International Journal on Advanced Science Engineering Information Technology

Vol.14 (2024) No. 2
ISSN: 2088-5334

Optimization of Machining Parameters on The Geometry Precision of Cortical Screw of Ti-6Al-4V ELI Using Gray Relational Analysis Method

Gusri Akhyar Ibrahim [a,*], Arinal Hamni [a], Yanuar Burhanuddin [a], Muhammad Yahya [a]

[a] *Departement of Mechanical Engineering University of Lampung, Bandar Lampung, 35141, Indonesia*
*Corresponding author: *gusri.akhyar@eng.unila.ac.id*

Abstract— **Titanium and its alloys have been widely developed in aerospace, biomedical, electronics, sports, and offshore. In the biomedical field, titanium alloy that has been widely used, based on its properties, is biocompatible for bone implants and not becoming a foreign thing in the body. This study aims to optimize to determine the optimal conditions for cutting parameters for the precision of the cortical thread screw geometry referring to the ISO 5835 standard. In this study, the cutting was carried out using a CNC lathe, where the machining parameters used were spindle rotation of 100, 200, and 300 rpm, depth of cut of 0.01, 0.02, and 0.03 mm, and types of lubricants in the form of synthetic oil, virgin palm oil, and virgin coconut oil. Data processing in this study is analyzed using the Gray Relational Analysis Method to get an optimal combination of cutting conditions. The significant factor that influences the precision of cortical thread is the depth of cut, which is a contribution of 98%. It can illustrate that the smaller depth of cut will produce better screw geometry. The optimum conditions for cutting parameters that deliver the best level of precision were obtained at a spindle speed of 100 rpm, depth of cut of 0.01 mm, and type of lubricant of coconut oil. Meanwhile, the screw surface damage is stacked chips as a result of the high temperature generated during the cutting process.**

Keywords— **GRA; cortical screw; precision; optimal; Ti-6Al-4V- ELI.**

Manuscript received 2 Aug. 2023; revised 7 Sep. 2023; accepted 24 Mar. 2024. Date of publication 30 Apr. 2024.

I. INTRODUCTION

Titanium and its alloys are known as materials that are widely used in various industrial fields, including the aerospace, biomedical, electronics, offshore, and automotive component industries [1], [2], [3]. Titanium and titanium alloys have been used on a large scale in the aircraft industry because these materials have superior properties, such as a good combination of strength-to-weight ratio at high temperatures (strength-to-weight ratio), fracture resistance properties, and corrosion resistance properties. corrosion resistant at high temperatures. Meanwhile, in the biomedical field, titanium alloy with the Extra Low Interstitial (Ti-6Al-4V ELI) has been developed for orthopedic applications [4]. This is because Ti-6Al-4V ELI has good biocompatibility in the body and has load-bearing capabilities and a relatively low elastic modulus to reduce the effect of stress shielding during implantation [3], [5]. The implantation of titanium material produces a low inflammatory, hypersensitivity, and allergic response when in contact with the body's biological environment [6]. Therefore, it is necessary to manufacture precision implant components with a low error rate. High precision can reduce side symptoms caused both during the implantation process and fixation [7].

Several challenges are associated with manufacturing aspects of titanium alloys such as shorter tool life, induced vibration and friction, and lower machining productivity [8], [9]. The low thermal conductivity of titanium causes damage to the material's surface being cut, resulting in poor surface quality, abrasion marks and microstructural damage. Therefore, it is necessary to have a good titanium-cutting process that minimizes the adverse effects on the resulting surface quality [1], [10].

The process of cutting Ti-6Al-4V ELI material for implant components with good biocompatibility is still limited due to the difficulty in machining, high production costs, and complex component geometries. One of the components of a bone implant is a bone screw, which is available in a variety of shapes and sizes. Each type of screw is determined by the dimensions of the screw, thread head, thread core, and end screw, according to the main use [11]. The main types of bone screws are cortical bone screws, cancellous bone screws, and locking head screws. The cortical (cortex) screw is a conventional screw with a shallow thread and a round head that fits into the compression holes of the DCP and LC-DCP plates. Meanwhile, its dimensions and tolerances are specified by the ISO 5835 standard, which refers to cortical bone screws as HA screws [12].

Referring to the results of previous studies [13], titanium is a complex material for machines because it has low thermal conductivity. The low thermal conductivity causes surface damage to the material, cutting in the form of abrasive traces, adhering material, and microstructural damage. This correlates directly with the precision of the size of the components produced. However, the surface damage is a result of the generated cutting temperature. High cutting temperatures contribute to accelerated tool wear. As tool wear increases, the contact area between the tool and the workpiece increases, causing a greater cutting force. Therefore, to obtain product quality or high precision, it is necessary to optimize the machining process for titanium implant components [14].

Optimizing threading parameters can be carried out on a single or multi-response response. In multi-response optimization, the influence of parameters is observed on several responses simultaneously. One method developed for the multi-response optimization process is Gray Relational Analysis (GRA) [14]. As stated by [15], the milling parameters for cutting tool wear and workpiece surface roughness were optimized using Taguchi and GRA methods. The results of his study stated that the optimal conditions for tool wear and surface roughness were obtained at a depth of cut of 1.5 mm, a spindle speed of 1280 rpm, and a cutting speed of 75 m/min. The GRA method obtained a combination of machining parameters in obtaining multi-response values (for tool wear and surface roughness) simultaneously, where the tool wear response value was 0.059 mm and surface roughness was 0.364 µm.

Therefore, this study aims to optimize threading parameters in a multi-response manner in producing cortical threads. The method used for the optimization process is Gray Relationship Analysis (GRA), while the machining process is a threading/turning process. The material used for the cortical screw or implant material is Ti-6Al-4V ELI. This is to obtain a high level of precision and a low level of damage to the surface of the screw component [16].

