INVESTIGATION OF SURFACE ROUGHNESS IN TAPER TURNING OF ALUMINIUM 6061 USING A COPY TAPER ATTACHMENT LATHE

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Abstract - This paper presents the research results on the influence of surface roughness during taper turning of Aluminium 6061 on a copy taper attachment lathe. The taper attachment lathe was designed and fully fabricated prior to the experiments in order to evaluate the stability of the equipment through its effect on the surface roughness of machined parts. In this study, the Taguchi method was applied to conduct the experiments. The experiments were carried out with a constant feed rate of S_d = 0.07 (mm/rev); V= 37.5 ÷ 45.5 (m/min); t= 0.10 ÷ 0.20 (mm) on aluminium 6061 material; A VCGT 110304 FN insert was used as the cutting tool and surface roughness R_a was measured using a Mitutoyo SJ-220 device. The experimental results demonstrate the relationship between cutting parameters (t, S_d, V) and surface roughness R_a during taper turning.

Key words - Copy taper attachment; taper angle; Aluminium 6061; surface roughness; Taguchi method.

1. Introduction

Methods for machining and forming components are classified into two groups: machining based on the relative motion trajectory between the cutting tool and the workpiece, such as cylindrical turning and taper turning, and machining based on the shape of the cutting tool, such as form turning and form milling [1]. At present, the copying principle is widely applied, especially in manufacturing processes for producing products with defined profiles. In the field of mechanical manufacturing, the copying method on lathes is capable of producing axisymmetric rotational products corresponding to fundamental forming methods [2], [3], [4].

A lathe is an indispensable piece of equipment in the mechanical engineering industry. Therefore, fixtures play an important role in improving product accuracy, facilitating operation and enhancing machine utilization efficiency. A copy taper attachment applies the copying principle to produce standard and non-standard tapered components. Among taper turning methods, the main causes of reduced component accuracy and increased machining time are the difficulties encountered during machine adjustment [2], [3]. Therefore, in order to improve the surface roughness quality of products, the adjustment mechanism must be simple; thus, the design and fabrication of a copy taper attachment for a lathe are necessary and have practical significance. This method of machining tapered surfaces is suitable for mass production and provides high efficiency [2], [3].

In practice, numerous scientific studies have been conducted on fixtures applied in mechanical manufacturing. However, most of them mainly address the fundamental theories of cylindrical turning [2], [3], [4]. Worldwide, several studies related to this field have been reported. Burton presented the operating principle and calculation formulas for turning using a copy taper attachment [5]. T. Kelly conducted research related to the depth of cut t and feed rate S_d when using a taper attachment [6]. V. Jagadeesha described the structural components and calculations involved in taper turning [7]. Emco provides the Emco-Mat 14D lathe, which includes a copy taper attachment mechanism, but no report has been published on the evaluation results of surface roughness achieved when machining with this equipment [8]. Several simulation principles of copy taper attachments have been implemented. However, studies evaluating surface quality during machining remain limited [9], [10], [11]. In Vietnam, research on this topic is still relatively new. The research group of T. N. Hai, T. X. Tai and N. T. Ly compared surface roughness when machining on lathes with spindle drives powered by an electric motor and by a hydraulic drive at the same roughness level, showing that a hydraulic drive system can be applied to machine-tool spindles [12]. N. D. Thang simulated the principle of a copy taper attachment using software to demonstrate the principles involved in taper turning [13].

Therefore, studies on the influence of component surface roughness during taper turning of aluminium 6061 alloy on a copy taper attachment lathe are needed to provide additional data for production applications. Accordingly, the study entitled: “Investigation of Surface Roughness in Taper Turning of Aluminium 6061 Alloy Using a Copy Taper Attachment Lathe” is highly necessary and serves as a basis for applying copy taper attachments to produce a variety of mechanical products that meet the requirements of the machine manufacturing industry.

