

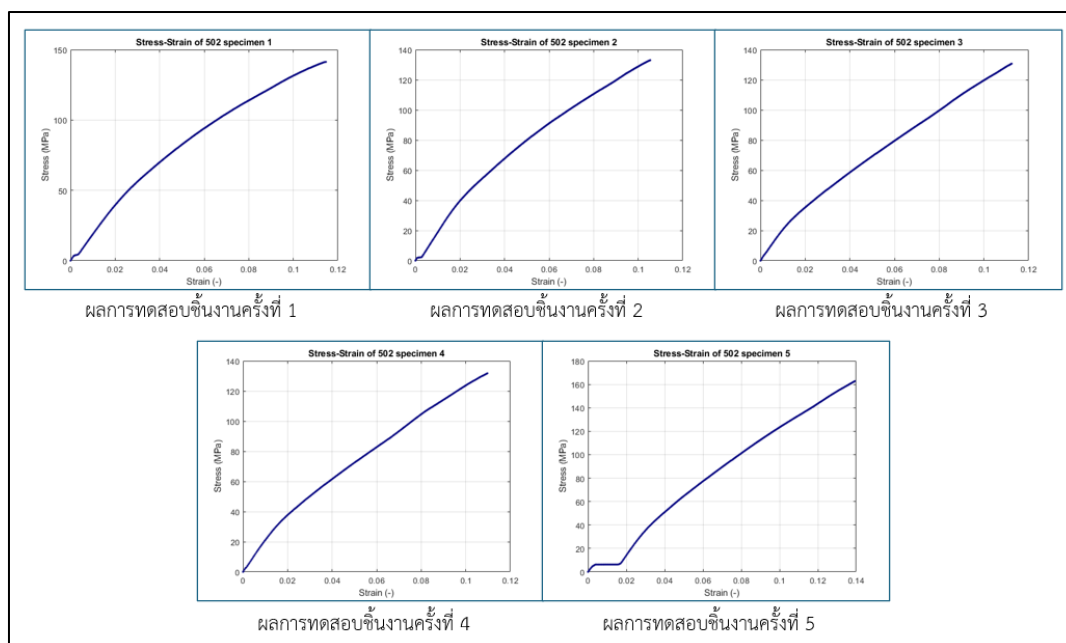
ภาคผนวก ก

ผลการทดสอบความแข็งแรงดึงจากส่วนที่ 1 ของการดำเนินการวิจัย

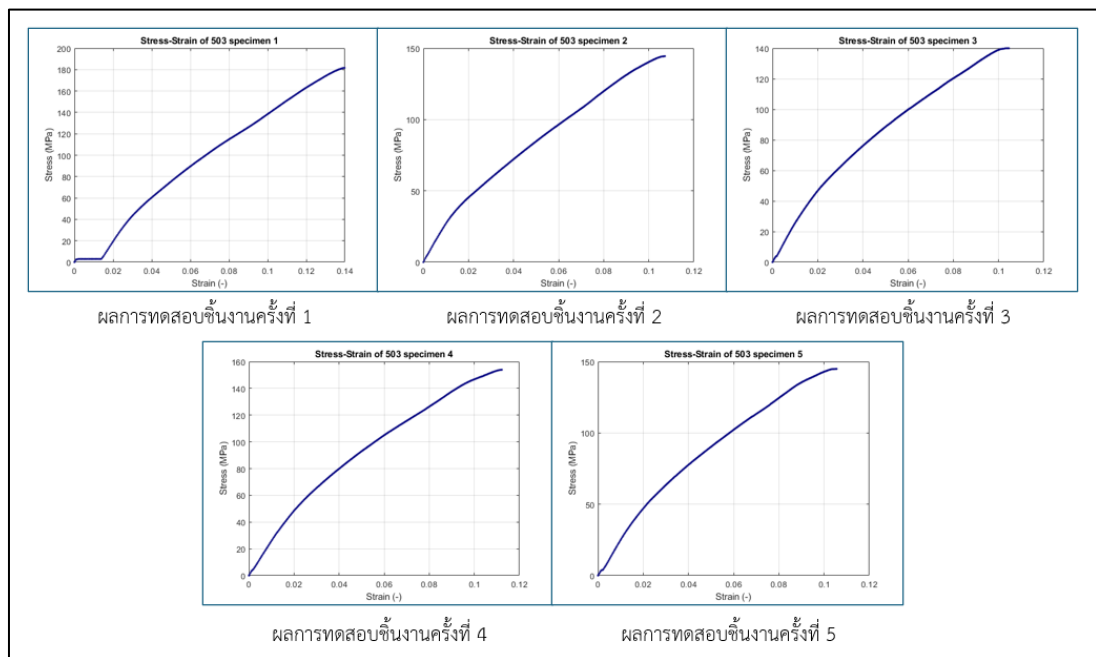
จากการทดสอบความแข็งแรงดึงของวัสดุคอมโพสิต ตามมาตรฐาน ASTM D3039 จากส่วนที่ 1 ของการดำเนินการวิจัยงานวิจัย ได้ผลทดสอบออกมาเป็นค่าของภาระแรงที่เครื่องทดสอบกระทำ (Load) และระยะการเลื่อนของคานทดสอบ (Machine extension) ซึ่งเมื่อนำค่าทั้งสอง ร่วมกับระยะขนาดของวัสดุที่วัดได้ มาคำนวณดังสมการที่ 2.1 และ 2.2 จะทำให้ได้ค่าของความเค้นและความเครียด ซึ่งสามารถนำพล็อตเป็นกราฟแสดงความสัมพันธ์ได้ดัง รูปที่ ก.1 ถึง ก.9.

ทุกการทดสอบของการทดสอบความแข็งแรงดึง ได้รูปแบบของกราฟแสดงความสัมพันธ์ระหว่างความเค้นและความเครียด คล้ายคลึงกับภาพจากทฤษฎีการทดสอบความแข็งแรงดึงของวัสดุเปราะ (รูปที่ 2.8 จากบทที่ 2) เนื่องจากเมทริกซ์ของวัสดุคอมโพสิตซึ่งพิมพ์จากโณนิกซ์ที่ปกคลุมอยู่ภายนอกชิ้นงาน เกิดความเสียหายก่อน วัสดุเสริมแรงที่อยู่ภายใน และเครื่องทดสอบแรงอเนกประสงค์หยุดทำงานอัตโนมัติ ซึ่งความเสียหายเช่นนี้มีค่าเท่ากับชิ้นงานได้เสียหายไปแล้วจึงทำให้วัสดุไม่มีช่วงการเกิดคอคอด

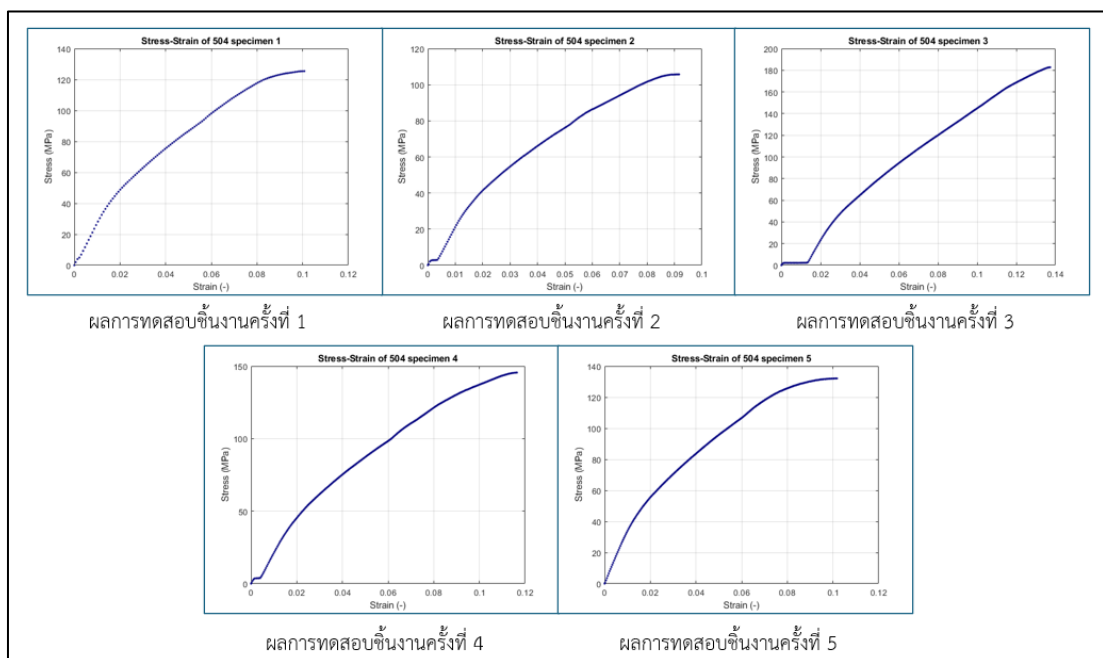
ในบางรูปจากผลการทดสอบ พบว่ามีช่วงที่ความเค้นมีค่าคงที่ในขณะที่ความเครียดมีค่าเพิ่มขึ้นอย่างรวดเร็วในช่วงเริ่มต้นของการทดสอบ สามารถสังเกตได้ชัดในผลการทดสอบชิ้นที่ 5 รูปที่ ก.1 ซึ่งช่วงการเพิ่มขึ้นของความเค้นดังกล่าวไม่ใช่ช่วงระยะคราก แต่เกิดจากปากกาจับชิ้นงานเกิดการครูดกับชิ้นงาน แต่ไม่ส่งผลต่อการทดสอบเนื่องจากการจับชิ้นงานยังอยู่ในช่วงระยะการจับ (Grip length)



