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Dimensional Error Analysis of Cortical Screw during Threading of Magnesium AZ31

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ABSTRACT

Developments in manufacturing to achieve large productivity and high-quality products in the modern era have necessitated the need of using suitable methods. Taguchi or robust design method has been implemented to optimise a process in a single response. This experiment aims to analyse the cutting parameters of geometrical errors of threads. Machining trials were conducted on the diameter of the workpiece (10, 14 and 18 mm), depth of cut (0.23, 0.3067 and 0.46 mm) and spindle speed (212, 318 and 424 rpm). Three responses, namely, pitch, height threads and angle thread error, were investigated. The external thread selected is metric M1,5 with three levels of three factors. Results show that spindle speed was the most significant factor that affected pitch error and height thread error. Depth of cut and diameter of the workpiece significantly affected thread angle error. The optimal condition to produce low thread angle error included machining at level 1 diameter of the tool, level 3 depth of cut of and level 3 spindle speed.

1. Introduction

Magnesium is an abundant element that is present in approximately 2% of the Earth's crust outer and is dissolved in the ocean. Magnesium is an important mineral in a stone base. Magnesium is a light superalloy material that has a density of 1.8 g/cm^3 [1]. Magnesium has the smallest density among other metals, such as iron and aluminium. In the automotive industry, magnesium and its alloy have been widely used because of they are very light and can reduce considerably the weight of automotive components [2,3]. A car and flight must be of light load because the light weight will reduce the total power requirement and energy consumption. As such, magnesium is the first choice in the aerospace industry. Super lightweight, strength-to-weight ratio and corrosion resistance are the main characteristics of materials required for aerospace body and other components.

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Magnesium also exhibits good mechanical properties, good electro-magneticity, high stability dimension, high power-to-weight ratio and corrosion resistance [4]. With its advantages and abundance in nature, magnesium has been developed as an alternative to iron. However, magnesium alloy has poor machinability because of easy flammability. Heat generated during machining can set the magnesium material to flame [5]. Therefore, machining with precise selection of parameters is important. Moreover, the quality of threaded screw depends on the machining condition, including the parameters of machining [6].

In the biomedical engineering field, magnesium and its alloys present compatible mechanical and physical properties to the human bone and the environment. Elastic modulus and density of magnesium are close to those of bone components, even if mismatches between implants and bone are removed [5,6]. However, the fundamental issues in using magnesium alloys to produce implant components is the machining process and the quality of components produced. The flammability of magnesium alloys is a crucial problem in machining because it is promoted by heating as a result of friction between the cutting tool and the workpiece material.

In machining, including the turning of magnesium alloy, some parameters affect the machined performance and quality of products. Cutting speed, feed rate, depth of cut, type of cutting tools and even machining methods contribute to machining results [7,8]. Machining magnesium should be controlled not to burn as a result of the high temperature employed. A thermograph can be used to observe the burning point of magnesium during machining. However, the defects of the machined surface of magnesium alloy have not been investigated. Cutting temperature is strongly related to surface damage and precision of screw components.

Low feeding and low depth of cut lead to a high risk for magnesium to be burnt [9]. When machining at high cutting speed, increasing the temperature can increase the possibility of magnesium being burnt. The source of the high cutting temperature is the friction between the carbide tool and the magnesium material. However, scholars have not studied the temperature at which the characteristics of magnesium change, leading to difficulty in cutting.

Liwei *et al.,* [10] determined a stress layer on the machining surface. Depth layers were determined by the cutting speed, which contributed to the hardness of the layers. The hardness level of the layers decreased with a reduction in the cutting speed. The hardness of the layers increased when the feed rate and depth cut were maintained at a high level or increased. Cutting parameters directly affect the machining results or performance. The hardness layers of a machined surface also affect the machine surface of the thread, causing errors of screw dimension [11,12].

