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A Study of LTC410 Composite Mold System to Improve Mold Manufacturing Process in Aerospace Industry

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Abstract

This research aims to investigate the design and manufacturing of composite molds using LTC410 composite mold material with the objective to improve the mold manufacturing process in Aerospace industry. The study will delve into designing the LTC410 composite mold system, product quality, costs, and manufacturing time by comparison with traditional mold. The research methodology comprises a fusion of theoretical analysis and practical experimentation of product B which is the prototype product of research. The research will commence by providing an overview of aluminum mold manufacturing methods, focusing on production costs and times. Then study with the design of a composite mold system by LTC410 being a mold material and SP-165 PU board is the pattern of composite mold. The results of the research indicate that in the composite mold design process, mold scaling is unnecessary due to the minimal expansion exhibited by LTC410 mold material at the curing temperature of 135 degrees Celsius. Conversely, tool scaling is needed when design the pattern mold SP-165 by the calculated mold scale value necessitates a value of 0.9978 when applied to the 3D simulation program. Additionally, composite molds demonstrate the potential to reduce mold manufacturing time by up to 44% and mold manufacturing costs by up to 46.6%, without compromising the company's production processes or the quality of the workpieces, as observed when compared with traditional mold.

Keywords
Mold Manufacturing Cost, Mold Manufacturing Time, Composite Mold System, Mold Scaling, Product Quality.

1. Introduction
The continuous advancements and research going into composite material technologies coupled with composite material’s outstanding capabilities over traditional aerospace alloys led to the rapid increase in popularity of composite materials in the aerospace industry. However, as the aerospace industry’s demand for composite component increases, so does the demand for more tooling. Tooling and molds represent a large portion of the entire production chain of composite components. Therefore, the tooling and mold’s quality, cost and lead times severely affect the cost of production, especially in large volume productions (Peng Hao Wang et al. 2019). Typically, the mold always made from aluminum or steel using conventional metal fabrication techniques which that can be time consuming and expensive cost to accomplish. Composite mold is the one of alternative tooling solutions by generally refers to a mold made from composite materials which can be produced using various mold-making techniques, such as hand lay-up, vacuum bagging, resin transfer molding (RTM), or compression molding, among others. By the properties advantage of composite material such as Strength-to-Weight Ratio, Design Flexibility, Thermal Insulation etc. let it has garnered substantial attention in the aerospace industry to applied composite material to manufacture molds.

For the described reasons above, the researcher's company intends to undertake a study composite mold with the objective of reduced both the time and cost associated with mold production. The research methodology comprises a fusion of theoretical analysis and practical experimentation of product B which is the prototype product of research as it has selected by the most affected with company's production under research limitation. The findings from this investigation will serve as a reference information for the company to considerate to use composite molds as potential alternatives for the future company's mold solutions.

This research aims to study the composite mold design, including consideration parameters in design process by using linear expansion formula calculate Coefficient of Thermal Expansion (CTE) of materials in composite mold system to reach the appropriate tool scaling in mold design process that will help to understand the design principles when applied with computer-aided design (CAD) programs. Moreover, the study is comprehensive mold manufacturing cost and lead time by studying directs mold manufacturing cost and lead time then compare with traditional mold. Composite mold performance validation is also included in the research by studies dimensional accuracy with process capability and surface finishing with paint adhesion test.

Through a comprehensive evaluation encompassing performance metrics, cost analysis, and production affected considerations, this research seeks to provide actionable insights that can drive advancements in aerospace mold manufacturing. The findings are poised to benefit industry stakeholders, fostering innovation and competitiveness in the dynamic aerospace industry.

1.1 Objectives

- To study the design of composite mold system LTC410.
- To study mold manufacturing cost by comparing with traditional mold.
- To study mold manufacturing lead time by comparing with traditional mold.
- To study product quality.
- To study composite mold performance.

2. Methods

2.1 Prototype

Primary design consideration factor is to provide for the coefficient of thermal expansion (CTE) which is used to calculate the expansion factor and the tool scaling in composite mold design process. The CTE equation is related to length and temperature of the part. Therefore, the prototype of this research must have suitable geometries to get the appropriate calculation in the tool design. Product B is selected to be a representative of company product to study in this research due to the product geometries similarity with the box which can refer dimensions to calculate the CTE.

