	0.42
Mold Coeff. of Thermal Expansion	1/C	0.0000035 to 0.000005

## 2.4 Fabrication of MEC Mold Insert

MEC materials are liquids mixed with metal fillers and eventually harden into solid material. Producing mold inserts using this epoxy mold technique requires a pouring block to hold the liquid MEC until it hardens, as well as reproduce the intended plastic product that will be used for mold injection molding [33], [34], [35]. Pouring block consists of two parts that will produce a mold insert (core and cavity) by considering the cooling channel, gating system, ejector pin, bushing, thread and including the master pattern as shown in Figure 6. The master pattern for the thick flat part is created on the base surface of the casting block using the same material as the block itself, through a machining process. This pouring block is produced using aluminum material with a thickness of 10 mm and is assisted by the components assembled to minimize the warping defect on the MEC mold insert (Core and Cavity) produced during the curing and cooling process. Epoxy mix with copper was used as the mold insert material in this research, with a 60% of the composition as shown in Table 3 [36]. Figure 7 shows the flow chart of fabrication mold insert process. The patterns of cavities insert with cooling channel, ejector pin, bushing, thermocouples and mold insert thread were already placed in the aluminum pouring block to be cast with MEC material.

Epoxy, hardener and filler were poured into their respective containers and weighed according to the specific volume ratios of the MEC mixture determined. The MEC mixture was stirred for 7 minutes until the filler particles well dispersed throughout the epoxy matrix. Then the MEC mixture was degassed in a vacuum chamber to remove air bubbles trapped during mixing [36]. Once the mixture was prepared, it was then poured into the pouring block core and cavity that had been prepared. After initial curing at room temperature for 24 hours, it was heated in the oven according to the heating level at 80 °C, 120 °C, 160 °C and 180 °C with a time interval of 4 hours to improve the adhesion properties between the filler and epoxy matrix [36]. After the curing process, the surface of MEC mold

insert has a minor warpage was observed and needs to be leveled on the surface of the core and cavity. The surface between the mold cavities needs to be slightly machined to remove the clearance between the core surface and the cavity when clamping. The range of machining that has been done on the surface is 0.1 - 0.2 mm.

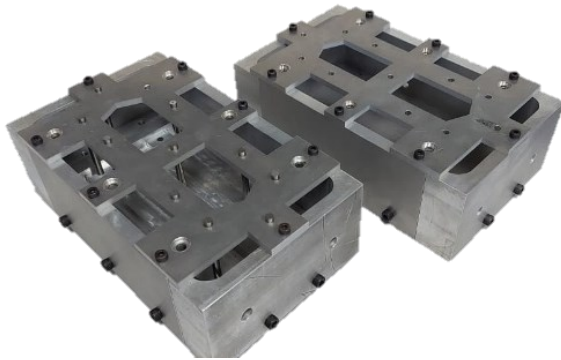


Figure 6 Pouring Block (core and cavity)

Table 3 Composition of MEC material under high thermal conductivity [36]

Property	Unit	MEC
Percentage composition	Filler	60
	Resin	% 27.67
	Hardener	13.33

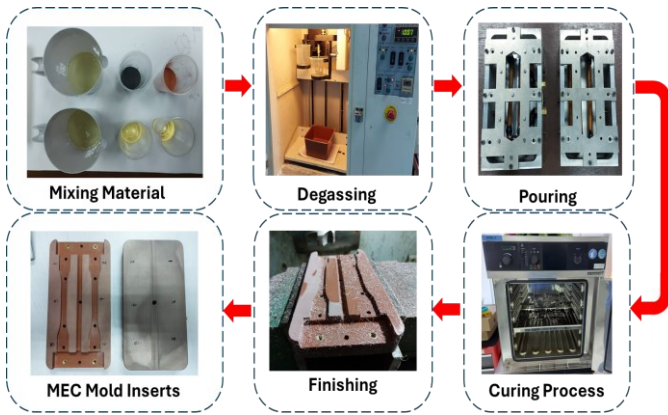


Figure 7 MEC Mold insert fabrication process flow

2.5 Mechanical Test for Molded Parts

Molded parts from the MEC mold inserts were measured and tested to see the quality and make comparisons with the existing mold inserts. Tensile strength test, shrinkage and surface roughness measurements were performed on the molded part during the testing process.