Treading is an important and specific process used to produce components for bone implants. Selection of the right setting of cutting parameters and conditions is important to obtain high-quality magnesium screws. Factors and machining conditions suitable for threading magnesium alloys remain unknown. Suseno conducted a series of experiments on the threading of magnesium alloy [13] and selected parameters such as spindle speed and depth of cut. Experimental results showed that increasing the depth cut increased the thread pitch error. However, increasing the spindle speed decreased the thread pitch error and thread angle error, thereby producing a machined surface with a smooth profile. The cutting parameters of the threading of magnesium alloy are important factors. However, the extent of the effect of cutting parameters on screw pick error and screw angle error has not been determined.

Therefore, the effect of cutting parameters on screw errors (pith errors, high peak errors and angle errors) should be comprehensively investigated to produce a screw with high precision and high-quality machined surface for cortical bone fracture implants. In this study, Taguchi method was implemented with an orthogonal array to determine the effect of cutting parameters on threaded screw errors [13-15]. The contribution of a single factor that affects threading errors should be determined. An orthogonal array with L9 (three factors and three levels for each) was selected to optimise the cutting parameters.

2. Materials and Methods

This experiment was conducted using CNC lathe machining at the Laboratory of Production Process University of Lampung and carbide inserted with a cortical mode as cutting tools (Figure 1). Magnesium alloy with 3% aluminium and 1% zinc, or called AZ31, was used. Prior to machining, samples were prepared in bar pieces with a diameter of 20 mm and a length of 200 mm (Figure 2). Threading was conducted under dry cutting conditions or without using lubrication or coolant because the cutting fluid can contaminate the environment and harm the operator. The outer layer of the workpiece material was cut to remove some surface damage and residual stress as a result of the production. This condition can influence the performance of the machining process.

Fig. 1. CNC lathe and cortical cutting tool used in this experiment

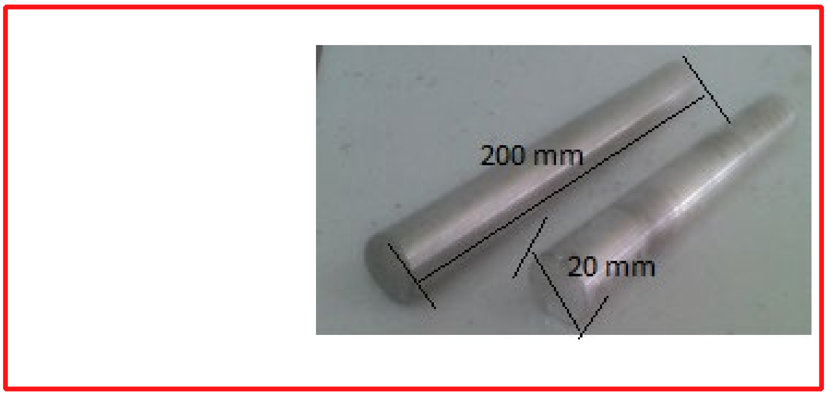

Fig. 2. Geometry of magnesium alloy AZ31 as workpiece material

The parameters selected for experimental trials were based on the design of Taguchi method with L9 orthogonal array. This method was implemented to obtain representative results with running experiments. Parameters used in this experiment included spindle speed of 212, 318 and 24 rpm (three levels) and depth of cut of the workpiece of 0.23, 0.30 and 0.46 mm (three levels). The diameters of the workpiece were M18×1.5, M14×1.5 and M10×1.5 (three levels). The number of experiments was 9 because the number of degrees of freedom needed was 8. Threading was conducted by controlling the cutting parameters to obtain the dimension of the pitch, thread height and thread angle under similar conditions. Every sample of the workpiece material was cut using a different cutting tool to validate the experimental data. Cutting was conducted in a few minutes until the depth of the cut reached 1.5 mm. Machining was then conducted on another sample one by one until all the target experiments were conducted completely.

The response parameters were thread pitch error, thread height error and thread angle error, which were determined using a confocal profile projector. After machining, the sample was placed into the chamber of the projector and measured the screw dimensions by using the lighting operator. Pitch error was measured by putting the sample in front of the display and then illuminating it with the lamp. The image of the sample was displayed on the screen and used to determine the distance between a pitch and another pitch (Figure 3). The same method was used to measure height error and angle error. Every measurement was conducted three times, and the average value was calculated. All collected data were analysed statistically to determine the effects of parameters on each response.