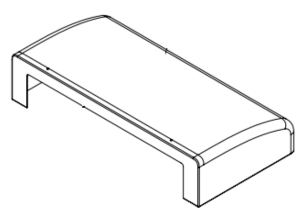


Figure 1. Product B is the prototype of this research.

2.2 Design process

The following steps define the design of composite mold process:

Step-1: Product requirements review, the product geometry and surface finish requirements are determined types of composite mold whether it should be male or female mold. Moreover, composite parts manufacturing process requirements are also defined the composite mold material properties.

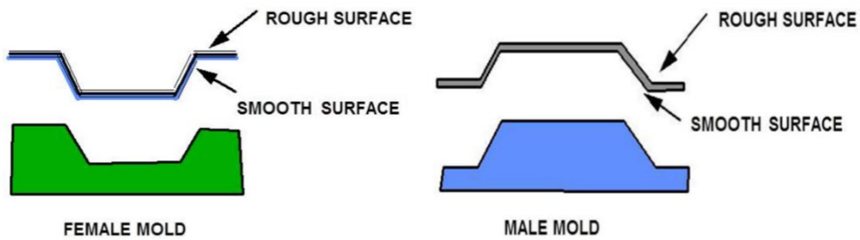


Figure 2. The different between female (left) and male (right) molds.

Step-2: Material selecting, the material of the product B is required to cure at 125˚C therefore, the composite mold materials must have heat resistance property more than that. This research has selected material as follow,

- LTC410 is the low temperature curing prepreg impregnated with epoxy resin as design to cure with low temperatures at 80 ˚C whilst giving the potential for high service temperature at 190 ˚C after post curing. It can be supplier on a variety of fabrics to meet cost and manufacturing requirements. This research selected LTC410 prepreg system with fiber reinforcement from SHD Composites to be a mold material due to its properties met the production requirements of product B and the price is cheapest than other materials that company have a quotation from suppliers.
- SP-165 is a High-Temperature polyurethane (PU) tooling board with served the service temperature at 115 ˚ C. it designed to produce patterns, prototypes, master model, fixtures, jig, and other tooling applications. The research selected this material from BATEX International to be a master plug since the heat deflection temperature is suitable with the mold material requirements and the price is cheapest than other materials which meet with the research objectives. Besides that, this material giving excellent surface after machining with computer numerical control machine (CNC).
- The consumables material for vacuum bag (VB) assembly comprises of polyester woven breather cloth, nylon bagging film, polyester peel ply, and sealant tape.

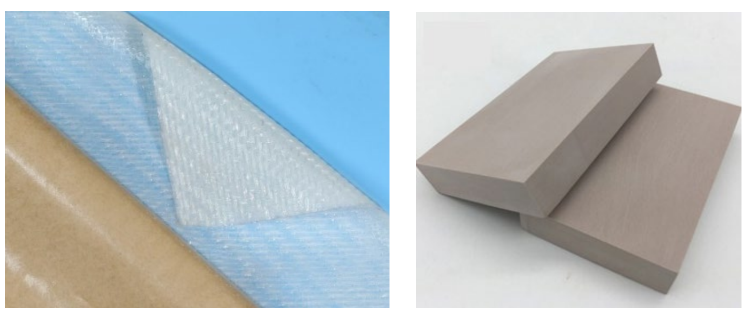


Figure 3. LTC410 prepreg system with fiber reinforcement (left), SP-165 Polyurethane tooling board (right).

Step-3: Composite mold design, the composite mold is created to represent the final shape, surface finish, and details of the final composite product. The product B is required smooth surface on the outside of part therefore, the composite mold type for this study is female mold.

Step-4: Master plug design, to create a mold, a master plug is required, the shape and surface finish of the master plug will be transferred to the mold. The fabrication technique of the mold is similar to fabricating a fiberglass part except that tooling materials (gel coat, resins, and cloth) are used to provide a durable mold that has low shrinkage and good dimensional stability. The mold type of master plug is always different with composite mold. Meaning, if the composite mold is female mold, Master plug must be male mold.

