OPTIMIZATION OF COMPRESSION MOULDING PARAMETERS ON MECHANICAL PROPERTIES OF STAINLESS STEEL 316L

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ABSTRACT: Compression moulding is one of the forming processes for metal powder compounded with thermoplastic materials. The compounded materials feed directly into a heated mould and compressed to form a final product. Recently, compression moulding process has received more attention due to the cost effectiveness as compared to the expensive forming processes such as injection moulding and isostatic pressing. This article focuses on the optimization compression moulding parameters on mechanical properties such as ultimate tensile strength, elastic modulus and percentage of elongation. The parameters of compression moulding selected are mould temperature, weight of material and pre-heat time. Taguchi method with L4 orthogonal array was implemented in this experiment. After optimization, it was found that the weight of material is the most significant parameter on the ultimate tensile strength and elastic modulus. Meanwhile, preheat time is the most significant for percentage of elongation. It was shown that mould temperature was not significant parameter for this experiment. Thus, the weight of material and preheat time are the most important parameters affected the mechanical properties of stainless steel 316L.

KEYWORDS: *Compression Moulding; Mechanical Properties; Optimization; Taguchi Method; Stainless Steel 316L*

1.0 INTRODUCTION

Compression moulding is a moulding technique in which a feeding material is placed into heated mould. Hydraulic press is used to press upper mould for molten material reaches every part of the mould. The material solidifies in the heated mould, and shaped into final product. The most typical materials used in compression moulding are compounded metal powder materials, glass mat thermoplastic materials, sheet moulding and rubber materials. The compounded metal powder used in metal injection moulding that is stainless steel 316L (SS316L) has been widely utilized in a variety of applications especially in the medical industries [1].

However, the investigation of the production of metal powder using compression moulding is not discussed widely despite of having a lower tooling cost without having sprue, runner and gate that can consume extra material like injection moulding process [2]. In term of parameters selection, mould temperature is the most selected parameter in the compression moulding process compared to other parameters such as compression pressure, compression time, preheat time and weight of material [3]. In compression moulding, investigations of mechanical properties are widely conducted especially on composite materials. For example. Edynoor et al. [4] studied the performance of kenaf fibre/epoxy reinforced aluminium laminates using compression moulding process.

In addition, Akhtar et al. [5] investigated the effects of the moulding temperature especially on the mechanical properties of MWCNT/NG/EP composites. As the moulding temperature increases, the elongation has increased. However, the elongation behaviour of the composite started to decrease at a heating temperature of 150°C. This response could be explained by the stability of the binder at higher temperatures. In addition, they also found that there was a significant decrease in the mechanical properties such as elastic modulus and flexural strength with increasing temperature from 25°C to 100°C.

Although the compression moulding process is widely used in the processing of composite materials, reports on the mechanical properties of the metallic material SS316L are still limited. Thus, this study aims to characterise the mechanical properties of the metallic material SS316L. This compression moulding process has been carried out to produce metallic material of SS316l compared to conventional manufacturing processes such as casting, forging, and machining. The findings from this study indicate the potential for the production of metallic material SS316L for the use of medical implant components.

2.0 MATERIAL AND METHODS

2.1 Preparation of Tensile Test Samples

Compression moulding approach consist of new material SS316L was performed in this study. The SS316L with multi-component binders feedstock was provided by Industrial Centre of Innovation in Biomedical SIRIM Berhad. The material was compressed using a hydraulic hot press Carver 4128 in a mould with a dimension (110 x 50 x 5) mm. After the compression, sample was kept in room temperature for 30min and finally the sample was removed from the mould.

Debinding was carried out in two steps. First step, the solvent debinding was performed by immersing the compressed sample in n-Heptane and heated in a water bath for 6 hours at 60°C to remove the major component of the binder. The sample was subsequently dried in a dry oven for several hours. Second step, the thermal debinding and sintering process have been combined and performed in a High Temperature Control Atmosphere Furnace. The thermal debinding occurred when the samples were heated from 30°C to 500°C followed by the sintering process at a temperature from 500°C until 1360°C. Figure 1 shows the sample before and after the sintering process and all samples were measured using a digital vernier caliper (Mitutoyo). From Figure 1(a), it clearly shows that green part of SS316L having 110mm in length. After the sintering process, the length decreases to 96mm as shown on Figure 1(b). Meanwhile, green part SS316L having 50mm in width as shown in Figure 1(a). After sintering process, the width decreases to 44mm as shown in Figure 1(b).