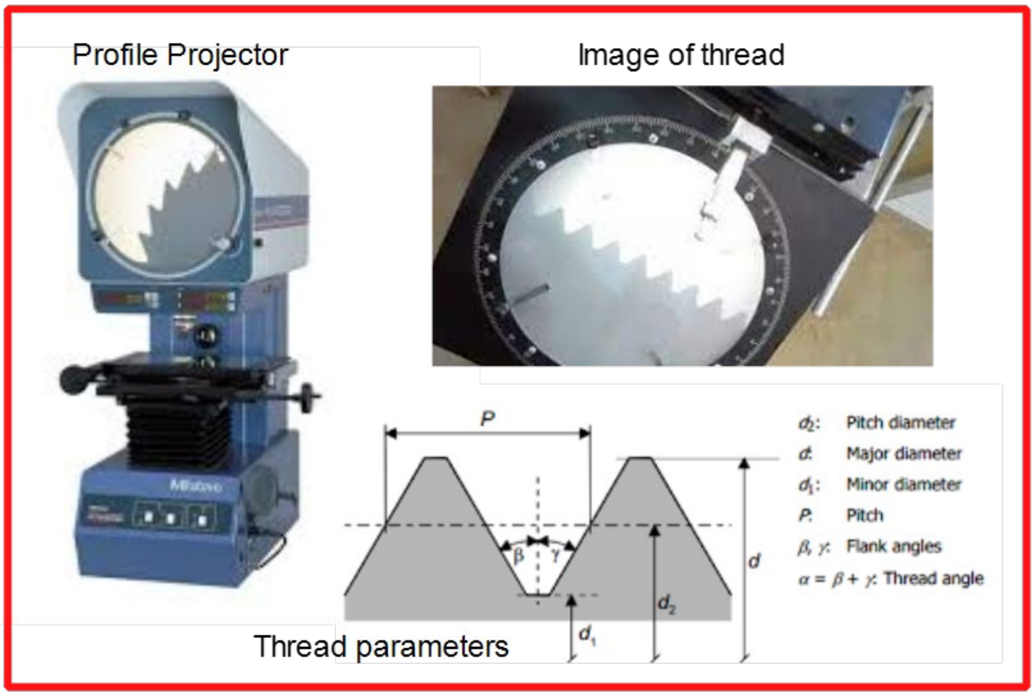

Fig. 3. Image in profile projector and measurement of the errors of pitch, height and angle

Prior to cutting, all factors at each level were determined. Table 1 shows the distribution of every combined setting parameter for each experiment run. Taguchi method was used to arrange the combinations with an orthogonal array. The experimental design was implemented using orthogonal array L9. Data were analysed to determine the factor with the most significant influence on each response and establish the optimal machining condition (combination of factors and levels) for every response. Signal-to-noise ratio was calculated because Taguchi method characterises data by using signal-to-noise ratio characteristics. A low signal-to-noise ratio should be used because it leads to a low value of errors.

Table 1
Taguchi method with orthogonal array L9

No	Diameter (mm)	Depth of cut (mm)	Spindle speed (rpm)
1	10	0.23	212
2	10	0.30	318
3	10	0.46	424
4	14	0.23	318
5	14	0.30	424
6	14	0.46	212
7	18	0.23	424
8	18	0.30	212
9	18	0.46	318

Statistical analysis was conducted on Minitab software, which can be freely downloaded. In Taguchi method, three factors, three levels for each and three responses for observation were used. No interaction between the factors was considered because of insufficient degree of freedom. Only the effects of a single factor on pitch errors, height errors and angle errors were analysed. ANOVA was used to calculate signal-to-noise ratio.