Tensile test - Weld lines are formed when the molten plastics that fill the cavities go through two separate directions and rejoin the two fronts of the melt during injection molding. The resulting weld line is due to multiple gating, variable part thickness,

obstacles and jetting. Wu and Liang [37] stated that weld lines weaken the strength of injection molded parts. Most researchers try to eliminate weld lines because they adversely affect the part's appearance and mechanical performance. Universal Testing Machine (UTM) was used to measure the tensile strength of the mold part with the test speed used in this research being 20 mm/min according to the ASTM standard D638 [38]. Ten specimens were used for tensile testing for each set of mold inserts and the set up for tensile testing is shown in Figure 8.



Figure 8 Tensile testing using UTM

The shrinkage of the molded part was measured following ISO standard 294 [39]. The shrinkage of the molded part was measured using a digital caliper, as shown in Figure 9. Ten specimens of each molding were chosen for the shrinkage measurement and measured 48 hours after the molding process. The specimens were removed from the gating system immediately after molding and stored at room temperature for 16 to 24 hours. Molding shrinkage can be calculated using Equation 3 for shrinkage in the parallel direction of the melt flow,  $S_{MP}$  (%), and Equation 4 for shrinkage in the normal direction of the melt flow,  $S_{Mn}$  (%). where  $l_c$  (mm) and  $b_c$  (mm) are the cavity's length and width, and  $l_1$  (mm) and  $b_1$  (mm) are the test specimen's length and width.

$$S_{MP} = 100 (l_c - l_1) / l_c \tag{3}$$

$$S_{Mn} = 100 (b_c - b_1) / b_c \tag{4}$$

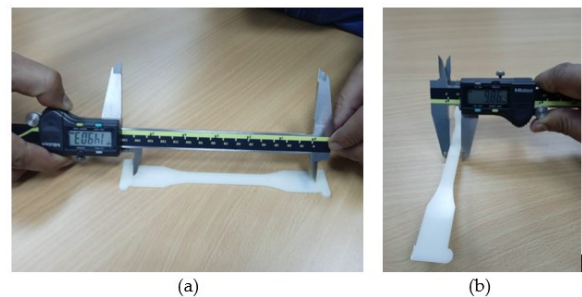


Figure 9 Shrinkage measurement in parallel and normal direction of the melt flow; (a) Parallel direction; (b) Normal direction

A surface roughness tester (Mitutoyo SJ-410 Portable surface roughness tester) was used to measure the surface roughness (Ra) of the molded parts produced by MEC mold inserts and the MEC mold insert cavities surface, as shown in Figure 10. The average value of five molded parts was measured at three different points and compared to the conventional metal mold P20. Smaller Ra values on mold surfaces resulted in a good surface finish. Surface roughness readings are taken on the machined surface and casting surface at cavities by considering three different points along each molded part, as shown in Figure 11.

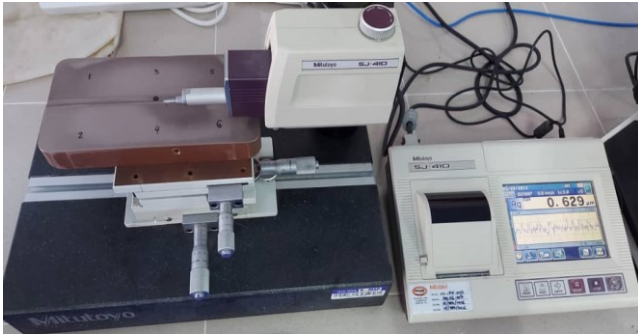


Figure 10 Surface Roughness tests

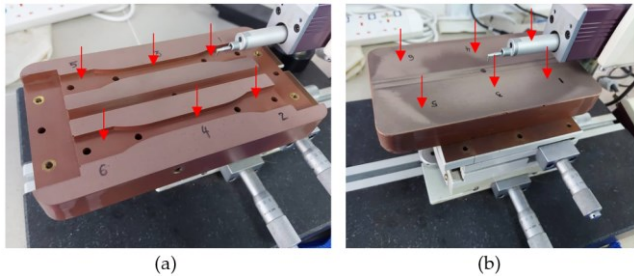


Figure 11 Surface Roughness on casting surface and milling surface; (a) Casting Surface; (b) Milling surface

### 3.0 RESULTS AND DISCUSSION

This section presents simulations and experimental work. Moldflow simulation suggests parameter settings to run the injection molding process using these MEC mold inserts. Furthermore, the evaluation and validation of the molded part that has been injected using this MEC mold insert are studied in terms of cooling time, molded part accuracy and the applicability of the MEC mold insert that has been produced.

