ASEAN
Journal of Scientific and Technological Reports
Online ISSN:2773-8752

Research article

Manufacturing Design and Cost Analysis for Customer-oriented Rubber Mat Product using Abrasive Waterjet Cutting

Kunlapat Thongkaew[1, 5*], Supapan Chaiprapat[2, 5], Chukree Daesa[3, 5], and Zaleha Mustafa[4]

[1] Faculty of Engineering, Prince of Songkla University, Songkhla, 90110, Thailand
[2] Faculty of Engineering, Prince of Songkla University, Songkhla, 90110, Thailand
[3] Faculty of Engineering, Prince of Songkla University, Songkhla, 90110, Thailand
[4] Faculty of Industrial and Manufacturing Technology and Engineering, Universiti Teknikal Malaysia Melaka, 76100, Malaysia
[5] Smart Industrial Research Center, Faculty of Engineering, Prince of Songkla University, Songkhla, 90110, Thailand
* Correspondence: kunlapat.t@psu.ac.th

Citation:
Thongkaew, K.; Chaiprapat, S.; Deasa, C.; Mustafa, Z. Manufacturing design and cost analysis for customer-oriented rubber mat product using abrasive waterjet cutting. *ASEAN J. Sci. Tech. Report.* **2025**, *28*(6), e259644. https://doi.org/10.55164/ajstr.v28i6.259644.

Article history:
Received: June 5, 2025
Revised: September 20, 2025
Accepted: September 27, 2025
Available online: October 19, 2025

Publisher's Note:
This article is published and distributed under the terms of the Thaksin University.

Abstract: Molding is a widely used technique for large-scale manufacturing of rubber products, ensuring profitability for companies. Advances in rubber-based products have significantly improved consumer satisfaction by fostering direct engagement between manufacturers and customers. This study aims to develop a framework for transforming a blank rubber mat into a custom-designed jigsaw rubber mats using abrasive waterjet (AWJ) cutting. Customers can design their own rubber mats and submit digital images, which are then processed and cut by a waterjet machine to create jigsaw rubber mats. The optimal cutting path was developed based on the number of cutting points and the similarity index to ensure precise cutting operations. The production cost was subsequently analyzed, as the uniqueness of each design influences it. The evaluation of toolpath optimization and AWJ cutting application revealed that the number of cutting points could be reduced by more than 50% compared to the original fine cutting points while maintaining a similarity index above 99%. This reduction significantly shortened cutting time. The manufacturing of customized jigsaw rubber mats incurs only a minor additional cost, approximately 13% of the overall manufacturing cost of regular rubber mats. These findings suggest that this approach could provide manufacturers with a competitive advantage by enabling the production of customer-oriented products that are both responsive and economically feasible.

Keywords: Customer-oriented design; rubber products; image processing; waterjet cutting; cost analysis

1. Introduction

Natural rubber is a key agricultural commodity in Thailand, a major exporter that supplies over a billion dollars' worth of raw materials and finished rubber goods worldwide [1]. As a polymer, rubber possesses unique structural properties that make it highly elastic and versatile, making it suitable for a wide range of applications, including tires, footwear, and seals. Typically, rubber products are manufactured through molding processes, including compression molding, transfer molding, and injection molding. Compression molding is ideal for simple-shaped products that require less precision, such as O-rings, oil seal rubber caps, and rubber mats. In contrast, injection molding is more suitable for complex products that demand higher accuracy [2]. Transfer molding is another option for manufacturers, as it requires a lower investment while still maintaining acceptable quality. In many cases, conducting a heat transfer analysis or computational fluid dynamics simulation is necessary to obtain critical data before mold design. The molding process relies on advanced technologies and highly skilled operators to ensure product quality and process efficiency [2]. However, the significant resources and effort required for mold manufacturing drive up costs considerably, including the high expense of mold materials. As a result, for molding to be economically viable, a substantial number of molded items must be produced to achieve economies of scale, a principle known as mass manufacturing [3].

As modern marketing strategies increasingly prioritize individual demands, mass production is gradually being replaced by the emerging system of mass customization. Mass-customized products effectively cater to consumers' desire for originality and uniqueness while allowing manufacturers to achieve profitable margins by adding sentimental value to their products [4]. Given the small production lot sizes—sometimes as small as a single unit for personalized premium products—agility and flexibility are crucial for business success. Customer involvement in product design has become a key competitive strategy to enhance product appeal. To accommodate diverse customer requirements, manufacturers must prepare their production processes in advance. Recognizing the inefficiencies of conventional mass production, industrialists are actively seeking more adaptive and agile production solutions. Technologies such as computer numerical control (CNC) machines, flexible manufacturing, and computer-integrated systems are being implemented to transition from mass production to mass customization, resulting in increased productivity, lower costs, and a wider range of product offerings [5]. Customizing rubber products presents a significant challenge due to the limitations of molding processes, which require large-scale manufacturing to be economically viable [6]. Alternative automated technologies can be considered, but their applicability must be carefully evaluated. In a typical production line, after the primary blanking process, a secondary post-cutting process is introduced to transform mass-produced items into more specific or customized products.

Manual cutting, often performed using a box cutter or bladed knife, is the simplest method for cutting industrial rubber products [7-9]. While this approach may appear cost-effective, manufacturers often overlook the hidden costs associated with rework and material waste resulting from poor cut quality. Additionally, manual cutting restricts each unit to a single, predetermined size. In contrast, die cutting requires a significantly higher initial investment, as dies must be custom-made for each application. The feasibility of die cutting should be assessed based on various cost factors, including machine operations, die design and production, maintenance, and potential reproduction. If the benefits of fast cutting outweigh the associated costs, die cutting becomes a desirable alternative. Non-conventional cutting techniques are gaining popularity in the industry due to their ability to handle complex materials and produce intricate shapes. Selecting the appropriate cutting process and machining operation is crucial for ensuring overall production success [10]. Mizzi et al. [11] investigated the use of laser cutting for manufacturing microstructure/auxetic rubber sheets. These structures have varying ligament thicknesses, which complicate the laser-cutting process and increase susceptibility to manufacturing issues, such as residual stress effects. Previous studies have explored the mechanism of abrasive waterjet (AWJ) cutting for rubber, revealing that material removal in rubber differs from that of metallic or brittle materials [12]. Rubber is primarily removed through shear and tensile forces created by the high-pressure waterjet, resulting in smooth cuts. Tangwarodomnukun et al. [13] developed a low-cost, sheet-based rapid prototyping technique for rubber sheets, utilizing a low-pressure waterjet to construct three-dimensional rubber sheet configurations layer by layer. The resulting prototype closely resembled the intended design.

AWJ cutting is emerging as a highly suitable automated technology for rubber cutting due to its distinct advantages, including the absence of thermal damage to the target material, high machining flexibility, and minimal environmental impact [14]. This technology enables the cutting of freeform shapes and produces smooth machined surfaces with high integrity [15]. Furthermore, unlike die cutting, AWJ cutting does not require tooling, which helps reduce costs, accelerate prototyping, and shorten production lead times. Although AWJ machining technology accommodates a wide range of materials, limited research has focused on the economic aspects of system investment and operational costs when applied to rubber [16-21]. Generally, abrasive particles account for approximately 60-70% of the total cost, while cutting speed has the most significant impact on output efficiency [16]. However, there has been minimal focus on analyzing the cutting factors that influence machining performance and cost for specific rubber materials.

