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Design And Fabrication Of Moulds Using Additive Manufacturing For Producing Silicone Rubber Products

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Abstract: This study explores the use of additive manufacturing (3D printing) for designing and fabricating moulds in silicone rubber product manufacturing. The research investigates the feasibility and effectiveness of utilizing additive manufacturing methods specifically tailored to silicone rubber materials. The study includes the design phase, where moulds are created using CAD software, considering factors like geometry, surface finish, and minimizing air entrapment. In the fabrication phase, moulds are produced using additive manufacturing techniques. The performance and quality of the moulds are evaluated through physical testing and compared to traditional mould fabrication methods. The results demonstrate the potential of additive manufacturing for producing high-quality silicone rubber products, offering advantages such as design flexibility, reduced lead times, and cost-effectiveness. Further improvement and optimization of the additive manufacturing process are identified as areas for future development.

Keywords: Design, Additive Manufacturing, Fabrication

1. Introduction

Additive manufacturing, also known as 3D printing, is a revolutionary technology that builds objects layer by layer using digital models. It offers design freedom, reduced waste, and rapid prototyping capabilities. Additive manufacturing allows for the creation of complex geometries and intricate structures, making it valuable in aerospace, medical, and automotive industries. It is more sustainable than traditional methods, as it minimizes material wastage. However, challenges remain in areas such as material selection, surface finish, dimensional accuracy, and production speed. Ongoing research aims to overcome these challenges and further expand the potential of additive manufacturing. Overall, additive manufacturing has the power to transform industries and drive innovation in manufacturing processes.[1]

This study focuses on utilizing additive manufacturing techniques to design and fabricate 3D-printed moulds using SolidWorks. The objectives include developing prototypes of the moulds using

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materials like ABS, PLA, and PETG, evaluating their mechanical properties, surface characteristics, and durability. Surface analysis will be conducted using scanning electron microscopes (SEM), and the Taguchi method will be employed for experimental design. Development Fused Deposition Modelling 3D-printed mould using material Acrylonitrile Butadiene Styrene (ABS), Polylactic acid (PLA) and Polyethylene terephthalate glycol (PETG) The study seeks to provide practical and innovative solutions for manufacturers, enabling them to produce high-quality silicone rubber products with improved operational efficiency, shorter lead times, and enhanced customization options.[2][3]

2. Materials and Methods

The seven steps of this study approach are as follows. These methods are what used in this study to get the outcomes for the straightforward design.

2.1 Materials

Scanning Electron Microscopes (SEMs) are advanced imaging tools that provide high-resolution surface analysis and characterization of materials. They utilize a focused electron beam to scan the sample surface, generating images and collecting data. SEMs offer magnifications ranging from a few times to several hundred thousand times, allowing for detailed examination of surface features. They provide information about surface topography, morphology, compositional variations.

Fused Deposition Modelling (FDM) is an additive manufacturing technology that uses thermoplastic materials to build three-dimensional objects. It involves melting and extruding a filament layer by layer to create the desired object. FDM offers specifications such as layer thickness, build volume, print speed, and material options, which impact the quality and characteristics of the printed objects. It is a popular choice for prototyping, product development, and small-scale manufacturing due to its affordability, ease of use, and ability to create complex shapes.

Silicone rubber is a highly versatile elastomer known for its excellent temperature resistance, flexibility, and chemical resistance. It offers reliable electrical insulation, biocompatibility, and weather resistance. With customizable hardness levels and compliance with food grade standards, silicone rubber finds applications in various industries such as automotive, aerospace, electronics, medical, and consumer goods.