#### 3.1 Analysis of Parameters Setting of Metal Epoxy Composite (MEC) as Mold Inserts

The moldability of parts, as well as important factors for plastic processing, were determined using Moldflow simulation software. Recommended molding parameters for the thick flat part, the sprue,

runner and gate were fitted to the parts for the simulation. MEC mold material settings were determined by the MEC mold insert properties and the injection parts were made of ABS material. The filling velocity profile, pressure to velocity (V/P) switch-over, Shot Material (SM), packing pressure, cooling time, packing time, mold temperature and melt temperature are all important parameters to consider in this analysis because it has a direct impact on the molded part's quality [40], [41]. The four types of analysis used were Molding Window analysis, Fill analysis, Fill+Pack analysis, and Cool analysis.

#### Mold and Melt Temperature Analysis Result

The Molding Window Analysis was used to determine the recommended mold temperature, melt temperature, and the values were selected at the point that reached the best quality, as shown in Figure 12. The quality ranged from 0 to 1, where 1 gives the highest quality [42], [43]. The recommended mold and melt temperatures, based on the highest quality point, were 65°C and 245°C, respectively.

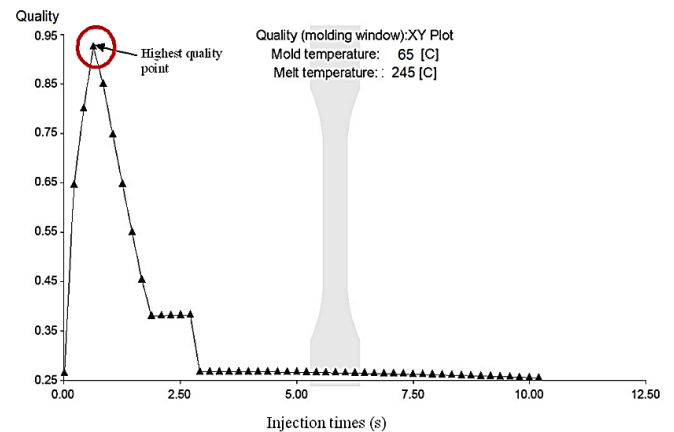


Figure 12 Quality versus injection time of thick flat part

#### Fill Analysis Results

The fill analysis was conducted to observe the flow of molten plastic into the mold cavities through the gating system. This analysis was based on recommended mold settings, melt temperatures, automatic filling control settings, V/P switchover, and default packing/holding controls. The analysis was conducted considering the cooling channel design. Filling time (s) and shear rate ( $s^{-1}$ ) were monitored, with the results depicted in Figure 13. These parameters, specifically the filling time and maximum shear rate obtained, served as references for determining the filling velocity of the profile. It's important to note that the maximum shear rate should not exceed the limit specified in the material database [44], [45]. Besides, the ram velocity was also calculated from the flow rate in Fill analysis. The

average flow rate of 9.5 cm<sup>3</sup>/s at the beginning and 11 cm<sup>3</sup>/s at the final stage were considered in the ram speed calculation. Therefore, the ram speed (mm/s) at the beginning and final stages were calculated using Equation 1. Thus, the ram velocity was calculated as follows (diameter of the reciprocating screw is 28 mm) is, ram speed at start (15.45 mm/s) and ram speed at final (17.89 mm/s). Moreover, SM is a starting ram position that was calculated using Equation 2 to determine the ram profile. SM is the volume of material in the barrel that is required to fill and pack the cavities during the injection molding process in one cycle and the volume needed is 60 mm. The first and second stages of the ram speed obtained from Equation 1 were 15 mm/s and 17 mm/s, respectively. The first stage is to fill the gating system and the second stage is to fill the mold cavities. After V/P switchover is reached, the packing phase will take place. The ram positions for the first stage are 44 mm were calculated according to the gating system volume. The ram position of V/P switch-over is 15 mm was also calculated using the same way according to the total volume of the parts and the gating system. V/P switch-over was set approximately when 99% mold was filled. At this position, the movement of ram will switch from velocity control to pressure control, which allows the packing process to take place.