II. Materials and Method

This experimental study used a thread machining process, where the CNC machine type is the Feeler FTC-350XL, as shown in Figure 1. The selected carbide cutting tools are a custom model for the cortical tool type (Figure 2), and the cutting tool dimensions are shown in Table 1. The workpiece used in this experiment is Ti-6Al-4V ELI, whose chemical composition is 6.1%Al, 4.0 %V, 0.11%C, 0.18%Fe, 0.11%O and the remand is Ti. Meanwhile, the tensile stress was 132 MPsi, the yield stress was 2% offset by 119 MPsi, and the elongation was 17/14%. The machining parameters used were at spindle rotation of 100, 200, and 300 rpm, depth of cut of 0.01, 0.02, and 0.03 mm, and lubricants type of synthetic oil, virgin palm oil, and virgin coconut oil. The threading process was carried out to manufacture HA 4.5 type cortical threaded screw, according to ISO 5835 standard.

Fig. 1 CNC lathe machine used in this experiment of Feeler FTC-350XL type.

Fig. 2 Cortical cutting tool of carbide material used in cutting Ti-6Al-4V ELI.

TABLE I
CARBIDE CUTTING TOOL DIMENSION WITH STANDARD FOR H.A 4.5 [7]

r_4	r_5	α	β	r		Diameter
1	0.3	35°	3°	12°	8°	HA 4.5

The trial experimental design used in this study is the Taguchi Method, where the selected parameters consist of 3 factors and 3 levels of each. Thus, the number of samples is 9 samples, following the L9 orthogonal array design, as shown in Table 2. Before machining trials were done, the manufacturing of screw threads began with creating a program to cut the surface of the workpiece (Ti-6Al-4V ELI). The cutting is used continuously until getting the dimensions of the screw threads [17].

The cortical threaded screw components that have been obtained by manufacturing with a threading process then were observed dimensions by using a profile projector. Dimension observation of cortical threaded screws was done by using a profile projector. The measuring was carried out on four responses, namely thread pitch distance, thread height, thread angle α, and thread angle β. Dimensional error measurement data is analyzed by using the Gray Relational Analysis Method. This method displays the results of the analysis in the form of the effect of each factor on the four response values simultaneously [18].

The cortical threaded screw components that have been obtained by manufacturing with a threading process then were observed dimensions by using a profile projector. Dimension observation of cortical threaded screws was done by using a profile projector. The measuring was carried out on four responses, namely thread pitch distance, thread height, thread

angle α, and thread angle β. Dimensional error measurement data is analyzed by using the Gray Relational Analysis Method. This method displays the results of the analysis in the form of the effect of each factor on the four response values simultaneously [19], [20].

TABLE II
ORTHOGONAL ARRAY L9

No	Spindle speed (rpm)	Depth of Cut (mm)	Lubricant
1	100	0.01	Syntetics
2	100	0.02	VPO
3	100	0.03	VCO
4	200	0.01	VPO
5	200	0.02	VCO
6	200	0.03	Syntetics
7	300	0.01	VCO
8	300	0.02	Syntetics
9	300	0.03	VPO

III. Results and Discussion

Table 3 shows the resulting data of measuring of dimensional error of cortical threaded screw for each cutting condition, consisting of screw peak Error, screw height error, and screw angle error. Generally, the screw pitch and screw height errors are at 0.002 – 0024 mm. They are very small errors, where the largest error value is 0.024 mm. This occurs in the cutting conditions of the spindle rotation speed of 100 rpm, depth of cut of 0.03 mm, and the type of lubricant used is virgin coconut oil. Meanwhile, for screw angle errors (both alpha and beta angles), the error value is greater, where the largest error value is 0.123°. This was obtained at the cutting conditions of the spindle rotation speed of 100 rpm, depth of cut of 0.03 mm, and the type of lubricant used was virgin palm oil. However, the dimensional error value of threads does not show a decrease trend, when the spindle speed is increased. Meanwhile, a depth of cut of 0.03 mm produces a large error value. Machining at the cutting speed of 100 m/min and depth of cut of 0.03 mm, produced a big error, due to probably high cutting force as long as the machining process [21]. The depth of cut of 0.03 mm is big when machining at a cutting speed of 100 m/min (low cutting speed) [22].

TABLE III
THE DIMENSIONAL MEASURING ERRORS OF CORTICAL SCREW

No	Thread peak error (mm)	Thread height error (mm)	Thread angle error(°)	
			α	β
1	0.010	0.005	0.041	0.051
2	0.017	0.018	0.055	0.061
3	0.023	0.024	0.066	0.079
4	0.008	0.003	0.043	0.071
5	0.015	0.014	0.059	0.083
6	0.021	0.019	0.078	0.093
7	0.006	0.002	0.056	0.080
8	0.012	0.009	0.077	0.096
9	0.018	0.011	0.089	0.123

Table 4 shows the value of the signal-to-noise ratio (SN ratio) of each cortical thread dimension error. The value of the SN ratio is determined based on calculations using the following formula.

SN Ratio = -10 log [xi(j)2] (1)

The distribution of the SN ratio values for each screw dimension error shows the same pattern as the error values, but the SN ratio values are smaller than the others. The SN ratio value of the smallest screw pitch distance error is 32.7854 mm. This occurs at the cutting conditions of the spindle rotation speed of 100 rpm, depth of cut of 0.03 mm, and the type of lubricant used is virgin coconut oil. Whereas, for the thread angle errors (both alpha and beta angles), the error value is big, where the smallest error value is 18.2019°. This was obtained at the cutting conditions of the spindle rotation speed of 100 rpm, depth of cut of 0.03 mm, and the type of lubricant used was virgin palm oil [23].