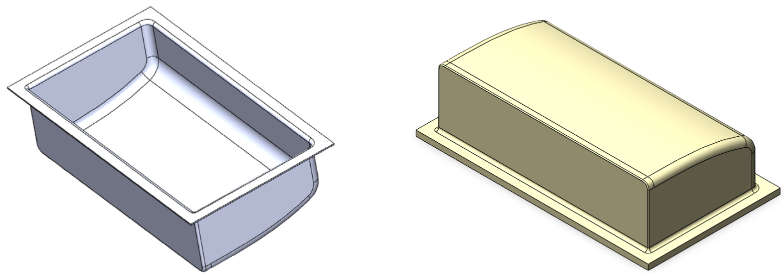


Figure 4. The designation of composite mold (left) and master plug (right) of the product B.

The coefficient of thermal expansion (CTE) is a measure of how much a material expands or contracts in response to changes in temperature. It quantifies the fractional change in size (length, area, or volume) of a material per unit change in temperature which express as,

$$\alpha = \frac{\Delta L}{(L_0 \times \Delta T)} \quad (1)$$

Where ΔL refers to the change in length, L0 is the original length and ΔT represents the change in temperature.

CTE is an important consideration for nearly all composite lay-up tooling since it impacts the final physical shape of the composite structure. Tool designs typically should be modified to compensate for the dimensional changes related to thermal expansion at elevated temperatures. The dimensional change of a tool can be calculated using the equations below, as well as a scaling factor that can be used to modify the geometry of a tool to compensate for expansion at elevated temperatures. The scaling factor is used to adjust for tool expansion at the maximum cure temperature, T_{cure}. The initial or starting temperature, $T_{initial}$, is typically room temperature. The variables $\propto_{tool}$ and $\propto_{part}$ represent the CTE of tool and part, respectively.

$$Expansion\ factor = (T_{cure} - T_{initial}) \times (\alpha_{tool} - \alpha_{part}) \quad (2)$$

Dividing one by one plus the expansion factor will provide the scaling factor, by which the tool will need to be adjusted to produce composite parts with the proper final size, shape, and dimensions. The optimized scaling factor will be applied with computer-aided design (CAD) program.

$$Tool\ scaling\ factor = \frac{1}{1 + Expansion\ factor} \quad (3)$$

In any design step (step 3 and 4) tool would start with CTE calculations (1) after that will find the tool scaling with equation (2) and (3) respectively. In case, material technical data sheet has provided the material CTE, the calculations can skip equation (1).

2.3 Manufacturing process

The composite mold is comprised 5 operation steps as follow,

Operation step 1: Master plug machining, once the master plug design is finalized, it needs to be accurately machined to ensure that the mold created from it will be precise. Machining involves using CNC (Computer Numerical Control) machines or other precision tools to form the plug to the exact specifications of the final part. 3 axis milling CNC machine is using for this research.

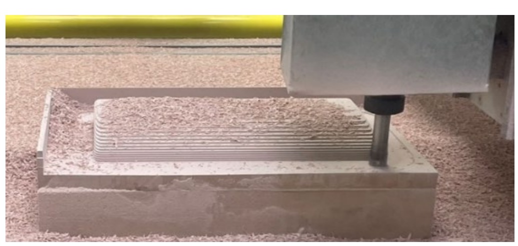


Figure 5. Master plug machining.

Operation step 2: Master plug surface preparation, after machining, the master plug may require additional processes to achieve the desired surface finish. This could involve sanding, polishing, or applying coatings to mimic the surface properties required for the final composite part. Sandpaper 180 grits is used for surface preparation process then sealed master plug with S120 board sealer from Easy Composites.

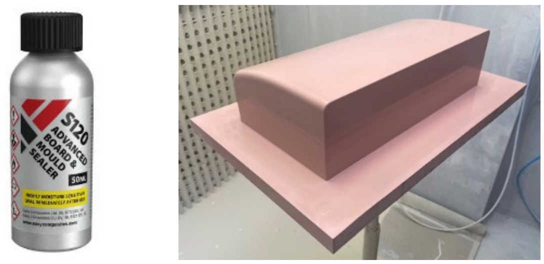


Figure 6. S120 board sealer (left) and master plug after finished surface preparation process.

