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Effects of Molding Parameters on MIM's Material Distribution using Numerical Simulation Method

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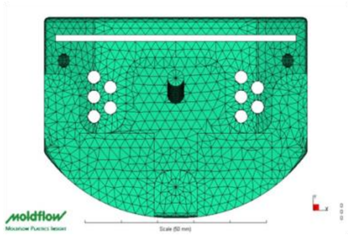
Graphical abstract



Abstract

In the competitive world in the global market, manufacturing industry is striving to produce products at high quality, shorter time and low cost. This can be achieved through proper design activities, with assist of finite element analysis (FEA) and computer aided design (CAD). The objective of this project is to study the effect of the molding parameters on the physical characteristics of surgery tool via MIM based on design of experiment (Taguchi method). This numerical results show the behavior of feedstock entering the mould during injection process and the possibility defects that might occur. The quality of the injected product depends on the selection of the feedstock as well as the parameters for injection molding such as injection temperature (A), mold temperature (B), flow rate (C) and injection pressure (D). From the analysis of Taguchi, the optimal levels of process parameters for the shortest filling time is [A_3(200ºC), B_1(80ºC), C_3(20 cm^3/s), D_3(260 MPa)]. Set of optimal parameters for the smallest shrinkage percentage difference is [A_1(180ºC), B_3(100ºC), C_3(20 cm^3/s), D_2(255 MPa)]. The most influence injection molding parameters are injection temperature and injection pressure. Follow by the flow rate.

Keywords: Design of experiment; numerical simulation; metal injection molding (MIM); physical properties

Abstrak

Dalam dunia pemasaran yang kompetatif, industri pembuatan berusaha untuk menghasilkan produk berkualiti tinggi dan cepat pada kos yang rendah. Ini boleh dicapai dengan aktiviti reka bentuk yang berkesan dengan bantuan analisa unsur tidak terhingga (FEA) dan reka bentuk terbantu berkomputer (CAD). Objektif projek ini adalah untuk mengkaji kesan parameter suntikan ke atas sifat fizikal alat pembedahan melalui MIM berdasarkan Reka bentuk Ujikaji (kaedah Taguchi). Keputusan berangka menunjukkan bagaimana bahan suapan memasuki acuan semasa proses penyuntikan dan juga kecacatan yang mungkin berlaku. Kualiti produk yang dihasilkan bergantung kepada pemilihan bahan suapan dan juga parameter-parameter penyuntikan acuan seperti suhu penyuntikan (A), suhu acuan (B), kadar alir (C), dan tekanan penyuntikan (D). Dengan analisis Taguchi, nilai optimum parameter-parameter untuk masa pengisian yang terpantas adalah [A_3(200ºC), B_1(80ºC), C_3(20 cm^3/s), D_3(260 MPa)]. Set parameter-parameter optimum untuk perbezaan peratus pengecutan terkecil adalah [A_1(180ºC), B_3(100ºC), C_3(20 cm^3/s), D_2(255 MPa)]. Parameter pengacuanan suntikan yang paling berpengaruh adalah suhu penyuntikan dan tekanan penyuntikan. Ini diikuti oleh kadar aliran.

Kata kunci: Pengacuanan suntikan logam (MIM); reka bentuk eksperimen; simulasi berangka; sifat-sifat fizikal