(a) (b)

Figure 1: Conditions of SS 316L samples (a) before sintering and (b) after sintering

In order to perform tensile testing, the sample was cut into a dumbbell-shaped according to ASTM E8M using wire-cut EDM machine Mitsubishi RA90. Tensile testing was performed on dumbbell-shaped specimens using tensile machine at a crosshead speed of 1mm/min using Universal Testing Machine 50kN (Instron). Mechanical properties were determined from three replicates for each sample and the specimen with a gauge length of 25mm.

2.2 Design of Experimental Method

Taguchi method was implemented as design experimental method. Two-level designs which low level and high level for experimental runs have been performed. Table 1 shows the three process parameters settings at two levels for the experiment. The selection of process parameter for mould temperature from 230°C to 290°C, weight of material from 110g to 134g and preheat time from 3min to 7min according from previous research [3]. Furthermore, Table 2 shows the design of experimental matrix that consists of the total four runs that was generated using statistical software.

Table 1: Process parameters of three factors with two level settings

Model	Level	
	Low	High
mould temperature (°C)	230	290
weight of material (g)	110	134
preheat time (min)	3	7

Generally, Taguchi method employs a special design of orthogonal array (OA) to learn the whole parameters space with a small number of experiments only. Some of most common orthogonal arrays (OA) are L4, L9, L12, L18 and L27. Furthermore, Taguchi method uses the signal-to-noise (S/N) ratio to qualify the quality characteristic deviating from the desired value. Basically, there are three objective functions for calculating the S/N ratio in the Taguchi method, which are smaller-is-better, larger-is-better and nominal-is-the-best. Since, the current research work focuses on maximizing the mechanical properties, the S/N ratio with larger-is-better characteristic was used to evaluate the quality characteristic using Equation 1 [6].

$$\frac{S}{N} = -10\ log_{10}\left[\frac{1}{N}\sum\frac{1}{y_1^2}\right] \quad (1)$$

where N is the total number of replications of each test run and yi is the response value in replication experiment ‘i’ carried out under the same experimental conditions for each test run. In addition, analysis of variance (ANOVA) was utilised as a statistical tool in the Taguchi method. The percent contribution of parameters affecting the response was investigated using this technique [7].

Table 2: Experimental result

Run	Parameters			Responses		
	Mould temperature (°C)	Weight of material (g)	Preheat time (min)	Ultimate tensile strength (MPa)	Elastic modulus (GPa)	Percentage of elongation (%)
1	230	110	3	95.19	39.30	1.08
2	230	134	7	157.34	44.97	2.36
3	290	110	7	120.05	43.91	1.88
4	290	134	3	120.30	44.36	1.74

3.0 RESULTS AND DISCUSSION

The three responses were investigated; ultimate tensile strength, elastic modulus, and percentage of elongation. The Taguchi method, the S/N ratio, and analysis of variance (ANOVA) are used to investigate the mechanical characteristics. The S/N ratio in Taguchi method measures the quality sensitivity to uncontrollable factors or error in the experiment. A higher S/N ratio is always preferable since a lower S/N ratio means a smaller product variance around the target value.

3.1 Ultimate Tensile Strength

In S/N ratio for the ultimate tensile strength, the larger the better characteristic arrangement was selected. Table 3 shows the corresponding S/N ratio after generated from the statistical software. The response table of S/N ratio for all parameters at different levels is shown in Table 4. From the table, the ultimate tensile strength is mostly influenced by the weight of material. Then it is followed by preheat time and mould temperature. From the ultimate tensile strength result, it can be seen that sample run number 2 can withstand more maximum stress which ultimate tensile strength with 157.34MPa before breaking compared to sample run number 1 (95.19MPa), run number 3 (120.05MPa), and run number 4 (120.30MPa).

Table 3: S/N ratio for ultimate tensile strength

Run	Mould temperature (°C)	Weight of material (g)	Preheat time (min)	Ultimate tensile strength (MPa)	S/N ratio
1	230	110	3	95.19	39.572
2	230	134	7	157.34	43.937
3	290	110	7	120.05	41.587
4	290	134	3	120.30	41.605

Table 4: Response table of S/N ratio for ultimate tensile strength

Level	Mould temperature (°C)	Weight of material (g)	Preheat time (min)
1	41.75	40.58	40.59
2	41.60	42.77	42.76
delta	0.16	2.19	2.17
rank	3	1	2

Graph of S/N ratio for ultimate tensile strength is presented in Figure 2. From the graph, the objective to find optimum parameters of ultimate tensile strength was achieved by combination for mould temperature at 230°C, weight of material at 134g, and preheat time at 7min. In Taguchi result, the highest mean of S/N ratio is selected as the optimum parameters as shown in Figure 2.