Most rubber producers in Thailand are small to medium-sized businesses, and there is still a lack of awareness regarding custom-oriented rubber products. Additionally, accurate cost estimation for custom rubber mats remains limited or poorly documented. Therefore, the objective of this study is to provide a framework for manufacturing customized jigsaw rubber mats, particularly for manufacturers seeking to reduce costs by adopting post-cutting with abrasive waterjet (AWJ) technology instead of creating a new mold. This approach allows manufacturers to optimize their resources, enhance industry competitiveness, and ensure long-term viability in a dynamic market. In this study, a mass-produced blank rubber mat was transformed into a personalized jigsaw rubber mat using a post-cutting procedure. The customer's design was processed to generate an optimal tool path using CNC code for AWJ cutting, which is well-suited for rubber cutting applications. A mathematical optimization model was developed to minimize manufacturing costs while maintaining cutting performance standards. This enhanced flexibility in accommodating diverse customer demands provides a significant competitive advantage for manufacturers.

2. Materials and Methods

2.1 Rubber Mat Manufacturing Process

Rubber mats are typically made from natural rubber compounds and are widely used as flooring overlays in kindergartens and nursing homes to provide a soft and continuous surface. These overlays play a crucial role in preventing injuries in the event of accidents. Figure 1 illustrates a typical production line for rubber blanks. The production process begins with a series of rubber compound processing steps, including procuring dried rubber sheets, mixing them with additives to achieve the desired properties, and calendaring the compound into rubber sheets. The rubber compound samples are then tested for polymerization properties, such as curing temperature and curing time, to determine the appropriate forming parameters in accordance with the Thai Industrial Standard Institute (TISI) 2377-2008 [22]. After testing, the rubber sheets are cut into smaller pieces and placed into molds, where they are shaped into rubber blanks with interlocking edges using compression molding.

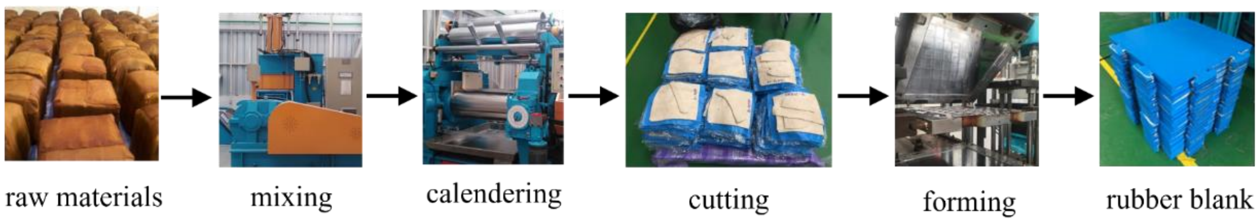


Figure 1. A rubber mat blank forming line.

2.2 Customized Rubber Mats Manufacturing Design and Cost Analysis

In this system, customers can create their own cutting designs for jigsaw rubber mats, resulting in unique, value-added products. A dedicated production line has been established specifically for this customized product, where rubber blanks are mass-produced and custom cutting is performed using automated and flexible machinery, as shown in Figure 2. A CNC abrasive waterjet cutting machine (Figure 2) is classified as soft automation, capable of cutting various materials using a high-pressure water jet stream. This machine effectively carves cured rubber sheets into customer-designed patterns with precision and efficiency.

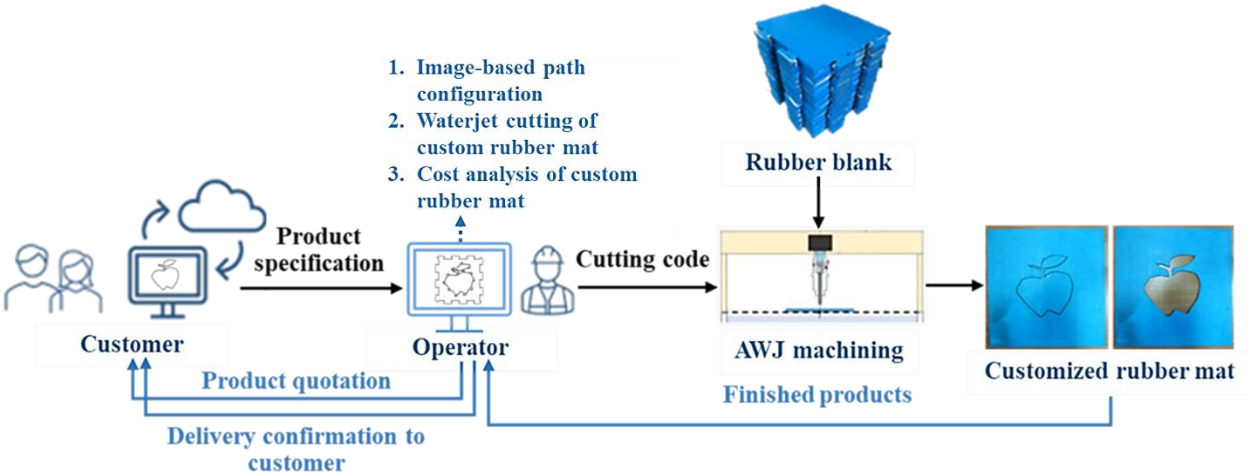


Figure 2. A proposed production line for customized rubber mats.

According to Figure 2, customers submit scribbled images along with product specifications, such as cutting dimensions, to an operator for the generation of cutting codes for the abrasive waterjet machine. Before setting the cutting paths based on the scribbled images, the operator enhances image quality using image processing techniques. To ensure that the cutting quality closely matches the original design, this method considers variables such as tolerance and spacing. Additionally, cost optimization is performed before selecting the cutting path and generating the NC code for the AWJ machine used to produce the customized rubber mats. The details of this process are explained in the following sections.

2.2.1 Image Pre-processing and Configuration of Cutting Paths

Customers can submit their design directly to the manufacturer for cutting on the rubber blank (Figure 3). If necessary, image pre-processing techniques such as resizing, filtering, and noise reduction can be applied to enhance image quality. The number of data points, or the points that the scribble passes through, can be substantial and will increase with higher resolution. These data points are used to configure the cutting path, which is established based on the image coordinate system [row (r), column (c)]. Although laser scanners and coordinate measuring devices already incorporate some pre-processing to extract data points from images, the resulting discrete data remain numerous and scattered in structure [23]. These raw data are not practically feasible for the cutting tool to follow, so they are selectively filtered to generate a set of consecutive edge data points.