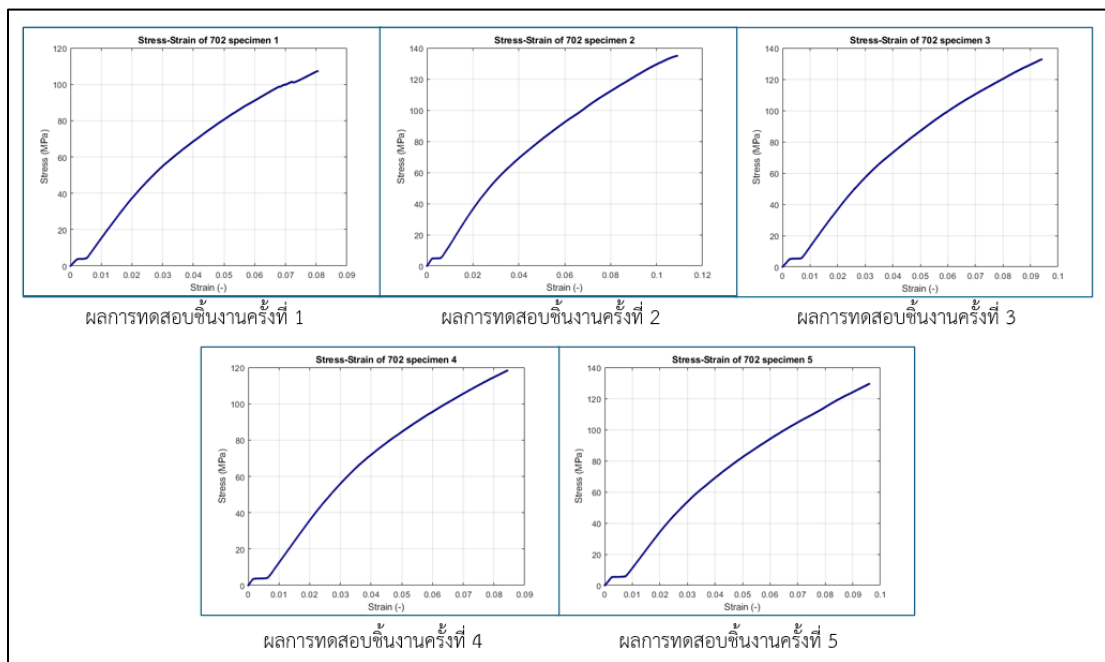
รูปที่ ก.1 ผลการทดสอบชิ้นงานที่พิมพ์ด้วยความหนาแน่น 50 เปอร์เซ็นต์ และวงแหวนไฟเบอร์ 2 วง



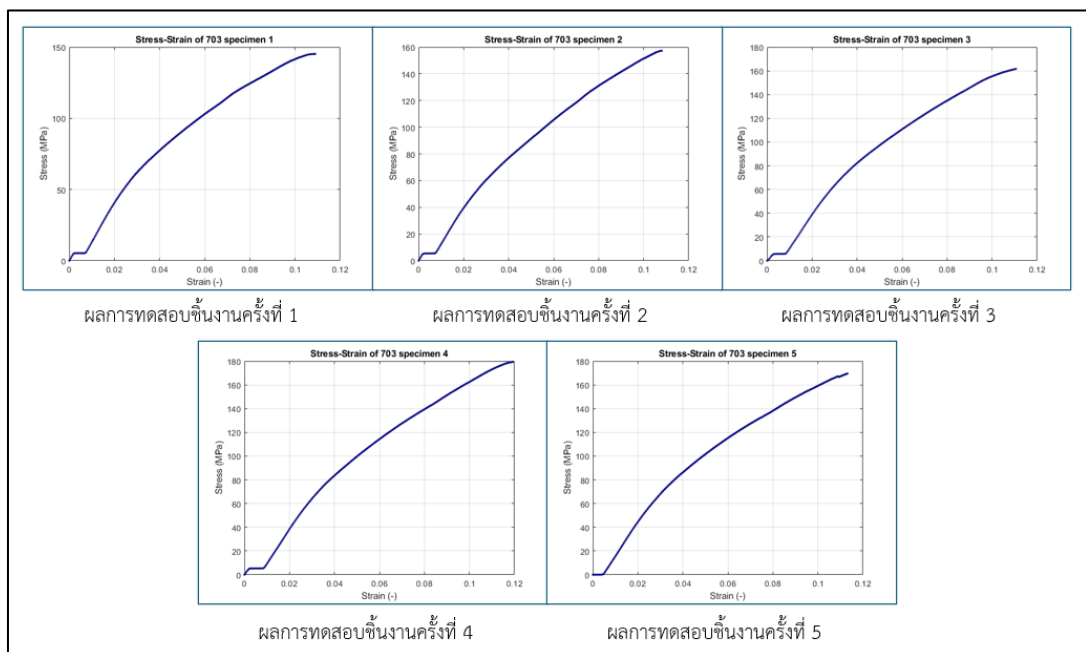
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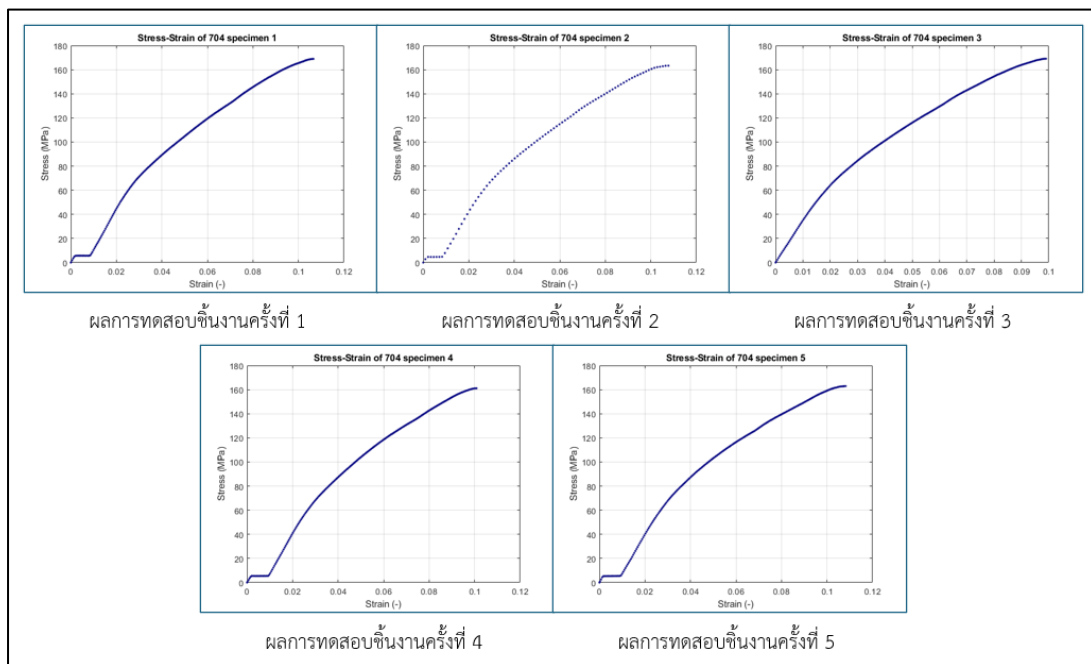
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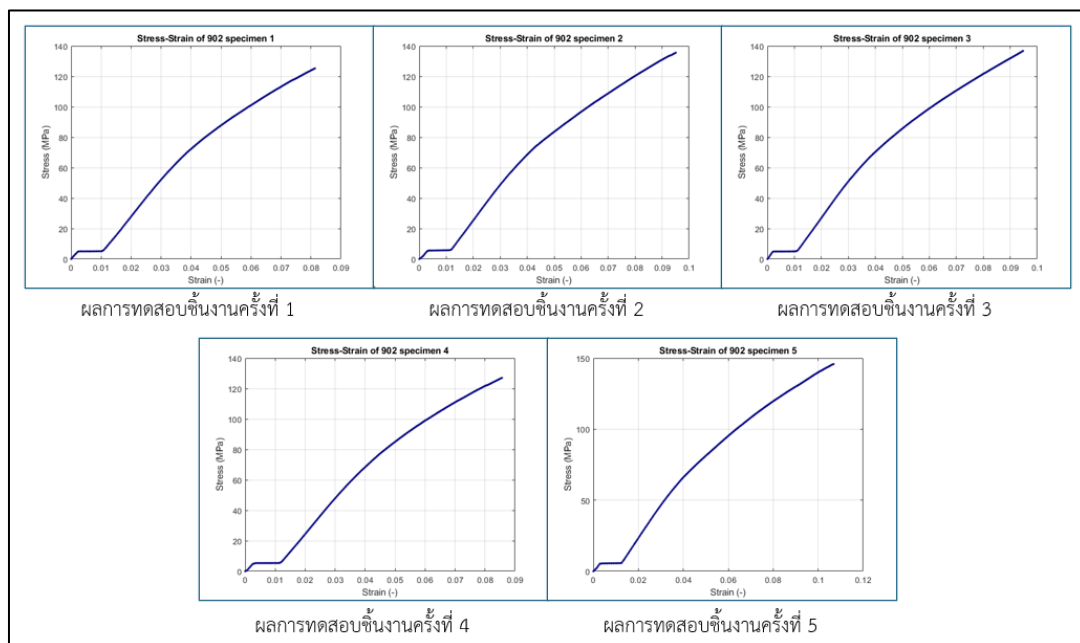
รูปที่ ก.4 ผลการทดสอบชิ้นงานที่พิมพ์ด้วยความหนาแน่น 70 เปอร์เซ็นต์ และวงแหวนไฟเบอร์ 2 วง



