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EFFECTS OF CUTTING PARAMETERS ON SURFACE ROUGHNESS OF MACHINING MARBLE WITH DIAMOND DISC

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Abstract – *Gemstone engraving on computer numerical control (CNC) machines has become gradually more popular. However, the surface quality of the material had many errors and inaccuracies after processing. Determining cutting parameters in marble processing was necessary for product quality. Cutting parameters determined the surface roughness of the product obtained after processing. This article presented the effects of cutting modes on surface quality after machining marble with diamond cutting discs. The study used experimental planning methods and ANOVA analysis of variance to evaluate empirical regression parameters. The results showed that the cutting speed parameter significantly influenced surface roughness. The surface roughness increased when the cutting depth parameter and tool feed increased. Research results could be applied to optimize cutting modes to limit material cracking and increase product surface quality.*

Keywords: ANOVA, CNC, diamond cutting discs, gemstone engraving, surface roughness.

I. INTRODUCTION

Marble is an extremely popular decorative and fine art stone for architectural purposes, carving, and jewelry use. Due to its aesthetic appearance and high value, the manufacturing and polishing process is often meticulously crafted to create a quality appearance that is widely popular in the market [1, 2]. However, marble is one of the brittle materials that breaks easily when exploited because its structure is easily affected. This is because geological continuity can affect the quality of marble, leading to micro and macro cracks [3]. Surface roughness is one of the most urgent requirements in the gemstone processing process. This parameter can be considered a factor in evaluating product quality and directly affects production costs. Because after the processing process, the product needs to be polished. The higher the shine, the higher the product value will be. To control and influence surface quality, it is necessary to have an accurate measurement system and good technical equipment for the production process. In machining, influences from external factors and conditions impact the material, and roughness is directly affected by surface texture, tool shape, and cutting conditions such as speed, cutting, feed rate, and depth of cut [4]. Many researchers have analyzed the manufacturing process and specific cutting parameters related to the machinability of marble and other natural stones made on computer numerical control (CNC) machines, which can significantly impact surface roughness [5–7]. The parameters that affect machining efficiency and roughness have been widely studied. However, the cutting mode's influence on the surface quality of stone materials after machining has not been accurately investigated and evaluated [2]. Diamond-cutting discs are commonly used tools for the gemstone carving process. The cutting mechanism of this tool includes diamond particles attached to the tool's surface, which will directly cut the material through the stone fracturing process. The cutting process is mainly affected by the mechanical and physical properties of the stone material, such as grain size and strength; different minerals

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have different effects on the cutting mechanism, adhesive abrasion, and diamond wear. Other factors that influence this process are the cutting force between the diamond and the material, the stress distribution, and the temperature inside the contact surface of the workpiece [8]. Many research projects aim to survey and test the influence of technological parameters on surface roughness in natural stone production. Ribeiro et al. [9] studied the influence of technological parameters on the roughness of granite after processing. Research results show a correlation between Knoop hardness and Amsler wear; material structure has the strongest influence on the brightness of granite surface. In stone milling, researchers investigate the wear of cutting tools with the help of force-measuring devices. To cut different types of natural stone, Polini et al. [10] investigated the diamond mill wear in the time domain during stone cutting using cutting force, and Turchetta et al. [11] experimented with stone machining performance using force and specific energy. The studies have examined the relationship between changes in tool wear and cutting force. Through the use of sensors, the axial force factors generated were measured. Research has shown that technological parameters significantly influence tool wear and cutting force. In addition, research also indicates that the wear rate of cutting discs can be improved by optimizing technological parameters. In the case of granite, the applied technological parameters (feed rate, cutting speed, and depth of cut) can significantly influence the surface roughness after rough machining. Research on the effects of different production parameters on the granite surface after cutting by Aydin et al. [12]. Microscopic observations of the material surface obtained after machining have shown that the average surface roughness projected on the surface increases due to increased cutting speed and cutting depth [12]. In general, when carving natural stone, such as granite or marble, the cutting mode affects the surface quality of the product. This will determine the quality and the value of the product.