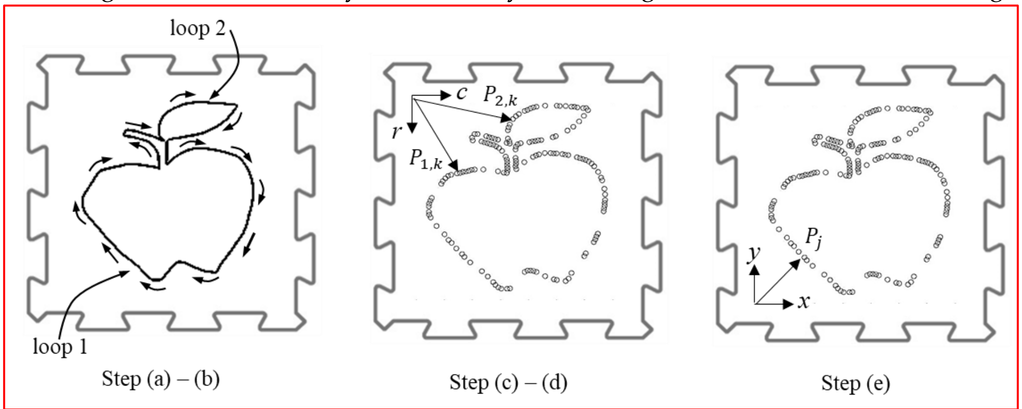


Figure 3. A sample of a cutting path configuration

Since rubber is elastic and flexible, machining errors can be more tolerable compared to other industrial materials. The cutting path can be determined through the following steps (Figure 3):

(a) Define path loop: Cluster the data points into different path loops.

(b) Create skeleton of the scribble: Within each loop, the data points are thinned to a one-pixel width spine. They are viewed as a skeleton of the scribble. The authors applied the skeletonization function in MATLAB 2023a to a binary image via the *bwmorph* function [24].

(c) Create data points: Although a band of the data points is compressed into a single pixel, the total number of points remains large, and their positions are very close to another. It is not technically and economically viable for the tool to follow, and the number of points must be reduced using a spacing factor. For any loop m at the i^{th} order, cutting points P can be explained by Eq. (1).

$$P_{m,i} \in C_{m1} \; if \; i = 1, 2s, 3s, ... \tag{1}$$

When s is a spacing factor

$C_{m,1}$ is a set of cutting points of the m^{th} loop after applying a spacing factor.

The scribble now becomes a series of connected linear segments. Their collinearity is evaluated to determine the redundancy of the points along the segment chain. The next point will be included in a set of cutting points if the deviation falls within a specified tolerance. This process is repeated until no points can be skipped further.

$$P_{m,k} \in C_{m2} \quad if \left\| (P_{m,k} - P_{m,k-1}) \times \frac{P_{m,k+1} - P_{m,k-1}}{\|P_{m,k+1} - P_{m,k-1}\|} \right\| \geq \mathrm{t} \tag{2}$$

When C_{m2} is the final set of cutting points of the m^{th} loop, and t is a specified tolerance

The tolerance t must be deliberately imposed. It is one of the cost drivers. Increasing the tolerance reduces the number of cutting points, thereby shortening the tool travel distance and machining time. However, if the tolerance is too wide, the number of cutting points will be fewer, resulting in the scribble becoming too rigid, less curvy, and deviating from the original image.

(d) Create image coordinate points: $P_{m,k}$, currently in the image coordinate space, is transformed into the machine coordinate system (Figure 3) using Eq. (2).

$$P^{M}_{m,k} = [T]P_{m,k} + V \tag{3}$$

$$T = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \tag{4}$$

where T is a transformation matrix and V is a translational vector indicating a position of the image coordinate space's origin with respect to the machine coordinate system.

(e) Create real coordinate points: This set of coordinates will subsequently need to be scaled to the real-world dimensioning.

At this stage, the total distance (D) that the tool will travel to complete the scribble can be calculated from

$$D = \sum_{i=1}^{n_m} \sum_{j=1}^{n_{pm}-1} \left| P_{j+1} - P_j \right| ; \quad P_j \in C_{m2} \tag{5}$$

when P_j is a vector of the cutting point j, n_m is the number of loops, and n_{pm} is the number of points in the m^{th} loop

The points along the cutting path are formatted into cutting code (CNC code). To ensure smooth cutting of the rubber mat, a header and additional commands are required. The most critical aspect of the cutting code is the selection of machining parameters. The following section will discuss the selection of appropriate waterjet machine parameters in relation to cutting quality and cost. An example of CNC code used for the cutting machine.

2.2.2 Abrasive Waterjet Cutting for Customized Rubber Mats

Abrasive Waterjet (AWJ) technology was adopted for post-cutting rubber jigsaw customization due to its distinct advantages, including the absence of thermal damage to target materials, high machining flexibility, and minimal environmental impact [25]. The investigation of AWJ cutting parameters affecting machining performance on rubber mats was conducted based on a preliminary study by Kirdwan et al. [26]. The feasible ranges of the parameters for through-cutting rubber mats were found to be 100-300 MPa of water pressure, 2000-4000 mm/min of cutting speed, 2 mm of standoff distance between the nozzle and the mat, and 350-370 g/min of abrasive mass flow rate of abrasive Garnet mesh 80. These parameters were configured on the Sunrise CUX400-SQ1313AWJ machine, which features an orifice diameter of 0.33 mm and a nozzle diameter of 1.02 mm, as shown in Figure 4(a). The AWJ machining technique operates by pumping ultra-high-pressure water through an aperture to create a jet beam, which is then mixed with abrasive particles in a mixing chamber, as illustrated in Figure 4(b). The AWJ travels through a focusing tube or nozzle, reshaping the jet beam before performing the cutting operation.

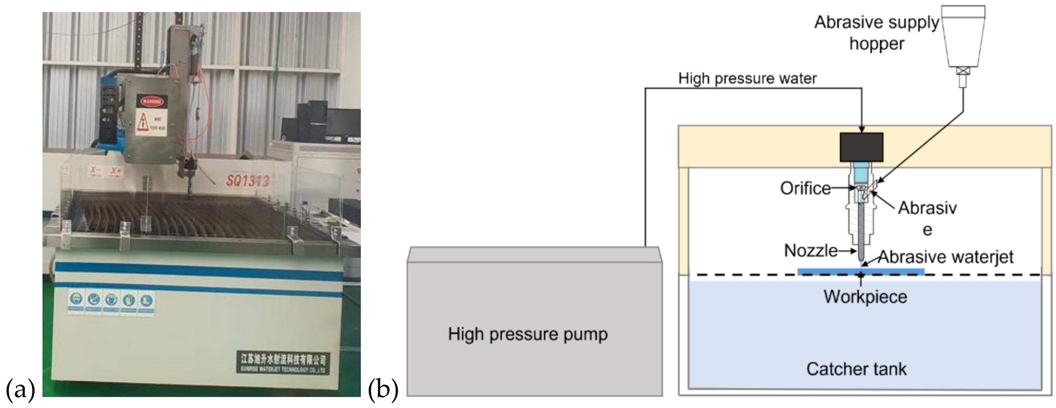


Figure 4. (a) an AWJ machine and (b) an AWJ machining system.

Two rubber mat sizes with the same rubber compound were selected for the experiments: a small mat measuring 200 mm × 200 mm × 5 mm and a large mat measuring 330 mm × 330 mm × 7 mm. The experimental setup for AWJ cutting on rubber mats is shown in Figure 5. The cutting performance indicators, including kerf width, kerf wall inclination angle, and cut surface roughness, were also evaluated.