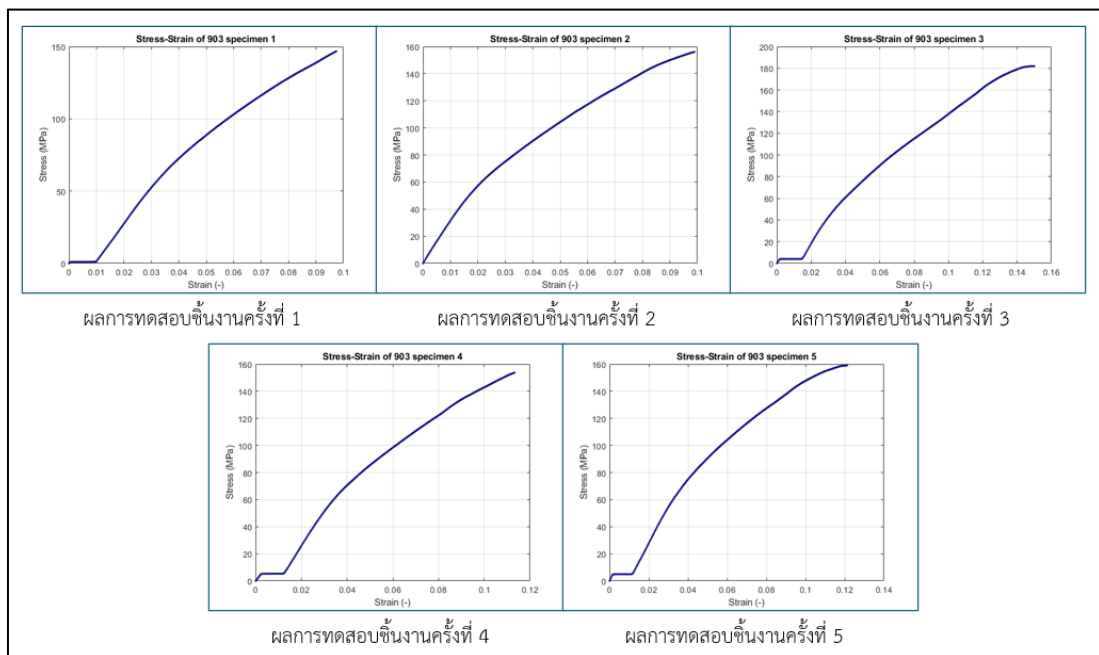
รูปที่ ก.5 ผลการทดสอบชิ้นงานที่พิมพ์ด้วยความหนาแน่น 70 เปอร์เซ็นต์ และวงแหวนไฟเบอร์ 3 วง



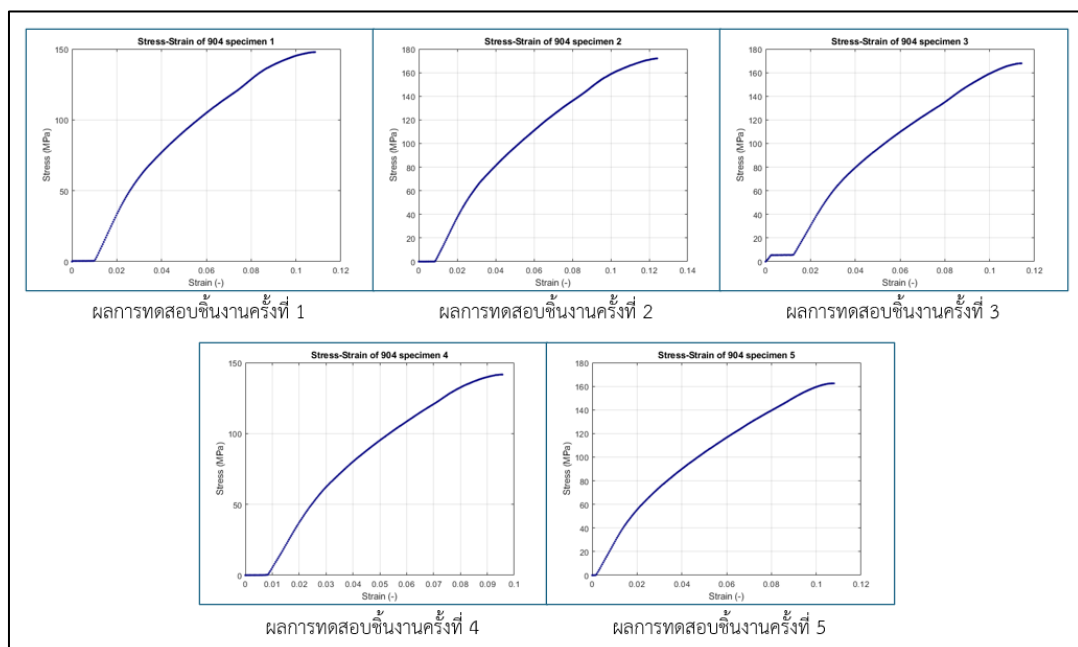
รูปที่ ก.6 ผลการทดสอบชิ้นงานที่พิมพ์ด้วยความหนาแน่น 70 เปอร์เซ็นต์ และวงแหวนไฟเบอร์ 4 วง