■1.0 INTRODUCTION

Metal Injection Molding process known as MIM is a manufacturing method that offers an alternative manufacturing process more cost effective for the commercial production of metal products in the form of complex and diverse. MIM technology is similar to a plastic mold injection process in which metal powders are blended with a binder to produce feedstock that can be injected using the same injection machines with the plastic mold injection process. Previous research found that optimization of the manufacturing process parameters based on try and error causes waste of material, cost and time [1]. Therefore, the objective of this project is to study effect of the molding parameters on the physical properties of surgery tool via MIM with Taguchi using numerical simulation. This technology is a suitable and costs effective to produce components which have small size, complex shape and in high precision in bulk quantity [2]. The higher the complexity of the mold geometry, the less reliable the predictions with conventional simulation tools are [3]. One of the common main drawbacks of all the programs is their lack of standard rheological models for powder filled feedstocks. In fact, most of the simulation tools use single phase models for the description of the feedstock [4] . This technology is used exclusively to produce vehicle components, equipment, petroleum refining, computer hardware, weapons, medical, surgical equipment and sports equipment [5], [6] . [7] using MoldFlow Plastic Insight to study the simulation of tungsten alloy in powder injection molding process. Design and economic limitations of traditional metalworking technologies, such as machining and casting, can be readily overcome by MIM. The process involves combining fine metal powders with plastic binders which allow the metal to be injected into a mould using equipment similar to standard plastic injection molding machines. Metal injection moulding (MIM) is divided into four major technological phases: mixing, injection moulding, debinding and sintering [8] . Powder metal with a certain size (µm) mixed with the binder as the particular composition to produce feedstock. Binder serves as a temporary vehicle to allow each particle powder metal is coated and mixed lubrication to ensure flow during the mixing process and during the molding process. Material feed shaped items then injected into the mold which you want to form a green part [9]. Palm stearin which is started developed by [10] was found to be a binder and successfully prepared the homogeneous feedstock. Research on palm stearin in MIM is still new and most of researchers mixing with stainless steel powder [10]. This paper attempts to inject the molded part of SS 316L powders mix with Palm stearin and polyethylene (PE) besides how to obtain defects free part. Defects that almost occur in MIM during injection process are weld lines, flashing, jetting and binder separation [11]. Therefore, optimization of the processing parameters is essential. Taguchi Design of Experiment (DOE) was used in this study to optimize the injection parameters and the experimental results are then transformed into a signal-to noise (S/N) ratio. Consequently, DOE for the injection parameter has been studied by [1] resulting a significant optimum injection parameter for MIM feedstock. Analysis of variance (ANOVA) also was used in this study to determine and rank the contribution factors which influence the quality characteristics. With the S/N ratio and ANOVA analyses, the optimal combination of the process parameters can be predicted. Therefore, with those information the objective is to study the effect of the molding parameters on the physical properties of surgery tool via MIM using Taguchi method can be optimised.

■2.0 MATERIALS AND METHODS

The feedstock used in this study consist of a the mixture of metal powder of stainless steel 316L and the binder consist of palm stearin and polyethylene (PE). The composition of the feedstock used in this study as shown in Table 1. The feedstock was then injected using Arburg Allrounder 850-210 320D injection molding machine.

Table 1 The composition of the metal powder and binder

Composition of the feedstock	**Metal Powder (65 %)**	**Binder (35 %)**	
	Stainless Steel SS 316L (size 10.21 µm)	Palm Stearin (60%)	Polyethylene (PE) (40%)

Moldflow Plastic Insight (MPI) 6.1 was used to simulate the flow of MIM feedstock within the mold cavity. Material feedstock used is of 65 % SS316L powder (size 10µm) and 35 % of binder (consisted of 60 % weight PS and 40 % PE). In lack of the material properties data, a substitute data model from MIM feedstock's properties characterized by Binet *et al*. (2005) is used as material input for the MPI simulation. It is believed that the closed similarity with our MIM feedstock composition can provide a reliable result on the preliminary study of the MIM filling inside the mold cavity. Products for MIM process are highly dependent on the properties of the feedstock [12]. Essential inputs material data for obtaining accurate result are: genetic algorithm (GA) fitted coefficients of PVT model and viscosity model, density and thermal conductivity.

In this study, four injection molding process parameters were investigated i.e., injection temperature, mold temperature, flow rate and injection pressure. Taguchi's orthogonal arrays (OA) of L_9 are used in this study and they consist of the ranges of MIM process parameters based on three-level and four different factors design of experiments as shown in Table 2. Physical defects of the short shot, weld lines, air trap, sink marks and warpage were the quality characteristics which to be investigated.