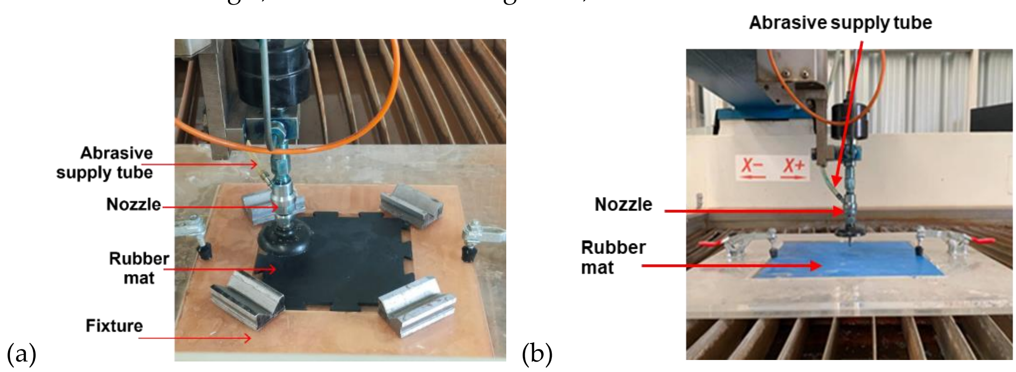


Figure 5. (a) a small mat and (b) a large mat.

The experiment involving the cutting of twelve rubber mat samples revealed that higher water pressure increased jet kinetic energy, resulting in a higher material removal rate and an increased kerf width. Conversely, a faster nozzle traverse speed resulted in reduced kerf width and depth but caused greater taper and surface roughness. Additionally, both the abrasive mass flow rate and standoff distance influenced kerf width and surface roughness. The rubber cutting removal mechanism is primarily caused by elastic deformation resulting from tensile and shear forces generated by the dynamic jet impact. During the initial cutting stage, the surface of the rubber mat was crushed when deformation exceeded its maximum threshold. A worn-down edge was observed at the kerf top edge (Figure 6(a)), and visible scratches appeared on the cut surface (Figure 6(b)), with the upper section being smoother than the lower section. As the depth of cut increased, jet impact energy decreased, resulting in varying degrees of rupture in the rubber's chemical bonds, leading to a rougher cut surface in the bottom zone [12]. A detailed analysis of the cutting mechanism can be found in Kirdwan et al. [26]. However, based on the cutting parameters considered in this study, the average machined surface roughness was measured at 3.15 μm, which was deemed acceptable for producing a jigsaw rubber mat with high-quality cuts.

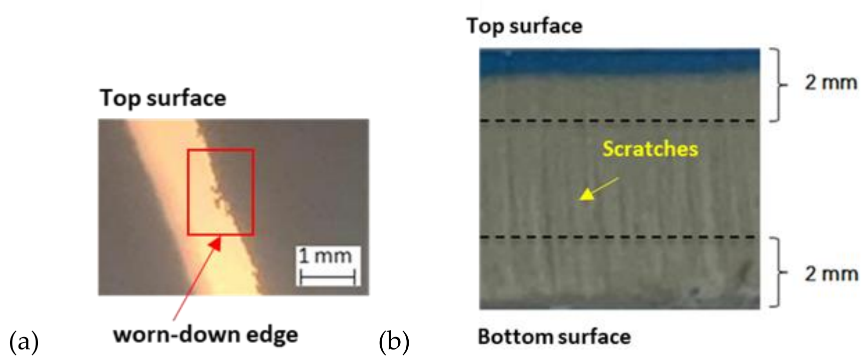


Figure 6. (a) A worn-down edge at the kerf top edge and (b) Scratches on the cut surface [27].

2.2.3 Cost Analysis for Customized Rubber Mats

Cost analysis is one of the key challenges in custom product manufacturing, as variations in unit features from one production lot to another often complicate the determination of overall product costs, particularly those related to cutting processes. Without accounting for these costs, manufacturers may struggle to establish competitive pricing necessary for market survival. In general, the cost of manufacturing jigsaw rubber mats is driven by two main activities: producing rubber blank jigsaws and performing AWJ post-cutting [26]. It is a well-known fact in manufacturing economics that costs can be broadly categorized into fixed and variable costs [28]. In the case of AWJ cutting, fixed costs are primarily influenced by expenses related to machine operations, the jet nozzle, maintenance, and parts replacement [27]. Meanwhile, changes in process parameters—such as water pressure, cutting speed, and abrasive flow rate—significantly impact variable costs. The calculation of AWJ cutting costs per hour was developed in a previous study [27]. That can be expressed as:

$$C_{T,awj} = C_1 + \left(c_{wa} \times \frac{\pi d^2}{4} \times \sqrt{\frac{2P_w}{\rho_w}}\right) + (c_{ab} \times m_{ab}) \quad (6)$$

where the first term of C_1 is the accumulated constant value, including the fixed cost of the AWJ machine system, the cost of tooling, labour, and electricity, as detailed in Table 1. The second and third terms represent the material costs associated with water and abrasive consumption, respectively. In these terms, c_{wa} and c_{ab} are the unit costs of water and abrasive, m_{ab} is the mass flow rate of abrasive consumption, d is the orifice diameter, Pw is the water pressure, and ρ_w is the water density. In this study, d and ρ_w are assumed at 0.33 mm and 997.05 kg/m^3 at 25 ºC, respectively.

From Equation (6), the cost of cutting ($C_{T,awj}$) is expressed in terms of cost per hour (currency unit/hr), which is not applicable in this study, where the variation from one design to another is so high. The cutting cost per piece ($C_{p,awj}$) is rather conclusive. It can be computed as a function of cutting speed and cutting length [27].

$$C_{p,awj} = L_t \times \left(C_{T,awj}/v\right) \quad (7)$$

where L_t is the cutting length (m) and v is the cutting speed (m/h). $C_{T,awj}$ can be determined in terms of the cutting cost per meter ($C_{m,awj}$). The constant values in Equation (6) can be obtained from the case study factory, as shown in Table 1, where a detailed analysis of AWJ cutting costs is discussed in Thongkaew et al. [27]. Thus, the cutting cost per meter under the condition of the case study factory can be expressed as:

$$C_{m,awj} = \frac{C_{T,awj}}{v} = \frac{1}{v}\left(5.05 + 2.49 \times 10^{-9} \cdot \sqrt{P_w} + 0.18 m_{ab}\right) \quad (8)$$

Table 1. Cost elements of the AWJ cutting from the case study factory [27]

Cost Element	Value	Cost	Note
- AWJ machining system cost (C_s)	2.00	USD / hr	The accumulated constant value (C1) from Eq. (6)
- Tooling cost (C_t)	1.66	USD / hr	
- Labor cost (C_l)	1.30	USD / hr	
-Electricity cost (C_e)	0.99	USD / hr	
-Unit cost of water (c_{wa})	0.63	USD / m^3	
-Unit cost of abrasive (c_{ab})	0.18	USD / kg	

Based on Equation (8), it is evident that the cutting cost is primarily influenced by cutting speed, water pressure, and the abrasive mass flow rate. Adjusting these parameters directly impacts cutting quality, as previously discussed. The interdependencies among these parameters can complicate cost analysis; however, an optimal solution exists and can be determined using Equation (9).

The minimum cutting cost function is constrained by a set of process parameters and is solved using the built-in *fmincon* function in MATLAB 2023a Optimization Toolbox [29], which allows for the minimization of a nonlinear multivariable equation under specified constraints.