รูปที่ ก.7 ผลการทดสอบชิ้นงานที่พิมพ์ด้วยความหนาแน่น 90 เปอร์เซ็นต์ และวงแหวนไฟเบอร์ 2 วง



รูปที่ ก.8 ผลการทดสอบชิ้นงานที่พิมพ์ด้วยความหนาแน่น 90 เปอร์เซ็นต์ และวงแหวนไฟเบอร์ 3 วง



รูปที่ ก.9 ผลการทดสอบชิ้นงานที่พิมพ์ด้วยความหนาแน่น 90 เปอร์เซ็นต์ และวงแหวนไฟเบอร์ 4 วง

ภาคผนวก ข

ผลงานวิจัยที่เกี่ยวข้องซึ่งได้รับการเผยแพร่ในระหว่างการศึกษา

รายชื่อบทความที่ได้รับการเผยแพร่ระหว่างการศึกษา

Petcharat, N., Wiangkham, A., Pichitkul, A., Tantrairatn, S., Aengchuan, P., Bureerat, S., ... & Ariyarat, A. (2023). **The multi-objective optimization of material properties of 3D print onyx/carbon fiber composites via surrogate model.** Materials Today Communications, 37, 107362.



The multi-objective optimization of material properties of 3D print onyx/carbon fiber composites via surrogate model

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ABSTRACT

Composite materials play a prominent role in modern engineering. The emergence of composite material technology has brought about a profound impact on almost, if not all industries. The aerospace industry, for instance, benefits greatly from composite materials. With composites, aircraft weight can be reduced while the structural strength is maintained. As with other classes of materials, 3D printing technique allows composite parts of high complexity to be fabricated with great precision. Additionally, with 3D printing, mechanical properties of the resulted part can be accurately customized and controlled by means of varying matrix-reinforcement proportions. As the composite material can be indefinitely customized in 3D printing, it is crucial to evaluate the mechanical properties of the printed specimen. While testing of printed specimens is usually possible, endless production and testing of specimens not only takes time and resources but also leads to extensive experimental waste. In this study, an optimization-based technique is proposed to determine the optimal 3D printing material proportion in order to reduce the need of unwarranted experimental waste and improve the efficiency of composite material selection process. The study aims to investigate the properties of Onyx/Carbon fiber composite material and the optimization of the 3D printing configuration to achieve desirable mechanical properties. The effects of the number of carbon concentric fiber rings and the percentage of infill density of Onyx used in 3D printing were examined. ASTM D3039 tensile tests were performed to obtain mechanical properties of the printed specimen. Considering the values of tensile strength and modulus of elasticity of the printed material, the printing configurations were optimized using a multi-objective non-dominated sorting genetic algorithm II (NSGA-II) with the Kriging model for objective function estimation. From the proposed optimization technique, it has been found that the maximum tensile strength is attained when the number of concentric fiber rings is equal to 3 while the percentage of Onyx infill density falls in the range of 86–90. Contrarily, the modulus of elasticity is maximized when the number of concentric fiber rings is equal to 4 with the percentage of Onyx infill density in the range of 70–75.

1. Introduction

Composite materials have become a prevalent material option in various engineering applications owing to their high strength-to-weight ratio, versatility, and customizability to fit certain needs., aerospace and

aviation industries are among examples where composite materials are extensively used to cater stringent requirements for lightweight materials with yet exceptional mechanical properties. Setlak [1] has presented the comparative characterization of the structural materials including composite material used in aviation structure and showed the

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example of aluminum-composite structure which prevents delamination and strongly propagating cracks in structure. Suchat [2] used the epoxidized natural rubber and nanosilica to improve the impact strength of epoxy nanocomposite as reinforced materials that composite material showed the great potential to be used as raw material for propeller blades of unmanned aerial vehicles (UAVs) based on physical properties evaluated within the scope of the study.

Composite material 3D printer is a composite-material specimen fabricating machine in which the type of materials, the geometry and the ratio of the material compositions can be configured, allowing the mechanical properties of the printed specimen to be controlled to meet diverse demands. Studies have been conducted in the recent years to explore various means to control mechanical properties of the printed materials as well as to explore potential applications of 3D printing technology. Li et al. [3] suggests that the geometry and fiber filament fill pattern significantly affect the tensile properties of 3D printed continuous carbon fiber reinforced thermoplastic composite material. The experiment performed by Ramalingam [4] shows that the hexagonal infill pattern possesses the optimum energy absorption over other patterns while inappropriate setting could lead to the unfitting properties. Experiment conducted by Sanei [5] demonstrates that 3D printed continuous carbon fiber onyx composite samples possess inferior mechanical properties to conventional carbon fiber reinforced epoxy specimens due to lower volume fraction of fiber and poorer properties of matrix. Nevertheless, the 3D printed composites hold great potential in various applications owing to rapid advancement in printing technology that allows the fiber direction to be precisely controlled.

Fabricating composite material with 3D printing offers a notable advantage of combining the flexibility of 3D-printing technique in which complex design can be easily handled with the customizable nature of composite materials where proportion of reinforcement and matrix can be controlled to achieve desirable properties. However, an inherent challenge of composite material 3D printing is to adjust the printing condition and to calibrate the proportion of matrix-reinforcement to achieve the optimum of mechanical properties in the printed components, aligning them to be suitable with their application, while minimizing material wastage.

In determining the optimal printing configuration, a combined optimization technique with a surrogate model is shown to provide satisfactory results. Surrogate models are used in various engineering applications including optimization problems where experiments are complex, expensive, or time-consuming. Such models are used for estimating a fitness or objective function landscape given that a set of training data is provided. In optimization, different surrogate models can be employed, including a radial basis function (RBF) interpolation [6], a response surface model (RSM) [7], a Kriging surrogate model [8], etc. Optimization techniques with surrogate model have been studied and proposed by a number of researchers. Bellary [9] used several Kriging variants along with a response surface approximation function to optimize the performance of a turbomachinery system. Leusink [10] used genetic algorithm and surrogate model based on CFD to design helicopter rotor blade with multi-fidelity optimization.

The Non-dominated Sorting Genetic Algorithm (NSGA-II) [11] is among the most prevalent algorithms used in optimization owing to its high level of scalability and capacity in handling large-scale and complex optimization problems with multiple decision variables and objectives. Studies have been conducted to incorporate NSGA-II in optimization. Ariyarat used NSGA-II is used in airfoil design optimization [12] and later in optimization of helicopter rotor blade design [13]. Zhou et al. [14] applied NSGA-II with multi-fidelity surrogate model to solve computationally expensive problems. Phiboon [15] also employed NSGA-II for multi-fidelity multi-objective airfoil design for fixed-wing UAVs. In order to ensure applicability and validity of the mechanical properties of the optimal composite, a standardized tensile test must be performed to precisely obtain the tensile properties of the material specimens. Among the standardized tests available, the test designated

Table 1

The mechanical properties of Onyx as composite based [20].

Properties	Test (ASTM)	Onyx
Tensile modulus (GPa)	D638	2.4
Tensile stress at Yield (MPa)	D638	40
Tensile stress at Break (MPa)	D638	37
Tensile strain at Break (%)	D638	25
Flexural strength (MPa)	D790	71
Flexural modulus (GPa)	D790	3.6
Izod impact notch (J/m)	D256 10A	330
Density (g/cubic meter)	-	1.2

Table 2

The mechanical properties of Carbon as continuous fiber [20].

Properties	Test (ASTM)	Carbon
Tensile strength (MPa)	D3039	800
Tensile modulus (GPa)	D3039	60
Tensile strain at Break (%)	D3039	1.5
Flexural strength (MPa)	D790	540
Flexural modulus (GPa)	D790	51
Flexural strain at break (%)	D790	1.2
Compressive strength (MPa)	D6641	62
Compressive Modulus (GPa)	D6641	0.7
Compressive strain at break (%)	D6641	105
Izod impact notch (J/m)	D256 10A	960
Density (g/cubic meter)	-	1.4

**Fig. 1.** Markforged X7 3D printer printing specimens.



Fig. 2. Visualization of laying specimen on Markforged X7 printing bed.

