COST ESTIMATION FOR POST ABRASIVE WATERJET CUTTING ON CUSTOMIZED JIGSAW RUBBER MATS

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ABSTRACT: Rubber items are usually made through molding, which requires a large manufacturing capacity to obtain economies of scale. Post-cutting enables rubber goods to be customized without an entirely new molding process. Abrasive waterjet (AWJ) cutting is currently used to cut rubber and other materials, but limited is known about its costs. In order to evaluate the feasibility of post-AWJ cutting technology for enhancing the value of rubber products, this study aims to estimate the post-abrasive waterjet cutting required for modifying plain rubber mats to customized jigsaw rubber mats. These distinctive goods can result in value-added products that increase manufacturers' revenue and competition. It was determined how much the production of rubber mats and the post-AWJ cutting operation would cost. The variables affecting the AWJ cutting cost and the cost of producing rubber mats were examined. After that, a case study of making jigsaw rubber mats was used to calculate the unit cost of the rubber mat and the post-AWJ cutting. It was discovered that the cutting quality of the

AWJ on the rubber mats was also acceptable. The additional cost for post-AWJ cutting is accounted for simply 2.97% of the overall production costs. As a result, post-AWJ cutting can be used to create jigsaw rubber mats, and it is appropriate for customized items that manufacturers can market for 50% more than a plain rubber mat.

KEYWORDS: *Rubber Mats; Abrasive Waterjet; Post Cutting; Cost Analysis*

1.0 INTRODUCTION

Para rubber is a perennial plant known as an important economic crop of Thailand [1]. However, most of Para rubber is in terms of raw materials, (e.g. ribbed smoked sheets (RSS) rubber) that have low product prices compared to processed products. Therefore, Thai government has launched policies to support the Para rubber industry in developing Para rubber products, such as rubber barrier, rubber mats, and latex mattresses [2]. To produce rubber products, the components of additives and rubber are specified to satisfy a given application, cost, and processability [3]. Rubber mats are a popular rubber product because they are commonly used as flooring in a variety of locations. Molds regulate the shape and dimensions of rubber mats [3]. In order to modify the shape and size of a mat, a new mold is required, but the development of a new mold is time-consuming and expensive as it required precise dimension and smooth surface roughness [4]. Recently, rapid customized products have become a challenge due to the competitive market [5]. This leads to the change from manufactured-oriented to customer-oriented [6]. The ability to provide customers with what they need while decreasing expenses and increasing customer value is key to ensuring their satisfaction. Manufacturing firms cannot respond to customer demands for customized goods using simply the convectional molding technique. Consequently, supplemental operations like post cutting are an alternate action that allows for different forms and sizes of rubber mats without the requirement for an entirely new molding process.

A review of the literature on cutting processes found that abrasive waterjet machining (AWJ) technology is appealing for cutting rubber mats because it is capable of machining a variety of materials [7]. The advantages of AWJ machining include the absence of thermal damage in the target materials, high processing flexibility, and a low impact on the environment, among other machining technologies [8]. Hu et al. [9] studied the mechanism of AWJ cutting on rubber and found that the material removal mechanism for rubber was different from metallic or brittle materials. Although AWJ machining technology is widely used for many materials, analysis of economic criteria related to AWJ system investment and operating cost is still required. Radovanovic [10-12] analyzed the investment and operating costs of the AWJ cutting systems and investigated the cost optimization of the AWJ cutting based on the process performances. However, understanding the impact of process parameters on operating costs remains unclear due to a specific cutting condition. Additionally, reported studies to indicate that little attention has been paid to rubber.

Based on reviewing aforementioned, the objective of this study is to evaluate the feasibility of applying post-AWJ cutting technology to transform plain rubber mats to customized jigsaw rubber mats in order to increase product value. Investigated were the production costs of rubber mats and the post-AWJ cutting technique. In addition, particular mathematical models for customized Jigsaw rubber surfaces were developed. It also investigated how the AWJ cutting parameters affected the cost of cutting. The results of cost estimation can assist manufacturers estimate the viability of utilizing AWJ technology to raise the cost of rubber mats and respond to niche products.