- Objective function

$$min\, C_{m,awj} = \frac{1}{v}\left(5.05 + 2.49 \times 10^{-9} \cdot \sqrt{P_w} + 0.18 m_{ab}\right) \quad (9)$$

- Constraints

(a) $120 \leq v \leq 240$ (m/h) (Constraint of cutting speed)
(b) $100\text{x}10^6 \leq P_w \leq 300\ \text{x}10^6$ (Pa) (Constraint of water pressure)
(c) $20.99 \leq m_{ab} \leq 22.21$ (kg/h) (Constraint of abrasive mass flow rate)
(d) $6.315 + 0.000332v - 0\ .000613P_w - 0.01065\ m_{ab} \leq 4$ (Constraint of surface roughness)
(e) $-1.087 - 0.00027v - 0\ .000674P_w + 0.00776m_{ab} \leq 2$ (Constraint of kerf width)

3. Results and Discussion

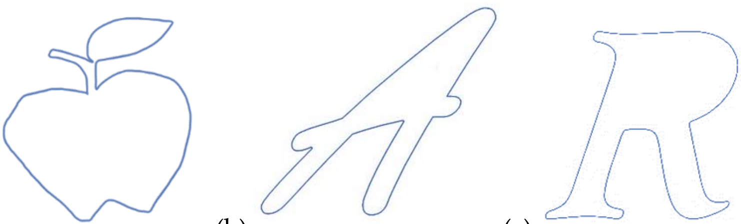
3.1 Customized Rubber Mats: Cutting Path Configuration

The spacing factor and tolerance of the cutting paths directly impact the number of cutting points and the cutting length. A larger spacing factor and higher tolerance result in fewer cutting points. However, this reduction can cause the processed image to deviate from the original design submitted by the customer. Therefore, selecting an appropriate spacing factor and tolerance is crucial to preserving the originality of the image while maintaining a cost-effective number of cutting points. In this study, a similarity index obtained from the *ssim* function in MATLAB 2023a was used to evaluate how closely the processed image matched the original design. The study considered the effects of cutting patterns, spacing factors, and tolerances. The spacing factor ranged from 2 to 10, while the tolerance was set between 0 and 1, as shown in Table 2. Table 2 presents the number of cutting points, cutting length, and similarity index for three cutting patterns—an apple, the letter "A," and the letter "R" (Figure 7)—in relation to variations in spacing factor and tolerance.

Table 2. The number of cutting points and similarity indices as affected by the spacing factors and the tolerances.

Spacing Factor (*s*)	Tolerance (*t*)	Apple		A		R	
		Cutting Points	Similarity	Cutting Points	Similarity	Cutting Points	Similarity
2	0	518	0.9948	507	0.9978	817	0.9977
2	0.5	517	0.9949	507	0.9978	817	0.9977
2	0.7	517	0.9949	507	0.9978	817	0.9977
2	0.8	360	0.9835	232	0.9726	720	0.9936
2	0.85	358	0.9831	231	0.9722	720	0.9936
2	0.9	56	0.9567	57	0.9656	72	0.9597
2	0.95	55	0.9562	57	0.9656	68	0.9587
2	1	45	0.9553	40	0.9641	52	0.958
3	0	387	0.9935	410	0.997	577	0.9968
3	0.5	340	0.9935	376	0.9969	445	0.9968
3	0.7	339	0.9935	376	0.9969	445	0.9968
:	:	:	:	:	:	:	:
8	0.85	153	0.9905	109	0.984	247	0.9943
8	0.9	143	0.9895	102	0.9802	237	0.994
8	0.95	130	0.9888	81	0.9788	186	0.9926
8	1	94	0.9851	73	0.9786	93	0.9865
10	0	161	0.9888	142	0.9941	222	0.9936
10	0.5	159	0.9888	133	0.9941	212	0.9936
10	0.7	157	0.9888	133	0.9941	212	0.9936
10	0.8	145	0.9883	106	0.9873	210	0.9935
10	0.85	140	0.9879	97	0.9854	209	0.9936
10	0.9	131	0.9871	79	0.9796	201	0.9932
10	0.95	126	0.9869	75	0.9804	156	0.9928
10	1	88	0.9859	66	0.9801	90	0.9851

Table 2 illustrates that the resulting tool paths undergo physical changes in response to adjustments in the spacing factor and tolerance. As these parameters increase, the number of cutting points decreases, simplifying both calculation and machining. However, this also causes the path to deviate significantly from the original scribble. Figure 8 further demonstrates the cutting routes generated with different spacing factors and tolerances.



(a) (b) (c)

Figure 7 (a) an apple, (b) the letter A, and (c) the letter R.

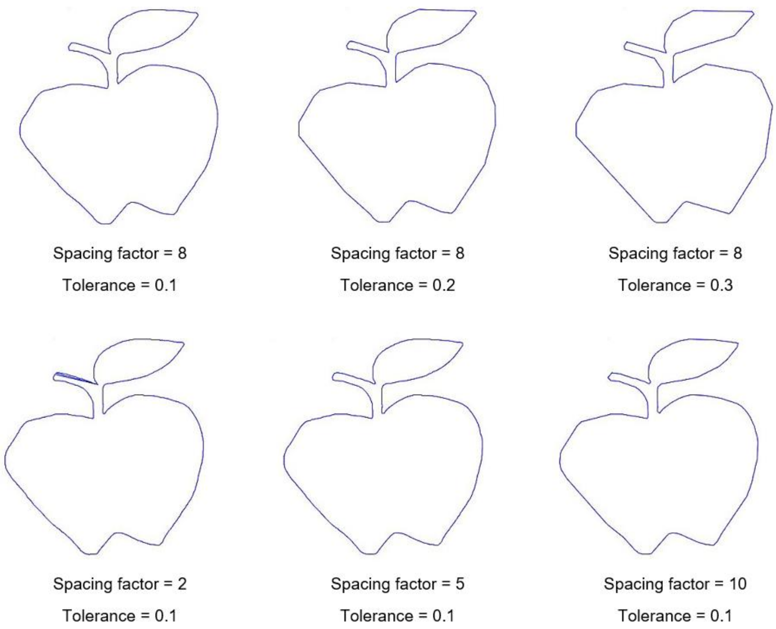


Figure 8. Examples of cutting paths at different spacing factors and tolerances.

However, as the degree of simplification increases, the similarity to the original design decreases. The number of cutting points and the similarity index were plotted across different spacing factors and tolerances to determine the optimal balance. Figure 9 highlights the optimal cutting points for each distinct cutting pattern (an apple, the letter "A," and the letter "R"). The optimal condition is identified at the point where the graph transitions abruptly to an almost horizontal line, indicating that further increasing the number of cutting points would provide only a marginal improvement in similarity. The recommended number of cutting points for the apple was 153, yielding a similarity index of 0.9905, with a spacing factor of 8 and a tolerance of 0.85. This represents a significant reduction from the original 2,040 cutting points while maintaining a high level of accuracy.