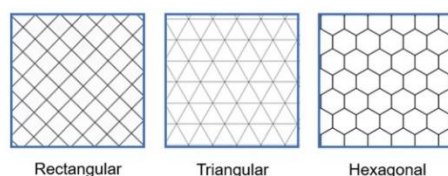


Fig. 3. The fill pattern example: (a) Rectangular pattern, (b) Triangular pattern, and (c) Hexagonal pattern.

by the American Society of Testing and Materials (ASTM) offers a systematic and easily repeatable testing procedure and hence is commonly used in research community. In Velmurugan experiment [16] the ASTM D638 has chosen to determine the tensile properties of reinforced and non-reinforced plastics, whereas in the 3D printed composite researches [3] and [5] the ASTM D3039 standard [17] for polymer composite is employed.

In this study, a pioneer method based on multi-objective optimization is proposed to determine the optimal 3D printing configuration of Onyx/Carbon fiber composite. The integration of the Kriging surrogate model and the NSGA-II optimization algorithm, aimed at optimizing both tensile strength and modulus of elasticity is performed. This combination has never been explored before in the field of composite material 3D printing design.

2. Multi-objective optimization

2.1. Specimen preparation and testing

2.1.1. Material

A composite material is a material consisting of 2 compositions referred to as Matrix and Reinforcement. In this study, Onyx, the fusion of engineering nylon and chopped carbon fibers, is selected as a matrix while Carbon fiber is used as a reinforcement. The mechanical properties of Onyx and Carbon, from the datasheet provided by Markforged [18], are shown in Tables 1 and 2, respectively. The combination of strength and lightweight of the two materials is the reason for the material option used in this study.

2.1.2. Printer specification

The experiment was conducted based on the capabilities of the Markforged X7. The composite material 3D printer is designed to meet the demand of using continuous fiber to reinforce the part of matrix as well as composite material whereas the model could be openly fabricated by 3D printing under the constraint of model dimension. Markforged X7 features printing bed which has the building volume of $330 \times 270 \times 200$ millimeter as shown in Fig. 1. Along with this build volume, it is capable of printing 5 specimens per one printing order at the same

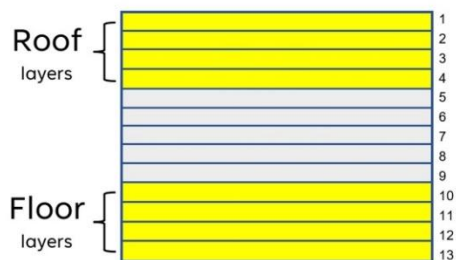


Fig. 4. Example of specimens has 4 roof layers, 4 floor layers and a total of 13 layers.

time as shown in Fig. 2.

2.1.3. Printing configuration

To investigate the effects of the matrix infill density and the number of concentric fiber rings of the reinforcement on the mechanical properties of the resulting composite, the printing configurations are controlled by adjusting the following settings: infill settings and reinforcement settings.

2.1.3.1. Infill settings. The matrix infill setting comprises of selections of infill pattern, infill density, roof & floor layers, and wall layers. Fig. 3 shows different infill patterns, each of which offers distinct advantages in the resulting specimen. According to the work done by RAMALINGAM [4], it was found that the hexagonal infill pattern possesses decent characteristics in terms of impact load or energy absorption. However, the rectangular pattern provides the widest range option to custom the fill density (0–92 %) when the triangular and the hexagonal pattern can be customized between 18 % and 62 % and 36–72 % respectively. The setting for roof & floor layers refers to the layers of total number of upper and lower matrix layer as depicted in Fig. 4. The wall layer setting refers to the number of solid matrices that are printed along the wall part.

2.1.3.2. Reinforcement settings. The isotropic fiber pattern routes fiber back and forth in a zig-zag manner accurately to simulate the layering found in traditional laminated composites, it can resist the bending force that results in tension load and compression load along the fiber direction which applied the tensile or compression loads in the right direction as shown in Fig. 5 demonstrates how the fiber resists the load in its right direction. The fiber orientation can be described by fiber angle as shown in Figs. 6 and 7. The fiber angle can be manually configured angle for each layer of fiber.

If the isotropic fiber filling option is selected, two concentric fiber rings are formed around the exterior of the specimens by default to ensure smoothly reinforced external surface. Nevertheless, the number of fiber rings can be adjusted to obtain desired reinforcement capability. The isotropic fiber filling option with different numbers of concentric fiber rings is shown in Fig. 8. The printing conditions for both Infill and Reinforcement settings are shown in Table 3.

2.1.4. Tensile testing configurations

In this study, a tensile test is performed to determine tensile properties of the printed composite including stress-strain response, tensile strength, and modulus of elasticity.

2.1.4.1. Shape of specimens and dimensions. It is a common practice to use a rectangular cross section specimen for ASTM D3039 standard test. According to the standard [3], it is advisory that the minimum length of

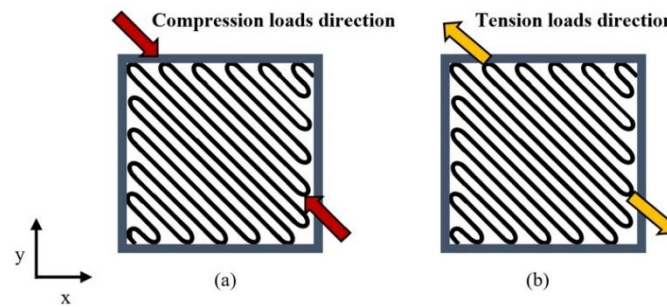


Fig. 5. Bending force in direction which can be resisted by fibers. (a) Compression loads (b) Tension load.

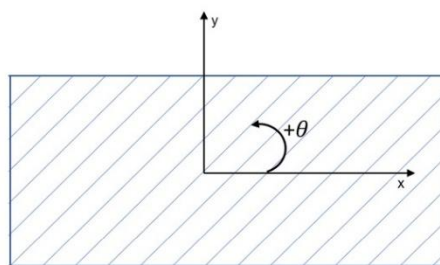


Fig. 6. Isotropic pattern specimens with concentric fiber rings.

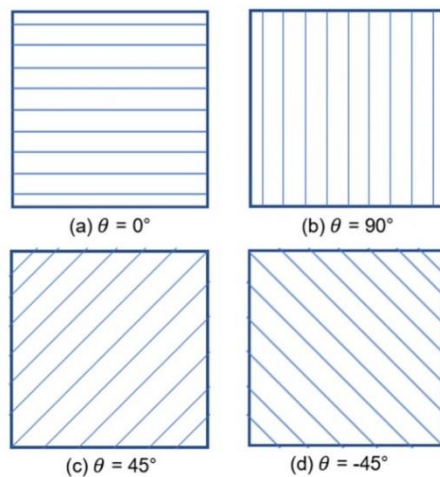


Fig. 7. Isotropic pattern with different fiber orientation.

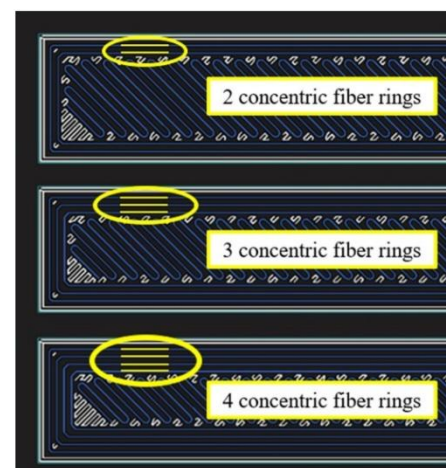


Fig. 8. Isotropic pattern specimens with concentric fiber rings.

Table 3

Printing customization for specimen.

Infill settings	
Fill pattern	Rectangular pattern
Fill density	50 %, 70 %, and 90 %
Roof & Floor layers	4
Wall layers	2
Reinforcement settings	
Total fiber layers	10
Fiber fill type	Isotropic fiber
Concentric fiber ring	2,3, and 4
Fiber angles (Degree)	45, -45

the specimen is computed using the following expression: In all experiments, 150 mm-long, 15 mm-wide specimens with 15-mm gripping length for each side, and 70-mm gauge length is used as shown in Fig. 8.