3. Results and Discussion

Table 2 shows the data measured using a profile projector when threading magnesium alloy under different cutting conditions. The response values are thread pitch errors, thread height errors and thread angle errors. The minimum thread peak error is 0.012667 mm, which is obtained at a diameter of 10 mm, depth of cut of 0.46 mm and spindle speed of 424 rpm. The maximum thread pitch error is 0.041500 mm, which is achieved at a diameter of 18 mm, depth of cut of 0.30 mm and spindle speed of 212 rpm. This finding indicates that the diameter of the cutting tool has bigger contribution than the depth of cut and spindle speed. Hence, the workpiece diameter contributes more significantly than the other factors. The lowest diameter of the workpiece produces a low thread pitch error because machining under this condition will generate low heat. The heat generated during machining contributes to surface damage to the machined surface [16]. In some cases, the machining temperature can impair the machined surface and reduce the machined surface quality.

Table 2
Experimental data on three types of errors (pitch, height and angle error) of threading operation

No	Pitch errors (mm)	Height error (mm)	Angle error (°)
1	0.037167	0.15420	0.4433
2	0.026833	0.07100	0.6933
3	0.012667	0.03833	1.5367
4	0.032167	0.04883	1.3633
5	0.020833	0.02617	1.7600
6	0.040333	0.15533	1.6400
7	0.030833	0.04033	0.8300
8	0.041500	0.07267	0.6733
9	0.034000	0.16150	1.8833

The lowest and highest angle errors have a big increment value. The lowest value of thread angle error is 0.4433°, and the highest angle error is 1.8833°. The highest thread angle error is obtained when operating at a high diameter of the tool and high depth of cut. Either the diameter of the tool or the depth of the cut contributes to the thread angle error. The diameter of the tool and the depth of the cut affect the thread angle error simultaneously.

Table 3 shows the calculation results of the S/N ratio by using the formula with Taguchi's characteristic of smaller is better for height error or pitch and angle error. In Taguchi-designed experiment, noise factors can be manipulated to obtain force variability and identify noise factor. A high value of the signal-to-noise ratio identifies a control factor that minimises the effect of noise factor on the response (Taguchi design). The highest S/N ratio for thread pitch error is 37.9495, which is achieved at a depth of cut 0.46 mm (high depth of cut). Hence, the depth of the cut contributes to the pitch error.

Table 3
S/N ratio responses

SNR height error	SNR pitch error	SNR angle error
16.2383	29.0773	7.0660
22.9748	31.4266	3.1816
28.3292	37.9465	-3.7318
26.2263	30.7022	-2.6918
31.6439	33.6250	-4.9103
16.1749	27.8868	-4.2969
27.8874	32.4564	1.6184
22.7729	26.2852	3.4358
15.8365	29.1186	-5.4984

3.1 Analysis of Thread Pitch Error

Table 4 shows the analysis of thread pitch error by ANOVA to determine the parameter that has the most significant effect and contribution to the pitch error. Only the spindle speed is a significant factor, with a significant value of 0.029 or with a contribution of 75.75%. The contributions of spindle speed for the diameter of the thread and depth of cut are 19.54% and 2.4%, respectively. Therefore, spindle speed should be controlled to produce minimal pitch error. Spindle speed determines the cutting speed. If the spindle speed increases, then the friction between the cutting tool and workpiece material decreases, so heat generated during machining is also low. This variable can affect the temperature of the cutting. The thread pitch error value in turning by the carbide tool was determined by the depth of cut and spindle speed, in which a high spindle speed contributes to pitch error [17]. Spindle speed has a strong correlation to heat generated during machining. However, the diameter of the thread has a more significant effect on the pitch error than the depth of the cut. The pitch error of the thread may be dominantly affected by cutting force as a result of the cutting speed. Meanwhile, the heat generated during machining as a result of spindle speed has a greater effect on thread pitch error than the depth of cut.