TABLE IV
SN RATIO DATA FOR CORTICAL SCREW ERRORS

No	Thread peak	Thread height	Thread angle α	Thread angle β
1	40.0000	46.0206	27.7443	25.8486
2	35.3910	34.8945	25.1927	24.2934
3	32.7654	32.3958	23.6091	22.0475
4	41.9382	50.4576	27.3306	22.9748
5	36.4782	37.0774	24.5830	21.6184
6	33.5556	34.4249	22.1581	20.6303
7	44.4370	53.9794	25.0362	21.9382
8	38.4164	40.9151	22.2702	20.3546
9	34.8945	39.1721	21.0122	18.2019

Table 5 shows the normalized SN ratio values for each type of screw dimensional error. This value is obtained from calculations using the following formula.

xi^* (k)= (xi(k)-min xi(k))/(max xi(k)-min xi(k)) (2)

xi^* (k) is the thread peak error at sample 1 = (40.0000-32.7654)/(44.4370-32.7654) = 0.6198

TABLE V
NORMALIZED VALUES OF SN RATIO OF CORTICAL THREAD ERROR

No	Thread peak	Thread height	Thread angle α	Thread angle β
	0.6198	0.6313	1	1
2	0.2250	0.1158	0.6210	0.7966
3	0	0	0.3857	0.5029
4	0.7859	0.8368	0.9385	0.6242
5	0.3181	0.2169	0.5304	0.4468
6	0.0677	0.0940	0.1702	0.3176
7	1	1	0.5977	0.4886
8	0.4842	0.3947	0.1869	0.2815
9	0.1824	0.3140	0	0

The normalized SN Ratio data obtained as shown in Table 5 can be categorized into two groups. The first group with the smallest value is represented by a value of 0 (zero). And then the second group with the highest value is represented by a value of 1 (one). Table 6 shows the resulting values of the deviation sequence (Δ), for a response to the maximum value, where the maximum value is one. Deviation sequence values can be calculated using the following equation.

Δ0i(k)= |x_0- x_i (3)

Δ at thread peak error for sample 1 = |1-0,6198| = 0,3802

TABLE VI

DATA OF DEVIATION SEQUENCE RESPONSE (Δ)

No	Thread peak	Thread height	Thread angle α	Thread angle β
1	0.3802	0.3687	0	0
2	0.7750	0.8842	0.3790	0.2034
3	1	1	0.6143	0.4971
4	0.2141	0.1632	0.0615	0.3758
5	0.6819	0.7831	0.4696	0.5532
6	0.9323	0.9060	0.8298	0.6824
7	0	0	0.4023	0.5114
8	0.5158	0.6053	0.8131	0.7185
9	0.8176	0.6860	1	1

Table 7 shows the Gray Relational Coefficient (GRC) value for each response (screw peak error, alpha and beta error, and screw height error), which is obtained by calculating using formula 4. Theoretically, the Gray Relational Coefficient depended on the Gray Relational Analysis. The Gray Relational Coefficient can be calculated using the following equation [24], [25].

$$\zeta i(k)=.\Delta min \quad 〖+\zeta\Delta max〗/(\Delta oi(k)+ \Delta max) \quad (4)$$

ζi at thread peak error for sample 1 = (0.0000+(0.5×1))/(0.3802+((0.5×1)) = 0.5681.

TABLE VII

DATA GREY RELATIONAL COEFFICIENT

No	Thread peak	Thread height	Thread angle α	Thread angle β
1	0.5681	0.5755	1	1
2	0.3921	0.3612	0.5688	0.7109
3	0.3333	0.3333	0.4487	0.5015
4	0.7002	0.7540	0.8905	0.5709
5	0.4230	0.3897	0.5157	0.4747
6	0.3491	0.3556	0.3760	0.4229
7	1	1	0.5542	0.4944
8	0.4922	0.4524	0.3808	0.4103
9	0.3795	0.4216	0.3333	0.3333

Table 8 is the Gray Relational Coefficient value for each response, which can be calculated using the following equation

$$\gamma\ i= 1/n \sum 〖\zeta i(k)〗 \quad (5)$$

γi at testing 1 = 1/4 ∑ 〖(0.5681+0.5755+1+1)〗 = 0.7859

The Gray Relational Grade (GRG) values were sorted to obtain a ranking, from the largest to the smallest value. The highest GRG value was 0.7859 (rank 1), while the smallest GRG value was obtained at 0.3669 (rank 9). The highest GRG value was obtained in the machining conditions of the spindle speed of 100 rpm, depth of cut of 0.01 mm, and the type of synthetic lubricant. Simultaneously, these three parameters have a better effect on the screw dimensional error rate.

TABLE VIII

DATA GREY RELATIONAL GRADE

No	GREG	Rank
1	0,7859	1
2	0,5083	4
3	0,4042	7
4	0,7289	3
5	0,4508	5
6	0,3759	8
7	0,7621	2
8	0,4339	6
9	0,3669	9

The more excellent value of Gray Relational Grade indicates that the parameter test results have better multi-response characteristics [26]. In Table 4.8, it can be seen that the 1st test has the highest Gray Relational Grade price of 0.7859. This shows that the condition of the cutting parameters in the 1st test gives the closest results to the optimum of the four observed responses. It is known that the value of the Gray Relational Grade formed from a combination of the four observational responses is smaller than 1. The possible value range for the GRA value is between 0-1 [27].

The highest Gray Relational Grade found from this study is 0.7859. This value is close to the value of the largest range (1). This can happen because the response of the observed error angle α and angle β has a different data trend with screw height error and screw peak errors. The error values for angle α and angle β have a value of 1, while the errors for screw peak and screw height are 0.5681 and 0.5755. The combined value of the error response is 0.7859 (showing the average value). Thus, it can be said that the value of the combined response or multiple responses is the combined coefficient of each of these.

Table 9 shows the analysis of variance for each Gray Relational Grade and each contributing factor to the multiple responses. The significant value of each factor is used to determine the magnitude of the influence of a factor on multiple responses, which is selected at 5%. Some recommendations for researched engineering, the significant value used is 0.05 – 0.10 percent, and using 5% is better to get a strong model.