2.0 METHODOLOGY

This study starts by analyzing the production of plain rubber mats in order to clarify the process stages and identify the factors influencing production costs. After this, post-AWJ cutting is considered for the additional cutting cost that transfers plain rubber mats to jigsaw rubber mats. The following section examines the improved mathematical models used to determine the production cost of rubber mats and the post-cutting cost of AWJ. In conclusion, the results of cost estimation are discussed, and recommendations are made to manufacturers regarding the economic viability of post- AWJ cutting application.

2.1 Production of Jigsaw Rubber Mats

The manufacturing process of jigsaw rubber mats include two main parts; production od plain rubber mats and post-AWJ cutting as shown in Figure 1. The details of each part are described in the following sub-topics

2.1.1 Production of Plain Rubber Mats

Raw materials including natural rubber, synthetic rubber, fillers (e.g., crumb), activators (e.g., stearic acid), accelerators, and anti-oxidant compounds are prepared prior to the production of plain rubber mats. Various raw materials are weighed according to formulation in batch size and prepared for the next mixing process. The raw materials are then fed into the mixing machine to form the rubber compound. After that, the compound rubber is put into a rolling machine to get rubber sheets. In the blank preparation step, the rubber sheets are cut into a shape corresponding to a mold size. Before having a molding process, the compound rubber needs to check the material properties according to its designed standard. In this study, the rubber mats follow to Thai industrial standard of rubber mats for flooring TISI 2377-2008 [13].

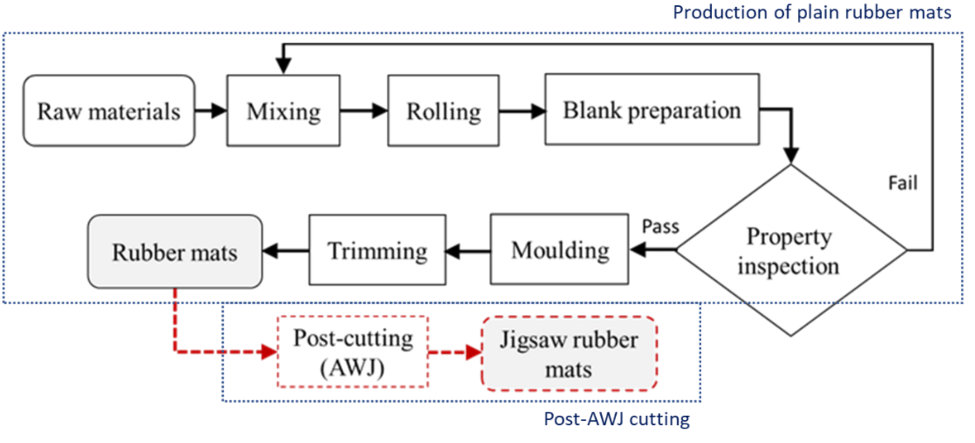
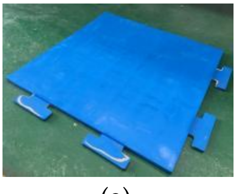
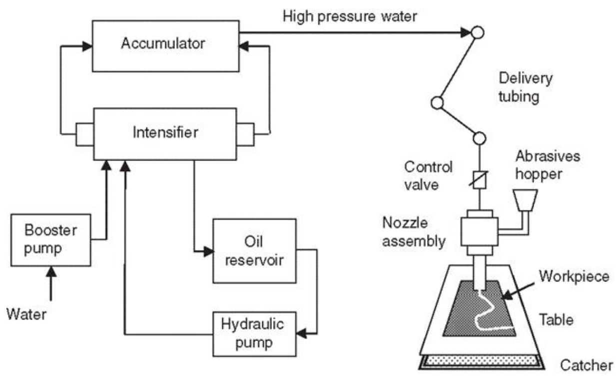


Figure 1: Manufacturing process of jigsaw rubber mats

During the molding process, the designed mold is set on a hydraulic pressing machine and the compound rubber sheets are placed in the mold. The curing process takes place in this process, whereas the temperature and curing time are set according to the properties of the compound rubber and molds designed. After the specified time, the rubber mat is removed from the mold and inspected the quality visually. Before finishing the process, the rubber mats are trimmed to remove flashes. The finished rubber mat is shown in Figure 2.(a) and is 330mm wide x 330 mm long and 7 mm thick.