Table 2 Injection parameters for three levels of Taguchi Design

Factor	**Parameter**	**Level 1 (–)**	**Level 2 (0)**	**Level 3 (+)**
A	Injection Temperature (ºC)	180	190	200
B	Mold Temperature (ºC)	80	90	100
C	Flow Rate (cm^3/s)	10	15	20
D	Injection Pressure (MPa)	250	255	260

■3.0 RESULTS AND DISCUSSIONS

Initially, the cutting jig 3D model volume was scaled 14.5 % larger due to nominal shrinkage value from green compact to finished sintered part [13]. The mesh model was built from 82802 of the 3D tetrahedral elements and has 15258 nodes. Global edge length is 2.9 mm and chord height control is 0.1 mm. 3D meshing was used because it represents a true entity model that provides us an insight of the simulated process.

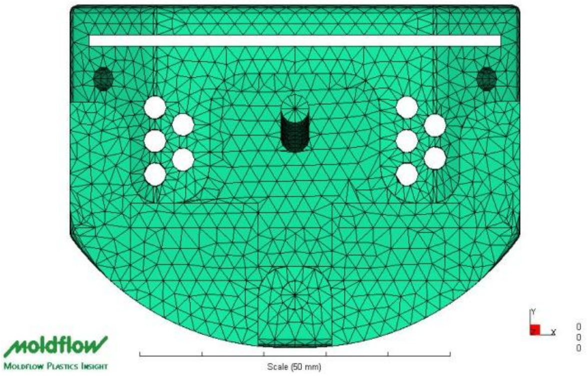


Figure 1 3D Model of Cutting Jig (Model of the 3D tetrahedral meshed cutting jig

MPI simulation was repeated with data conversion process parameters to obtain reasonable and satisfactory results and no short shots occurred. The method of trial and error is done to find a suitable range of process parameters. Most of the initial trial simulations produce a short shot. So the higher the injection pressure tried to alleviate them. Injection temperature variation is not recommended because it can affect the material properties and the very high injection temperature will also cause degradation with a polymer binder of low melting point. The simulation results and minimum number of gates needed only one injection site and its location marked with a yellow cone, are shown in Figure 2.

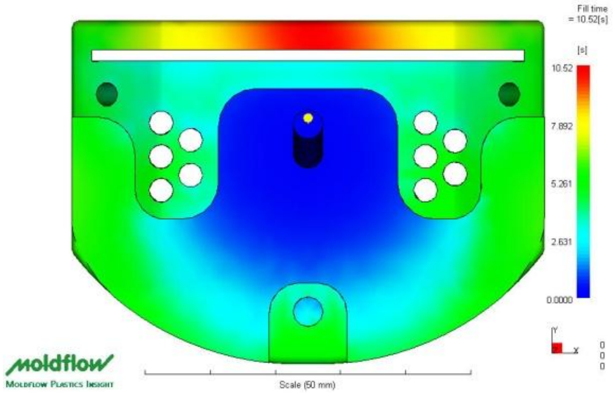


Figure 2 Perfect simulation results and injection gate locations of cutting jig

Figure 3 shows the main effects plot for the S/N ratio for fill time. The main effect plot shown in Figure 3 indicates that the highest point is the optimum parameter for each factor. Initially, without considering any interactions Figure 3 indicates A_3, B_1, C_3 and D_3 as the optimum. From the analysis of Taguchi, the optimal levels of process parameters for the shortest filling time is (A_3, B_1, C_3, D_3), an injection temperature of 200 ºC, mold temperature 80 ºC, flow rate 20 cm^3/s and 260 MPa injection pressure. High injection pressure needed to overcome the resistance due to a thinner flow path [14].

Figure 4 shows the main effects plot for the S/N ratio for bulk temperature difference. The main effect plot shown in Figure 4 indicates that the highest point is the optimum parameter for each factor. Initially, without considering any interactions Figure 4 indicates A_1, B_1, C_3 and D_3 as the optimum. From the analysis of Taguchi, the optimal levels of process parameters for the smallest bulk temperature difference is (A_1,B_1,C_3,D_3), the injection temperature of 180 ºC, mold temperature of 80 ºC, flow rate of 20 cm^3/s and injection pressure of 260 MPa.