TABLE IX

ANOVA GRG

Source	DF	Adj SS	Adj MS	F-*Value*	P-*Value*	Contribution (%)
Spindle speed	2	0.004309	0.002154	4.11	0.196	2
Depth of Cut	2	0.235395	0.117697	224.46	0.004	98
Lubricant	2	0.000078	0.000039	0.07	0.931	0
Error	2	0.001049	0.000524			
Total	8	0.240830				

Table 9 shows that the most dominant factor affecting the precision of the screw geometry is the depth of cut, while the spindle rotation speed and the type of lubricant have no significant effect. The F-Value for the depth of cut is 224.46, and this value is bigger than the table's F value of 19.33. Thus the depth of cut can be said to have a significant effect on the response of multiple screw errors. Meanwhile, the F value for rotational speed is 4.11, and this value is smaller than the F table value of 19.33. Thus, this factor is said to have no significant effect on the multi-thread error response. The same thing was also found for the lubricant type, where this factor did not have a significant effect on the multiple screw error responses.

The same condition can also be observed when observing the P value, where the significant value of the depth of the cut factor is smaller than 0.05. The significant value of the depth of the cut factor is 0.004, so this factor has a significant effect on the error rate of multi-thread cortical responses. The depth-of-cut factor correlates directly with the magnitude of the cutting force, giving a real impression of the error rate. If the depth of the cut is large, it will increase the cutting force required to cut. An increased depth of cut will cause contact between the workpiece and the tooltip to become bigger, causing a larger friction area [3], [28]. The large contact area between the workpiece and the cutting tool increases the cutting force. This friction area also increases the temperature generated during the cutting process, so it has the potential to reduce the workpiece's durability [2]. Theoretically, when a metal material is heated, its structure will change, including in this case its strength or durability. This situation is no exception in the thread machining process, where cutting generates heat so that it weakens the properties of the material.

Table 9 also shows that the significant value of the depth of cut factor is very dominant, namely 98%, so it can be said that the depth of cut has a very significant effect on all cortical thread error responses. This is because the cortical thread has a different geometry from the matrix thread, so the depth of cut is a very influential factor. The curvature of the alpha and beta angles in the cortical thread causes a wider cutting area. In addition to increasing the width of the contract area between the tool and the workpiece, curved cuts are more difficult to perform than straight shapes. The track plane with curved geometry is longer, so the frictional area is also getting bigger. Therefore, cutting a larger area required a greater force as well. The cuts that form alpha and beta angles on cortical threads are a unique feature of cortical thread machining, including in this case the role of depth of cut [25].

Table 10 shows the Mean response Gray Relational Grade multi-response, where the depth of cut factor is ranked 1. This shows that the depth of cut is the factor that has the most influence on all responses. Using the mean value of the GRG response or using the P value, both show that the depth of the cut factor is the most dominant factor in the multi-response error rate. This shows the alignment between the data in the Anova table and the mean response.

TABLE X
MEAN RESPONSE GREY RELATIONAL GRADE

Level	Spindle speed (A)	Depth of Cut (B)	Lubricant(C)
1	0.5661	0.7590	0.5319
2	0.5185	0.4643	0.5347
3	0.5210	0.3823	0.5390
Delta	0.0476	0.3766	0.0071
Rank	2	1	3

As the results obtained from the analysis of variance and the mean value ranking, it has shown the same conclusion. However, these results can also be confirmed using the main effects plot for the means graph for the Gray Relational Grade value as shown in Figure 3. The value of the main effects plot for means Gray Relational Grade can be seen from the magnitude of the slope of the resultant line (angle) formed. The greater angle formed between the resultant line and the x-axis, it can be said that the significance value of the factor has a large effect. From Figure 3, it is known that the depth of cut has a greater angle or a greater degree of slope, so it is said that this factor has the most influence on the combined response of the Gray Relational Grade. As previously stated, the depth of cut factor has a significant effect because the contact area that occurs during cutting is larger, requiring a large cutting force as well.

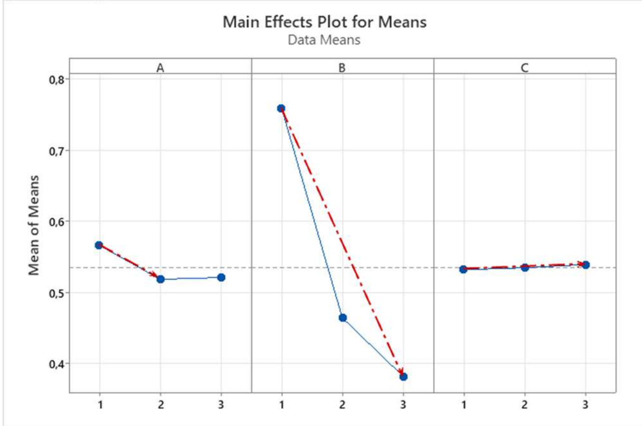

Fig. 3 Main effects plot for means Grey Relational Grade

An increase in the depth of the cut also causes the cutting temperature to rise, causing the tool to wear out more quickly. This makes the depth of cut has the most influential role in the accuracy of the screw top distance, screw height, and screw angle together [29]. Meanwhile, two factors have a very small inclination angle, which is the spindle rotation speed and the type of lubricant. The increase of spindle rotation speed was followed by a decrease in slight precision, so the angle formed is small also. The use of different lubricants does not indicate any significant errors. There is no formation of a significant resultant line angle, so it is said that the use of lubricants does not have a significant impact on the error of response. Thus, it is clear that the main effects plot for means GRG can be used to confirm the significant influence of factors, which have previously been obtained using P and F values

Figure 3 also shows the combination of factors that produce the optimal screw precision response or that provide the best level of precision. Optimal conditions are obtained by selecting the largest value, namely the spindle rotation of 100 rpm (level 1), the depth of cut of 0.01 mm (level 1), and the VCO lubricant type (level 3). Thus the optimum conditions for machining cortical threads to produce the best level of precision are carried out under parameter A1B1C3. The spindle rotation speed is directly correlated with the friction between the workpiece and the cutting tool [30]. As we all know, theoretically, high rotational speeds produce high heat, so the potential for damage is greater or the durability of the workpiece decreases [2], [12]. However, this study did not show that the spindle rotation speed had a significant effect.