Operation step 3: Vacuum bag laminating, vacuum bagging a clamping method that uses atmospheric pressure to secure the resin-coated components of a laminate to the mold until the laminate cures. This research paper based on composite tool process instruction from Toray Advanced Composites by symmetric layup 10 layers multi-direction (0˚/90 ˚/±45 ˚) of fiber/epoxy composites (GF/Ep) to provide laminates earn quasi-isotropic properties. Quasi-isotropic properties achieved nearly isotropic mechanical properties (similar strength and stiffness in all directions), making it versatile to multi-directional load which composite mold fall within this category.

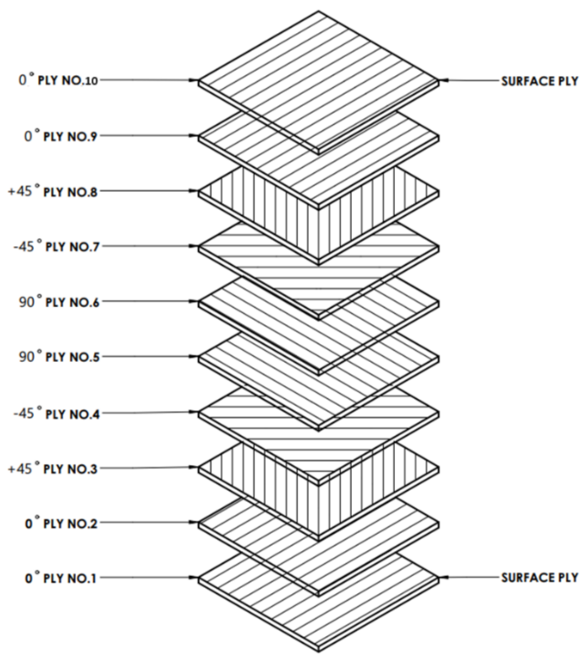


Figure 7. Fabricating symmetric 10 layers of quasi-isotropic laminates.

Operation step 4: Curing, curing in composites refers to the process of applying heat, pressure, or chemical additives to transform the composite materials from a liquid or semi-liquid state to a solid state. This process is crucial for the development of the desired mechanical properties and final shape of the composite material. This research is applied initial cure for LTC410 tooling prepreg material at 80°C for 4 hours with the oven.

Operation step 5: Post curing, post curing is the process of exposing a part or mold to elevated temperatures to speed up the curing process and to maximize some of the material's physical properties by expedite the cross-linking process and properly align the polymer's molecules. Much like heat treatment process in metal manufacturing. LTC410 is required freestanding (off the master plug) post cure in the oven at 180°C for 16 hours.

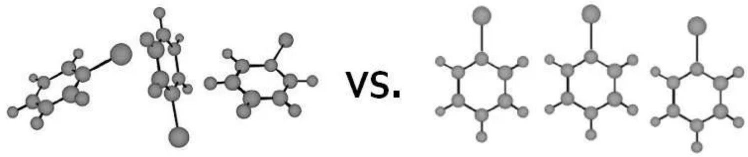


Figure 8. Polymers molecules before and after post curing.

Curing profile for initial cure is according to material technical data sheet whilst post curing profile is based on composite tool process instruction from Toray Advanced Composites due to the heat ramp up is suitable for company's oven machine, to get more understanding find initial and post curing profiles as below,