**Fill + Pack Analysis Results**

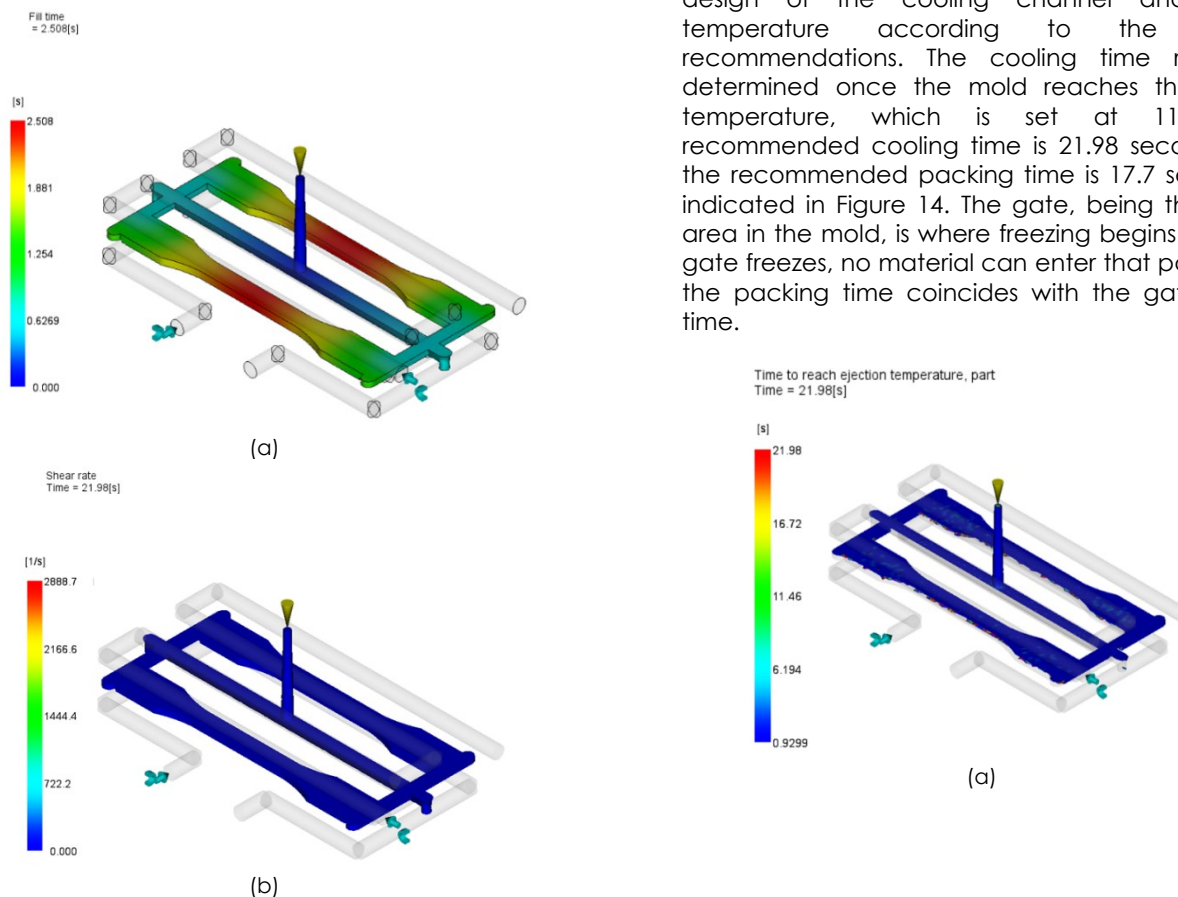
The results of the fill analysis are used to determine the value of the packing pressure. The mass of the part is evaluated by increasing the packing pressure until no or only a small change in the mass of the part occurs. The results of the mass of the molded part with various packing pressures are shown in Table 4. The mass of the part shows a slight increase with increasing packing pressure up to 70 MPa. The mass of the part remains 17.5 g even after a packing pressure of 80 MPa is applied. These results indicate that a packing pressure of 70 MPa is sufficient.