When the rotation speed is increased, the heat generated will be higher. However, the influence of other parameters (in this case the depth of cut) is far greater than the spindle speed. Thus it can be said that the spindle speed factor has an influence, but it is very small compared to the influence of the depth of cut factor. This is different from cutting matrix threads, where the matrix thread has a straight contact area between the tool and the workpiece. Meanwhile, in cortical thread cutting, the contact area between the workpiece and the cutting tool forms a curved path, so the required force is greater. On the other hand, the amount of cutting force required depends on the area of contact between the cutting tool and the workpiece material [19].

Based on the measurement data, it can be seen that the largest error value and the smallest error value of the cortical threaded screw geometry. The smallest screw pitch error (Figure 4a) is 0.006 mm, which is obtained in the cutting conditions of the spindle rotation speed of 300 rpm, depth of cut of 0.01 mm, and the type of VCO lubricant. While the largest screw pitch error (Figure 4b) is 0.023 mm, which is obtained in the cutting conditions of the spindle rotation speed of 100 rpm, depth of cut of 0.03 mm, and the type of VCO lubricant. Visually, the measurement results of the screw peak distance error that has been carried out can be seen in Figure 4. The smallest peak distance error value is 0.3% while the largest peak distance error is 1.3%. When compared to the standard of error, the permissible error value is 1 mm. However, when referring to this standard, the results obtained are still within the tolerances allowed. Even the error value obtained is much smaller than the tolerance value

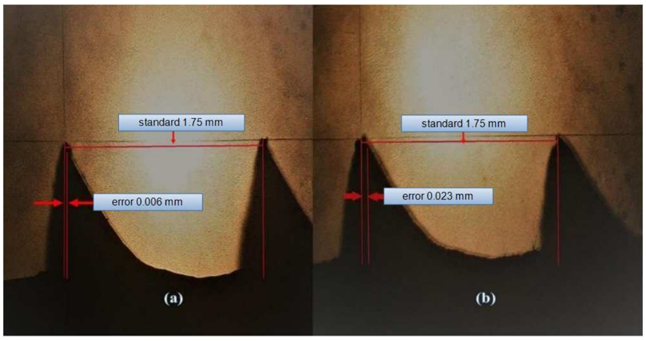

Fig. 4 The comparison between the smallest and largest screw peak errors at different machining conditions

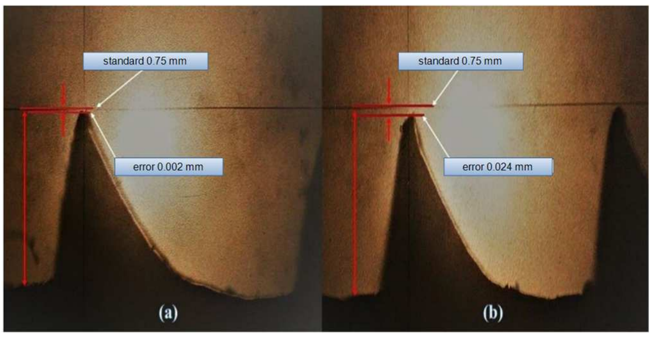

Fig. 5 The Comparison between the smallest and largest screw height errors under different machining conditions.

Figure 5 shows the smallest thread height error rate (Figure 5a) of 0.002 mm, which is obtained under cutting conditions with a spindle rotation speed of 300 rpm, a depth of cut of 0.01 mm, and the type of VCO lubricant. While the highest screw height error rate (Figure 5b) is 0.024 mm, which is obtained in cutting conditions with a spindle rotation speed of 100 rpm, a depth of cut of 0.03, and the type of VCO lubricant. In the presentation, the smallest error value is 0.1%, while the largest error value is 1.3%. The standard tolerance for peak thread error is 5%. The largest screw peak error value (1.3%), is much smaller than the tolerance value (5%). Thus, the error rate is acceptable because it still gets the allowable tolerances. In detail, the visualization of the screw peak error comparison can be seen in Figure 5.

Figure 6 shows the resulting observation on the smallest (a) and largest (b) angle α error values, where the α angle error value is 0.041°. This value was obtained under the conditions of cutting at a spindle rotation speed of 100 rpm, a depth of cut of 0.01 mm, and a type of synthetic lubricant. While the value of the largest angle error α (b) is 0.089°, which is obtained in cutting conditions with a spindle rotation speed of 300 rpm, a depth of cut of 0.03 mm, and the type of VPO lubricant. Visually the screw angle error α is measured as shown in Figure 6. The largest angle error α is 0.25%, where this value is considered small so that it can be said that the error obtained is still within the allowable range. The maximum error value is still below the standard 1%.

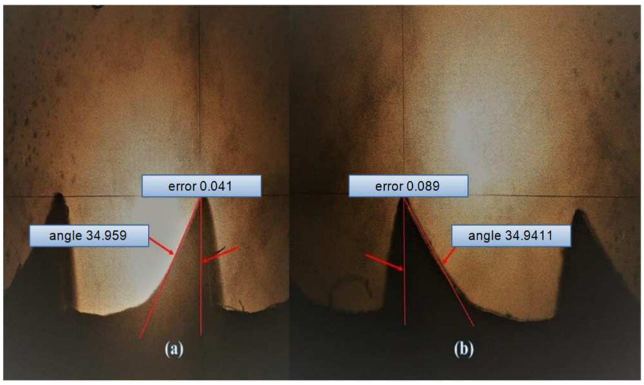

Fig. 6 The comparison between the smallest and largest screw angle errors α at different cutting conditions.

As shown in Figure 7, the smallest β angle error value is 0.051°, obtained under cutting conditions with a spindle rotation speed of 100 rpm, a depth of cut of 0.01 mm, and a type of synthetic lubricant. The biggest β angle error is 0.123°, obtained in the cutting conditions with a spindle rotation speed of 300 rpm, a depth of cut of 0.03 mm, and the type of VPO lubricant. How to measure the angle and angle error β in detail, as shown in Figure 7.