(a)

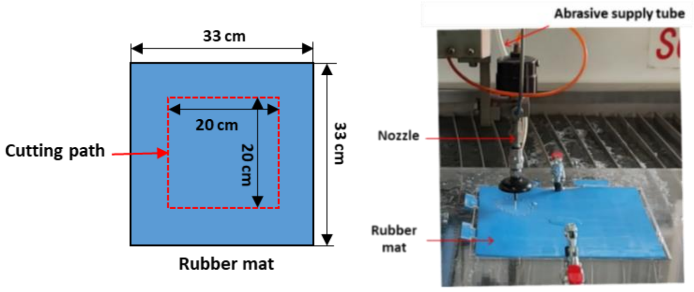


(b)

Figure 2: Finished rubber mat: (a) a rubber mat and (b) an AWJ machining system [14].

2.1.2 Post AWJ Cutting for Jigsaw Rubber Mats

Figure 2(b) illustrates the principle of ultrahigh AWJ machining process where the ultra-high water pressure created by an intensifier pump passes through an orifice to perform a high-velocity waterjet. The AWJ cutting process depends on a large number of process parameters such as water pressure, abrasive mass flow rate, cutting speed, etc. [15]. The optimum cutting condition depends on the property of the target workpiece [15]. In this study, square cutting was defined to create a jigsaw rubber mat as shown in Figure 3(a). The AWJ machine employed was Sunrise CUX400-SQ1313, which the water pressure can be up to 460 MPa. An orifice of 0.33 mm in diameter and a nozzle tube of 1.02 mm in diameter were used in the experiment. Garnet abrasives of 80 mesh with the abrasive mass flow rate of 5.83 g/s was applied. The AWJ cutting parameters were defined at 200 MPa in water pressure, 50 mm/s in cutting speed and 3 mm in standoff distance. The cutting parameter was defined according to preliminary study and the study of Shanmugam et al. [16]. The experimental set up of AWJ cutting on a rubber mat is shown in Figure 3(b). The characteristics of rubber mats cut by the AWJ including kerf width, kerf angle, and machined surface roughness were investigated using a Mitutoyo PJ-A3000 profile projector and Mitutoyo sj-310 surface roughness tester.



(a) (b)

Figure 3: Jigsaw rubber mat: (a) a cutting path and (b) experimental setup of AWJ cutting

2.2 Cost Estimation for Jigsaw Rubber Mat Production

The evaluation cost of the jigsaw rubber mat production was conducted to assess the potential advantages of applying this AWJ cutting technique. In this section. the analysis of rubber mat production cost is firstly presented, then the cost of AWJ post cutting to create the jigsaw rubber mats is later discussed.

2.2.1 Cost Estimation for Plain Rubber Mat Production

In economics, the evaluation of production costs includes fixed and variable costs [15]. The fixed costs involve the costs that are unaffected by changes in activity level over a feasible range of operations for a given capacity. On the other hand, the variable costs, on the other hand, depending on the change in activity level. For the rubber mat production, the cost was analyzed from the relationship between the process and costs. The model is developed in unit cost that is the ratio of production cost and production volume as [18]:

$$C_{T,r} = \frac{\left(C_{F,r} + C_{V,r}\right)}{N_r} \tag{1}$$

where $C_{T,r}$ is the unit cost of rubber mat (Baht/piece), $C_{F,r}$ is the fixed cost of rubber mat production (Baht/day), $C_{V,r}$ the variable cost of rubber mat production (Baht/day) and N_r *is* the number of rubber mats produced per day. From Equation (1), the fixed cost component is determined based on equipment or machines cost ($C_{e,r}$), tooling or maintenance cost ($C_{t,r}$), building or land cost ($C_{b,r}$), and overhead cost ($C_{o,r}$), expressed as:

$$C_{F,r} = C_{e,r} + C_{t,r} + C_{b,r} + C_{o,r} \tag{2}$$

The value of $C_{e,r}$ can be calculated by:

$$C_{e,r} = \frac{I_r - C_{s,r}}{D_r} \tag{3}$$

where I_r is the investment cost of the machines, $C_{s,r}$ is the machine scrap value and D_r is the depreciation period of machines. Mostly, the $C_{s,r}$ is approximately estimated by 20-40% of the investment cost, and the depreciation period of machines is defined at 5 years [18]. The calculation of $C_{t,r}$ was determined by 5% of the investment of the equipment, i.e. $0.05I_r$. The values of $C_{b,r}$, and $C_{o,r}$ are from the factory rental, and the wage of a production manager, an accountant, and a laboratory officer. The variable cost calculation ($C_{V,r}$ in Equation (1)) can be considered from the factors of raw material cost ($C_{m,r}$), direct labor cost ($C_{l,r}$), and energy cost ($C_{ee,r}$) as:

$$C_{V,r} = C_{m,r} + C_{l,r} + C_{ee,r} \tag{4}$$

The cost of raw materials ($C_{m,r}$) can be determined by the integration of compound rubber components expressed by:

$$C_{m,r} = \sum_{i=1}^{n} cr_i \times Qr_i \text{ , } i\text{: the components of compound rubber} \tag{5}$$

where cr_i and Qr_i are the unit cost and consumption volume of each component (i). With the rubber mat production, the direct labor cost ($C_{l,r}$) is counted for 6 people, whereas the cost of energy consumption $C_{ee,r}$ is from the electricity and water usage.

2.3 Cost Estimation of Post AWJ Cutting for Jigsaw Rubber Mats

The mathematical models for determining the AWJ cutting cost is first discussed in cost per hour and then converted to the cost per piece corresponding to the cutting condition. This cost calculation is the additional expense of the rubber mat production cost as shown in Figure 1. The unit cost of the AWJ cutting ($C_{T,awj}$) was also analyzed both in fixed cost ($C_{F,awj}$) and variable cost ($C_{V,awj}$), similarly as the cost of rubber mat production:

$$C_{T,awj} = \frac{\left(C_{F,awj} + C_{V,awj}\right)}{N_{awj}} \quad (6)$$

where N_{awj} is the number of jigsaw rubber mats produced per hour. The equipment cost ($C_{e,awj}$) and the tooling cost ($C_{t,awj}$) were considered for the fixed cost, $C_{F,awj}$, that can be expressed by:

$$C_{F,awj} = C_{e,awj} + C_{t,awj} \quad (7)$$

The $C_{e,awj}$ is determined from the AWJ machining system as:

$$C_{e,awj} = \frac{\left(I_{awj} - C_{s,awj}\right)}{D_{awj}} \quad (8)$$

Where I_{awj} is the investment cost of AWJ machining system, $C_{s,awj}$ is the scrap value of AWJ machine D_{awj} is the depreciation period of the AWJ machine. The value of $C_{s,awj}$ was defined by $0.4I_{awj}$ and the value of D_{awj} was determined at 5 years. The tooling cost ($C_{t,awj}$) was an account from the summation of the maintenance cost ($C_{ma,awj}$) and the cost of wear parts of the orifice and nozzle as ($C_{w,awj}$):

$$C_{t,awj} = C_{ma,awj} + C_{w,awj} \quad (9)$$

The $C_{ma,awj}$ is estimated approximately $0.05I_{awj}$, and the $C_{w,awj}$ is given by:

$$C_{w,awj} = C_{w,ori} + C_{w,noz} \quad (10)$$

Where $C_{w,ori}$ is the wear cost of an orifice that can be calculated by the orifice price, c_{ori}, divided by the orifice lifetime, l_{ori}, (i.e. c_{ori}/l_{ori}). The wear cost of a nozzle, $C_{w,noz}$, can be calculated similar as the orifice as c_{noz}/l_{noz}, where c_{noz} is the nozzle price and l_{noz} is the nozzle lifetime. In this study, the unit prices of orifice and nozzle were 330 Baht and 1,685 Baht with the orifice lifetime of 40 h/ piece and the nozzle lifetime of 90 h/ piece. The determination of variable cost for the AWJ cutting is expressed as:

$$C_{v,awj} = C_{m,awj} + C_{l,awj} + C_{ee,awj} \tag{11}$$

Where $C_{m,awj}$ is the material cost, $C_{l,awj}$ is the labor cost and $C_{ee,awj}$ is the energy cost for AWJ cutting. The $C_{m,awj}$ includes the costs of water and abrasive consumption. The abrasive consumption (Q_{ab}) was defined from the cutting parameter, while the volume of water used for AWJ cutting can be estimated from the water pressure as:

$$Q_w = A_0 \sqrt{\frac{2P_w}{\rho_w}} \tag{12}$$

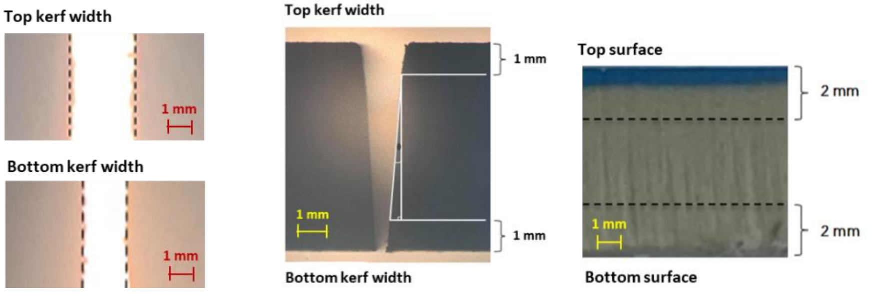
Where A_o is the cross-sectional area of an orifice, P_w is the water pressure and ρ_w is the water density. The A_o can be expressed as $A_o = \pi d^2/4$, where d is the orifice diameter of 0.33 mm. The water pressure (P_w) used in this study was 200 MPa. Substituting the value of A_o, P_w and ρ_w (i.e. ρ_w = 998.2 kg/m^3) in Equation (12). Thus, the water consumption corresponds to the cutting parameters as:

$$Q_w = 5.18 \times 10^{-4} \sqrt{\frac{2 \times 200 \times 10^6}{998.2}} = 0.33 kg / s \tag{13}$$

3.0 RESULTS AND DISCUSSION

3.1 Characteristics of Jigsaw Rubber Mats

The characteristics of machined workpieces are normally investigated in machined kerf formation (kerf width and kerf taper angle) and machined surface roughness. The characteristics of the AWJ cutting are shown in Figure 4. It has been found that the top kerf width is larger than the bottom kerf width Figure 4(a) and (b). The kerf characteristic is also similar as other cut materials such as, ductile materials [8] or composite materials [16]. However, the cutting is not quite sharp as the surface of the rubber presents elastic deformation when the waterjet impacts the rubber. This is comparable to the Hu et al. study [9]. The material removal mechanism is mainly caused by the elastic deformation under the tensile and shear forces [9]. The stability of the jet movement during cutting might be another reason affecting the straightness of the cutting. However, the cutting performance is still acceptable. The creation of the kerf is considered to be the result of the reduction in the kinetic energy of the jet as the jet cuts deeper into the workpiece [15]. For the machined surface roughness (Figure 4(c)), it can be classified according to two distinct zones: the upper smooth zone (2 mm from the top), and the lower striation or waviness zone (2 mm from the bottom). This is because the jet has sufficient energy to cut a target material consistently, resulting in a smooth surface in an upper zone. With an increase in depth of cut, however, the jet kinetic energy is reduced and unsteady, causing a waviness zone [15]. Similar to the study by Hu et al. [9], the difference in surface roughness was induced by the stretching energy of the jet and the strength of chemical bonds in rubber, where the jet energy at the lower zone can a few of bonds, leading to an uneven cut. With the cutting condition employed in this study, the results of the top kerf width were 1.59 mm, while the bottom kerf width was 1.46 mm. The kerf taper angle was 2.63º, and the top and bottom machined surface roughness was approximately 3.85 µm and 4.24 µm, respectively.



(a) (b) (c)

Figure 4: Characteristics of the AWJ cutting: (a) top view of kerf characteristics, (b) side view of kerf characteristics and (c) machined surface roughness abrasive

3.2 Cost Estimation of Jigsaw Rubber Mat Production

3.2.1 Production Cost of a Plain Rubber Mat

The production cost of rubber mats was determined according to the equations presented in 2.2.1 (Equation (1) to (5)) The information for calculating the production cost is illustrated in Table 1. From Table 1, the values of the fixed cost ($C_{F,r}$) and the variable cost ($C_{V,r}$) are 14,397.61 Baht/d and 40,828.38 Baht/d, respectively. According to the manufacturing of rubber mats, the rubber mats are produced 64 pieces/batch with a cycle time of 45 minutes. As such, with 8 hours working per day, the rubber mats can be made up to 9 batches/d or 576 pieces/d (N_r). Substituting the values of $C_{F,r}$, $C_{V,r}$, and N_r in Equation (1), the unit cost of the rubber mat is given by:

$$C_{T,r} = \frac{(14397.61 + 40828.38)}{576} = 95.88\, Bath / piece \tag{14}$$

Table 1: Cost information for producing plain rubber mats

Elements of fixed costs	Value	Unit	Elements of variable costs	Value	Unit
1. Equipment cost ($C_{e,r}$)	1,853,519	Baht/y	1. Raw material cost ($C_{m,r}$)	35,973	Baht/d
1.1 Investment cost (I_r)	15,265,996	Baht	1.1 Raw material cost	3,997	Baht
1.2 Scrap value ($C_{s,r}$)	5,998,402	Baht	1.2 Number of batches	9	Batch/d
1.3 Depreciation period (D_r)	5	y	2. Labor cost ($C_{l,r}$)	2,040	Baht/d
2. Tooling cost ($C_{t,r}$)	763,300	Baht/y	2.1 Number of operators	6	pp.
3. Building cost ($C_{b,r}$)	720,000	Baht/y	2.2 Payment rate/operator	340	Baht/d
4. Overhead cost ($C_{o,r}$)	406,560	Baht/y	3. Energy cost ($C_{ee,r}$)	2,815	Baht/d
5 Number of working days	260	Day/y			
Total fixed cost ($C_{F,r}$)	14,398	Baht/d	Total variable cost ($C_{V,r}$)	40,828	Baht/d

3.2.1 Post-AWJ Cutting Cost

The cost of the AWJ cutting was calculated using the equations presented in topic 2.2.2 (Equations (6) to (13)). The cost was considered in both fix cost and variable cost, similar as Radovanović study [10]. The information for calculating the AWJ cutting cost is shown in Table 2. The percentage of variable cost is higher than the fixed cost. The variable cost is mainly caused by the consumption of abrasives although the optimum condition is applied, according to study of Radovanović study [11]. According to the AWJ post cutting, the rubber mat was cut in the square size of 200 mm x 200 mm, to make a jigsaw rubber mat (Figure 3(a)). This results in the length cut to the square perimeter of 800 mm (L_r). The cutting used in this study was set at 50 mm/s (V_r). Thus, the cutting time (t_c) per piece is given by:

$$t_c = L_r / V_r \tag{15}$$

Besides the cutting time, the time consumption of loading/unloading the rubber mats on the AWJ machine (t_u) was also considered at 20 s. Substituting the values of L_r and V_r in Equation (15) and including the load/unload time, t_{ur}, thus the total time used for the AWJ cutting process (t_{awj}) is expressed as:

$$t_{awj} = t_c + t_u = (800/50) + 20 = 36\, s/\,piece \tag{16}$$

Table 2: Cost information for post-AWJ cutting

Elements of fixed costs	Value	Unit	Elements of variable costs	Value	Unit
1. Equipment cost ($C_{e,awj}$)	66	Baht/h	1. Raw material cost ($C_{m,awj}$)	126	Baht/h
1.1 Investment cost (I_{awj})	1,151,02	Baht	1.1 Water consumption (Q_w)	0.20	m^3/h
1.2 Scrap value ($C_{s,awj}$)	460,409	Baht	1.2 Unit cost of water (c_w)	14	Baht/m^3
1.3 Depreciation period (D_{awj})	5	y	1.3 Abrasive consumption	21	Kg/h
1.4 Machining utilization time	2,080	h/y	1.4 Unit cost of abrasive (c_{ab})	6	Baht/kg
2. Tooling cost ($C_{t,awj}$)	55	Baht/h	2. Labor cost ($C_{l,awj}$)	43	Baht/h
2.1 Maintenance cost ($C_{ma,awj}$)	28	Baht/h	2.1 Labour cost for 1 people	340	Baht/d
2.2 Cost of orifice wear ($C_{w,ori}$)	8	Baht/h	2.2 Working hour per day	8	h/d
2.3 Cost of nozzle wear ($C_{w,noz}$)	19	Baht/h	3. Energy cost ($C_{ee,awj}$)	3	Baht/h
Total fixed cost ($C_{F,awj}$)	121	Baht/h	Total variable cost ($C_{V,awj}$)	172	Baht/h