Table 1: L4 Taguchi Orthogonal Design

L4 Taguchi Orthogonal Design			
Experiment	**Layer Thickness (µm)**	**Curing Temperature (°C)**	**Curing Time (hours)**
1	50	120	¼
2	50	80	½
3	100	120	½
4	100	80	¼

2.2 Methods

Flow Chart for Design and Fabrication of Moulds:

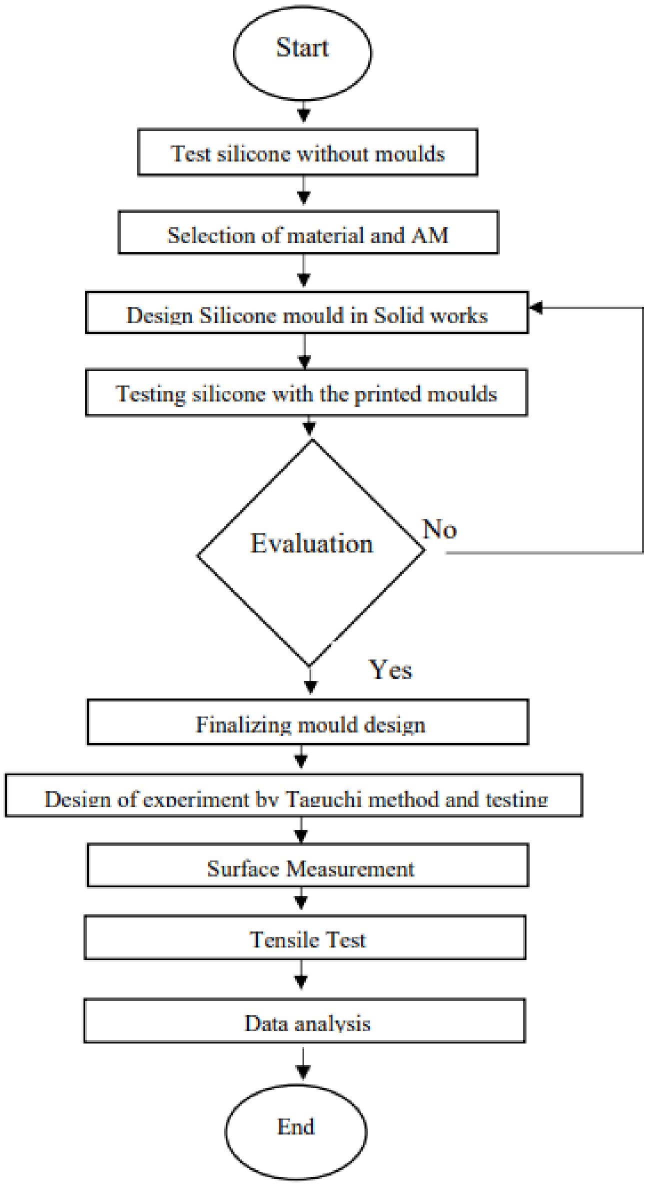


Figure 1: Flowchart for Design and Fabrication of Mould

2.3 Equations

Young modulus's formula;

$$E = \frac{\sigma}{\varepsilon}$$

E = Young's Modulus pressure unit
σ = Uniaxial stress or uniaxial force per unit surface
ε = Strain

3. Results and Discussion

The observations were made while conducting the experiments on various silicone samples made utilising the straightforward mould shape are highlighted in this section of the paper. This study has made use of the equipment found in the Material Science Lab, Rapid Manufacturing Lab, Nanostructure

Lab and Polymer Lab at University Tun Hussein Onn Malaysia, including lab ovens for curing silicone samples and 3D printers (SLA) for printing moulds. Took pictures of the silicone surface using a scanning electron microscope. The SEM software is used to create images of the silicone samples.

3.1 Step 1: Study Of The Material (Silicone Rubber)

In this study, silicone samples were cured at various temperatures to observe their behaviour under normal atmospheric pressure. The focus was on physical characteristics such as stickiness, deformation, removability from the surface, and the presence of trapped air bubbles. The results from Table 1.2 revealed that higher temperatures and longer curing times reduced stickiness and improved shape and structure. The samples were easier to remove from the surface, but an increased number of air bubbles were observed. These findings provided insights into the changes in silicone properties during curing without a mold. The next phase of the study involves testing the behavior of silicone rubber inside different 3D printed molds to further understand its characteristics.