This study presents the effect of cutting mode on the marble surface after machining with diamond cutting discs on CNC milling machines. The research process will provide input parameters, including cutting speed (V), feed rate (f), and depth of cut (d) set for machining on Fusion 360 software. Roughness measuring device Lext to check the marble surface after machining gives R_a value results. The experimental planning method and ANOVA analysis of variance were used in the study to evaluate and build a regression function on the surface roughness of marble materials. Besides, the research explores the influence of input values on the surface roughness of marble materials, thereby selecting the optimal cutting mode to make machining more effective and cost-saving. The smoothness of the surface of brittle objects increases the life of cutting tools.

II. EXPERIMENT DESIGN

The processing of gemstones depends on many different factors. The meticulousness and skill of the craftsman will create quality fine art products. Auto processing with CNC machining can replicate a table from one product to many products with the same shape. However, each machining method must go through specific machining processes, as shown in Figure 1. The preparation steps of the stone workpiece will affect the entire manufacturing process, from which shaping and machining can be considered rough. Manual processing goes through a rough shaping stage and then a shaping step. Automatic machining involves selecting the cutting mode, performing rough machining, and finishing machining. Choosing the cutting mode to process each type of stone needs to be carefully prepared because this step will cause damage to the material, such as the quality of the machined surface, causing wear on the cutting tool, the appearance of cracks, and the like. Therefore, the study investigates the influence of cutting modes on the surface quality of marble after machining to reduce cutting tool wear and breakage of machined materials, then proceeds with finishing machining, cleaning the workpiece, and polishing the product.

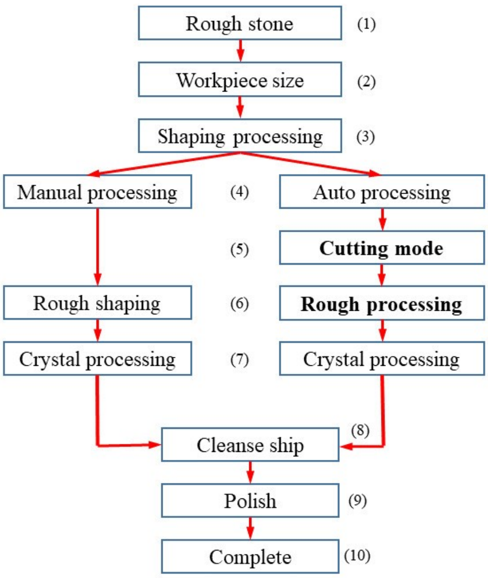

Fig. 1: Gemstone carving process

The experimental process was conducted on a small desktop CNC milling machine designed and manufactured to specialize in engraving brittle and fragile fine art stone materials such as marble, sapphire, and quartz. The primary vibrations of the tool follow the three axes: X, Y, and Z. The Y axis is the direction of the depth of the cut. Rotating the A and B axes affects the engraving of arcs and curves on the object shown in Table 1. Machining is in the range size of 60 × 60 × 60 mm, and spindle speed can be changed to 0∼18,000 PRM [13, 14].

Table 1: CNC milling machine parameters

Parameters	Value
X, Y, and Z axis limits	100 mm
Rotation angle of the A axis	180^0
Rotation angle of the B axis	360^0
Spindle speed	0~18,000 PRM
Cutter size	∅ (3~8) mm × 60 mm
Material size	60 × 60 × 60 mm^3

Source: Author's summary [4, 6, 7]

Fig. 2: Marble samples used in the experiment

Table 2: Physical properties of marble

Parameters	Value
Hardness	3~4 Mohr
Density	2,5~2,65 kg/m^3
Compressive intensity	1800~2100 kg/cm^3

Source: Author's summary [4, 6, 7]

The fixture is designed to fix the sample and position the shear force sensor. Force Sensitivity Range (FSR) cutting force sensors in the range of 0∼10.02 Newtons type FSR 400 is used. FSR can measure applied force in the range of 100 g∼10 kg. To reduce the temperature generated during the cutting process, a water-cooling system is continuously supplied until the end of the machining process. The processing material is green marble, a precious stone used in fine arts, decoration, and gemstone carving, as shown in Figure 2. The experimental sample has dimensions of 23 mm × 10 mm × 15 mm for 13 workpieces. The hardness of the material ranges from 3 to 4 on the Mohr scale, as shown in Table 2. Green marble has a chemical composition including CaO, SiO_2, Fe_2O_3, MgO, and Al_2O_3 [15]. Marble is composed mainly of calcite, dolomite, or the remaining minerals. The chemical composition of marble includes the following main components: 38∼42% Lime (CaO), 20∼25% Silica (SiO_2), 2∼4% Alumina (Al_2O_3), 1.5∼2.5% oxide (NaO and MgO), and 30–32% ($MgCO_3$ and others). The cutting tool is a diamond cutting disc in the