With the AWJ cutting time, t_{awj}, the number of jigsaw rubber mats can be produced per hour corresponding to the cutting condition as:

$$N_{awj} = \frac{3600}{36} = 100\, piece/h \tag{17}$$

Substituting the values of $\boldsymbol{C_{F,awj}}$, $\boldsymbol{C_{V,awj}}$, and N_{awj} in Equation (6). Thus, the total cost of AWJ cutting is given by:

$$C_{T,awj} = \frac{(121+172)}{100} = 2.93\, Bath/piece \tag{18}$$

Therefore, the unit cost of the jigsaw rubber mat ($C_{T,jr}$) can be calculated from the summation of the unit cost of rubber mat, $C_{T,r}$, (Equation (14)) and the unit cost of AWJ post cutting, $C_{T,awj}$, (Equation (18)) as:

$$C_{T,jr} = 95.88 + 2.93 = 98.81\, Bath/\,piece \tag{19}$$

From the cost estimation for post-AWJ cutting on a customized jigsaw rubber mat, it can be seen that the total cost for producing the jigsaw rubber mat ($C_{T,jr}$) was 98.81 Bath compared to 95.88 Baht for the plain rubber mat, an increase of approximately 2.97 %. As a result of the cost-cutting addition, the jigsaw rubber mat can be sold for 50% more than a plain rubber mat. The cost of cutting an AWJ varies depending on the length of the cut (L_r) under the same cutting conditions. Each cutting required less than 40 seconds to complete, including setup time. This makes it efficient for application in industry. The machined surface roughness was less than 5 μm when cutting quality was considered, which usually means further processing is not necessary. Other benefits of the AWJ include low impact on the environment and no thermal damage to the rubber mat [9]. The AWJ cut is an attractive option for producing customized jigsaw rubbers with fast the customer responds, enhancing product value. However, more study is required to determine the optimal AWJ cutting condition in terms of economic factors, as discussed in Radovanovi's works [11, 12]. In accordance to the Radovanovi study [10], decreasing the amount of abrasive used for AWJ cutting can reduce costs. A higher cutting capacity caused by an increase in water pressure and cutting speed. Based on the findings of the experiment, the investment in AWJ machines can be reduced by employing a lower-pressure pump, as rubber mats require lower pressures compared to materials with high strength, such as titanium [19]. In a later investigation, it will be established what the optimal AWJ cutting conditions are, how these factors compare to other post-cutting processes (such laser cutting), and how much product is required to satisfy the economic requirements.

4.0 CONCLUSION

The objective of this study is to analyze the feasibility of utilizing AWJ cutting technology to increase the price of a standard rubber mat to a customized jigsaw rubber mat. This technology was conducted during the post-cutting process to change the rubber mats to jigsaw rubber mats. The process started with an examination of rubber mat manufacturing and the AWJ cutting operation. Then, the factors affecting the cost of production were examined. The proposed mathematical models to evaluate the unit cost of the rubber mats and the post-AWJ cutting was analyzed to justify the investment in this technology from an economic point of view. According to the study, the unit cost of rubber mats was 95.88 Baht per unit, whereas the unit cost of AWJ post cutting was 2.93 Baht per unit. The additional expense of cutting was slightly 2.97% of the total cost of production. The time required for each cutting was less than one minute, which is acceptable for industrial use. AWJ cutting can also provide the jigsaw rubber mat with acceptable qualities, such as smooth surface roughness that does not require further finishing operation. It appears that AWJ cutting is feasible for customized products that require a diversity of cutting patterns and an immediate response time. As a result, a manufacturer can increase the value of a rubber mat by more than 50%.

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AUTHOR CONTRIBUTIONS

K. Thongkaew (Author): conceptualization, methodology, development of cost estimation models for the production of plain rubber mats and cutting according to the AWJ, cost calculation for a jigsaw rubber mat; T. Naemsai (Author): performing experiments of post-AWJ cutting, observing AWJ cutting qualities on jigsaw rubber mats; Z. Mustafa: analysis of the feasibility of post-AWJ cuts, writing-reviewing literatures. All authors read and approved the final manuscript.

CONFLICTS OF INTEREST

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

REFERENCES

[1] W. Wangpimool, K. Pongput, N. Tangtham, S. Prachansri and P.W. Gassman, "The Impact of Para Rubber Expansion on Streamflow and Other Water Balance Components of the Nam Loei River Basin, Thailand", *Water*, vol. 9, no. 1, pp. 1-20, 2017.

[2] J.N. Simon, N. Nuthammachot, K. Techato, K.E. Okpara, S. Channumsin, R. Kaewthongrach and Md.S.K. Sarkar, "Para Rubber (Hevea brasiliensis) Feedstock for Livelihoods Opportunities in Southern Thailand: Analysis of Socioeconomic Productivity Potentials

and Security", *Sustainability*, vol. 14, pp. 1-21, 2022.