Table 2: Observations from testing silicone rubber

Process variables		Observations				
Material for mould or sample		Silicone Rubber				
Temperature in °C		Set 1	Set 2			
		120	80	90	100	110
Time/ Layer Thickness		15 Min	½ Hour	½ Hour	½ Hour	½ Hour
Number of trials		1	2	3	4	5
Stickiness	Very	✓				
	Moderate		✓	✓	✓	
	Not					✓
Deformation	Moderated	✓	✓			
	Structured			✓	✓	✓
Removability	Easy		✓	✓	✓	✓
	Difficult	✓				
Air bubbles	Less					
	Moderate	✓				
	High/ Many		✓	✓	✓	✓

3.2 Step 2: Selection of Material And Am Process

Figure 2: Basic for Design and Fabrication of Moulds

In this study, it was observed that the two materials previously tested were not able to withstand the high temperature required for curing. As a result, the decision was made to use Tenlog 3D printers and PLA material for creating the mould. The PLA printing settings were determined and the mould design was produced using Solidwork software, with specific dimensions for the cavity. This approach aims to overcome the temperature limitations of the previous materials and provide a suitable solution for the mould fabrication process.

Figure 3: PLA mould Design 1

The mould displays a poor surface smoothness using the same printing parameters that used to print simple patterns. Desire the PLA printing to have a high surface polish. Conducted testing using the same mould. Figure 1.7 show the mould cavity that has 44mm diameter and 18.5 height. The samples that were collected had a very rough surface texture, and there were numerous air bubbles lodged in the silicone rubber. Therefore, made the decision to using PLA material when using FDM to manufacture the moulds. The below table 3 shows the observations captured of curing of silicone sample with the basic design of the moulds with the different materials like PLA, ABS and PETG.

Table 3: Observation from different mould

Product Material		Sillicone Rubber				
Material for mould or sample		PETG	ABS	PLA		
Trials		Set 1	Set 2	Set 3	Set 4	Set 5
Temperature in °C		120	120	120	120	80
Time/ Layer Thickness		½ Hour	½ Hour	½ Hour	15 Min	½ Hour
Stickiness	Very	✓	✓			
	Moderate					
	Not			✓	✓	✓
Deformation	Moderated	✓	✓			
	Structured			✓	✓	✓
Removability	Easy			✓	✓	✓
	Difficult	✓	✓			
Air bubbles	Less			✓	✓	✓
	Moderate		✓			
	High/ Many	✓				

3.3 Step 3: Finalizing Mould Design

In this step of the study, the focus was on creating a stable mould design through a process of trial and error. Design 1 was initially created, but during testing, it was observed that the moulds deformed due to several factors. These factors included the thin walls of the mould, the thermal expansion of silicone during the curing process, and a lack of rigid supports between the bottom base and top cap of the mould. Based on these observations, it was concluded that Design 1 needed to be improved to address these issues and ensure a more stable mould design.

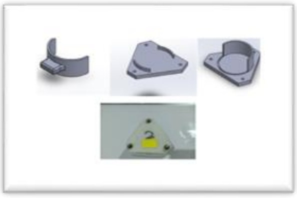
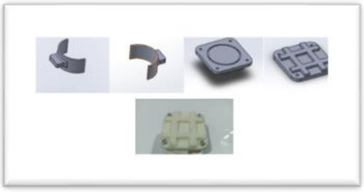




Figure 4: Design 2 **Figure 5: Design 3** **Figure 6: Design 4**

Design 2. The improved mould design showed minimal deformation, leading to several positive observations on the silicone samples. The surface quality of the samples was good, with a reduced intensity of air bubbles. However, the samples were difficult to remove from the mould, and they did not exhibit stickiness. Through a comparison with earlier experimental findings, it was determined that the presence of air bubbles in the silicone samples was attributed to the deformations in the mould. Overall, the improved mould design successfully addressed the issue of air bubble formation, resulting in high-quality silicone samples.