2. Parameters and characteristics of the copy taper attachment

2.1. Calculation parameters

To calculate and determine the taper angle, the following formula is applied [4]:

$$tan\alpha^\circ = \frac{D-d}{2l} \quad (1)$$

In this formula, the parameters used for calculating the taper angle are illustrated in Figure 1 and described in Table 1.

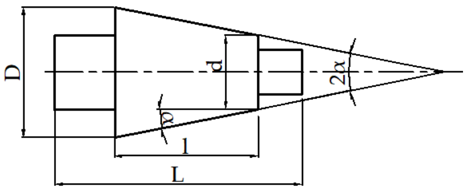


Figure 1. *Parameters for calculating the taper angle*

In this study, the author conducted experiments with the inclination angle corresponding to the standard Morse taper No. 3 [14].

Table 1. *Symbols used in the calculation*

No.	Symbol	Description	Unit
1	D	Large diameter	mm
2	d	Small diameter	mm
3	L	Workpiece length	mm
4	l	Taper length	mm
5	α	Inclination angle	°
6	2α	Taper angle	°
7	N_{dc}	Motor power	kW
8	n	Spindle speed	rpm
9	t	Depth of cut	mm
10	S_d	Longitudinal feed rate	mm/rev
11	V	Cutting speed	m/min
12	R_a	Surface roughness	µm

2.2. Operating principle and characteristics of the copy taper attachment

This method applies the principle based on the inclined movement of the turning tool relative to the rotational centre axis of the workpiece to form the tapered surface of the component. The trajectory of the turning tool is guided by the copy taper attachment, which is rigidly mounted on the lathe, as shown in Figure 2 [11].

During machining, the cross-slide carriage (7) slides along the guideway of the copy taper attachment in the sliding groove and is directly connected to the slider on the guide bar of the copy taper attachment (8), as shown in the experimental design model in Figure 3. The inclination angle is adjusted according to either a standard taper or a non-standard taper. The feed motion is parallel to the direction of the copy taper attachment [13].

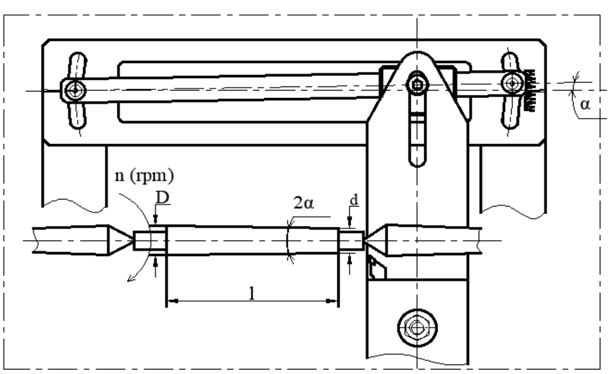


Figure 2. *Operating principle of the copy taper attachment*

The experimental machine design model shown in Figure 3 has the following characteristics: the cutting conditions and machining length can be adjusted to meet the required specifications; the taper angle can be easily adjusted and the required surface roughness quality R_a can be achieved.

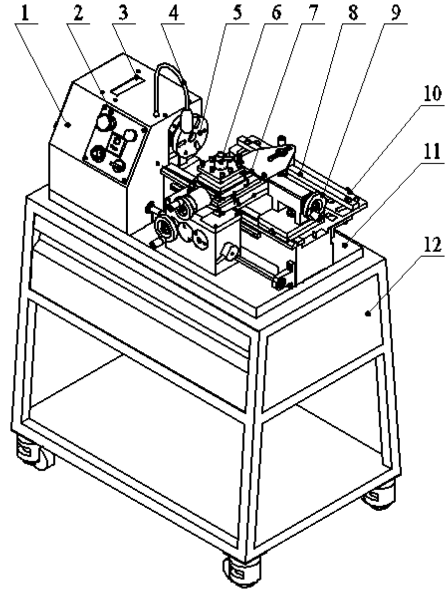


Figure 3. *Experimental machine design model*

The components and detailed parts of the machine model are listed and described in Table 2.