2.1.4.2. Tensile testing procedure. As shown in Fig. 9, all specimens are marked with lines to indicate the gage length and the gripping length.

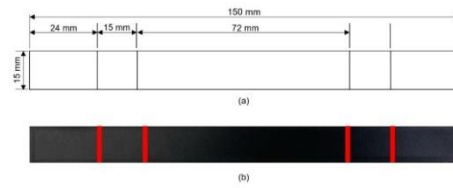


Fig. 9. Standard rectangular tensile specimens: (a) tensile specimen size and (b) tensile specimens.

Table 4

The tensile test design factors.

Factor	Level of factor		
	Low	Medium	High
Infill density (%)	50 %	70 %	90 %
Concentric fiber ring	2	3	4

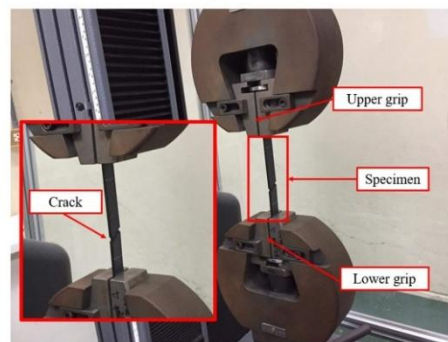


Fig. 10. Tensile testing specimen is tested in the universal testing machine (UTM).

The gage length is used to ensure that the test result is valid while the grip length is used to indicate the clamping distance between the grips. After the specimen is attached to the Universal Testing Machine (UTM) and is firmly gripped, an upward load is applied at the upper while the end of the lower grip is fixed. During the test, the upward load at the upper grip is gradually increased until the specimen breaks. The test is performed using 100 kN Lloyd UTM with a 2 mm/min loading rate.

2.1.5. Design of experiment

The full factorial design is selected to design the tensile testing experiment as the method allows estimation of the main effects as well as the interactions between factors. By testing all possible combinations of factors and levels, the full factorial design provides the relationship between the factors and the design variables. The experimental design was carried out using a general full factorial design with 2 factors and 3 levels, as listed in Table 4. Each of the 9 specimen conditions is subjected to 5 tensile tests, resulting in the total of 45 experiments being conducted. Fig. 10.

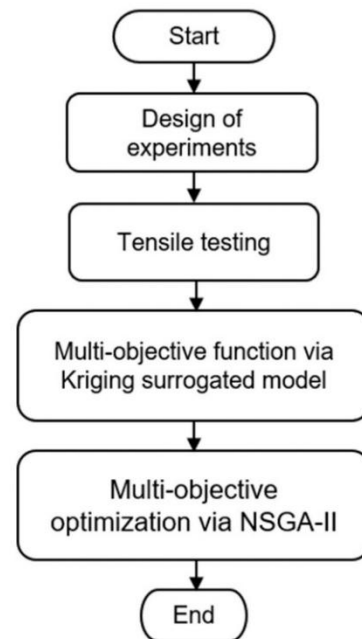


Fig. 11. Operation process of Multi-objective optimization for tensile properties of 3D print Onyx/carbon fiber.

2.2. Multi-objective optimization for tensile properties of 3D print Onyx/carbon fiber

In this study, the multi-objective optimization process involved designing the tensile testing experiments using a full factorial design. A surrogate model is then constructed using kriging model based on the experimental design variables. The NSGA-II algorithm is employed to obtain the Pareto solution and to maximize both the tensile strength and the modulus of elasticity of the specimens. The process of optimization is presented in the Fig. 11.

2.3. Multi-objective function via Kriging surrogate model

Surrogate models are utilized in multi-objective optimization to approximate the values of objective functions and constraints as exact evaluations of these functions are often computationally expensive. Kriging is considered one of the most practical surrogate models to be used in multi-objective optimization since the model offers fast yet accurate approximation of objective functions and constraints. This greatly reduces the computational cost and improves optimization efficiency, leading to improvement in solution quality especially for computationally expensive problems. In order to train the kriging surrogate model, input-output data is necessary. In this work, the input consists of the design variables obtained from experiment whereas the output the response variables, i.e., the objective functions.

The ordinary kriging method predicts the unknown function as shown in following

$$\hat{y}(x) = \mu(x) + \epsilon(x) \quad (1)$$

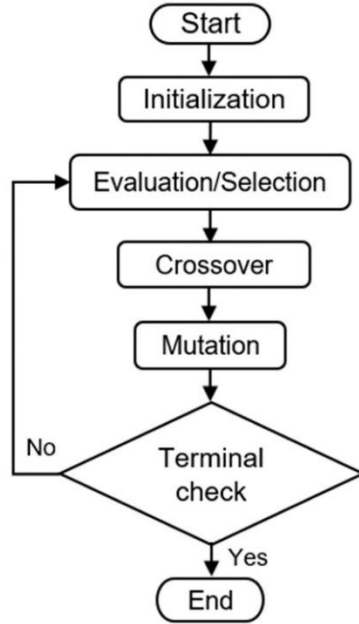


Fig. 12. Operation process of genetic algorithm.

Where $\mu(x)$ denotes a global model and $\epsilon(x)$ denotes a local model.

In Eq. (1), the unknown function can be predicted using an ordinary kriging method as described in [8]. Using Gaussian random function, the sample points x can be interpolated. The correlation between $Z(x_i)$ and $Z(x_j)$ is related to the distance between the two corresponding points, x_i and x_j . The distance function between points x_i and x_j is described using the following equation.

$$d(x_i, x_j) = \sum_{k=1}^m \theta^k |x_i^k - x_j^k|^2 \quad (2)$$

where $\theta^k (0 \leq \theta^k \leq \infty)$ is the k^{th} element of the correlation vector parameter, θ . The correlation between points x_i and x_j is defined as

$$\text{Corr}[Z(x_i), Z(x_j)] = \exp[-d(x_i, x_j)] \quad (3)$$

The kriging prediction can be described as follows

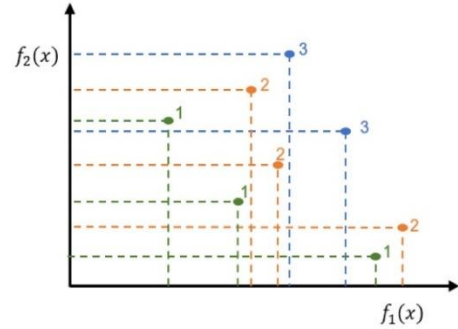
$$\hat{y}(x) = \mu(x) + r^T R^{-1} (F - \mu) \quad (4)$$

where $Z(x_i)$ represents a local deviation from the global model [19], $F = [f(x_1), f(x_2), f(x_3), \dots, f(x_n)]^T$ is the value of the evaluated function value at $X = \{x_1, x_2, x_3, \dots, x_n\}$, R denotes the $n \times n$ matrix in which the (i, j) entry is $\text{Corr}[Z(x_i), Z(x_j)]$, n is the number of sample points, and r is the vector in which the i^{th} element is

$$r_i(x) = \text{Corr}[Z(x), Z(x_i)] \quad (5)$$

In the original kriging model, it is assumed that $\mu(x)$ is constant, and the estimate for $\mu(x)$, denoted as $\bar{\mu}$, is given by

$$\bar{\mu} = [\mu(x), \mu(x), \mu(x), \dots, \mu(x)] \quad (6)$$

Fig. 13. Ranking by NSGA-II (Minimization f_1 and f_2).