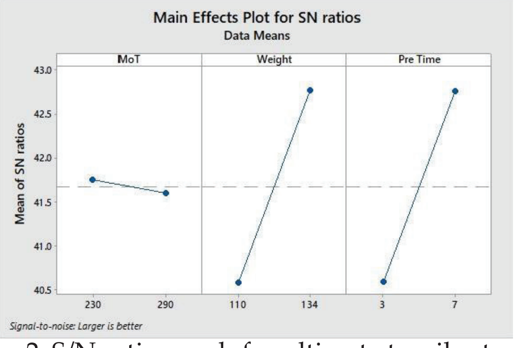

Figure 2: S/N ratio graph for ultimate tensile strength

The optimum parameters were taken from S/N ratio graph in Figure 2 which mould temperature 230°C, weight of material 134g and preheat time 7min. The experimental test was performed to find the value ultimate tensile strength and it was found that the value of ultimate tensile strength was 157.55MPa which was 0.13% different from run number 2. The ANOVA result is represented in Table 5. From the table, the weight of material has the highest percentage of contribution with 49.45% followed by preheat time 48.66% and mould temperature 1.88%. From the analysis result, the mould temperature shows less significant to the ultimate tensile strength where the weight of material and preheat time are dominant to the ultimate tensile strength result. The weight of material and preheat time were significant due to the homogeneity of the molten polymer to bind the metal powders and the compaction of compounding resulting metal powder particles near to each other. During the diffusion process taking place of the compact compounding, diminish the pores resulting in densification of the part improving the ultimate tensile strength. The result found by Selamat et al. [8] has considered temperature, pressure, preheat duration and compression duration to optimize tensile strength. They implemented the Taguchi method and successfully obtained larger values of tensile strength with combination of high pressure, long preheat and compression time.

Table 5: ANOVA result for ultimate tensile strength

Parameters	DOF	Sum of squares	Percentage of contribution (%)
mould temperature(°C)	2	37.09	1.88
weight of material (g)	2	973.4	49.45
preheat time (min)	2	957.9	48.66
error	0		
total	6	1968.4	100

3.2 Elastic Modulus

In S/N ratio for elastic modulus, the larger the better characteristic arrangement was selected. Table 6 shows the corresponding S/N ratio after generated from the statistical software. The response table of S/N ratio for all parameters at different levels is shown in Table 7. From the table, elastic modulus is mostly influenced by the weight of material. Then it is followed by preheat time and mould temperature. From the elastic modulus result, it can be seen that sample run number 2 (44.97GPa) has the highest stiffness compared to sample run number 1 (39.30GPa), run number 3 (43.91GPa), and run number 4 (44.36GPa).

Table 6: S/N ratio for elastic modulus

Run	Mould temperature (°C)	Weight of material (g)	Preheat time (min)	Elastic modulus (GPa)	S/N ratio
1	230	110	3	39.30	31.888
2	230	134	7	44.97	33.059
3	290	110	7	43.91	32.851
4	290	134	3	44.36	32.940

Table 7: Response table of S/N ratio for elastic modulus

Level	Mould temperature (°C)	Weight of material (g)	Preheat time (min)
1	32.47	32.37	32.41
2	32.90	33.00	32.95
delta	0.42	0.63	0.54
rank	3	1	2

Graph of S/N ratio for elastic modulus is presented in Figure 3. From the graph, the objective to find optimum parameters of elastic modulus was achieved by combination for mould temperature at 290°C, weight of material at 134g, and preheat time at 7min.

Figure 3: S/N ratio graph for elastic modulus

Optimum parameters on S/N ratio graph shows that mould temperature 290°C, weight of material 134g, and preheat time 7min were not similar which that were set in the experimental run. The experimental test of elastic modulus was performed and found that the result of elastic modulus was 46.97 MPa which higher 4.26% from experimental run number 2. It shows that the maximum combination all parameters increase the elastic modulus. The ANOVA result is represented in Table 8. From the table, the weight of material has the highest percentage of contribution to 46.41% followed by preheat time 33.76% and mould temperature 19.83%. Based on the analysis result, it is found that the mould temperature also shows less significant to elastic modulus and the weight of material and preheat time are dominant to elastic modulus. This similar result was also found by Yu et al. [9] where the increase of heat and volume of compound plays as important role to improve the mechanical properties.