Figure 5 shows the main effects plot for the S/N ratio for shrinkage percentage difference. The main effect plot shown in Figure 5 indicates that the highest point is the optimum parameter for each factor. Initially, without considering any interactions Figure 5 indicates A_1, B_3, C_3 and D_2 as the optimum. The results for shrinkage variation, set of optimal parameters for the smallest shrinkage percentage difference is (A_1, B_3, C_3, D_2), which the injection temperature of 180 ºC, mold temperature of 100 ºC, flow rate of 20 cm^3/s and injection pressure of 255 MPa.

Figure 6 shows the main effects plot for the S/N ratio for sink marks index. The main effect plot shown in Figure 6 indicates that the highest point is the optimum parameter for each factor. Initially, without considering any interactions Figure 6.0 indicates A_1, B_3, C_3 and D_3 as the optimum. Sink marks index differences are analyzed to determine the uniformity distribution of the mold and Taguchi analysis results provide a set of optimal parameters for the difference in **THE SMALLEST SINK MARKS INDEX IS (A1, B3, C3, D3), WHICH THE INJECTION TEMPERATURE OF 180 °C,** mold temperature of 100 ºC, flow rate of 20 cm^3/s and injection pressure of 260 MPa.

3.1 Analysis of Variance (ANOVA)

The purpose of this ANOVA analysis is to determine the parameters of the act significantly on the quality effect. ANOVA provides effective measurements, the standard estimate for the impact factor and the standard error of prediction. ANOVA did not measure the data directly, but to establish standards and data about the desired output. ANOVA test methods for determining the distribution of variations of significant parameters for each response studied. In this study, the confidence level used was 95 %. If the P value is smaller than 0.05, then it is considered as significant factor. In addition, the level of influence of each significant factor can be determined by looking at the value of F-test is the value of the parameter a larger factor. ANOVA results for each response are summarized in Table 3 until Table 5.