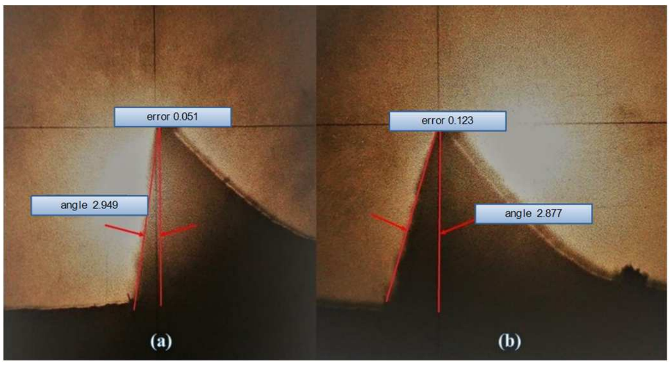

Fig. 7 The comparison between the smallest and largest screw angle error values β at different cutting conditions.

The damage to the cutting tool edge affected the angle β. This error is caused by friction between the cutting tool and the workpiece during the cutting process. The generated heat during machining was high, even more than the eutectoid temperature of titanium so it can damage the surface of thread. The wear and tear that occurs on the cortical cutting tool has a direct impact on the formation of the cortical tool path [20], [27], so it causes a size deviation from the actual size. Theoretically, changes in the β angle occur more easily because the β angle is directly related to the worn tool edge. The edge of the flank wears out after cutting the workpiece several times. The worn flank tool contributes to the formation of cortical threaded edges.

Figures 8, 9, 10, and 11 are profiles of cortical threaded bolts of Ti-6Al-4V ELI material at cutting conditions with a depth of cut of 0.03 mm and different spindle rotation speeds (100, 200, and 300 rpm, respectively). Meanwhile, Figure 8 shows the surface profile of the cortical Ti-6Al-4V ELI screw thread at optimum cutting conditions, which is reached at the spindle rotation speed of 100 rpm, depth of cut of 0.01 mm, and the type of VCO lubricant. In general, the surface profile of the cortical threaded screw produced is almost the same, there are not many differences. However, there is surface damage including non-uniform thread height, the presence of chips that are still attached to the threads, and the top of the thread that still looks rough. Either the thread height is not uniform or there is a chip sticking to the thread, this is caused by the friction that occurs during the cutting process. Meanwhile, the chip that sticks is caused by the high cutting temperature during machining, so the chip is heated until it sticks (not enough time to remove the patch).

However, the defects present at optimal conditions in the form of non-uniformity of the thread surface and the presence of adhering chips. This damage can occur because titanium has the property of easily reacting with other materials at high temperatures, especially with titanium materials. On the other hand, titanium also has a low thermal conductivity, causing surface damage to the workpiece in the form of residual metal still attached to the screw. Many previous studies have concluded that the machining of titanium tends to be more difficult at high temperatures due to its low conductivity and easy reaction with other materials. Therefore, some researchers recommend cutting titanium with a better lubricant, because the lubricant will reduce friction while cooling the rubbing surfaces.

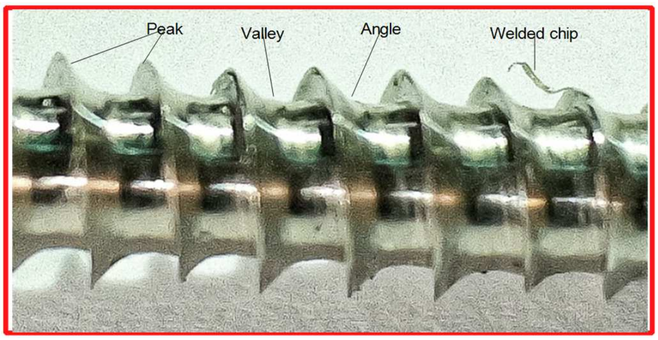

Fig. 8 Cortical Ti-6Al-4V ELI screw produced under optimal cutting conditions (spindle rotation speed of 100 rpm, depth of cut of 0.01 mm, and type of VCO lubricant)

In the results of cortical thread products of Ti-6Al-4V ELI material with the CNC lathe machining process, it was found that there was damage that occurred. The damage tends to occur in cutting conditions with a depth of cut of 0.03 mm at each spindle rotation of 100 rpm, 200 rpm, and 300 rpm. In the following, the damage that occurs to the screw thread will be displayed sequentially starting from Figure 9, Figure 10, and Figure 11 below.

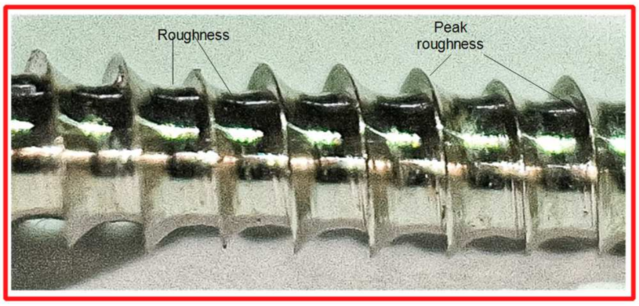

Fig. 9 Cortical Ti-6Al-4V ELI screw produced under cutting conditions with a spindle rotation speed of 100 rpm and a depth of cut of 0.03 mm

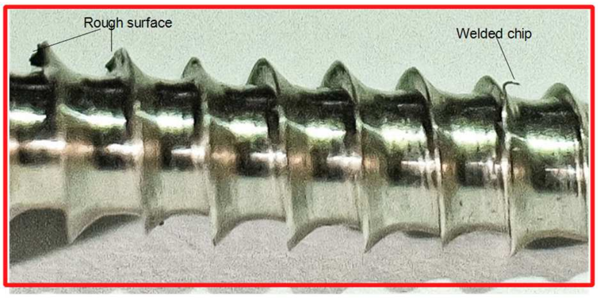

Fig. 10 Cortical Ti-6Al-4V ELI screw produced under cutting conditions with a spindle rotation speed of 200 rpm and a depth of cut of 0.03 mm