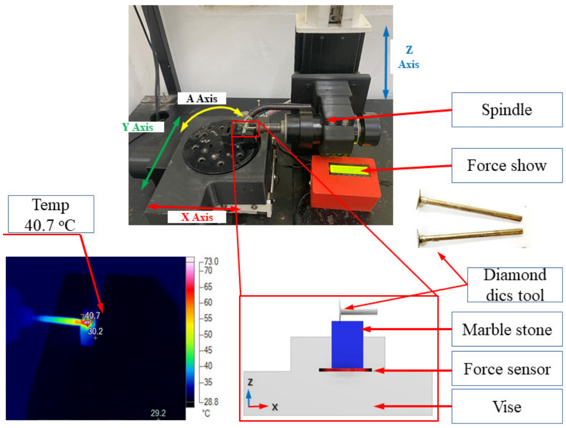

Fig. 3: Experimental setup on CNC milling machine

form of a T-shaped disc with a cutting diameter of 8 mm; this tool is used to carve jade manually, engrave stone, and polish metal surfaces. The experimental setup on the CNC milling machine is described in Figure 3. The 150 times and 500 times magnified surfaces of the cutting edge are depicted in Figure 4a and Figure 4b. Figure 4b shows a cutting wheel with a diamond density of 50 pieces in 500 μm and an average diamond grain size in the range of 98∼22 μm was fabricated through electroplating.

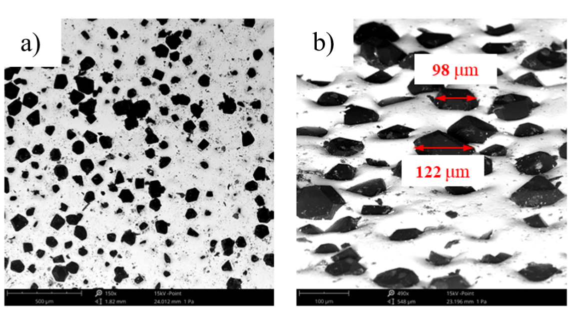

Fig. 4: Distribution and size of diamond particles on the cutting disc tool: a) The distribution of diamond particles is magnified 150 times; b) The diamond grain size on the cutting wheel was enlarged 500 times

A. *Experimental parameters*

Experiment on the effect of cutting mode on marble surface quality used the experimental planning Taguchi matrix method, including 13 experiments corresponding to three input variables, including cutting speed (V), feed rate (f), and depth of cut (d). The output factor is the surface roughness R_a(μm). In which V is selected in the range of 2,000∼4,000 mm/min, f from 200∼600 mm/min, and d in the range of 0.5∼1.5 mm. The largest and smallest experimental limits of the region selected according to planning are: V_{min} = 2,000 mm/min; f_{min} = 200 mm/min; t_{min} = 0.5 mm; V_{max} = 4,000 m/min; f_{max} = 600 mm/min; d_{max} = 1.5 mm. The values in experiments are presented in Table 3.

Table 3: Variation values in the experiment

Factors	***V*** **(mm/min)**	***F*** **(mm/min)**	***D*** **(mm)**
Level 1	2,000	200	0.5
Level 2	3,000	400	1
Level 3	4,000	600	1.5
Variability	1,000	200	0.5

Source: Author's summary [4, 6, 7]

The cutting process takes place from large-sized diamond particles directly abraded on the stone's surface, removing debris after machining to create the machined surface. The particles create scratches and abrasions due to the action of friction between the stone surface and the diamond particles on the cutting tool [11]. In the experiment, the T-shaped diamond cutting wheel performing cutting depth mainly concentrated on the diamond grains at the edges of the cutting tool. Diamond particles in the surface remaining on the cutting tool will create an experimental surface. Excessive wear reduces the ability to retain diamond particles and the life of parts. The machining process will occur when the diamond cutting wheel starts cutting when loaded with the program according to the parameters V, f, and d changed in each experiment. Limiting the cutting path in one machining session to length L. Parameter V is made according to the fixed number of revolutions of the spindle motor. At the same time, f is the motion parameter in the

Z direction at a cutting force F_v. The depth of cut d moves along the X axis cutting with a cutting force F_r, as shown in Figure 5.