Table 8: ANOVA result for elastic modulus

Parameters	DOF	Sum of squares	Percentage of contribution (%)
mould temperature(°C)	2	4.000	19.83
weight of material (g)	2	9.364	46.41
preheat time (min)	2	6.812	33.76
error	0		
total	6	20.176	100

3.3 Percentage of Elongation

In S/N ratio for the percentage of elongation, the larger the better characteristic arrangement is selected. Table 9 shows the corresponding S/N ratio after generated from the statistical software. The response table of S/N ratio for all parameters at different levels is shown in Table 10. From the table, the percentage of elongation is mostly influenced by the preheat time. Then it is followed by the weight of the material and mould temperature. From the percentage of elongation result, it can be seen that sample run number 2 (2.36%) also has the highest ductility when compared to sample run number 1 (1.08%), run number 3 (1.88%), and run number 4 (1.74%).

Table 9: S/N ratio for percentage of elongation

Run	Mould temperature (°C)	Weight of material (g)	Preheat time (min)	Percentage of elongation (%)	S/N ratio
1	230	110	3	1.08	0.6685
2	230	134	7	2.36	7.4582
3	290	110	7	1.88	5.4832
4	290	134	3	1.74	4.8110

Table 10: Response table of S/N ratio for percentage of elongation

Level	Mould temperature (°C)	Weight of material (g)	Preheat time (min)
1	4.063	3.076	2.740
2	5.147	6.135	6.471
delta	1.084	3.059	3.731
rank	3	2	1

Graph of S/N ratio for percentage of elongation is presented in Figure 4. From the graph, the objective to find optimum parameters of percentage of elongation was achieved by combination for mould temperature at 290°C, weight of material at 134g, and preheat time at 7min.

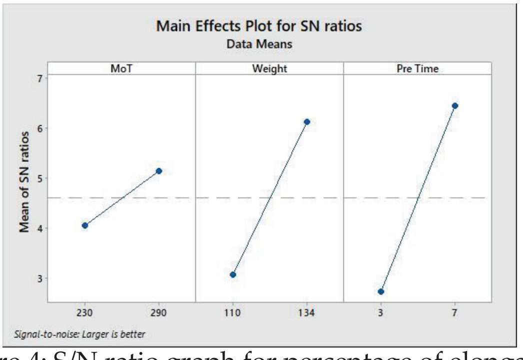

Figure 4: S/N ratio graph for percentage of elongation

The optimum parameters from the S/N ratio graph shows that mould temperature 290°C, weight of material 134g, and preheat time 7min. After validation process the percentage of elongation found was 2.45%. The percentage of elongation increases by 3.81% from 2.36% at run number 2 to 2.45% after implemented the optimization parameters. The increase of the parameters as result increases the percentage of elongation due to the compressibility and flow properties of the metal powders during compression process [10]. Table 11 shows that preheat time has the highest percentage of contribution with 60.22% followed by weight of material 38.81% and mould temperature 0.97%. From the analysis result, the mould temperature also shows less significant to the percentage of elongation where the preheat time and weight of material are dominant to the percentage of elongation result. The preheat time was dominant due to the homogeneity of the molten polymer to bind the metal powders. The result is similar as conducted by Wang et al. [11] where they have studied the main factors affecting the mechanical properties of the composite structure by considering the hot air temperature, preheating time, moulding pressure, and pressing holding time as their parameters during sheet preheating.

Table 11: ANOVA result for percentage of elongation

Parameters	DOF	Sum of squares	Percentage of contribution (%)
mould temperature(°C)	2	0.00810	0.97
weight of material (g)	2	0.3249	38.81
preheat time (min)	2	0.5041	60.22
error	0		
total	6	0.83710	100

In this study, the characteristic mode selection using larger-is-better for ultimate tensile strength, elastic modulus and percentage of elongation shows that the importance of the strength of materials. SS316L that widely used in the MIM fabrication of biocompatible metals as implant devices such as wires, sutures, wire mesh, cardiac pacemaker housing and more as reported by Hamidi et al. [12] has a low cost compared to other biocompatible metals. However, the fabrication of biocompatible metals became restricted because of complex design geometry, high cost of raw materials as well as the waste of material resulting from the unused feed system in MIM. Alternatively, compression moulding process could reduce the production costs due to its simpler process and more suitable process to produce of small parts. In the future, the advantage of using compression moulding process could help minimising the cost and it also has the ability to manufacture in a small quantity at very competitive cost compared to the other technique.