**Table 4** Part mass result of variable packing pressure

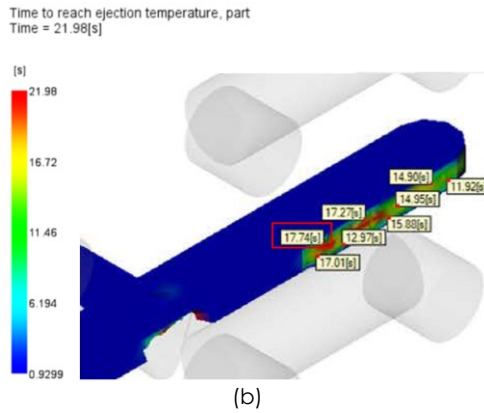
Packing pressure (MPa)	Part mass (g)
43.9	17.0
43.9	17.1
43.9	17.3
60.0	17.4
70.0	17.5
80.0	17.5

**Cool Analysis Results**

Cool analysis is carried out with consideration the design of the cooling channel and coolant temperature according to the software recommendations. The cooling time results are determined once the mold reaches the ejection temperature, which is set at 110°C. The recommended cooling time is 21.98 seconds, while the recommended packing time is 17.7 seconds, as indicated in Figure 14. The gate, being the smallest area in the mold, is where freezing begins. Once the gate freezes, no material can enter that part. Hence, the packing time coincides with the gate freezing time.



**Figure 13** Result from Fill analysis; (a) fill time ; (b) shear rate



**Figure 14** Result from cool analysis; (a) Recommended cooling time; (b) Recommended packing time

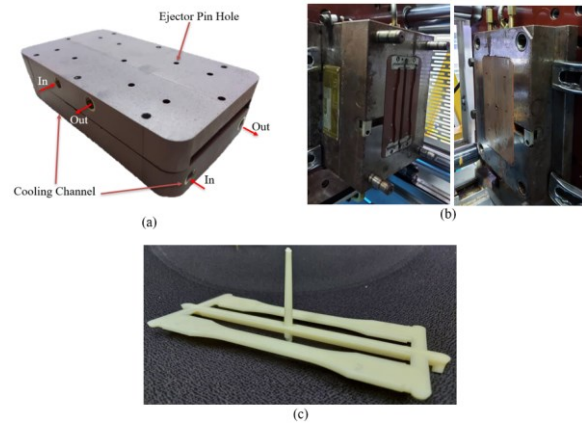
Table 5 summarizes the recommended injection molding parameters based on the Moldflow simulation. These findings were used as a guide in the next stage of this research. All the values meet the requirements of an injection molding machine because the machine specifications and limits were established directly during the simulation study.

**Table 5** Summary of simulation result

Parameter	Actual value	
	MEC	P20
Mold temperature (°C)	65	68
Melt temperature (°C)	245	245
Fill time (s)	2.5	2.6
Initial ram speed (mm/s)	15	15
Final ram speed (mm/s)	18	17
Initial ram position (mm)	60	60
Second ram position (mm)	44	40
Cushion (mm)	5	5
P/V switch-over position (mm)	15	15
Packing pressure (MPa)	54	70
Packing time (s)	17.7	10
Cooling time (s)	21.98	12

**3.2 MEC Mold Insert Trials**

The mold insert trial was conducted using MEC mold insert using an injection molding machine, Nissei NEX1000, in the Teaching Factory, Faculty of Mechanical Engineering and Technology, Universiti Malaysia Perlis. In practice, the molding condition settings for MEC materials are set lower than conventional metal molds, particularly the melt temperature, injection and packing pressure due to the low thermal conductivity of MEC mold inserts [46]. Figure 15 shows the MEC mold insert installed on the mold base on a hybrid mold and the molded part produced using this MEC mold insert. The machine parameters were prepared, such as coolant inlet temperature, melt temperature, cooling time and packing pressure according to the Moldflow analysis results as presented in Table 5.