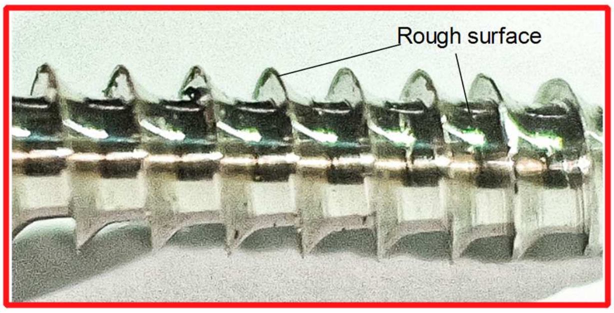

Fig. 11 Cortical Ti-6Al-4V ELI screw produced under cutting conditions with a spindle rotation speed of 300 rpm and a depth of cut of 0.03 mm.

IV. Conclusion

The conclusion that can be drawn from this study is that the factor that significantly influences the multi-response by using Gray Relational Grade is the depth of cut. Depth of cut is the dominant factor in cutting titanium cortical threads because the depth of cut factor is directly correlated with the cutting force. The shape of the thread side track that forms a curve requires a greater force during the cutting process. The significance value (P) is 0.004 or a contribution percentage of 98%. The cutting conditions for cortical Ti-6Al-4V ELI threads that resulted in a minimum error rate were a spindle rotation speed of 100 rpm (level 1), depth of cut of 0.01 mm (level 1), and virgin coconut oil (VCO) lubricant type (level

3). Observations on the screw surface profile indicated that the screw surface was damaged, including non-uniform screw height and the presence of welded chips. This is caused by the highly generated heat during the cutting process so that the chipped material sticks to the top of the thread. Damage in the form of sticking chips is also triggered by the titanium alloy having low thermal conductivity so that the cutting temperature accumulates at the top of the thread.

ACKNOWLEDGMENT

We are grateful to the Research and Service Institution of the University of Lampung for supporting the completion of the experiment, including financial support. The acknowledgment also proposes to the Mechanical Engineering Department and Production Laboratory to allow the use of the equipment and facilities until all experiment activities are finished.

REFERENCES

[1] E. Saputra, G.A. Ibrahim, S. Harun, E. Supriyadi, A. Patihawa, "Burr mechanism at micro milling process of Ti 6Al-4V ELI in dry cutting," Mechanical Engineering Department of University of Lampung. Vol. 11, No. 3., 2020. doi: 10.21776/ub.jrm.2020.011.03.1.

[2] G. A. Ibrahim, B. Yanuar, A. Yasir, "Burr formation analysis when micro milling Ti-6Al-4V ELI using end mill carbide insert," PalArch Journal Of Archaeology of Egypt, Vol. 7, No 9, 2020. https://archives.palarch.nl/index.php/jae/article/view/4558

[3] A. I. Gusri, H. Arinal, "Analysis of cutting wear when drilling of magnesium of AZ31 by using Taguchi Method," Jurnal Teknik Mesin – ITI, Vol. 4, 2020. doi: 10.31543/jtm.v4i1.342

[4] I. Siregar, F. N. M. Dzulkifli, J. B. Saedon, M. S. "Investigation of Ti-6Al-4V surface integrity from milling process," IOP Conf. Series: Materials Science and Engineering 851 (2020) 012056, doi:10.1088/1757-899X/851/1/012056.

[5] S. Harun, Y. Burhanuddin, G. A. Ibrahim, "The Effect of Cutting Parameters on Surface Roughness and Morphology of Ti-6Al-4V ELI Titanium Alloy during Turning with Actively Driven Rotary Tools," Journal of Manuf. Mater. Process. Vol. 6. Ed. 5, 2022. doi:10.3390/jmmp6050105.

[6] J. K. Gunawarman, J. Affi, A. Sutanto, D. M. Putri, N. F. Nuswantoro, H. Fajri, D. H. Tjong, M. Manjas, "Adhesion Strength of Hydroxyapatite Coating on Titanium Materials (Ti-6Al-4V ELI) for Biomedical Application," IOP Conference Series: Materials Science and Engineering hal 1-9, 2020. doi: 10.25105/ms.v11i2.7448.

[7] T. Kim, C. W. See, X. Li, D. Zhu, "Orthopedic implants and devices for bone fractures and defects: Past, present and perspective" Engineered Regeneration, Vol. 1, Pg. 6-18. 2020, doi:10.1016/j.engreg.2020.05.003.

[8] G. A. Ibrahim, E. Saputra, S. Harun, E. A. Supriyanto, A. Patihawa, "Surface roughness during micro-machining of Ti 6Al- 4V ELI (Extra Low Interstitial)," TURBO Vol. 8 No. 2. 2019. doi:10.24127/trb.v8i2.1057.

[9] J. A. Gonsalves, S. N. Nayak, G. Bolar, "Experimental investigation on the performance of helical milling for hole processing in AZ31 magnesium alloy," Journal of King Saud University Engineering Science, Vol. 34, Issue 5, pg. 366-374, 2022.

[10] A. C. Araujo, G. Fromentin, G. Poulachon, "Analytical and experimental investigations on thread milling forces in titanium alloy," International Journal of Machine Tools and Manufacture, Vol. 67, pg. 28-34, 2023. doi:10.1016/j.ijmachtools.2012.12.005.

[11] Z. Dzulfikri, C. Y. Huang, J. T. Lin, Y. J. Cjien, "Experimental investigation of novel internal thread fabrication: A drill thread milling," CIRP Journal of Manufacturing Science and Technology, Vol. 44. Pg. 126-137, 2023. doi:10.1016/j.cirpj.2023.05.006.

[12] S. Karabulut, M. Bilgin, "Friction drilling of AA7075-T6 and AZ31B alloys under dry and oil containing ceramic particulates" Journal of Manufacturing Process, Vol. 65, pg. 70-79, 2021. doi:10.1016/j.jmapro.2021.03.016.