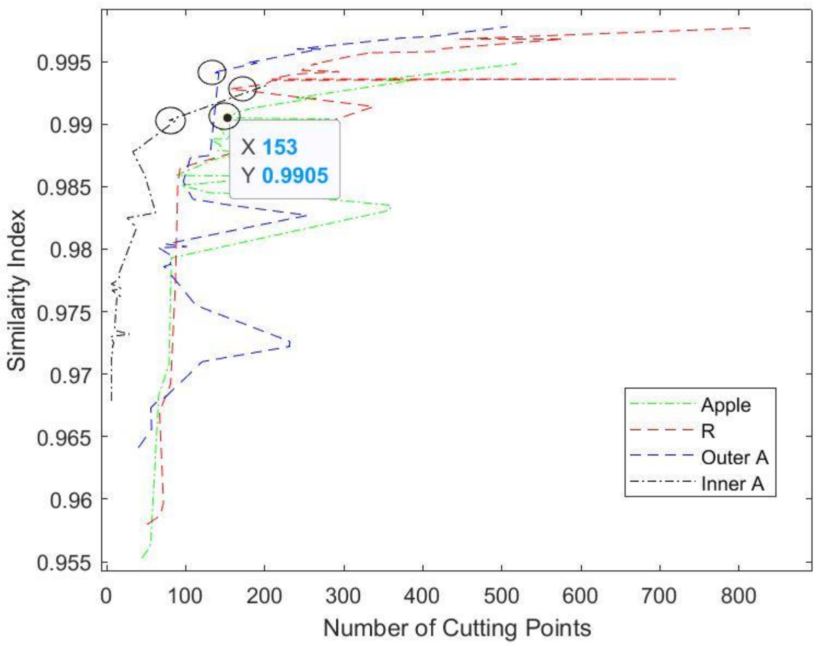
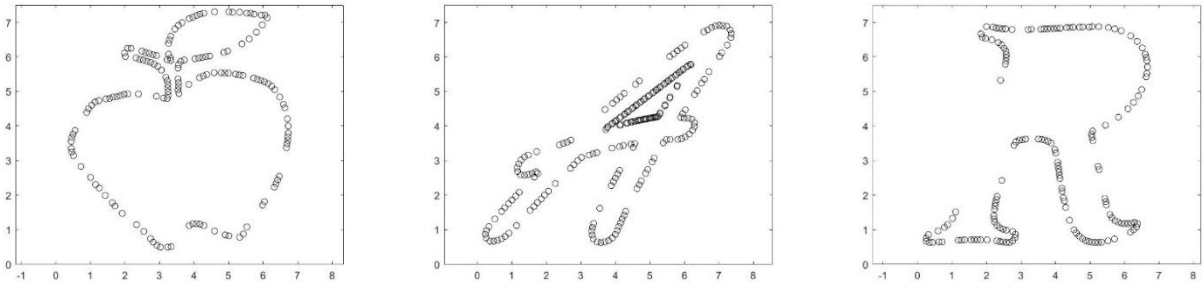


Figure 9. Similarity indices vs. No. of cutting points corresponding to spacing factor and tolerance.

The number of cutting points is initially reduced by adjusting the spacing factor. As the spacing factor increases, the path appears more like a chain of linear segments, resulting in a lower similarity index. As shown in Table 2, when the tolerance is small, most cutting points (pixel-wise) are retained, leading to a very high similarity. However, when the tolerance is increased, some points can be excluded as long as they remain within the allowable range.



(a) (b) (c)

Figure 10. The cutting paths of (a) the apple, (b) the letter A, and (c) the letter R.

The points are more concentrated in areas where the curve changes direction abruptly, as observed in Figure 10. The selected tool paths for the apple, the letter "A," and the letter "R" demonstrate a significant reduction in the number of cutting points from their initial values, resulting in fewer than 200 points. Although the letter "A" appears to be composed mainly of straight lines, some segments gradually change direction, resulting in more cutting points than expected. Using the similarity index helps identify the optimal parameters for generating an efficient tool path.

3.2 Samples of Customized Rubber Mats: Cutting Cost Analysis

After determining the optimal cutting path, a cost analysis of the cutting process was conducted, taking into account economic considerations. Using the *fmincon* function to solve Equation (9) for the minimum cutting cost, the optimal cutting parameters were established as follows: 100 MPa water pressure, 4000 mm/min (or 240 m/hr) cutting speed, and an abrasive mass flow rate of 350 g/min (or 20.99 kg/h). Under these conditions, the unit cutting cost per meter ($C_{m,awj}$) was calculated using Equation (8), resulting in a cost of 0.37 USD/m. In addition to similarity considerations, the number of cutting points also influences the cutting length, which directly affects the cutting cost. Table 3 provides an example of the cutting cost for the apple at different numbers of cutting points. The apple, the letter "A," and the letter "R" were all cut to create customized jigsaw rubber mats using the recommended tool paths and cutting parameters shown in Figure 11.

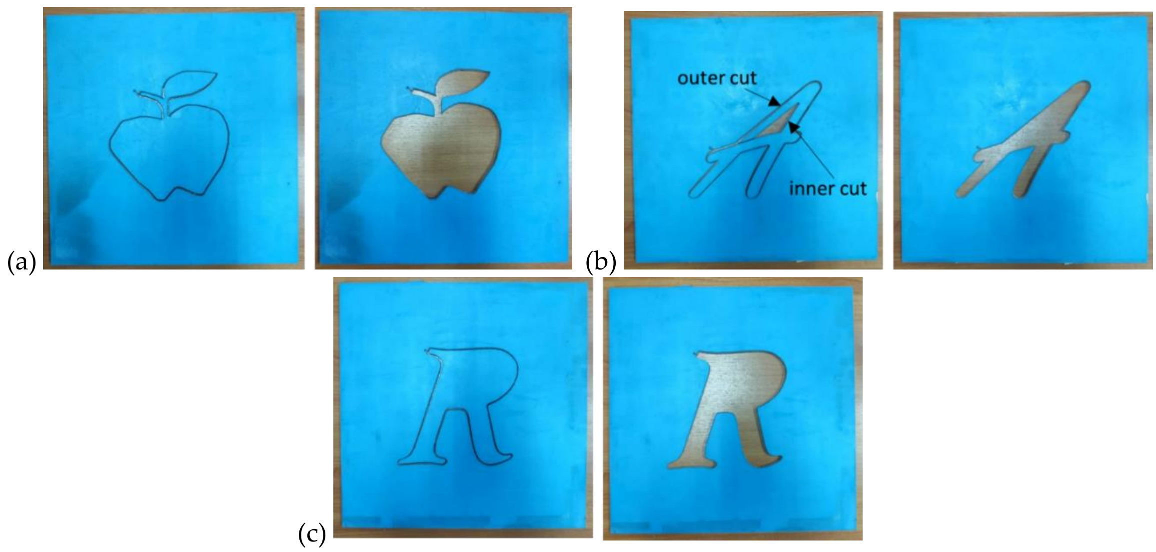


Figure 11. (a) apple shape, (b) A letter, and (c) an R letter.

Table 3. Cutting costs are affected by the cutting point and cutting distance of the apple.