**Figure 15** (a) MEC mold inserts; (b) Mold inserts fix to mold base and install to injection molding machine;(c) Molded parts

As seen in Figure 16, the molded parts were labeled and separated appropriately after cooling for about half an hour. Molded parts for validation of experimental works on the mechanical properties were selected based on complete cavity filling, with reduced visual defects such as sink marks and warpage. Lower injection speeds of 15 mm/s were applied to MEC mold inserts, while melt temperatures of 245°C were applied throughout the heating zones for ease of melt flow through the runners and impression. The packing pressure time or holding time of molded parts is an important factor in reducing sink marks [40], [42], [47]. Furthermore, the packing pressure in the MEC mold insert was set at 55 MPa for 17.7s to allow packing and solidification of the molded parts.

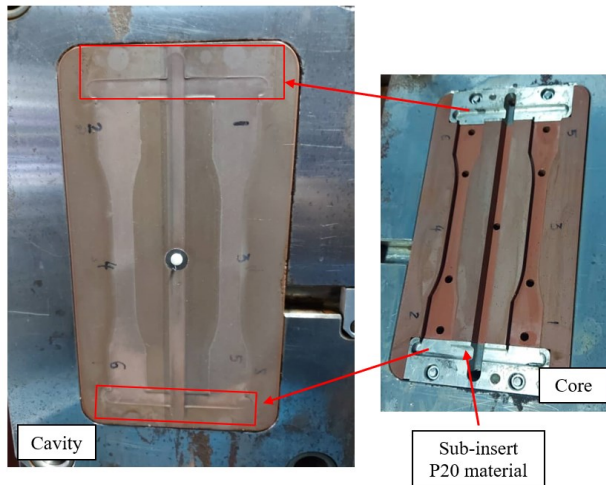


**Figure 16** Molded parts from MEC mold insert

**MEC Mold Defect**

MEC mold inserts could withstand the pressure, and after the injection process, it was found that there was a slight defect on the surface of the MEC mold insert (cavity) during the packing phase, as shown in Figure 17. This defect occurs due to the use of materials with different hardness, which is the sub-insert (gating) part that uses P20 material installed on the MEC mold insert (core). The purpose of designing the installation of sub insert is intended for further

research to study the effect of changing the flow direction of molten plastic filling the cavities. Although the surface area of the product has not been affected, this portion of the sub-insert must be produced using the same MEC material to avoid this effect. However, the dimensions, mass of the molded parts and the condition of the MEC mold insert cavity product area are consistent without any defects such as chipping, crack, wear and warping after injecting 300 shots.



**Figure 17** Defect on mold insert (cavity) caused by sub-insert during packing phase

### MEC Mold Insert Cooling Time

The results of the cooling time obtained from simulations and experimental works for MEC mold insert with a reading of 60 injected molded parts. Based on the actual trials, the total cooling time of the injection molding process was measured for both MEC and P20 mold inserts with straight cooling channels averaged 23.3s for MEC inserts and 12s for P20 inserts. Since the parameters are set based on the results of the Moldflow simulation that has been performed, the comparison of cooling times for experiments and simulations for P20 inserts and MEC mold inserts is equivalent, with a small difference. It has been found that the cooling time obtained by using MEC mold inserts is 23.3s (Average) and the difference in results between the actual experiment compared to the Moldflow simulation is 21.9s (6%). Referring to previous researchers [33], [48], the results of cooling time obtained indicate a very significant difference between the simulation and the actual experiment. Khushairy *et al.* [48] stated that because the epoxy mold doesn't have embedded cooling system, this has an important impact on the cooling time with the actual experiment's cooling time was found to be 2 times that of the simulation. Due to this reason, the use of a cooling system helps improve the cooling time performance of MEC mold inserts [33], [49], [50]. Based on the results obtained, the findings of this research are practical and hold significant

application potential in the injection molding industry, particularly during the mold design stage.

### 3.3 Result of Molded Part Testing and Measurement

The analysis results based on experimental work and the test of the molded part produced from MEC mold insert compared to P20 mold insert. The test performed on the mold part is a tensile strength test, measuring shrinkage and surface roughness.