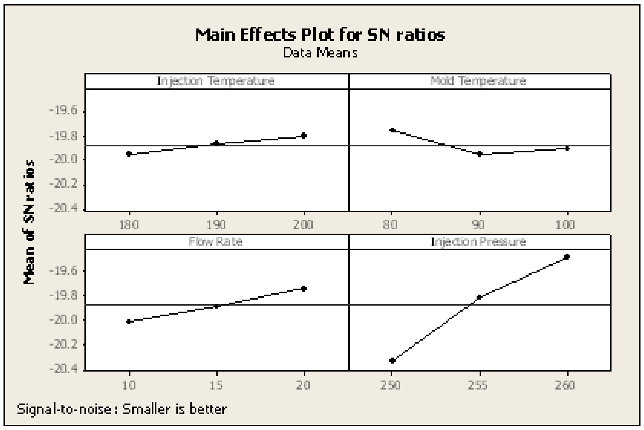


Figure 3 Main effects plot for the S/N ratio for fill time

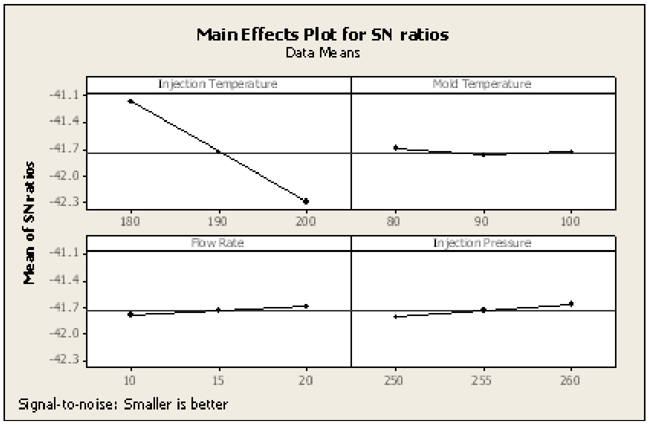


Figure 4 Main effects plot for the S/N ratio for bulk temperature difference

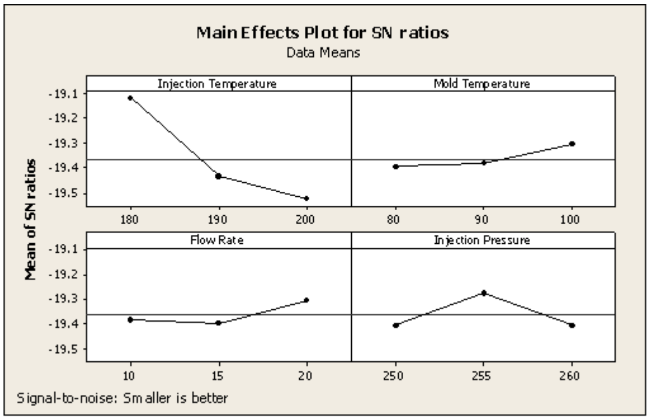


Figure 5 Main effects plot for the S/N ratio for shrinkage percentage difference

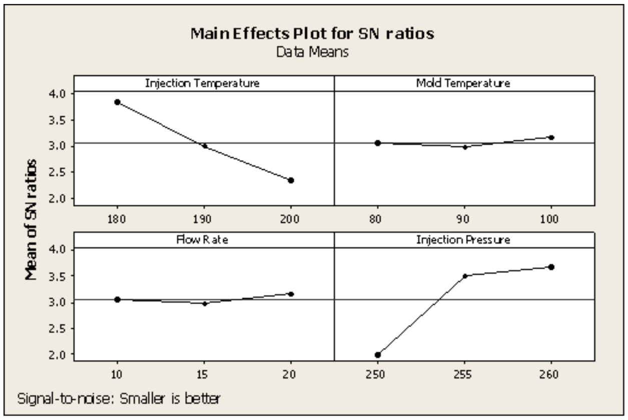


Figure 6 Main effects plot for the S/N ratio for sink marks index

Table 3 ANOVA results for fill time

Source	**Degree of Freedom**	**Sum of Square**	**Mean Square**	***F***	***P***
Injection Temp.	1	0.04824	0.04824	3.45	0.137
Mold Temp.	1	0.04167	0.04167	2.98	0.159
Flow Rate	1	0.14602	0.14602	10.45	0.032
Injection Pressure	1	1.43668	1.43668	102.82	0.001
Error	4	0.05589	0.01397		
Total	8	1.72850			

Table 4 ANOVA results for difference in bulk temperature

Source	**Degree of Freedom**	**Sum of Square**	**Mean Square**	***F***	***P***
Injection Temp.	1	380.010	380.010	912.03	0.000
Mold Temp.	1	0.528	0.528	1.27	0.323
Flow Rate	1	2.356	2.356	5.66	0.076
Injection Pressure	1	5.940	5.940	14.26	0.020
Error	4	1.667	0.417		
Total	8	390.502			

Table 5 ANOVA results for difference in volumetric shrinkage

Source	**Degree of Freedom**	**Sum of Square**	**Mean Square**	***F***	***P***
Injection Temp.	1	0.28506	0.28506	14.45	0.019
Mold Temp.	1	0.01404	0.01404	0.71	0.446
Flow Rate	1	0.00993	0.00993	0.50	0.517
Injection Pressure	1	0.00004	0.00004	0.00	0.967
Error	4	0.07891	0.01973		
Total	8	0.38797			

Table 6: ANOVA results for difference in sink index

Source	**Degree of Freedom**	**Sum of Square**	**Mean Square**	***F***	***P***
Injection Temp.	1	0.022302	0.022302	11.77	0.027
Mold Temp.	1	0.000004	0.000004	0.00	0.964
Flow Rate	1	0.000005	0.000005	0.00	0.960
Injection Pressure	1	0.029023	0.029023	15.32	0.017
Error	4	0.007577	0.001894		
Total	8	0.058911			

3.1.1 Fill Time

ANOVA analysis for the fill time response, it is found that there are two factors which parameters are significant with P value of flow rate is 0.032 and the injection pressure value P is 0.001. However, the influence of injection pressure is the dominant factor with value of F at 102.82 compared to the mold temperature is only 10.45. Mold filling with the MIM feedstock is dependent on viscous flow of the mixture into the cavity[11] . [9] report at the high flow rate, the feedstock will fill the cavity shortest than low flow rate.[9] also report that filling time is shortened at the high flow rate. Time and the injection pressure will determined the feedstock flow rate into the cavity, the higher injection pressure more easily feedstock move and fill the cavity. Longer injection time demand higher pressure to fill the cavity [8]. The factor contributing to high pressure is the complexity of the mold [1].