Design 3. The observations on the silicone sample indicated a reduction in air bubbles, a non-sticky nature, and an improved surface quality compared to Design 2. As a result, the mould design was upgraded from Design 3 to Design 4 and underwent further revisions for improvement. This progression was driven by the goal of achieving better outcomes in terms of reduced air bubbles, non-stickiness, and enhanced surface quality in the silicone samples.

Design 4. The test using mould design 4 yielded positive results for the silicone samples. The surface quality was good, showcasing a well-structured appearance. The samples were easily removed from the moulds, and their overall appearance was visually appealing compared to other mould design examples. Additionally, there were no visible air bubbles present in the samples. These observations indicate that mould design 4 successfully addressed the previous issues and achieved improved outcomes in terms of surface quality, structure, ease of removal, and absence of air bubbles in the silicone samples.

3.4 Step 4: Design Of Experiments By Taguchi Method And Testing

Using 3D printing (FDM) with varied layer thicknesses (50 and 100 microns) to create several mould sets of the finalised design (Design 4) using the material (PLA) based on the matrix presented in table 1. Evaluation the silicone samples using 50µm and 100µm layer-thick moulds in the next stage in accordance with the experiment matrix created using Taguchi experimentation.

Figure 7: Silicone sample obtain from Taguchi Experimentation

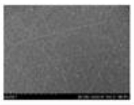
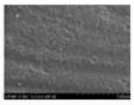
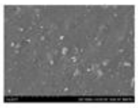
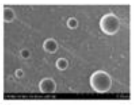
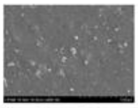
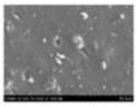
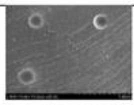
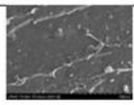
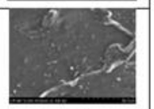
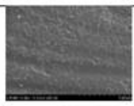
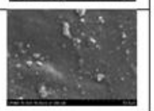
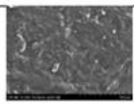
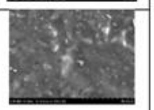
Table 4: Observation of Silicone Rubber using Taguchi Experimentation

Product Material		Sillicone Rubber			
Material for mould or sample		PLA Mould Design 4			
Trials		D1	D2	D3	D4
Temperature in °C		120	80	120	80
Time		¼ Hour	½ Hour	½ Hour	¼ Min
Layer Thickness in µm		50	50	100	100
Stickiness	Very				
	Moderate				
	Not	✓	✓	✓	✓
Deformation	Moderated				
	Structured	✓	✓	✓	✓
Removability	Easy	✓	✓	✓	✓
	Difficult				
Air bubbles	Less	✓	✓	No air bubbles	
	Moderate				
	High/ Many				

3.5 Step 5: Surface Measurement and Analysis

To capture the surface of the silicone samples by using Scanning Electron Microscope (SEM). In this step, analysed the images and generated the surface of the silicone samples to the magnifications x50, x500 and x5000. The result images created by SEM Software are displayed in table 1.5 below. Using PLA printed 50µm and 100µm moulds, demonstrated the comparison of silicone samples that were cured at various temperatures and times with the reference silicone sample.