4.0 CONCLUSION

In this article, the optimization of compression moulding parameters such as mould temperature, weight of material, and preheat time on mechanical properties of SS316L using Taguchi method was studied. The weight of material was the most influential parameter for the ultimate strength and elastic modulus. Further, the most significant parameter for percentage of elongation was preheat time. In addition, after optimization process, the highest value of ultimate tensile strength was similar with run number two. Meanwhile, there was 4.26% improvement in elastic modulus and 3.81% for percentage elongation after the optimization process. It can be concluded that mould temperature parameter is less significant parameter as compared to the weight of materials and preheat time parameter.

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AUTHOR CONTRIBUTIONS

N.I.M. Ali: Investigation, Data Collection, Writing – Original Draft; M.A.M. Ali: Supervision, Data Curation; M.S. Salleh: Writing - Review & Editing; S. Subramonian: Methodology, Formal Analysis; M.I.H.C. Abdullah: Validation, Visualization; M. Yamaguchi: Project Administration.

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission and declare no conflict of interest on the manuscript.

REFERENCES

[1] P. J. Jol, A. M. Amin, M. H. I. Ibrahim, Z. W. Zhong and S. Shamsudin, "Debinding process of SS316L metal injection moulding under argon atmosphere", *Journal of Advanced Manufacturing Technology*, vol. 14, no. 2(2), pp. 259-276, 2020.

[2] M. A. M. Ali, N. Idayu, S. Sivaraos and M. Yamaguchi, "Optimization of injection machine parameters on high tensile strength of polypropylene/fibreglass", *Journal of Advanced Manufacturing Technology*, vol. 16, no. 3, pp. 69-80, 2022.

[3] N. I. M. Ali, M. A. M. Ali, S. Maidin, M. A. Sulaiman, M. S. Salleh and M. H. A. Bakar, "Review on experimental design, process parameters and responses of compression moulding process," in *Intelligent Manufacturing and Mechatronics SympoSIMM 2021*, 2022, pp. 407-414.

[4] O. Edynoor, A. R. M. Warikh, S. H. Yahaya and T. Moriga, "Study on performance of kenaf fibre/epoxy reinforced aluminium laminates (kerall) via compression moulding technique", *Journal of Advanced Manufacturing Technology,* vol. 14, no. 3, pp. 1-15, 202.

[5] M. N. Akhtar, A. B. Sulong, A. Umer, A. B. Yousaf and M. A. Khan, "Multi-component MWCNT/NG/EP-based bipolar plates with enhanced mechanical and electrical characteristics fabricated by compression moulding", *Ceramics International*, vol. 44, pp. 14457–14464, 2018.

[6] G. Boopathy, J. Udaya Prakash, K. Gurusami and J. V. Sai Prasanna Kumar, "Investigation on process parameters for injection moulding of nylon 6/SiC and nylon 6/B4C composites", *Materials Today: Proceedings*, vol. 52, pp. 1676–1681, 2022.

[7] N. Aini, I. Nasiruddin and M. Afian, "Determination of optimised solvent debinding parameters of injection moulded 316L stainless steel using Taguchi approach", *Materials Today: Proceedings*, vol. 16, pp. 2357–2366, 2019.

[8] M. Z. Selamat, A. N. Kasim, S. D. Malingam and M. A. M. Daud, "Optimization of compression molding parameters for pineapple leaf fiber reinforced polypropylene composites using Taguchi method," in *Proceedings of the 6th International Conference and Exhibition on Sustainable Energy and Advanced Materials*. Lecture Notes in Mechanical Engineering, Springer Singapore, 2020, pp. 129–140.

[9] M. Yu, H. Mao, R. Huang, Z. Ge, P. Tian, L. Sun, Q. Wu and K. Sun, "Mechanical and thermal properties of R-high density polyethylene composites reinforced with wheat straw particleboard dust and basalt fiber", *International Journal of Polymer Science*, vol. 2018, 2018.

[10] J. Hlosta, D. Žurovec, L. Jezerská and J. Zegzulka, "Effect of particle shape and size on the compressibility and bulk properties of powders in powder metallurgy," in *Proceedings 25th Anniversary International Conference on Metallurgy and Material*, Czech Republic, 2016, pp. 1394-1399.

[11] Y. Wang, X. Li and H. Sui, "Numerical investigation and mold optimization of the automobile coat rack compression molding", *Advances in Materials Science and Engineering*, vol. 2021, pp. 1-19, 2021.

[12] M. F. F. A. Hamidi, W. S. W. Harun, M. Samykano, S. A. C. Ghani, Z. Ghazalli, F. Ahmad and A. B. Sulong, "A review of biocompatible metal injection moulding process parameters for biomedical applications", *Materials Science and Engineering C*, vol. 78, pp. 1263–1276, 2017.