3.1.2 Difference in Bulk Temperature

Bulk temperature represents the flow of energy in the area. Area with continuous flow shows high specific energy content and its value dropped rapidly when the flow stops at a certain area (Binet *et al*. 2005). For the bulk temperature difference, there are three factors which parameters significantly influence the injection temperature, flow rate and injection pressure with the P value is 0.000, 0.076 and 0.020 respectively. However, injection temperature is the greater influence of the value of F at 912.03 against the injection pressure is valued at 14.26 and the flow rate is only worth 5.66. During the melt is injected into the mold, the temperature gradient between the mold and the melt is large and result in the flow loss of heat to quickly and freeze. Freezing and cooling too quickly will generate residual stresses in the body and cause cracks occur.

3.1.3 Difference in Volumetric Shrinkage

Shrinkage difference or variation needs to be predicted to improve the mold design so that tight tolerance at the particular functional area can be controlled. Even though the green compact will undergoes debinding and sintering before proceed to the final product, but the shrinkage variation need to be controlled at the minimal level so that warpage will not be occurred as result of product non-uniform shrinkage. In the case of the shrinkage percentage difference, there is only one factor found to be significant parameters of the injection temperature to the value of P 0.019 and the value of F at 14.45. Other factors had no significant influence because the P value is greater than 0.05.

3.1.4 Difference in Sink Index

Sink mark is another quality prediction factor and its measurement value is in the sink mark index percentage. Sink mark usually occur in areas of thicker cross-section, or at the location opposite to the ribs and internal fillet. However, the occurrence of sink mark can be improved by a longer packing time. Because the thickness of the cutting jig products is high, the impact of sink mark should be reviewed even though the sink mark does not influence the strength of the product. Sink index differences are analyzed to determine the uniformity distribution of the mold. In ANOVA study for sink index difference, parameter factors that found to be significant are the injection temperature and the injection pressure to give a significant influence with their P values were 0.027 and 0.017 respectively. However, the injection pressure showed a greater influence to the value of F at 15.32 compared to the injection temperature is only 11.77. To prevent sink mark occurs, the temperature parameter to be controlled carefully [6].

In outward, from Taguchi and ANOVA analysis of each response is a set of optimum parameters vary, this is equivalent with a study conducted by Jamaluddin [1]. From this study, found the optimum parameters that affect the process of injection molding in the range of the parameter set is a factor of injection temperature and injection pressure. Injection temperature and injection pressure are two parameters which have an enormous influence on the MIM process is equivalent to the results by Mohamad *et al*. (2011) and Jamaluddin *et al*. (2008).

■4.0 CONCLUSION

The simulation of the MIM process, performed with commercial FEM software, has allowed welling predicting the material flow of the molded part. The good agreement between numerical and simulation results have been obtained in all steps of the filling progression from both qualitative and quantitative points of view.. Through Taguchi and ANOVA method, the effect and optimization of process parameter parameters in injection molding of SS 316L powder and binders of PS and PE to produce the quality of green part were successfully investigated. The optimization of process parameters through the factor experimental designs has been identified. For example, the optimal levels of process parameters for the shortest filling time is [A_3(200ºC), B_1(80ºC), C_3(20 cm^3/s), D_3(260 MPa)]. Based on ANOVA results, the most influence molding parameters on the physical properties are injection temperature and injection pressure. This is followed by the flow rate. Injection temperature and injection pressure is significant because of the feedstock's flow properties is controlled and determined by these parameters. The mold temperature is a factor in the least affects the MIM process in the production of cutting jig. Further research need to be carried out to make a comparison between experimental and simulated data for physical and mechanical properties of molded parts.

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