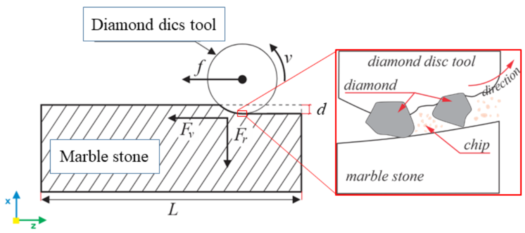

Fig. 5: Mechanism of machining experimental samples using diamond cutting discs

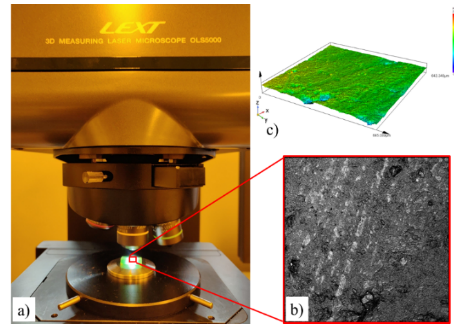

Fig. 6: Arrangement for measuring material surface roughness on Lext measuring device: a) Conduct sample measurements; b) Measuring sample surface; c) Surface measurement results after machining

B. Measurement surface roughness

After machining, the samples will be checked for surface roughness on a 3D laser microscope OLS5000-SAF Lext (Olympus, Inc., Japan) with 10 × to 100 × magnification with aberration at 405 nm. To ensure highly reliable measurement results, the experimental sample will be measured five times with Objective lens measurement parameters: Mplapon20 × Lext; zoom: 1×, Pitch: 1.2. The experimental sample surface size chosen for measurement is 645.089 × 643.348 (μm). The measurement setup of the surface roughness is depicted in Figure 6.

Table 4 shows the measurement results of the surface roughness after processing. The marble samples have been evaluated for each experiment to obtain surface roughness measurements of marble. The samples conduct direct measurements on an area located on the surface before and after machining, and the final R_a values of the measurements are determined by the average value. The roughness of 13 experiments was determined from 2,11∼2,64 (μm). The difference in measurement results of each experiment is not much when processing natural stone materials. The brittle nature of the material can explain this; during the machining process, the contact of the diamond particles on the cutting disc directly on the surface of the marble is not uniform, and the selected cutting mode is not uniform. However, the cracking on the sample surface is only at a low level.

Table 4: Results and logarithm of cutting parameters affecting R_a

No	V (mm/min)	f (mm/min)	d (mm)	R_a (µm)	ln$V$	Lnf	ln$d$	ln R_a
1	4,000	600	1	2.11	8.34	6.46	0	0.75
2	4,000	200	1	2.31	8.34	5.38	0	0.84
3	3,000	200	1.5	2.43	8.01	5.38	0.4	0.97
4	3,000	600	1.5	2.47	8.01	6.46	0.4	0.91
5	4,000	400	0.5	2.35	8.34	6.11	-0.73	0.85
6	3,000	200	0.5	2.44	8.01	5.38	-0.73	0.91
7	4,000	400	1.5	2.15	8.34	6.11	0.4	0.85
8	2,000	200	1	2.64	7.60	5.38	0	0.97
9	3,000	400	1	2.41	8.01	6.11	0	0.99
10	2,000	400	0.5	2.63	7.60	6.11	-0.73	0.96
11	2,000	400	1.5	2.6	7.60	6.11	0.4	0.95
12	3,000	600	0.5	2.48	8.01	6.46	-0.73	0.91
13	2,000	600	1	2.55	7.60	6.46	0	0.94

Source: Author's summary [4, 6, 7]