#### Tensile Strength Result

Trapezium X software records raw data during the test procedure, which represents tensile strength and elongation results. The responses obtained during this test procedure are elongation and force, which are converted into values of tensile strength in various areas such as yield point, maximum strength, tensile modulus, and strain [51], [52], [53]. Based on the mold test, MEC mold insert cooled 50-70% slower than the P20 mold insert, hence increasing internal stress in the molded parts [48]. As a result, the tensile strength of the molded parts made from MEC molded inserts was higher (16%) than P20 molded parts and peaked at maximum tensile values between an average of 47.5 MPa and 40.8 MPa, respectively, as shown in Figure 18. These findings are consistent with earlier research [48], [54], which proved that the tensile strength of injection-molded part produced from cast resin mold inserts is 12% - 25% higher than that of steel mold inserts.

Elongation was three times higher for MEC molded parts than for P20 molded parts. Yield points were reached between 2.5% to 4% elongation for P20 mold inserts and 3.5% to 8.5% elongation for MEC mold inserts, respectively. All specimens broke after reaching the maximum elongation of their original length for both molded parts. Most specimens failed in the middle, while others failed in the neck. It is observed that this failure occurs at the location where there is a weld line defect due to the fusion of plastic melt from two directions. The result of this finding is in line with the findings of previous studies, which is that the effect of the weld line will weaken the strengthening of the product [42], [43]. It was also found that the speed at which the tension test is performed influences the results obtained and the selection of the correct speed according to the ATSM standard allows failure to break in weak places throughout the specimen tested [38], [48], [55]. Figure 19 and Figure 20 show cracks in the middle and neck area of the molded parts produced using MEC mold inserts and P20 Mold inserts.

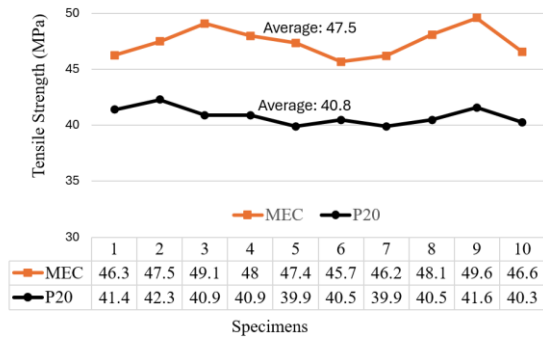


Figure 18 Tensile strength results of molded part



Figure 19 Tensile strength specimen failure area for MEC molded part

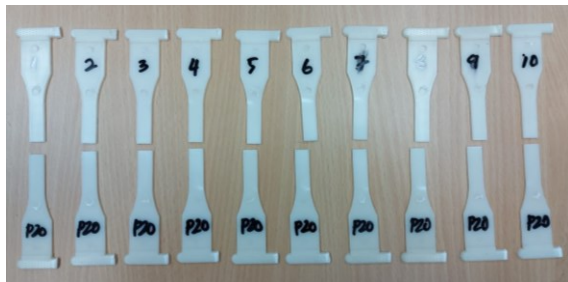


Figure 20 Tensile strength specimen failure area for P20 molded part

**Shrinkage Measurement**

The graphs plotted in Figure 21 and Figure 22 show that the percentage of shrinkage in both directions on the molded part for the P20 mold insert is better and consistent compared to the mold part from the MEC mold insert. It is known that injection mold shrinkage is mainly controlled by heat and pressure during the molding process [46], [56]. The results obtained are similar to the case of [34], which indicate that when using epoxy molding blocks, the holding pressure used is lower and the slow heat transfer in the epoxy mold results in greater shrinkage.

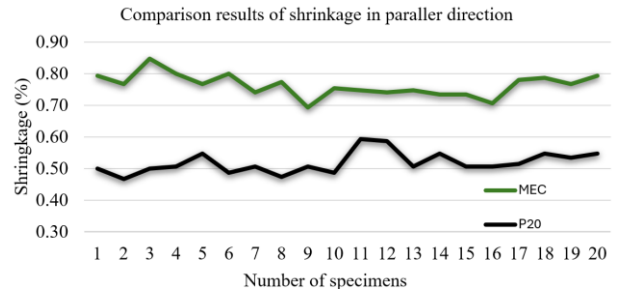


Figure 21 Comparison of shrinkage results in the parallel direction of the molded part from MEC and P20 mold inserts