Spacing Factor	Tolerance	Cutting Point	Cutting Length (mm)	Similarity	Cutting Time (s)	Cutting Cost (USD)
2	0	518	828.04	0.9948	12.4206	0.3064
2	0.5	517	828.04	0.9949	12.4206	0.3064
2	0.7	517	828.04	0.9949	12.4206	0.3064
2	0.8	360	824.99	0.9835	12.3749	0.3052
2	0.85	358	824.99	0.9831	12.3749	0.3052
2	0.9	56	814.32	0.9567	12.2148	0.3013
2	0.95	55	814.32	0.9562	12.2148	0.3013
2	1	45	813.56	0.9553	12.2034	0.3010
:	:	:	:	:		:
8	0.85	153	745.49	0.9905	11.1824	0.2758
8	0.9	143	745.49	0.9895	11.1824	0.2758
8	0.95	130	745.24	0.9888	11.1786	0.2757
8	1	94	744.98	0.9851	11.1747	0.2756
10	0	161	742.44	0.9888	11.1366	0.2747
:	:	:	:	:		:
		Average	792.3031	0.9817	11.8845	0.2932
		Std. Dev.	39.4897	0.0151	0.5923	0.0288

Table 4 presents the cutting time and cutting cost for each design, calculated using Equation (9), with cutting parameters set at a water pressure of 100 MPa, a cutting speed of 4000 mm/min, and an abrasive mass flow rate of 350 g/min. According to a previous study, the estimated production cost of a rubber blank mat was 2.90 USD per piece [27]. With the recommended cutting parameters, the post-AWJ process yielded a jigsaw rubber mat at an estimated cost of 0.37 USD per piece, adding only 12.76% to the overall manufacturing cost of the blank mat. Additionally, this cutting process operates at a very high speed, requiring less than 12 seconds per piece, making it a commercially viable option for typical industrial applications.

Table 4. Cutting time and cutting the cost of each scribble with selected parameters.

Scribble	Spacing Factor	Tolerance	Cutting Point	Cutting Length (mm)	Similarity	Cutting Time (s)	Cutting Cost (USD)
Apple	8	0.85	153	745.490	0.99	11.182	0.2758
A	10	0.7	133	702.82	0.99	10.542	0.2600
R	10	0.95	156	771.40	0.99	11.571	0.2854

Based on the analysis, personalized jigsaw rubber mats can be efficiently produced using AWJ cutting in a short time, incurring only an additional cost of approximately 13% of the total production cost of blank rubber mats. This remarkably low cost is achieved through the flexibility and agility of soft automation. The combination of imaging techniques for generating AWJ tool paths and optimizing cutting parameters has proven to be an economically viable solution for meeting custom demands. While this approach is designed to simplify the design and manufacturing processes of custom rubber mats, it also accommodates a wide range of product configurations at a competitive cost, comparable to that of mass-produced goods.

3.3 Manufacturing Cost Comparison of Customized Rubber Mats

Figure 12 presents a comparative analysis of the production costs for customized jigsaw rubber mats manufactured using three different techniques: molding, die cutting, and AWJ cutting. The costs of these manufacturing methods are displayed in relation to the quantity of finished products. The cost of traditional molding was calculated based on the fixed cost of a new mold, approximately $ 3,600, along with the variable cost of producing a rubber blank mat, which was $ 2.90 per unit [27]. The cost of die post-cutting was estimated by combining the total unit cost of manufacturing a blank rubber mat with the cost of die post-cutting, which includes expenses for a swing arm machine, labor, and electricity. The cost per piece for die cutting was approximately 9.15 USD. The cost of AWJ post-cutting was determined by adding the total unit cost of manufacturing a blank rubber mat to the AWJ post-cutting cost, which was 0.37 USD per piece.

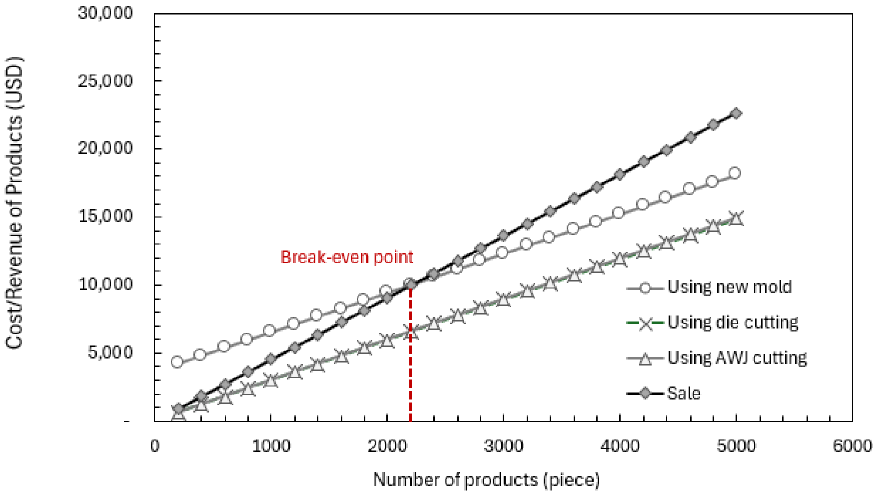


Figure 12. Customized rubber mat production costs of molding, die cutting, and AWJ cutting.

It was assumed that the unit sale price of a jigsaw rubber mat was 50% higher than its manufacturing cost, resulting in an estimated sale price of approximately 4.54 USD. According to Figure 12, the breakeven point for using the molding method was around 2,200 pieces, whereas both die cutting and AWJ cutting could generate a profit from the very first piece. However, die cutting required additional time for the production of a new die by a subcontractor, which could take up to a week. Thus, the findings indicate that AWJ post-cutting is a more suitable method for producing small quantities of customized products, offering a rapid response time and lower manufacturing costs without the need for new mold or die investments.

4. Conclusions

In this study, abrasive waterjet (AWJ) cutting was employed to transform a blank rubber mat into a custom-designed jigsaw rubber mat. This approach enhances the competitiveness of small enterprises by enabling them to offer more value-added products tailored to specific or personalized customer requirements. Once a customer's design is submitted, an AWJ cutting plan is automatically generated, along with an estimate of the production cost. To preserve the originality of the design, it is essential for manufacturers to carefully control tool path parameters, such as the spacing factor and tolerance, as these vary depending on the design. The findings of this study indicate that the additional cost of post-cutting with AWJ to produce customized jigsaw rubber mats was only approximately 13% of the total production cost. This is relatively low in comparison to the conventional method of creating a new mold. The comparative analysis further confirmed that post-AWJ cutting is well-suited for producing small to medium quantities of customized rubber mats, due to its rapid response time and lower manufacturing costs, which are achieved by eliminating the need for new mold investments. Additionally, automated machining processes, such as AWJ cutting, have become increasingly affordable in recent years. Therefore, the approach demonstrated in this study holds significant potential for small manufacturers, enabling them to leverage agility and responsiveness to remain competitive.

5. Acknowledgements

This research was financially supported by the Natural Rubber Innovation Research Institute, Prince of Songkla University (Grant No ENG62010975). The authors would also like to thank the Faculty of Engineering, Prince of Songkla University, for facility support, as well as Pornteap Kirdwan for operational support, and Rattaphum Agricultural Cooperative Ltd. for providing resources for AWJ machine rubber blanks.

Author Contributions: Conceptualization, K.T. and S.C.; methodology, K.T. and S.C.; validation, C.D. and S.C.; formal analysis, K.T.; data curation, K.T.; writing—original draft preparation, K.T.; writing—review and editing, Z.M. and S.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Rubber Innovation Research Institute, Prince of Songkla University (Grant No ENG62010975).

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] Bank of Thailand. Thailand Exports: Agriculture: Rubber. CEIC Data. https://www.ceicdata.com/en/thailand/exports-by-product-group/exports-agriculture-rubber (accessed 2022-01-26).