The quality of the marble surface after machining was measured and observed using a Lext measuring device, as shown in Figure 7. The surface morphology after machining was selected with five results according to the R_a values of 2.11 μm, 2.31 μm, 2.47 μm, and 2.64 μm to evaluate the surface condition according to each experiment. Images form the microscope shown the marble surface is primarily affected, and the possibility of breaking the stone surface also appears in a few locations. In Figure 7a, with cutting parameters with V = 4,000 mm/min, f = 600 mm/min, d = 1 mm, R_a = 2.11 μm, the cracks appear to be very low density and small size. This significant uniformity means that in this cutting mode, the cutting force is evenly distributed during the cutting process. When the surface roughness value R_a = 2.31 μm, as shown in Figure 7b, the cutting surface gradually appears grooves created by the diamond particles on the cutting tool during the cutting process, and many microscopic cracks appear. Figure 7c illustrates the surface roughness of marble when machined with cutting parameters V = 3,000 mm/min, f = 600 mm/min, d = 1.5 mm, the greater the number of microscopic cracks. Scratches caused by cutting tools also increased dramatically due to the large cutting force of the diamond cutting disc acting on the marble surface, affecting the cutting process. As shown in Figure 7d, the surface roughness after machining has a value of R_a = 2.64 μm with machining parameters V = 2,000 mm/min, f = 200 mm/min, d = 1 mm, which seems to have appeared a lot. The crack is macroscopic, the size of the crack is more significant and more profound, and the cut grooves and scratches during the machining process also appear more clearly.

III. RESULTS AND DISCUSSION

The mathematical model of the cutting surface roughness of marble depending on the technological parameters (V, f, d) when machining with diamond cutting discs is described by the following nonlinear Equation (1).

$$R_a = C_1 \times V^{C_2} \times f^{C_3} \times d^{C_4} \quad (1)$$

In which: R_a is the surface roughness (μm); c1, c2, c3, and c4 are coefficients determined during the experiment. To determine the constant and exponent of the equation, this mathematical model is linearized using a logarithmic function that is rewritten in Equation (2).

$$\ln R_a = \ln C_1 + c_2 \ln V + c_3 \ln f + c_4 \ln d \quad (2)$$

The linear model has the form of Equation (3).

$$y = q_0 + q_1 x_1 + + q_2 x_2 + + q_3 x_3 \quad (3)$$

Excel software with the Regression tool shows the results of variance analysis in Table 5. Equation (3) will correspond to Equation (4).

$$y = 3.10596 - 0.00019x_1 - 0.00013x_2 - 0.0625x_3 \quad (4)$$

Variance analysis shows that the theoretical F of 0.000168 is less than 0.5, so the obtained regression Equation (5) is consistent with reality. The dependence equation of R_a to the parameters V, f and d will be presented in Equation (5).

$$R_a = 22.33065 \times V^{-0.00019} \times f^{-0.00013} \times d^{-0.0625} \text{ } (\mu\text{m}) \quad (5)$$

Equation (5) gives a graph of the relationship between R_a and technology parameters (V, f, d), as shown in Figures 8, 9, and 10. Results of regression analysis of R_a to (V, f, d) show that the R Square value is 0.8831 and the Fisher standard comparison between the calculation is 22.663, which is greater than the theoretical value, thus showing that one of the partial coefficients is different, from zero and the statistical significance is high.

Figures 8, 9, and 10 presented the influence of cutting mode on the quality of the marble surface after machining when cutting speed V was set in the ranges of 2,000~4,000 mm/min, feed rate f changes in the range of 200~600 mm/min, the cutting depth d ranges 0.5~1.5 mm, the output result of the surface roughness of the following marble ranges from 2.11~2.64 μm. As seen in Figure 8, the parameter f = 600 is fixed, the value of the parameter d increases, the R_a value increases, the V value increases, and the R_a value decreases. Figure 9 depicts the effects of V, f on R_a when d = 1.5. When the value of parameter V increases, the surface roughness value R_a decreases, the value of tool feed f decreases, and the R_a value decreases when fixing parameter d = 1.5 mm. In Figure 10, when the value f increases, the value of R_a decreases, and the price t increases, R_a increases. In short, when the feed rate parameter f and the depth of cut parameter d increase, the surface roughness R_a increases.