[3] A. Mohajerani, L. Burnett, J. V. Smith, S. Markovskia, G. Rodwell, M.T. Rahman, H. Kurmus, M. Mirzababaei, A. Arulrajah, S. Horpibulsuk and F. Maghoolc. "Recycling Waste Rubber Tires in Construction Materials and Associated Environmental Considerations: A Review", *Resources, Conservation & Recycling*, vol. 155, pp. 1-17, 2020.

[4] M.M. Faiz, M. Hairizal, A.B. Hadzley, M.F. Naim, T. Norfauzi, U.A.A. Umar, A.A. Aziz and S. Noorazizi. "Effect of Hydraulic Pressure on Hardness, Density, Tool Wear and Surface Roughness in the Fabrication of Aluminum Based Cutting Tool", *Journal of Advanced Manufacturing Technology*, vol. 13, no. 2. pp. 23-37, 2019.

[5] Y. Qi, Z. Mao, M. Zhang and H. Guo. "Manufacturing Practices and Servitization: The Role of Mass Customization and Product Innovation Capabilities", *International Journal of Production Economics*, vol. 228, no., pp. 1-10, 2020.

[6] H. Sihombing, M.M.H. Megat Ahmad, M.Y. Yuhazri and S. Rusman, "The Design of Product Identified Towards the Cognitive Styles", *Journal of Advanced Manufacturing Technology*, vol. 14, no. 1. pp. 75-88, 2020.

[7] A.Y.C. Nee and A.Y. Ching, *Handbook of Manufacturing Engineering and Technology.* London: Springer-Verlag, 2015.

[8] J. Wang, *Abrasive Waterjet Machining of Engineering Materials.* Switzerland: Trans Tech Publications, 2003.

[9] Y. Hu, Y. Kang, X.C. Wang, X.H. Li, X.P. Long, G.Y. Zhai and M. Huang, "Mechanism and Experimental Investigation of Ultra High Pressure Water Jet on Rubber Cutting", *International Journal of Precision Engineering and Manufacturing*, vol. 15, no. 9, pp. 1973-1978, 2014.

[10] M. Radovanovic, "Abrasive Waterjet Cutting Cost", *Nonconventional Technologies Review,* vol. 1, pp. 97-102, 2007.

[11] M. Radovanovic, "Cost Optimization of Abrasive Water Jet Cutting using GA," *Tribological Journal BULTRIB*, vol. 3, pp. 70-75, 2013.

[12] M. Radovanovic, "Multi-Objective Optimization of Process Performances when Cutting Carbon Steel with Abrasive Water Jet", *Tribology in Industry*, vol. 38, no. 4, pp. 454-462, 2016.

[13] Thai Industrial Standard. "Rubber Flooring," TIS 2377-2008, 2008.

[14] J.Y. Sheikh-Ahmad, *Machining of Polymer Composites, in Nontraditional Machining of FRPs.* Boston: Springer, 2009.

[15] Y.M. Ali and J. Wang, "Impact Abrasive Machining", in *Machining with Abrasives*, M.J. Jackson and J.P. Davim, New York, Springer-Verlag, 2011 pp. 385-419.

[16] D.K. Shanmugam, T. Nguyen and J. Wang, "A Study of Delamination on Graphite/epoxy Composites in Abrasive Waterjet Machining", *Composites Part A: Applied Science and Manufacturing*, vol. 39, no. 6, pp. 923-929, 2008.

[17] P. Krachangphiphop, J. Wannasin and N. Meemongkol, "Process-Based Cost Modelling for Gas Induced Semi-Solid-Processed Below-Knee Prosthesis", *International Journal of Production Research*, vol. 56, no. 4, pp. 1361-1368, 2018.

[18] D.G. Newnan, T.G. Eschenbach and J.P. Lavelle, *Engineering Economics Analysis 13th edition.* Oxford: Oxford University Press, 2017.

[19] L. Dekster, N.E. Karkalos, P. Karmiris-Obratański and A. Markopoulos, "Evaluation of the Machinability of Ti-6Al-4V Titanium Alloy by AWJM Using a Multipass Strategy", *Applied Sciences*, vol. 3, no. 6, pp. 1-16, 2023.