[2] Isayev, A. I. *Injection and Compression Molding Fundamentals*; Marcel Dekker Inc.: New York and Basel, **1987**. https://doi.org/10.1201/9780203750810

[3] Murthy, B. S.; Eifler, T.; Howard, T. J.; McMahon, C. Mass Production Tools and Process Readiness for Uniform Parts—Injection Molding Application. *J. Polym. Compos.* **2017**, *5*(3), 311–320.

[4] Fogliatto, F. S.; Silveira, G. J. C.; Borenstein, D. The mass customization decade: An updated review of the literature. *Int. J. Prod. Econ.* **2012**, *138*(1), 14–25. https://doi.org/10.1016/j.ijpe.2012.03.002

[5] Wang, Y.; Ma, H. S.; Yang, J. H.; Wang, K. S. Industry 4.0: a way from mass customization to mass personalization production. *Adv. Manuf.* **2017**, *5*(4), 311–320. https://doi.org/10.1007/s40436-017-0204-7

[6] Doner, R.; Abonyi, G. Upgrading Thailand's Rubber Industry: Opportunities and Challenges. *Thammasat Econ. J.* **2013**, *31*(4), 44–66.

[7] Mitsomwang, P.; Nagasawa, S.; Kuroiwa, H.; Fukushima, Y. Deformation Analysis of Silicone Rubber Sheet Subjected to Keen WC Blade Indentation. *Int. J. Autom. Technol.* **2024**, *8*(5), 761–772. https://doi.org/10.20965/ijat.2014.p0761

[8] Kojima, M.; Nagasawa, S.; Igarashi, Y. Cutting Characteristics of Silicone Rubber Sheet with Respect to Indentation Velocity of Keen Wedge Blade. *J. Jpn. Soc. Technol. Plast.* **2020**, *61*(708), 1–6. https://doi.org/10.9773/sosei.61.1

[9] Mispan, M. S.; Mustafa, A. H.; Sarkawi, H.; Jidin, A. Z. Low-cost and portable automatic sheet cutter. *Int. J. Electr. Comput. Eng.* **2020**, *10*(5), 5139–5146. https://doi.org/10.11591/ijece.v10i5.pp5139-5146

[10] Mizzi, L.; Salvati, E.; Spaggiari, A.; Tan, J. C.; Korsunsky, A. M. Highly stretchable two-dimensional auxetic metamaterial sheets fabricated via direct-laser cutting. *Int. J. Mech. Sci.* **2020**, *167*, 105242. https://doi.org/10.1016/j.ijmecsci.2019.105242

[11] Mizzi, L.; Salvati, E.; Spaggiari, A.; Tan, J. C.; Korsunsky, A. M. A decision guidance framework for non-traditional machining processes selection. *Ain Shams Eng. J.* **2018**, *9*(1), 203–214. https://doi.org/10.1016/j.asej.2015.10.013

[12] Hu, Y.; Kang, Y.; Wang, X. C.; Li, X. H.; Long, X. P.; Zhai, G. Y.; Huang, M. Mechanism and Experimental Investigation of Ultra High-Pressure Water Jet on Rubber Cutting. *J. Precis. Eng. Manuf.* **2014**, *15*(9), 1973–1978. https://doi.org/10.1007/s12541-014-0553-0

[13] Tangwarodomnukun, V.; Koomsap, P.; Chowdhary, A. A Preliminary Study of Applying Waterjet for Rapid Prototyping. Presented at The 11th Asia Pacific Industrial Engineering and Management Systems Conference, Melaka, Malaysia, **2010**.

[14] Natarajana, Y.; Murugesan, P. K.; Mohan, M.; Khan, S. A. L. A. Abrasive water jet machining process: a state of art of review. *J. Manuf. Processes* **2020**, *49*, 271–322. https://doi.org/10.1016/j.jmapro.2019.11.030

[15] Chen, J. F.; Yuan, Y. M.; Gao, H.; Zhou, T. Y. Smoothing strategy for corner of small curvature radius by abrasive waterjet machining. *Adv. Manuf.* **2023**, *11*(2), 390–406. https://doi.org/10.1007/s40436-023-00443-3

[16] Andersson, U.; Holmqvist, G. Strategies for Cost- and Time-effective Use of Abrasive Waterjet Cutting. Presented at WJTA American Waterjet Conference, Houston, Texas, **2005**.

[17] Radovanovic, M. Abrasive waterjet cutting cost. *Nonconventional Technol. Rev.* **2007**, *1*(1), 97–102.

[18] Radovanović, M. Cost optimization of abrasive water jet cutting using GA. *Tribol. J. BULTRIB* **2013**, *3*(3), 70–75.

[19] Ciupan, E.; Ciupan, C.; Lungu, F. The cost estimation of a water jet cutting process using artificial neural networks. *Nonconventional Technol. Rev.* **2018**, *22*(4), 26–30.
[20] Radovanovic, M. Multi-Objective Optimization of Abrasive Water Jet Cutting Using MOGA. In *23rd International Conference on Material Forming (ESAFORM 2020)*; Elsevier: Amsterdam, **2020**, *47*, 781–787. https://doi.org/10.1016/j.promfg.2020.04.241
[21] Kuagoolkijgarn, P.; Koomsap, P. Applying Image Processing for Rapid Customization of Multi-Color Nested Pattern Products. In *New World Situation: New Directions in Concurrent Engineering. Advanced Concurrent Engineering*; Springer: London, **2010**; pp 401–414. https://doi.org/10.1007/978-0-85729-024-3_40.
[22] Thai Industrial Standard Institute. Rubber Flooring: TIS 2377-2008; Thai Industrial Standard: Thailand, **2008**.
[23] Feng, H. Y.; Teng, Z. Iso-planar piecewise linear NC tool path generation from discrete measured data points. *Comput.-Aided Des.* **2005**, *37*(1), 55–64. https://doi.org/10.1016/j.cad.2004.04.001
[24] MathWorks. *Image Processing Toolbox User Guide*; The MathWorks, Inc: **2023**.
[25] Wang, J. *Abrasive Waterjet Machining of Engineering Materials*; Trans Tech Publications Inc, **2003**. https://doi.org/10.4028/www.scientific.net/MSFo.19
[26] Kirdwan, P.; Thongkaew, K.; Daesa, C.; Chaiprapat, S. Influence of Abrasive Waterjet Cutting on Efficiency of Cutting Rubber Floor Mats. *J. King Mongkut's Univ. Technol. North Bangkok* **2025**, *35*(1), 1–12. https://doi.org/10.14416/j.kmutnb.2024.09.004
[27] Thongkaew, K.; Naemsai, T.; Mustafa, Z. Cost Estimation for Post Abrasive Waterjet Cutting on Customized Jigsaw Rubber Mats. *J. Adv. Manuf. Technol.* **2023**, *1*(1), 1–16.
[28] Krachangphiphop, P.; Wannasin, J.; Meemongkol, N. Process-based cost modelling for gas induced semi-solid-processed below-knee prosthesis. *Int. J. Prod. Res.* **2018**, *56*(4), 1361–1368. https://doi.org/10.1080 00207543.2017.1364441
[29] MathWorks. *Optimization Toolbox User Guide*; The MathWorks, Inc: **2023**.