[13] Q. He, Y. Jiang, X. Jing, H. Zhou, B. Fu, "Research and Optimization of Process Parameters for Internal Thread Forming Based on Numerical Simulation and Experimental Analysis" Materials, pg. 2-22. doi:10.3390/ma15093160

[14] S. Sulaiman, M. Alajmi, W.N. Wan Isahak, M. Yuduf, M. Sayuti, "Dry milling machining: Optimization of cutting parameters affecting surface roughness of Aluminium 6061 using the Taguchi Method," International Journal of Technology, Vol. 13, No. 1, 2022. doi :10.14716/ijtech.v13i1.4208.

[15] L. P. Giri, Y. Burhanuddin, G. A. Ibrahim, "Optimization milling parameters on tool wear and surface roughness during cutting magnesium using Metode Taguchi dan Grey Relational Analysis," Jurnal Turbop, Vol 9, No 1, 2020. doi:10.1016/j.measurement.2022.111757

[16] R. Binali, M. Kuntoglu, D. Y. Pimenov, U. A. Usca, M.K. Gupta, M. D. Korkmaz "Advance monitoring of hole machining operations via intelligent measurement systems: A critical review and future trends" Measurement, Vol. 201, 2022. doi:10.1016/j.measurement.2022.111757.

[17] A. Shastri, A. Nargundkar, A. J. Kulkarni, L. Benedicenti, "Optimization of process parameters for turning of titanium alloy (Grade II) in MQL environment using multi CI algorithm," SN Applied Sciences Vol. 3, No. 226, 2021. doi:10.1007/s42452-021-04197-0

[18] S. Khani, S.S. Haghighi, M.R. Razfar, M. Farahnakian, "Optimization Of Dimensional Accuracy In Threading Process Using Solid-lubricant Embedded Textured Tools," Industrial Engineering Department. Amirkabir University of Technology, 2021.

[19] A.N. Dahnel, M.H. Fauzi, N.A. Raof, S. Mokhtar, N.K.M. Khairussaleh, Tool wear and burr formation during drilling of aluminum alloy 7075 in dry and with cutting fluid, Mater. Today:. Proc. (2022). doi:10.1016/j.matpr.2022.01.110.

[20] Y. Bai, F. Wang, R. Fu, J. Hao, L. Si, B. Zhang, W. Liu, J.P. Davim, A semi-analytical model for predicting tool wear progression in drilling CFRP, Wear 486 (2021), 204119. doi:10.1016/j.wear.2021.204119.

[21] R.K. Das, S.K. Ngaihte, R. Prasad, A. Kakoti, R. Hoque, S.K. Sahu, N. Badgayan, "Experimental Investigation into electric discharge machining of Ti-6Al-4 V ELI alloy: An insight into biomedical applications," Materials Today Processing, Vol. 46, pp. 30–35, 2020. doi:10.1016/j.matpr.2020.05.608.

[22] D.Y. Pimenov, M. Mia, M.K. Gupta, A.R. Machado, I.V. Tomaz, M. Sarikaya, W. Kapłonek, "Improvement of machinability of Ti and its alloys using cooling-lubrication techniques: A review and future prospect," Journal of Materials Research and Technology, Vol. 11, pp. 719–753, 2021. doi:10.1016/j.jmrt.2021.01.031.

[23] G.A. Ibrahim, A. Hamni, A. Suseno, "The effect of cutting parameters when threading process of magnesium alloy AZ31 on geometrical threading precision", Journal Energy and Manufacture, Vol, 12, No. 1, pp. 1-6, 2019. doi: 10.24843/JEM.2019.v12.i01.p01.

[24] I. Takashi, H. Masahiro, T. Kazushige, "Machining temperature and accuracy of magnesium alloy AZ31 with deep-hole small drilling", International Journal of Automation Technology, Vol. 15, No. 4, pp. 448-456, 2021. doi: 10.20965/ijat.2021.p0448..

[25] Gusri, A.I, Deky, N.D.P., Yanuar, B., Arinal, H., Suryadiwansa. "Design of cortical screw cutting tool by using Reverse Engineering Method", Aplikasi Mekanika dan Energi: Jurnal Ilmiah Teknik Mesin, Vo. 9, No. 2, 2023, pp. 109-114.

[26] Y. Lou, L. Chen, H. WuID, S. Tou, "Influence of cutting velocity on surface roughness during the ultra-precision cutting of titanium alloys based on a comparison between simulation and experiment, " . Jurnal of PLoS ONE, Vol. 18, No. 7, 2023, doi.org/10.1371/journal.pone.0288502

[27] N. Danish, A.H. Musfirah, "Optimization of Cutting Parameter for Machining Ti-6Al-4V Titanium Alloy," Journal of Modern Manufacturing System and Technology, Vol. 6, No. 1, pp. 53-57, 2022, doi: 10.15282/jmmst.v6i1.7465.

[28] Q. Zhao, Q. Sun, S. Xin, Y. Chen, C. Wu, H. Wang, J. Xu, M. Wan, W. Zeng, Y. Zhao, "High-strength titanium alloys for aerospace engineering applications: A review on melting-forging process," Materials Science and Engineering A, 2022, Vol. 845, doi: 10.1016/j.msea.2022.143260.

[29] G. Singh, N. Sharma, D. Kumar, H. Hegab, "Design, development and tribological characterization of Ti–6Al–4V/hydroxyapatite composite for bio-implant applications," Materials Chemical and Physic, 2020, Vol. 243. doi:10.1016/j.matchemphys.2020.122662.

[30] I.P. Okokpujie, L.K. Tartibu, "Comparative study of the effect of dry, mineral oil, and TiO2 nano-lubricant on tool wear during face-milling machining of Ti-6al-4v-Eli using carbide tool insert," Mathematical Modelling of Engineering Problems, Vol. 9, No. 2, doi:10.18280/mmep.090224.