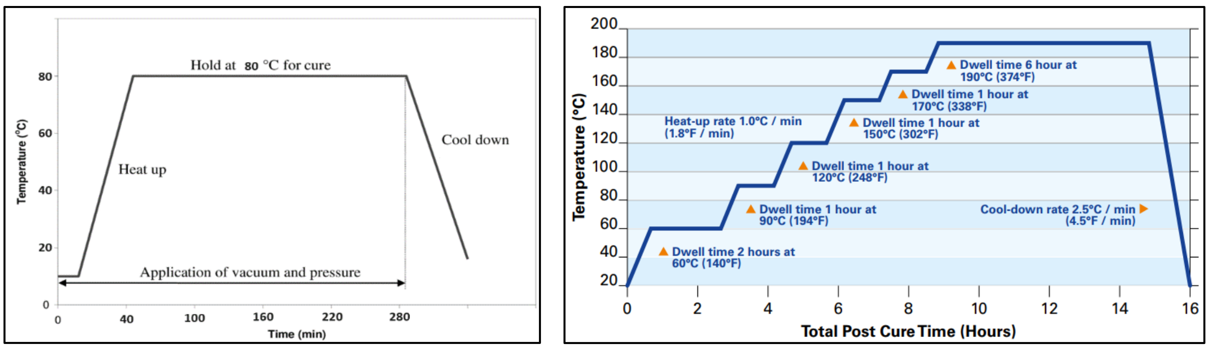


Figure 9. Initial cure (left) and Post cure profiles (right).

2.4 Performance analysis

The aim of this study is to conduct composite tool performance by using statistical tool to analyze dimensional stability. Process capability analysis can determine how a process performs relative to its requirements or specifications (Peder, 2012). A process capability index can be described as identifying the behavior of a process compared to the engineering specifications. These measures are often called capability or performance indices. Capability indices is applied widespread in industries (Arzak et al., 2020). The most common capability indices used in the manufacturing are Cp, Cpk, Pp and Ppk which Cp and Cpk is process capability index but Pp and Ppk is process performance index. Both are measures of process capability, but they differ in terms of the data used (Variance vs. Standard deviation). Besides, process capability index is often used for long-term assessment of stable processes, assuming the process is in statistical control, but process performance index is used for long-term assessment of initial run processes. This research applied process performance index (Pp and Ppk) to investigate the dimensional accuracy because this research is the initial run of composite mold by sample is 10 pcs of product B. The two formulas for Pp and Ppk are.

$$Pp = \frac{USL-LSL}{6S},\ \ Ppk = \min\left(\frac{USL-\bar{X}}{3S}, \frac{\bar{X}-LSL}{3S}\right) \tag{4}$$

Where USL and LSL are the specification interval, S is the standard deviation and $\bar{X}$ is the process mean by the higher value of Pp and Ppk is meaning process have a great performance. For example, if it is greater than 1.33, which corresponds to the percentage of non-conforming items of 63 parts per million(ppm), process performance is satisfactory for a centered process. The quality conditions and the corresponding Cp values are reported in Table 1 (Gabriele and Stefano, 2017) which can also applied interpreting with other process capability indexes.

Table 1. Quality Conditions and Cp values for centered process. (Gabriele and Stefano, 2017)

Quality Condition	Cp
Super Excellent	$Cp \geq 2.0$
Excellent	$1.67 \leq Cp \leq 2.00$
Satisfactory	$1.33 \leq Cp \leq 1.67$
Capable	$1.00 \leq Cp \leq 1.33$
Inadequate	$0.67 \leq Cp \leq 1.00$
Poor	$Cp < 0.67$

2.5 Mold manufacturing cost and lead time analysis

Determination of the selling price of a product or service is directly affected by the cost of production. Cost of production is a term to show the sacrifice of economic resources in the processing of raw materials into finished product (Rumanintya, 2017) which comprise by 3 groups of raw material cost, labor cost, factory overhead cost. The meaning of each word has described in Analysis of Production Cost Calculations Using Process Costing Method in Suli Tofu Factory (Rumanintya, 2017). This study conducted by collected the composite mold manufacturing cost to compare with aluminum mold where direct material cost calculating by the cost of the raw materials and components used to create a mold, labor and factory overhead costs have calculated together by using company's labor rate as 12.78 (USD/hrs.) in the calculation. Besides, the aluminum mold as used in this study is the current company's production mold of product B.