It is defined as

$$\mu(x) = \frac{1^T R^{-1} F}{1^T R^{-1} 1} \quad (7)$$

The parameter, θ , in the kriging model can be determined using maximum likelihood estimation (MLE) given by the following equation

$$\ln(\mu, \sigma^2, \theta) = -\frac{n}{2} \ln(\sigma^2) - \frac{1}{2} \ln(|R|) \quad (8)$$

Maximum Likelihood Estimation (MLE) is an m -dimensional nonlinear optimization problem without any constraints, which can be solved using a genetic algorithm (GA) as proposed by Goldberg and Holland [20]. For a given θ , the variance σ^2 can be calculated from

$$\sigma^2 = \frac{(F - \bar{\mu})^T R^{-1} (F - \bar{\mu})}{n} \quad (9)$$

The mean squared error, $s^2(x)$ at point x of this function can be calculated using the following equation

$$s^2(x) = \sigma \left[1 - r^T R^{-1} r + \frac{(1 - 1^T R^{-1} r)^2}{1^T R^{-1} 1} \right] \quad (10)$$

where 1 denotes an n -dimensional unit vector.

2.4. Multi-objective optimization via non-dominated sorting genetic algorithm II

NSGA-II is a powerful and widely used algorithm for multi-objective optimization that has several key advantages. It handles multiple conflicting objectives by generating a set of non-dominated solutions and maintains diversity among solutions using a crowding distance measure. NSGA-II can also handle problems with constraints is capable of handling large-scale problems. Additionally, it is a robust algorithm that quickly converges to the Pareto front. These features make NSGA-II a versatile and effective algorithm for solving a wide range of optimization problems.

The ordinary genetic algorithm (GA) is a searching algorithm that uses the genetic operators such as the selection, crossover and mutation. The simple genetic algorithm flowchart is shown in Fig. 12.

The Nondominated Sorting Genetic Algorithm II (NSGA-II) is an improved version of NSGA and is widely employed in solving multi-objective problems. NSGA-II is represented by nondominated points and crowding distance sorting. Elitism is used to select the individuals for the next generation, and the new generation is filled sequentially with each front until the population size is increased, as depicted in Fig. 13.

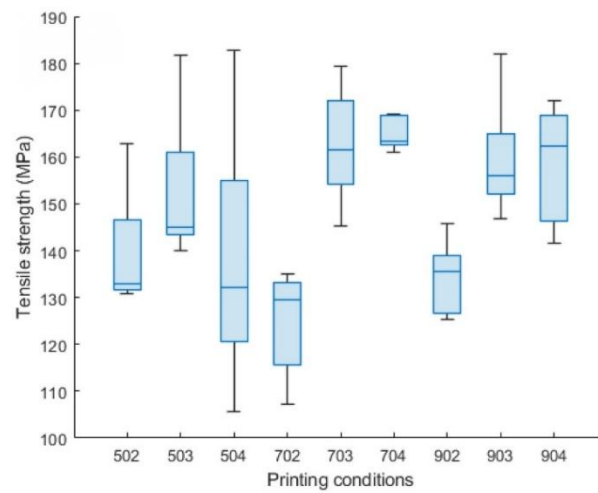


Fig. 14. Results of Tensile strength from various 3D Onyx/carbon fiber printing conditions.

In this work, The NSGA-II is selected to find the pareto solution to maximize the tensile strength and modulus of elasticity of the specimens.

3. Design problems for multi-objective optimization

The 2 objectives of the optimization problem are to maximize the value of tensile strength as well as the modulus of elasticity. The optimization problem can be expressed as.

Maximize: Tensile strength.

Maximize: Modulus of elasticity.

The 2 parameters in this optimization problem are the percentage of Onyx infill density and the number of concentric fiber rings. Each of the parameters has 3 levels for optimization as given below:

Infill density: 50 %, 70 % and 90 %.

Concentric fiber ring: 2, 3 and 4.

The design space is defined by the percent infill represented as continuous data with the upper and the lower bounds of 90 % and 50 %,

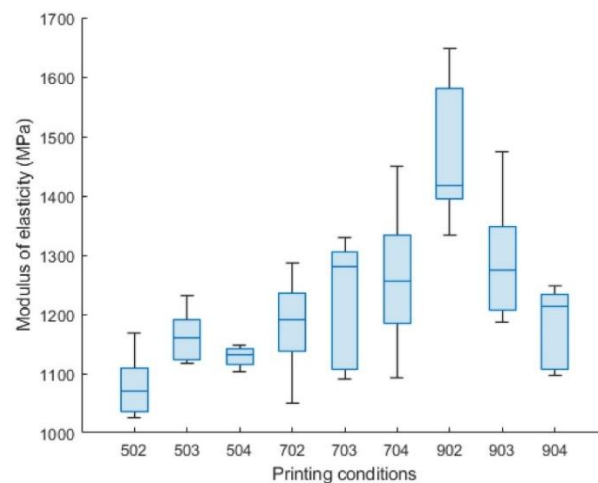


Fig. 15. Results of Modulus of elasticity from various 3D Onyx/carbon fiber printing conditions.

Table 5
Analysis of variance of tensile strength of specimens.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	8	8562.4	1070.3	4.94	0.000
Linear	4	5856.4	1464.1	6.76	0.000
Infill density	2	366.7	183.3	0.85	0.437
Concentric Fiber ring	2	5489.8	2744.9	12.67	0.000
2 Way Interactions	4	2706	676.5	3.12	0.026
Infill density*Concentric fiber ring	4	2706	676.5	3.12	0.026
Error	36	7800.1	216.7		
Total	44	16362.5			

Table 6
Analysis of variance of Modulus of elasticity of specimens.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	8	509404	63676	7.18	0.000
Linear	4	265557	66389	7.48	0.000
Density	2	250034	125017	14.09	0.000
Concentric Fiber ring	2	15523	7762	0.87	0.426
2 Way Interactions	4	243847	60962	6.87	0.000
Infill density*Concentric fiber ring	4	243847	60962	6.87	0.000
Error	36	319482	8875		
Total	44	828887			

respectively. The quantity of concentric fiber ring is represented as discrete data with the upper and the lower bounds of 4 rings and 2 rings, respectively. The surrogate model is then constructed through the Kriging method.

4. Result and discussion

4.1. Tensile properties of onyx/carbon fiber composite

The printed specimens are tested for tensile properties as designated by ASTM D3039. Each specimen is named using a 3-digit number. The first 2 digits refer to the percent infill and the last digit refer to the number of concentric fiber rings. The results of the tensile tests indicate that the tensile strength of the composite increases with the number of concentric fiber rings. A similar trend is observed for the modulus of elasticity, which also increases with the infill density. However, at the infill density of 90 %, the result shows that a smaller quantity of concentric fiber rings results in a higher value of the modulus of elasticity. The maximum values of tensile strength and modulus of elasticity are obtained by the optimum proportion of matrix together with the optimum quantity of concentric fiber rings. The maximum tensile strength is obtained with 70 % infill (Matrix density). While the tensile strength at 90 % infill is less than the value at 70 % infill as noted from Fig. 14, the observation is likely due to large experiment variance. For the modulus of elasticity, the highest value is attained at 90 % infill with 2 concentric fiber rings as observed from Fig. 15. The higher modulus of elasticity indicates that the 90 % infill specimen has a superior strain-to-elongation ratio compared to other specimens.

The results obtained from the experiment show that both percent infill density and the number of concentric fiber rings individually affects the tensile strength and the modulus of elasticity. Fig. 14 shows that the tensile strength value is increased with the trend of increasing the number of concentric fiber rings. The tensile strength being increased is due to the increasing of the volume fraction of the reinforcement fibers that has more value tensile strength than Onyx according to datasheet in Tables 1 and 2.

Additionally, the modulus of elasticity value increases with percent of infill density as shown in Fig. 15. As infill density increases, the

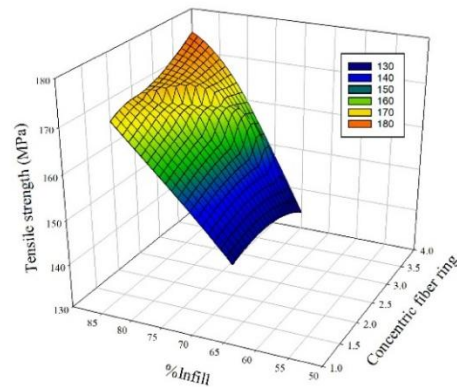


Fig. 16. Effect of parameters to Tensile strength of the optimal specimens.