Table 4
Analysis variance of thread pitch error

Source	DF	SS	Seq SS	MS	F	P	Contribution (%)
Diameter of thread	2	18.889	18.889	9.445	8.63	0.104	19.54
Depth of cut	2	2.362	2.362	1.181	1.08	0.481	2.4
Spindle speed	2	73.229	73.229	36.615	33.45	0.029	75.75
Residual error	2	2.189	2.189	1.095			
Total	8	96.669					

Figure 4 and Table 5 show the optimal result of SN ratio analysis on the thread pitch error by using various cutting parameters, where spindle speed and diameter of the tool are dominant factors. The optimal condition of cutting parameters was determined by selecting the maximum value of the SN ratio. The optimal condition includes the diameter of the tool of level one (A1), the depth of cut of level three (B3) and the spindle speed of level three (C3). Machining under the optimal condition will produce the best result of thread with minimal errors. Table 5 also shows that spindle speed is the first parameter that has the highest contribution. Similar to the data of ANOVA, the most significant contributing factor is spindle speed, with a contribution value of 75.75%. The spindle speed is the most significant factor that affects the thread pitch error because of the heat generated during machining. In this experiment, the material used is magnesium alloy, and magnesium has a low flash point. When machining at a low flash point, the structure of the material is easily affected by temperature [16,18]. Therefore, the thread error when machining magnesium alloy is mainly affected by the high temperature as a result of the friction when cutting the tool place.

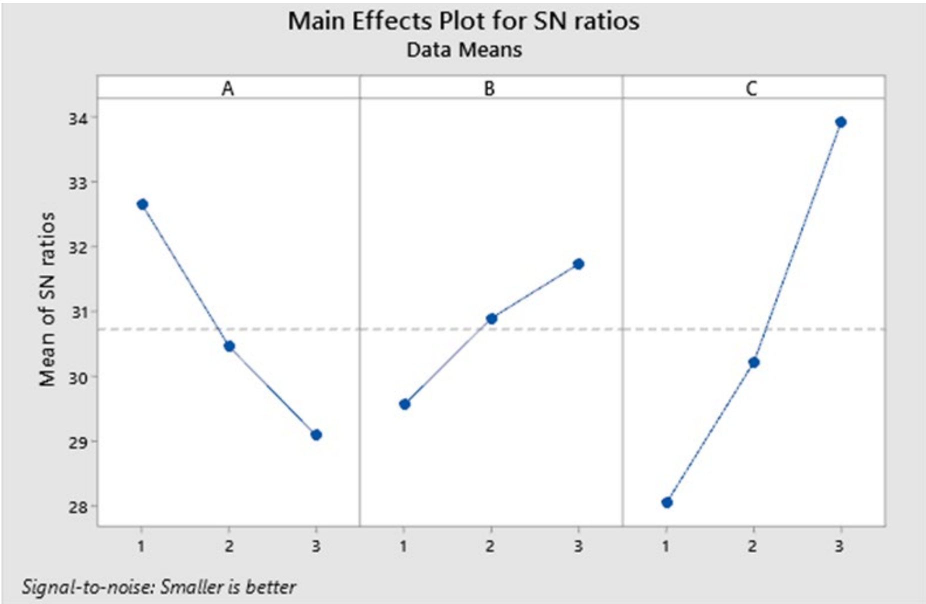

Fig. 4. Graphic error of pitch

Table 5
Mean response error of pitch

Level	Diameter of thread (mm)	Depth of cut (mm)	Spindle speed (rpm)
1	32.82	30.75	27.75
2	30.74	30.45	30.42
3	29.29	31.65	34.68
Delta	3.53	1.21	6.93
Rank	2	3	1

3.2 Analysis of Thread Height Error

Table 6 shows the ANOVA results of the thread height error. The three cutting parameters (diameter of thread, depth of cut and spindle speed) do not significantly contribute to the thread height error. However, the spindle speed has more contribution than the other parameters. The contribution of the spindle speed factor is 66.66%. A previous research stated that increasing the spindle speed can reduce the thread height error during the machining of magnesium alloy under dry conditions or machining without coolant. Spindle speed is the most significant factor that contributes to the thread height error [19]. Although spindle speed is not a significant factor affecting the thread height error, it has sufficient contribution. However, for thread height error response, all parameters have no significant effect during machining magnesium alloy under certain machining conditions.