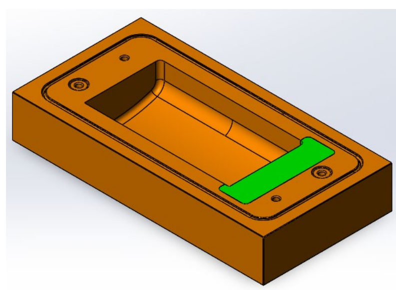
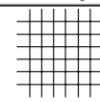
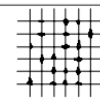
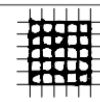
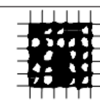


Figure 10. Aluminum mold of product B.

Manufacturing lead time is the time it takes to produce a product or service. It includes the time duration from the start of the manufacturing process to the point where the product or service is ready for delivery. A short production lead time is better since it ensures customers need quickly (Sisay et al., 2022). This topic aim to study production lead time of two different mold fabrication methods by comparing between composite and traditional (aluminum) molds. The data collected from actual manufacturing lead time of mold's product B.

2.6 Product quality analysis

In additional to the dimensional requirements of product B, there are also requirements painting for final product. Adhesion is one of the essential properties in the paints and coatings industry. It ensures the layer (or paint film) remains adhered to the surface for long, especially under aggressive conditions. The nature of adhesion has a direct relation with the durability and quality of a coating. Crosscut & Pull-off tests is a method of determining the resistance of paints and coatings to separation from substrates by utilizing a tool to cut a right-angle lattice pattern into the coating, penetrating all the way to the substrate. The test method is executed according to ISO2409:2020. The sample panel size is 70x100 mm that made from composite and aluminum molds for 3 pcs each then the result can interpret test results by classified with the following scale in accordance with standards as

Classification	Description	Appearance of surface of cross-cut area from which flaking has occurred[a] (Example for six parallel cuts)
0	The edges of the cuts are completely smooth; none of the squares of the lattice is detached.	
1	Detachment of small flakes of the coating at the intersections of the cuts. A cross-cut area not greater than 5 % is affected.	
2	The coating has flaked along the edges and/or at the intersections of the cuts. A cross-cut area greater than 5 %, but not greater than 15 %, is affected.	
3	The coating has flaked along the edges of the cuts partly or wholly in large ribbons, and/or it has flaked partly or wholly on different parts of the squares. A cross-cut area greater than 15 %, but not greater than 35 %, is affected.	
4	The coating has flaked along the edges of the cuts in large ribbons and/or some squares have detached partly or wholly. A cross-cut area greater than 35 %, but not greater than 65 %, is affected.	
5	Any degree of flaking that cannot even be classified by classification 4.	—

[a] The figures are examples for a cross-cut within each step of the classification. The percentages stated are based on the visual impression given by the pictures and the same percentages will not necessarily be reproduced with digital imaging.

Figure 11. Classification of test results according to ISO2409:2020

3. Design validation

Before proceeding to make final composite mold, the trial is necessary step to validate the design which any issues will adjusted and iterated during the validation process. The dimensions of product B that serve for this research is length and width which are dimensions controlled from forming process. CTE of LTC410 and SP-165 have provided by material technical data sheet as $2x10^{-6}K^{-1}$ and $64x10^{-6}K^{-1}$ respectively meaning the design can skip equation (1) in tool scaling calculations process. The tool scaling from calculating process will be obtained 1 and 0.9966 for composite mold and master plug. After applied on CAD program and proceed, actual dimensions result was shown in table 2 as

Table 2. Actual dimensions of design validation trial comparing with dimension requirements.

Requirement	Length 381.00±0.75 mm.	Width 199.30±0.50 mm.
Product B	380.21	199.01
Composite mold	380.19	198.97
Master plug	379.51	198.54
CAD program	379.59	198.51

From dimensions result in table 2 found, the length of final product doesn't meet the dimensions requirements of product B and the rest is in minimum specification of tolerances which does not meet the intended design objectives to require the dimension within mean range. After reverse calculations, the failure is caused by unappropriated tool scaling in master plug design process due to the CTE of master plug material as indicated in technical data sheet is the maximum CTE of material (at 115˚C), but actual process is not used fully material performance (at 80˚C) therefore, the design need to re-calculate by use actual dimensions from table 2 with equation (1) then calculate tool scaling with (2) and (3). After recalculated, the new CTE of master plug material is $42x10^{-6}K^{-1}$ and the tool scaling of master plug is 0.9978. The table 3 is the actual dimensions result after adjustment.