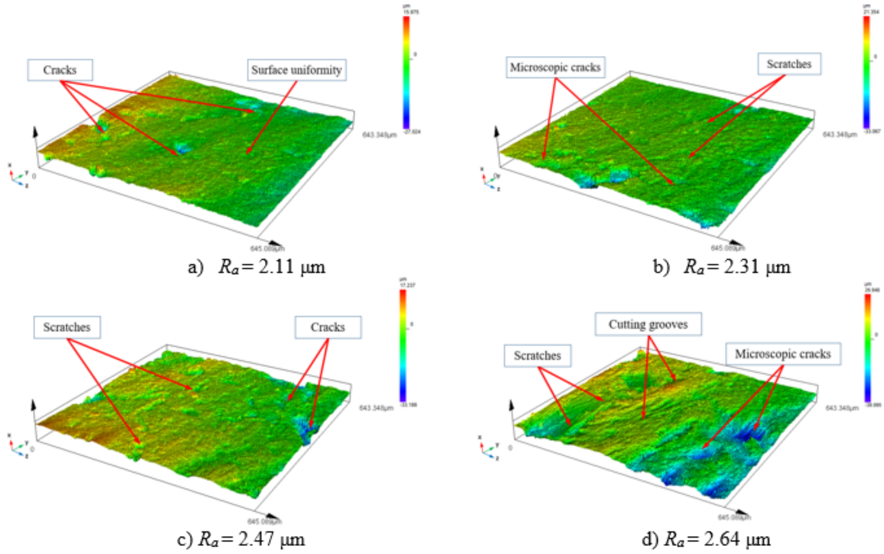

Fig. 7: Measurement results of marble surface morphology R_a

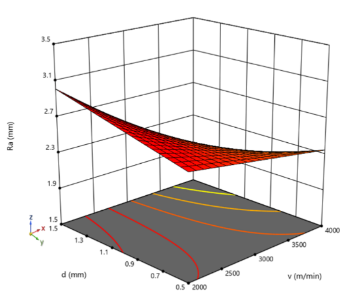

Fig. 8: Effects of V, d on R_a when f = 600 mm/min

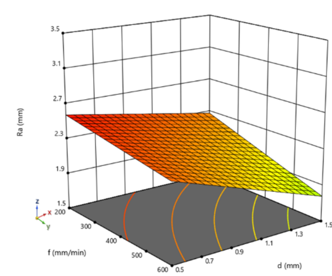

Fig. 10: Effects of f, d on R_a when V = 2,000 mm/min

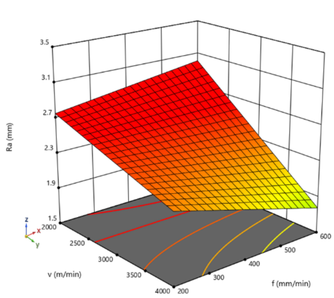

Fig. 9: Effects of V, f on R_a when d = 1.5 mm

The experimental results show a consistent relationship between machining parameters and surface roughness, which agrees with the results of previous studies [4–7]. That is, the depth of the cut parameter has a minor influence on surface roughness compared to the amount of feed and cutting speed. According to the experimental conditions of this study, the increase or decrease of technological parameters for marble materials when machining with diamond cutting discs can choose the appropriate cutting mode to meet the

Table 5: Variance analysis of the influence of technological parameters (V, f, d) on R_a

Regression statistics				
Multiple R	**R Square**	**Adjusted R Square**	**Standard Error**	**Observations**
0.9397	0.8831	0.8441	0.0658	13

ANOVA					
	df	**SS**	**MS**	**F**	**Significance F**
Regression	3	0.2946	0.098	22,6630	0.0002
Residual	9	0.0390	0.0043		
Total	12	0.3335			

	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**	**Lower 95%**	**Upper 95%**
Intercept	3.1060	0.0977	31.7992	1.477E	2.8850	3.3269	2.8850	3.3269
V	-0.0001	2.33E	-8.0569	2.092E	-0.0002	-0.0001	-0.0002	-0.0001
f	-0.0001	0.0001	-1.1280	0.2885	-0.0004	-0.0001	-0.0004	0.0001
d	-0.0625	0.0465	-1.3428	0.2122	-0.1678	0.0428	-0.1678	0.0428

Source: Author's summary [4, 6, 7]

requirements. The optimal cutting mode for the smallest surface roughness in this study with V, f, and d are 4,000 mm/min, 600 mm/min, and 1mm, respectively.

IV. CONCLUSION

This study presented experimental machining of marble with diamond cutting discs to investigate the influence of cutting mode on surface quality. The process of designing samples and measuring marble roughness using the Lext measuring device has been updated. The experimental planning method and ANOVA analysis of variance to build the regression function are presented. Research results show that the cutting speed parameter has the most influence on surface roughness. When the cutting speed increases, the value of Ra will decrease. On the other hand, when the f and d values increase, the value of Ra will increase. Increasing or decreasing the technological parameters for natural stone processing materials can optimize and select the appropriate cutting mode, thereby limiting the cracking of the material and growing surface quality.

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