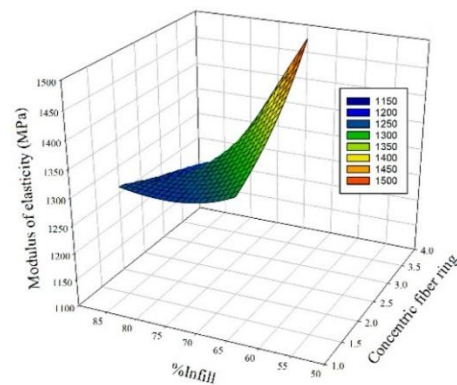


Fig. 17. Effect of parameters to Modulus of elasticity of the optimal specimens.

material filaments are more closely packed together, resulting in a more rigid structure. Moreover, the greater density reduces the presence of gaps within a specimen, affecting the increased stiffness of the specimen.

The results of the tensile strength and the modulus of elasticity from the experiment, considered by the analysis of variance at the 0.05 level of significance, are shown in Tables 5 and 6, respectively. For the Tensile strength analysis from Table 5, It found that the value of P-value for the analysis of infill density was found to be 0.437 and it is greater than alpha level. However, the analysis for two-way interaction, P-value was found to be 0.026 with the F-value of 3.12, indicating that the interaction of the infill density and the number of concentric fiber ring has a significant impact on the tensile strength of the specimens. Despite the fact that the null hypothesis for individual factors was not rejected by the statistical analysis, the statistical significance of interaction of two factors is worth a mention. Similar to the analysis of variance of the Modulus of elasticity from Table 6, it is also found the P-value for the analysis of the number of concentric fiber rings to be 0.426 whereas all others P-value were found to be zero including the two-way interaction of the infill density and the number of concentric fiber rings. The results suggest that the interaction of these two factors is significantly

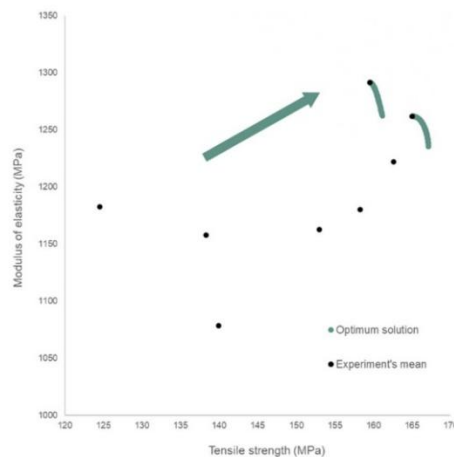


Fig. 18. Pareto frontier and optimal direction.

influenced by the modulus of elasticity.

In summary, while the analysis of variance does not provide the conclusive evidence against the null hypothesis for individual factor, the interaction between the infill density and the number of concentric fiber rings appeared to have a significant impact on both the tensile strength and the modulus of elasticity.

4.2. Multi-objective function via Kriging

The influence of parameters (Percent infill and number of concentric fiber rings) on the tensile strength of the solutions and on the modulus of elasticity of the solution constructed via Kriging surrogate model are represented by the three-dimensional surfaces as shown in Figs. 16 and 17, respectively. Since both infill density and concentric fiber ring affect the tensile strength and modulus of elasticity individually, a multi-objective optimization design technique was applied in order to find the optimum configurations.

4.3. Optimization results via NSGA-II

The results of multi-objective optimization are shown as pareto frontier in Fig. 18. The relationship of the design variables (parameters) and the objective functions are shown with the Parallel Coordinate Plot in Fig. 19. It is observed that the maximum tensile strength is achieved when the specimens contain 3–4 concentric fiber rings as demonstrated with red lines from Fig. 19 that the tensile strength of the optimized data are maximized around 180 MPa when the specimens contain 3–4 concentric fiber rings. Additionally, it is found that the maximum modulus of elasticity is achieved when the specimens infill density is 90 % as demonstrated with the green lines in Fig. 19. Further increase in the percent infill does not lead to improvement in modulus of elasticity due to a higher volume of onyx.

4.4. The reliability of optimization

The reliability of the multi-objective optimization is evaluated by cross validation method. Fig. 19 shows the tensile strength result with the R-Square value of 0.95716. The plot of the modulus of elasticity is given in Fig. 20 with the R-Square value of 0.90289 indicating that the data is less distributed compared to the case of the tensile strength. Fig. 21.

5. Conclusions

This study presents the optimum solution of Onyx/Carbon fiber 3D composite material printing condition obtained from Multi-objective single fidelity optimization using NSGA-II algorithm and kriging surrogate model. The design variables of the optimization are the percent infill (matrix density) and the quantity of concentric fiber rings. The objectives of the optimization are to maximize tensile strength and modulus of elasticity. The specimens were manufactured with 3D composite material printer and were tested with the procedure designated by ASTM D3039 standards. The tested results are used in the optimization procedure as well as to provide the optimum solution represented as the pareto frontier with the optimal direction. The PCP plot that provides the information of optimum proportion between the percent infill and the quantity of concentric fiber ring is also presented. Using previously described methodology, it is observed that

- an increase in the number of concentric fiber rings led to a corresponding increase in the material tensile strength.

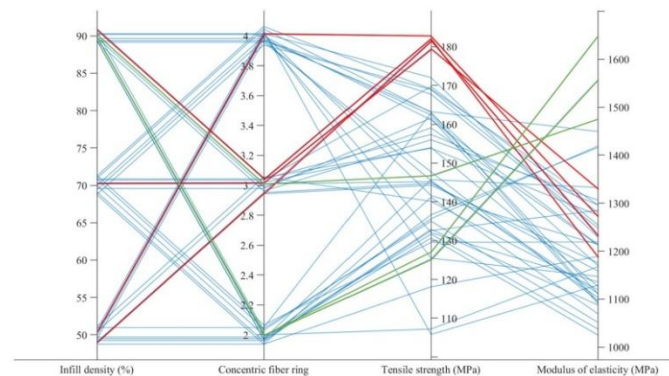


Fig. 19. The Parallel Coordinate Plot of non-dominated solution.

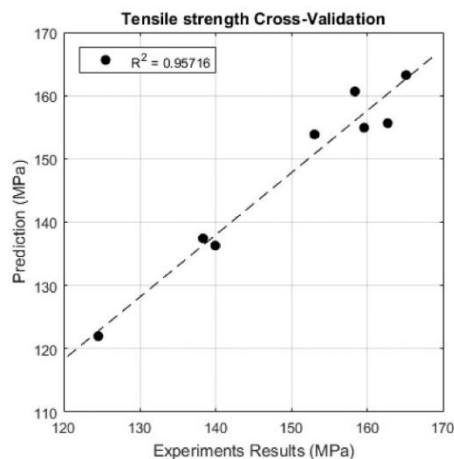


Fig. 20. Tensile strength cross validation.

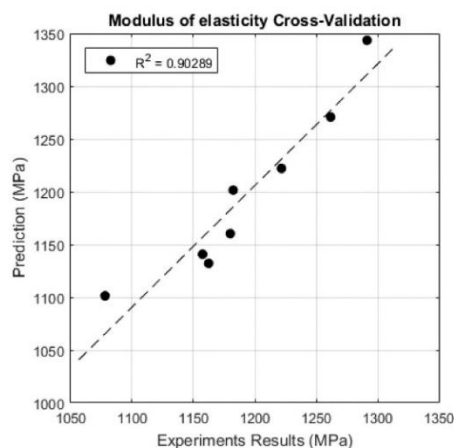


Fig. 21. Modulus of elasticity cross validation.

- The modulus of elasticity increases with both the number of concentric rings as well as the infill density. However, when the infill density is 90 %, a lower quantity of concentric fiber rings leads to a higher modulus of elasticity value.
- The maximum tensile strength is attained when the number of concentric fiber rings is 3 and the percent infill is in the range of 86–90.
- The maximum modulus of elasticity is reached when the number of concentric fiber rings is 4 and the infill density is between 70 % and 75 %.

- The R-Square values of cross validation between the results from experiment and the prediction model of tensile strength and modulus of elasticity are 0.95716 and 0.90289, respectively.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sujin Bureerat reports financial support was provided by National Research Council of Thailand.

Data availability

No data was used for the research described in the article.

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