Table 2. *Structure of the copy taper attachment lathe*

No.	Component	Function
1	Change gear box	Feed rate S_d
2	Control cabinet	Controls the operation of the lathe
3	Speed gearbox	Transmission ratio 1/2
4	Machine lamp	Illuminates the machining area
5	Faceplate	Transmit rotational motion to the workpiece
6	Tool post	Holds the turning tool
7	Carriage	Provides longitudinal and transverse motion
8	Slide bar	Guides the taper attachment
9	Tailstock	Holds the centre
10	Copy taper attachment	Adjusts angle α
11	Chip tray	Collects chips
12	Tool table	Stores machine tools

3. Experimental investigation of the effect of surface roughness in taper turning

3.1. Experimental equipment

The copy taper attachment lathe model was designed, fabricated and operated based on the copying method. The equipment has the technological capability to machine standard tapered components such as tool-holder sockets, lathe centres, taper shafts and standard taper sleeves according to TCVN 136:2007 [14], as well as non-standard tapers.

The experimental equipment has the following specifications: a brushless motor with a power of

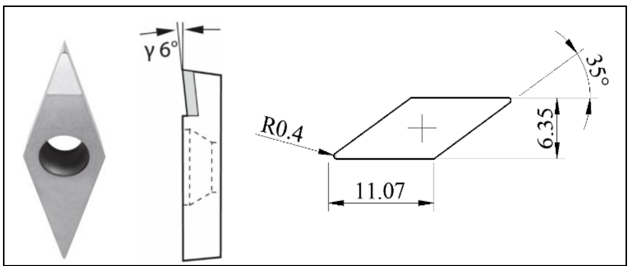
N_{dc}= 0.55 kW which drives the spindle through a mechanical transmission system and a dedicated control circuit board. The spindle operates within a continuously variable speed range of n= 250 ÷1440 (rpm). The longitudinal feed rate S_d is obtained through a change gear set and a mechanical transmission system, with S_d= 0.07 (mm/rev) according to the technical specifications of the equipment.

The fabricated and completely assembled experimental copy taper attachment lathe model is shown in Figure 4.

Figure 4. *Experimental machine model*

For the cutting experiment, the author selected the cutting tool, parameters and insert designation according to Garant, as presented in Table 3 [15].

Table 3. *Turning insert parameters*



No.	Description	Tool parameter
1	ISO standard	VCGT 110304 FN
2	Tool nose radius	0.4 (mm)
3	Insert material type	PCD
4	Depth of cut t	0.10 ÷ 2.5 (mm)
5	Feed rate	0.03 ÷ 0.4 (mm/rev)
6	Cutting speed for Al< 10% Si	300 ÷ 2000 (m/min)

In this study, based on the experimental equipment, the cutting conditions (t, S_d, V) were selected according to the recommendations of Garant. The parameters are shown in Table 4 and the experiments were conducted under dry cutting conditions without the use of coolant.

Table 4. *Cutting conditions t, S_d, V*

t (mm)	S_d (mm/rev)	V (m/min)
0.10	0.07	37.5
0.15	0.07	41.5
0.20	0.07	45.5

3.2. Measuring instruments

In this experiment, the following measuring instruments were used to inspect the machined components:

- Mitutoyo 530-312 vernier caliper [16].
- Mitutoyo 2046A-80 dial indicator [17].
- Viber X4 rotational speed measuring device [18].
- Mitutoyo SJ-220 surface roughness tester [19].
- Inspection tool for Morse taper No. 3 standard taper shafts [14].

3.3. Experimental material

The workpieces were prepared before machining and their dimensions are shown in Figure 5. The material used was aluminium 6061 alloy [20].

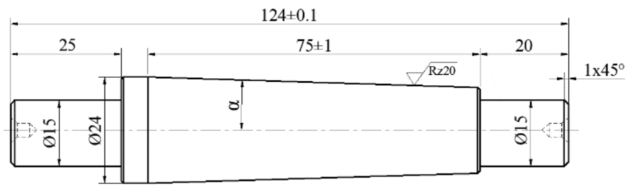


Figure 5. *Workpiece before machining*

The dimensions and shape of the component after machining are shown in Figure 6.