Table 3. Actual dimensions of design validation trial after adjustment.

Requirement	Length 381.00±0.75 mm.	Width 199.30±0.50 mm.
Product B	381.05	199.33
Composite mold	380.95	199.12
Master plug	380.35	198.96
CAD program	380.30	198.90

Table 3 shown the dimensions result of final product after adjusting tool scale of master plug. The dimensions are meeting the requirements of product B and within mean range. To summarize the composite mold design by using LTC410 tooling prepreg and SP-165 PU tooling board, in this system the CTE of tooling prepreg is 2x10-6K-1 according to material technical data sheet, but the actual CTE of master plug material is 42x10-6K-1. Furthermore, the tool scaling applied is 1 for composite tool design (the material has little or no expansion) and 0.9978 for master plug design process. This research has successful to find the optimize tool scaling for this composite mold which the mold will apply for other validations.

4. Results and Discussions

4.1 Cost and Lead time analysis result

This study aims to study the mold manufacturing cost and lead time of two different mold fabrication methods. The study will start with cost analysis, direct materials cost of aluminum mold was provided in table 4 and composite mold in table 5 then the direct labor and manufacturing overhead cost were shown in table 6 and 7 respectively. The summarize of cost analysis for both mold types have shown in table 8 and 9.

Table 4. the direct materials cost of aluminum mold.

Materials	Q'ty	Unit	Price (USD)
Aluminium 6061T6 (Size 665x345x115 mm.)	1	pcs	666.61
Aluminium 6061T6 (Size 245x80x105 mm.)	1	pcs	
Cutting tools and other accessories	n/a	n/a	221.92
Total (USD)			888.53

Table 5. the direct materials cost of composite mold.

Materials	Q'ty	Unit	Price/Unit (USD)	Subtotal (USD)
LTC410 Surface ply	0.8	mm^2	34.2	27.36
LTC410 Bulk ply	3.76	mm^2	41.7	156.79
SP-165 PU board	0.5	pcs	515.63	257.82
Consumable material	n/a	n/a	n/a	13.91
Total (USD)				455.88

Table 6. the direct labor and manufacturing costs of aluminum mold.

Process	Duration (hrs.)	Labor rate (USD/hrs.)	Subtotal (USD)
CNC set up	3	12.78	6.39
Rough machining	6	12.78	76.68
Semi-finish machining	15	12.78	191.7
Finish machining	33	12.78	421.74
Assembly	2	12.78	25.56
Total (USD)			754.02

Table 7. the direct labor and manufacturing costs of composite mold.

Process	Duration (hrs.)	Labor rate (USD/hrs.)	Subtotal (USD)
CNC set up	0.5	12.78	6.39
Master plug machining	8	12.78	102.24
Master plug surface preparation	2.5	12.78	31.95
Laminate and Vacuum bagging	3	12.78	38.34
Curing	5	12.78	63.90
Post curing	17	12.78	217.26
Total (USD)			460.08

Table 8. the total costs of aluminum mold manufacturing.

Cost	Price (USD)
Direct material	888.53
Direct labor and overhead	754.02
Total (USD)	1642.55

Table 9. the total costs of composite mold manufacturing.

Cost	Price (USD)
Direct material	455.88
Direct labor and overhead	460.08
Total (USD)	915.96

Based on the result in table 8 and 9 shown the manufacturing costs summary of two different fabrication methods, the total manufacturing cost is 1642.55 and 915.96 USD for aluminum and composite molds respectively. The composite mold can reduce the cost of materials and process 726.59 USD or 44.24 percentage which the cost of materials and manufacturing processes for composite molds is generally lower, making them a more economical choice upfront cheaper than aluminum mold in this study.

The result of lead time study has been represented by table 6 and 7 where the sum of manufacturing time of aluminum mold is 59 hours, and the manufacturing time of composite mold is 33 hours sequentially, the composite mold can reduce 26 hours or 44.06 percentage. Besides, composite mold decreases CNC machine capacity utilization because polyurethane is generally less dense than aluminum which lower density means that less material needs to be removed during machining, leading to faster machining times.