Table 6
Analysis of variance of thread height error at various cutting parameters

Source	DF	SS	Seq SS	MS	F	P	Contribution (%)
Diameter of thread	2	11.15	11.15	5.575	0.33	0.751	4
Depth of cut	2	48.95	48.95	24.473	1.46	0.407	17.42
Spindle speed	2	187.28	187.28	93.642	5.58	0.152	66.66
Residual error	2	33.57	33.57	16.786			
Total	8	280.95					

Figure 5 and Table 7 show an advanced analysis of SN ratio responses by using Taguchi method when machining magnesium alloys to produce a thread component. Among the three factors, only spindle speed shows a considerable contribution. Similar to the data in Figure 5, Table 7 displays the spindle speed as the most contributing factor to the thread height error.

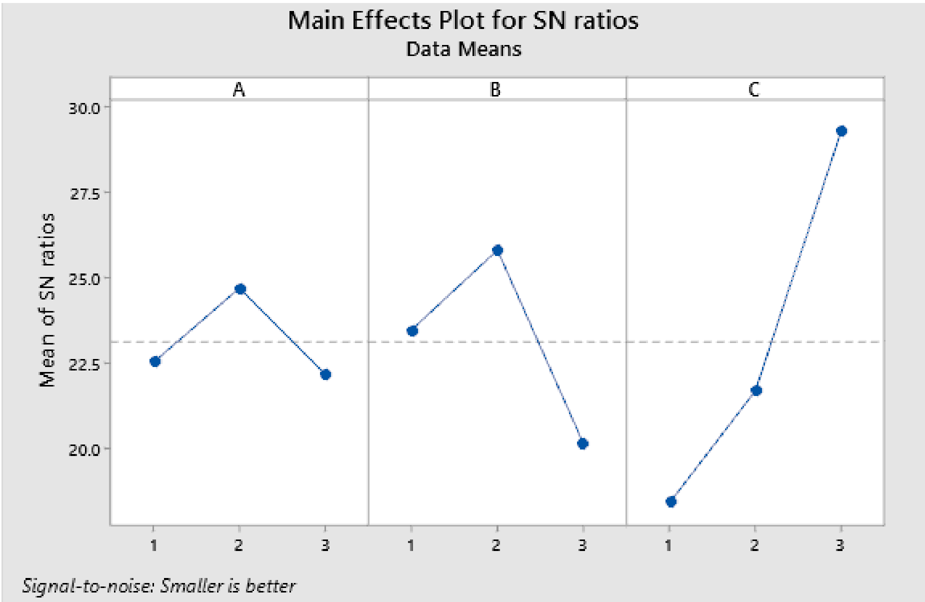

Fig. 5. Graphic of thread height errors during machining magnesium alloy

Table 7
SN response at various cutting parameters

Level	Diameter of thread (mm)	Depth of cut (mm)	Spindle speed (rpm)
1	22.51	23.45	18.40
2	24.68	25.80	21.68
3	22.17	20.11	29.29
Delta	2.52	5.68	10.89
Rank	3	2	1

3.3 Analysis of Thread Angle Error

In Table 8, the ANOVA results of the thread angle error response show a significant value and contribution for every parameter. The first factor is the depth of cut, which significantly affects the thread angle error, with a significant value of 0.041 or 4.1% (significant criterion is 5%). The second factor is the diameter of the thread, with a significant value of 0.05 (5%, still including in boundary significant value). The depth of cut has the highest contribution to the thread angle error, with a contribution of 42.66%. The contribution of the diameter thread is 35%. The depth of cut has a strong correlation with cutting force, that is, machining at a high depth of cut produces high cutting force [18,20]. The angle error will decrease when cutting at a high depth of cut. Machining at a high depth of cut is better than machining at a low depth of cut. Besides feed rate, the machined surface or the surface roughness was determined by the depth of cut, and the dimension error depended on the surface roughness [21].

Table 8
Analysis of variance of threads angle error during machining of magnesium alloy

Source	DF	SS	Seq SS	MS	F	P	Contribution (%)
Diameter of thread	2	57.640	57.640	28.820	19.14	0.050	35
Depth of cut	2	70.163	70.163	35.081	23.30	0.041	42.61
Spindle speed	2	33.867	33.867	16.933	11.25	0.082	20.57
Residual error	2	3.011	3.011	1.506			
Total	8	164.681					

Figure 6 and Table 9 show the optimal condition for cutting parameters during machining of magnesium alloy by using carbide tools. The optimal condition includes level one diameter of the tool (A1), level one depth of cut (B1) and level one spindle speed (C1). Machining by threading at low-level cutting parameter produces the lowest angle error. Machining at a low-level cutting parameter is suitable to obtain minimal thread angle error. However, Figure 6 or Table 9 shows that the depth of cut has more contribution than the other parameters.