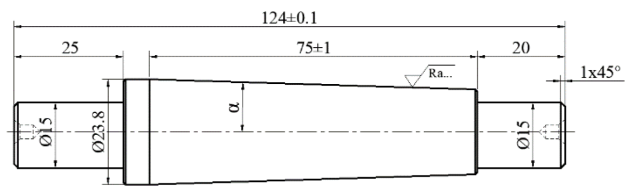


Figure 6. *Component after machining*

3.4. Experimental method

At present, various experimental methods are available, such as fractional and full factorial experimental designs; second-order experimental designs, including type B or FCCCD, type D, Box–Behnken designs, and others; and the Taguchi method [21], [22], [23], [24], [25]. In this study, the author applied the Taguchi method because it offers several advantages and is more suitable for the experimental conditions.

In this study, the requirement was that the machined component should achieve the lowest possible surface roughness. Therefore, a minimization problem was applied and the response value y_i was required to be minimized according to the "smaller-the-better" criterion. It is calculated using the following formula [21]:

$$\frac{S}{N} = -10log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (2)$$

Where: n is the number of repeated experiments.

The cutting process causes material deformation and separation from the workpiece under the action of cutting forces. This is a complex process involving many simultaneous phenomena, including cutting forces, plastic deformation, heat generation and built-up edge formation [21].

The factors affecting the surface roughness quality of the component are mainly the cutting conditions (t, S_d, V). In addition, surface quality is also affected by other factors such as equipment rigidity, workpiece clamping, workpiece material, cutting tool and others [21].

Due to limitations in the experimental conditions and the equipment adjustment capability for the feed rate S_d the author investigated the effects of two factors on the surface roughness quality R_a (μm) of the component: depth of cut t= 0.10 ÷ 0.20 (mm) and cutting speed V= 37.5 ÷ 45.5 (m/min). In addition, the feed rate was kept constant at S_d= 0.07 (mm/rev) to ensure stability during the experiment.

According to the Taguchi method [21], the author selected the L_9 (9TN) orthogonal array, consisting of **9 experiments.** Each experiment was repeated n= 5 times, with two influencing factors and three levels, as shown in Table 5.

Table 5. *Factors and levels*

No.	Factor	Symbol		Level			Range
		Natural	Coded	Low	Medium	High	
1	Depth of cut	t	x_1	0.10	0.15	0.20	0.05
2	Cutting speed	V	x_2	37.5	41.5	45.5	4

According to the Taguchi method, the experimental design matrix was established and the experimental results are shown in Table 6.

Table 6. *Experimental results and S/N ratio*

Run	Factor		Number of measurements					Response value y_i R_a (μm)	S/N ratio
	t	V	L1	L2	L3	L4	L5		
1	1	1	0.801	0.807	0.809	0.811	0.817	0.809	8.831
2	1	2	0.658	0.662	0.666	0.669	0.675	0.666	10.520
3	1	3	0.585	0.589	0.592	0.595	0.599	0.592	11.543
4	2	1	0.571	0.576	0.579	0.582	0.587	0.579	11.736
5	2	2	0.524	0.529	0.532	0.535	0.540	0.532	12.471
6	2	3	0.586	0.590	0.592	0.594	0.598	0.592	11.543
7	3	1	0.557	0.562	0.565	0.568	0.573	0.565	11.949
8	3	2	0.654	0.659	0.662	0.665	0.670	0.662	10.573
9	3	3	0.594	0.599	0.602	0.605	0.610	0.602	11.398

To determine the influence level of the factors, the S/N ratio and ANOVA analysis were used [24] - [28]. According to Formula (2), the author calculated the S/N ratios and the results are presented in Table 6. The mean S/N value for each level, representing the performance index at that level, was calculated for each level of each factor using the following formula [21]:

$$\eta_{mj} = Mean\left(\frac{S}{N}\right) = \frac{1}{p}\sum_{i=1}^{p}\left(\frac{S}{N}\right)_i \quad (3)$$

Where: p is the number of elements at the same level of factor j.