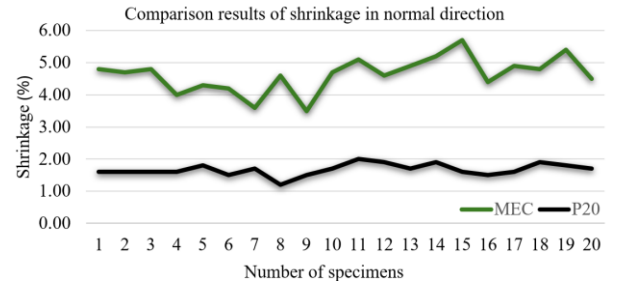


Figure 22 Comparison of shrinkage results in the normal direction of the molded part from MEC and P20 mold inserts

**Surface Roughness**

The surface roughness reading obtained from the MEC and P20 mold inserts on the surface of the molded part is shown in Table 6. According to the results, P20 has a lower roughness value of Ra: 0.191 μm when compared to the MEC mold insert, Ra: 1.249μm (casting surface), and Ra: 2.251μm (machine surface). Meanwhile, for the injection molded part from the MEC mold insert surface, the surface roughness value from the casting process is slightly better than the value from the machining process. The surface roughness of the molded part is dependent on the surface roughness of the mold cavity itself, where the two surfaces are in contact with each other. The extent of surface roughness on the MEC material's surface and the occurrence of porosity in the epoxy matrix are both impacted using fillers with a high composition [35], [57].

Table 6 Average surface roughness values from molded part

Mold Inserts	Molded part surface roughness Ra (μm)					Avg	
	S1	S2	S3	S4	S5		
MEC	Casting surface	1.56	1.49	0.90	1.27	1.01	1.24
	Machining surface	1.98	2.56	2.30	2.10	2.30	2.25
P20		0.17	0.21	0.16	0.19	0.20	0.19

### Summary of Mechanical Tests for Molded Parts

Molded parts from MEC mold inserts show a higher tensile strength of about 16% compared to parts from P20 molds. The elongation of the molded part from the MEC insert also showed the same response, where it was three times that of the P20 molded part. There is a deficiency in the quality of parts injected using MEC material as a mold insert because it has low thermal conductivity and a low-pressure setting in the cavity compared to P20. This affects the cooling rate of the insert and changes the microstructure and physical properties of the molding process and part. Mold part quality is determined by dimensional accuracy, appearance condition, or strength according to management goals. In this research, the quality of parts injected with the P20 mold insert is better than that of the MEC mold insert. However, the value difference is insignificant and still lies within the acceptance region.

### 4.0 CONCLUSION OF RESEARCH

This research aims to fabricate MEC mold inserts using RT technique and analyze cooling time performance and mold part quality based on mechanical testing and shrinkage measurement. It also improves cooling time performance by using a straight cooling channel system embedded into the mold insert. This research also shows a reducing cooling time in the margin of error between simulation and experiment which is in the lower range than 10%. While the tensile strength specimens had slightly improved the tensile modulus and reduced elongation as compared to using P20 molded parts. The surface roughness of the MEC is influenced by the fabrication process. The fabrication process of MEC mold insert requires pouring block, and the design of pouring block is one of the important factors where it can save time for the secondary process, fabrication cost, the accuracy of the mold, and it can also reduce warping effect on the material during the curing process.

The MEC mold insert has been successfully tested in which the plastic specimen was injected 300 times for the tensile test, with no failure effects observed on the mold cavity. Failure of the MEC mold insert can occur during injection, possibly due to either a packing pressure rate that exceeds the compressive strength of the MEC material and also a high maximum temperature of the molded part. This investigation contributes to the body of knowledge by offering innovative ideas to improve the capabilities of alternative tooling fabrication methods. The proposed research findings will assist countless mold manufacturers and design businesses throughout the world, allowing mold inserts made of MEC material in product development, short-term batches, and customization.

Future work on MEC material may examine mold quality and performance for extending the mold life via continuing the investigation on fillers in the form of fibers, comparisons between spherical and irregular shapes will be conducted. This comparative analysis will focus on understanding how the morphology of fillers, whether spherical or irregular, affects the mechanical and thermal properties of the composite material and the resulting molded parts. Investigate the effect of injection molding on the structure of the mold by varying the types of thermoplastics such as acrylic, ABS, PC and PS as molten plastic materials that have different melting temperatures.

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### Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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