Table 5: Result from Scanning Electron Microscope (SEM)

EXPERIMENT	MAGNIFICATION X50	MAGNIFICATION X500	MAGNIFICATION X5000
Reference Sample			
Sample 1 50µm 120°C ¼ Hour			
Sample 2 50µm 80°C ½ Hour			
Sample 3 100µm 120°C ½ Hour			
Sample 4 100µm 80°C ¼ Hour			

The presence of air bubbles in silicone samples can be attributed to improper mould design, specifically inadequate runner and gate configurations that lead to turbulent flow and air entrapment. Thicker mould layers are preferred to minimize air bubble formation, as thinner layers have a higher likelihood of trapping air during the filling process. PLA mould silicone samples, created with appropriate design and material properties, showed no air bubble formation and exhibited a smooth surface similar to samples made by injection moulding. This indicates that the mould design and PLA material were effective in producing high-quality silicone samples without air bubbles

3.6 Step 6: Tensile Test

To study the mechanical behaviour of silicone rubber after getting into the mould with various heat and curing times, the sample was performing tensile tests. This test helps to assess the material's behaviour under tension, providing valuable insights into its strength, elasticity, and elongation characteristics. During the tensile test, the sample is clamped into a testing machine, which applies a controlled force in one direction, typically along the longitudinal axis of the specimen. The machine records the applied force and the resulting deformation. The table 6 show the result with tensile test.

Table 6: Result from tensile test

Sample	Thickness, mm	Width, mm	Gauge length, mm	Max_ Force, N	Max_ Disp, mm	Max_ Stress, N/mm2	Max_ Strain, %	Young Modulus , ε
1	5.6	13.3	22	48.1	48.65	0.6458	221.1	0.002920
2	5.6	13.3	22	65.65	44.84	0.9485	203.8	0.004654
3	5.6	13.3	22	58.95	49.03	0.7915	222.9	0.003551
4	5.6	13.3	22	42.525	42.18	0.571	191.7	0.002978

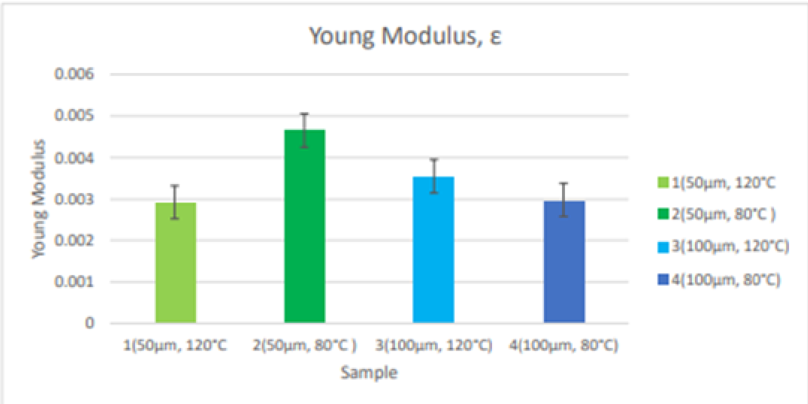


Figure 8: Graph Sample vs Young Modulus

The graph in figure 8 above show between the young modulus and the sample. For silicone rubber, As the temperature decrease, Young's modulus generally increases. This result was shown in sample 2 and sample 4 with a low temperature of 80°C.Young's modulus typically falls within a relatively low range due to its elastomeric nature. The value can vary depending on factors such as the specific formulation of the silicone rubber, and its curing conditions. It is important to note that temperature, strain rate, and other external conditions can all affect Young's modulus of silicone rubber. At elevated temperatures, the elastic behaviour of silicone rubber becomes more pronounced. It becomes more deformable and exhibits greater elasticity.

4. Conclusion

Additive manufacturing is a rapidly evolving industry with a lot of research going on. This study is concentrated on design and fabrication of moulds to produce silicone rubber and to conduct study about the surface of the obtained silicone samples. A study on samples made from simple mould geometry and determined that it is possible to develop a mould for creating silicone rubber items using additive manufacturing. The important findings of this study are that PLA is suitable for making moulds for silicone rubber products, that lower temperatures than recommended can be used for curing, that pre and post curing can be combined, that factors such as layer thickness, curing temperature, and curing time have the least influence on the surface quality of the silicone sample, plays an important role in the better outcome of the surface quality of the silicone sample. This study also demonstrates that the complexity of the shape is not a barrier to using PLA as a mould material.

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