4.2 Dimension stability analysis

Collecting data width and length for 10 samples of product B was shown in Table 9 then applying process capability methodology to validate composite mold performance. The process performance (Pp and Ppk) calculation and values have been shown in Table able 10 & Table 11

Table 10. The measured values of the width and length of product B.

Sample	Requirement	
	Length (mm) 381±0.75	Width (mm) 199.3±0.5
1	381.08	199.33
2	381.06	199.32
3	381.05	199.28
4	381.01	199.35
5	381.04	199.25
6	381.06	199.34
7	381.07	199.33
8	381.00	199.31
9	381.09	199.27
10	381.02	199.30

Table 11. The process performance calculation and result of product B.

Index	Length	Width
Average ($\bar{X}$)	381.05	199.31
Standard deviation (S)	0.03	0.03
USL	381.75	199.8
LSL	380.25	198.8
Pp (4)	8.33	5.55
Ppu = $\frac{USL-\bar{X}}{3S}$	7.77	5.03
Ppl = $\frac{\bar{X}-LSL}{3S}$	8.83	5.19
Ppk (4)	7.77	5.03

Process capability analysis for this case study data shown in table 10. From this table, Pp = 8.33, Ppk = 7.77 for the length, and Pp = 5.55, Ppk = 5.03 for the width of product B. This study analysis revels that Pp is not equal Ppk which implies that the process is not exactly centered (described by Histogram graph). A process will be considered stable when it's average and standard deviation are constant over time therefore, we can conclude this study as the composite mold have excellent dimension stability when Ppk more than 1.67.

4.3 Product quality validation

Product quality has validated by cross-cut adhesion test according to standardized methods ASTM D3359 or ISO 2409 which there are the one of customer requirements of product B. the paint adhesion result can be accepted at class 0 only. Table 12 has shown test results of crosscut adhesive test; all samples arranged Class 0 which can conclude final product that made form composite mold have a good paint adhesion property.

Table 12. The result of crosscut test.

Sample	Picture	Result
1		Class 0
2		Class 0
3		Class 0

4.4 Discussion

This research endeavor has encompassed a comprehensive exploration of various applications utilizing composite molds. The outcomes of this investigation align with the research objectives. Specifically, the composite mold's capacity to yield workpiece quality remains on par with that of traditional molds. The composite mold demonstrates a notable advantage in terms of shorter production times and lower costs compared to traditional counterparts. Despite the overall satisfactory test results, it is imperative to acknowledge certain limitations encountered during the research process. Notably, limitations in the availability of raw materials constrained the sample size for the dimensional stability tests outlined in Section 4.2. Due to the elevated cost of producing these specimens, the study was restricted to analyzing only 1 0 specimens, which may not fully adhere to statistical principles. Composite mold durability test does not provide in this research by the research limitations as well. However, this limited sample size does provide foundational insights for evaluating the performance characteristics of composite molds. Furthermore, it is important to note a potential area of concern regarding design validation discrepancies, particularly when transitioning from prototype B to larger-scale parts. Such discrepancies highlight the complexity of scaling up designs and warrant further investigation in future research endeavors.

5. Conclusions

Base on the data provided, it is evident that composite molds can maintain equivalent production quality compared to traditional molds while offering significant advantages in terms of production time and cost efficiency. Specifically, the study reveals that composite molds exhibit a remarkable reduction in mold production time by 38.98% and a substantial cost saving of 44.24% when compared to traditional molds. These findings underscore the operational benefits and cost-effectiveness associated with adopting composite molds in manufacturing operations. Moreover, one notable advantage highlighted in the study is the reproducibility of composite molds. Unlike traditional molds, composite molds can be easily reproduced if the master plug remains in good condition. This capability eliminates the need to invest in new raw materials for each reproduction, further reducing production costs and enhancing resource utilization. The study highlights that for the same budget allocated to mold production, manufacturers have the potential to produce two composite molds in contrast to only one aluminum mold. This dual capacity for composite molds translates into increased production output, reduced waiting times, and enhanced manufacturing efficiency.

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