The mean values at the levels of the factors in Table 7 were determined according to Formula (3) as follows:

$$t_1 = \frac{1}{3}\sum_{i=1}^{3}\left(\frac{S}{N}\right)_i = \frac{1}{3}\left[\left(\frac{S}{N}\right)_1 + \left(\frac{S}{N}\right)_2 + \left(\frac{S}{N}\right)_3\right]$$

$$= \frac{1}{3}[8.831 + 10.520 + 11.543] = 10.298$$

Similarly, the remaining mean values were calculated and the results are shown in Table 7.

Table 7. *Factors affecting surface roughness based on S/N ratio [21]*

No.	Factor level	Calculation	Factor	
			t	V
1	Level 1	Eq. (2)	10.298	10.839
2	Level 2	Eq. (2)	**11.917**	11.188
3	Level 3	Eq. (2)	11.306	**11.495**
4	Mean (m)	(1+2+3)/ 3	11.174	11.174
Optimal cutting parameters			**t_2**	**V_3**

According to the calculation of the factors affecting surface roughness based on the S/N ratio in Table 7, the optimal parameters are **t_2V_3** với: t_2= 0.15 (mm); V_3= 45.5 (m/min).

ANOVA analysis was performed to evaluate the effects of t and V on the surface roughness quality R_a during the machining of aluminium 6061 alloy, as presented in Table 8.

Table 8. *ANOVA analysis for R_a*

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)	Rank
t	2	0.023	0.011	1.722	0.289	82.14	1
V	2	0.005	0.002	0.353	0.723	17.86	2
Error	4	0.026	0.007				
Total	8	0.054				100	

The ANOVA analysis in Table 8 shows that the contribution ratio of the depth of cut t to the surface roughness quality R_a is 82.14%, which is higher than that of the cutting speed V, at 17.86%.

The confirmation experimental results indicate that the optimal cutting condition is **t_2V_3**, with a surface roughness value of R_a= 0.603 (μm).

Based on the ANOVA analysis and the confirmation experimental results, the optimal cutting condition for machining aluminium 6061 alloy on the copy taper attachment lathe is **t_2V_3**. The error in R_a compared with the predicted value is 0.011, which satisfies the machining requirements.

Some experimental images obtained during the study are presented below:

+ The workpiece was mounted between two centres, as shown in Figure 7(a).

+ The spindle speed of the experimental machine was checked at n_3= 600 (rpm) corresponding to the cutting speed V_3, as shown in Figure 7(b).

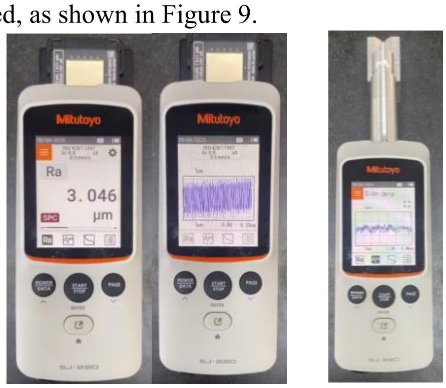
(a) *(b)*

Figure 7. *Workpiece setup diagram (a), spindle speed inspection (b)*

+ Images of the machined component samples are shown in Figure 8.

Figure 8. *Component samples after machining*

+ The surface roughness of the sample components after machining on the experimental equipment was measured, as shown in Figure 9.



(a) *(b)*

Figure 9. *Calibration process of the surface roughness tester (a), workpiece setup for surface roughness measurement (b)*

The chart in Figure 10 shows the effects of the parameters t and V according to the S/N ratio.

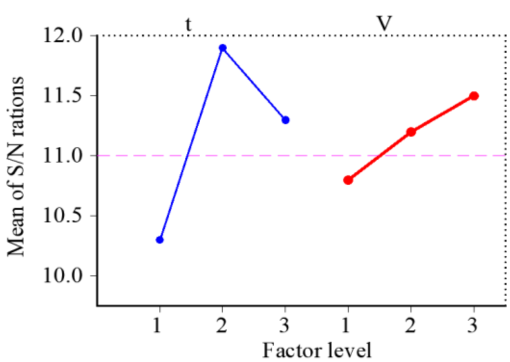


Figure 10. *S/N ratio results*

4. Conclusion

The research and experimental results indicate that:

- The copy taper attachment lathe operated stably under the cutting conditions of S_d= 0.07 (mm/rev); V= 45.5 (m/min); t= 0.15 (mm) achieving a surface roughness quality of R_a= 0.592 (μm) with an error of 0.011.
- The ANOVA analysis results show that the contribution ratio of the depth of cut t to the surface roughness quality R_a was 82.14%, which was higher than that of the cutting speed V, at 17.86%.
- The structure of the copy taper attachment components is easy to machine, assemble, adjust and has practical application significance. It is suitable for mass production and provides high efficiency.

In the future, further studies should be conducted on the influence of feed rate variation and on other materials, such as steel or non-ferrous metals, in order to further expand the applicability of this research.

RERERENCES

[1] M. P. Groover, *Fundamentals of Modern Manufacturing: Materials, Processes and Systems*, 7th Edition. NJ: Wiley, 2021.

[2] T. V. Dich, *Turning Technology*, NJ: Science and Technology Publishing House, 2007.

[3] T. T. San, H. Tri and N. T. Hung, *Mechnical Practice: Turning - Milling - Grinding*. NJ: Science and Technology Publishing House, 2010.

[4] D. V. Linh, N. N. Dao and T. T. San, *Practical Guide to Turning Technology*. NJ: Da Nang Publishing House, 2008.

[5] Walter. E. Burton, "Lathe Taper Attachment", *Neme-s.org*, January, 1962. [Online]. Available: http://www.neme-s.org/Model_Engineer_Files/Popular_Mechanics-Lathe_Taper_Attachment.pdf [Accessed Apr. 14, 2026].

[6] T. Kelly, "Project on copy turning", *Production Engineer*, vol. 46, no. 11, pp. 651–660, Nov. 1967. https://doi: 10.1049/tpe.1967.0089.

[7] V. Jagadeesha, "A STUDY ON COMPONENTS OF LATHE MACHINE", *Asian Journal of Multidimensional Research (AJMR)*, vol. 11, pp. 111-112, 2022.

[8] *Instruction Manual Emcomat 14*, Ref.-no. EN 2203, Edition B2011-09, Emco, Australia, 2011.

[9] Summary Planet, "Taper turning", *summaryplanet.com*, 2001. [Online]. Available: https://www.summaryplanet.com/engineering/taper-turning.html [Accessed Apr. 16, 2026].

[10] L. Virasak, *Manufacturing Processes 4-5*. NJ: Open Oregon Educational Resources, 2026.

[11] The US Army, "How to Use a Lathe", *americanmachinetools.com,* [Online]. Available: https://www.americanmachinetools.com/how_to_use_a_lathe.htm [Accessed Apr. 14, 2026].

[12] T. N. Hai, T. X. Tuy, and N. T. Ly, "Research samples'surface roughness of Turning lathes when spindle driven by a hydraulic motor", *The University of Danang - Journal of Science and Technology*, vol. 11, no. 120, 2017.

[13] N. D. Thang, "Tapered turning attachment 1", *technologymag.net,* April, 08, 2018. [Online]. Available: https://www.technologymag.net/mo-phong-co-cau-co-khi-do-ga-tien-con-1/ [Accessed April 14, 2026].

[14] *Machine tools - Self - holding tapers for shanks*, TCVN 136:2007, 2007.

[15] Hoffmann Group, "Indexable insert for turning VCGT 110304 FN, PKD (7°)", *hoffmann-group.com*, October, 22, 2025. [Online]. Available: https://cdn.hoffmann-group.com/dsh/en-GB/dsh_en-gb_39851.pdf [Accessed April 16, 2026].

[16] Mitutoyo, "Vernier Caliper 0-150 mm", *mitutoyomall.vn*, October, 2021. [Online]. Available: https://www2.mitutoyo.co.jp/eng/useful/

catalog-2021/html5.html#page=229 [Accessed April 16, 2026].

[17] Mitutoyo, "Dial indicator 2046A-80", *mitutoyomall.vn,* October, 2021. [Online]. Available: https://www2.mitutoyo.co.jp /eng/useful/catalog-2021/html5.html#page=395 [Accessed April 14, 2026].

[18] Viber, "Vibration Measurement Instruments", *benchmarkpdm.com*, December, 2020. [Online]. Available: https://benchmarkpdm.com/ wp-content/uploads/2020/12/datasheet_viberx4.pdf [Accessed April 14, 2026].

[19] Mitutoyo, "New SJ-220", *measure.mitutoyo.com*, February, 2025. [Online]. Available: https://mitutoyo.com/webfoo/wp-content/uploads/SJ-220_E15036-US.pdf [Accessed April 14, 2026].

[20] S. Kalpakjian, S. R. Schmid, *Manufacturing Engineering and Technology in SI Units*, 8th Edition. NJ: Pearson, 2022.

[21] N. H. Loc, *Textbook of Experimental Design and Analysis*. NJ: VNU-HCM University Press, 2025.

[22] N. H. Son and T. D. Son, "Determining the coefficient in the Taylor formula when processing Aluminium Alloy [AlSi5Zn4Cu] using TiN-coated knife on CNC lathe", *The University of Danang - Journal of Science and Technology*, vol. 23, no. 4, pp. 113–120, 2025. https://doi: 10.31130/ud-jst.2025.042

[23] N. K. Trieu *et al,* "Development and Characterization of a Thermoforming Apparatus Using Axiomatic Design Theory and Taguchi Method", *Journal of Mechanical Engineering Research and Developments*, vol. 43, no. 6, pp. 255-268, 2020. https://doi.org/ 10.21203/rs.3.rs-33447/vl

[24] P. N. Q. Huy *et al*, " Studying the Effects of Cutting Parameters on Surface Roughness in Milling of Aluminium Alloy using The Taguchi" *Journal of Mechanical Engineering Research and Developments*, vol. 23, no. 11, pp. 54-59, 2025. https://doi: 10.31130/ud-jst.2025.23(11).331

[25] C. D. Kiet, N. C. Trung, N. K. Trieu, and P. A. Duc, "Study the Influence of Operating Parameters on the Thickness Uniformity of Thermoformed Products of a Labscale Thermoforming Device using the Taguchi Method", *Journal of Mechanical Engineering Research and Developments*, vol. 22, no. 7, pp. 6-11, 2024. https://jst-ud.vn/jst-ud/article/view/9008/6238

[26] T. C. Cong, "Application of Adaptive Neuro-Fuzzy Inference System for Predicting Surface Roughness in Turning AISI 304 Steel", *Journal of Mechanical Engineering Research and Developments*, vol. 23, no. 2, pp. 88-92, 2025. https://doi: 10.31130/ud-jst.2025.573

[27] T. C. Chi, L. V. Tuan, N. V. Tuu, and T. V. Tuong, "Optimization of the Effect of Processing Parameters on Surface Roughness and Material Removal Rate in CNC Milling of Al-7075 Material", *TNU Journal of Science and Technology*, vol. 228, no. 02, pp. 103–110, Dec. 2022. https://doi: 10.34238/tnu-jst.6965.

[28] P. V. Bong, T. V. Hoi, and T. V. Dich, "Modelling the Effect of Cutting Parameters on Surface Microhardness in Turning SUS304 Austenitic Stainless Steel", *Journal of Science & Technology*, vol. 57, no. 03, pp. 75–79, June. 2021.