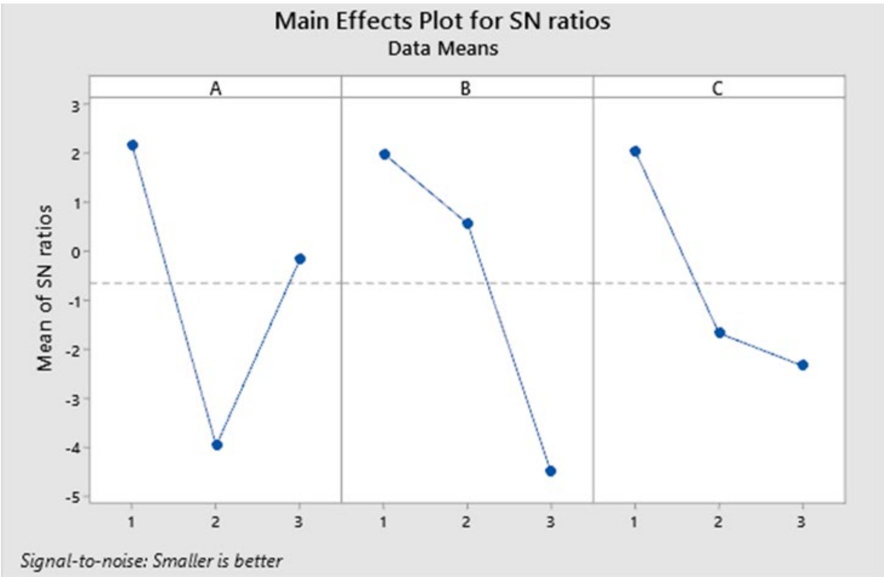

Fig. 6. Optimal parameter that produces minimal angle error

Table 9
Ranking factor of thread angle error when threading magnesium alloy

Level	Diameter of thread (mm)	Depth of cut (mm)	Spindle speed (rpm)
1	2.1719	1.9976	2.0683
2	-3.9663	0.5691	-1.6695
3	-0.1480	-4.5090	-2.3412
Delta	6.1383	6.5066	4.4095
Rank	2	1	3

3.4 Scanning Electron Microscope Analysis

Figure 7 shows thread dimension errors observed using a scanning electron microscope (SEM). Some of the observed errors include peak thread distance error, thread height error, α angle error and β angle error. Observations using SEM for these errors are precise because the boundaries being measured are clear. The peak thread distance error is 0.025 mm. The planned peak thread distance is 1.75 mm, while the measured peak distance is 1.725 mm. The peak thread distance error is 1.4%, which is considered significant because it exceeds the standard error value of 1%. However, the workpiece surface and thread peaks exhibit a smooth surface, so the error is still allowed. A smooth surface will facilitate the installation of threaded bolts because of lack of obstructions. Hu Shi *et al.,* [17] stated that thread errors are caused by heat. High temperatures during drilling can result in errors because of axial heat movement in the threaded bolt. The surface of the threaded screw has the highest temperature because it directly interacts with the cutting tool, which can cause other materials to adhere to the threaded surface.

The thread height error is 3.6%, and the α angle error is 12.3%. These errors are suspected to be a result of heat generated during cutting. Tool wear is another cause of the thread dimension error. The longer the tool is used, the more it wears down, thereby directly affecting the surface of the thread it forms. Changes in α and β curvatures at the edge of the cutting tool, when they have been altered due to wear, will result in the thread surface similar to the dimensions of the worn tool [18]. However, temperature is a dominant factor that influences changes in the condition of the threaded screw surface. Surface quality, in part, is determined by errors in thread dimensions.

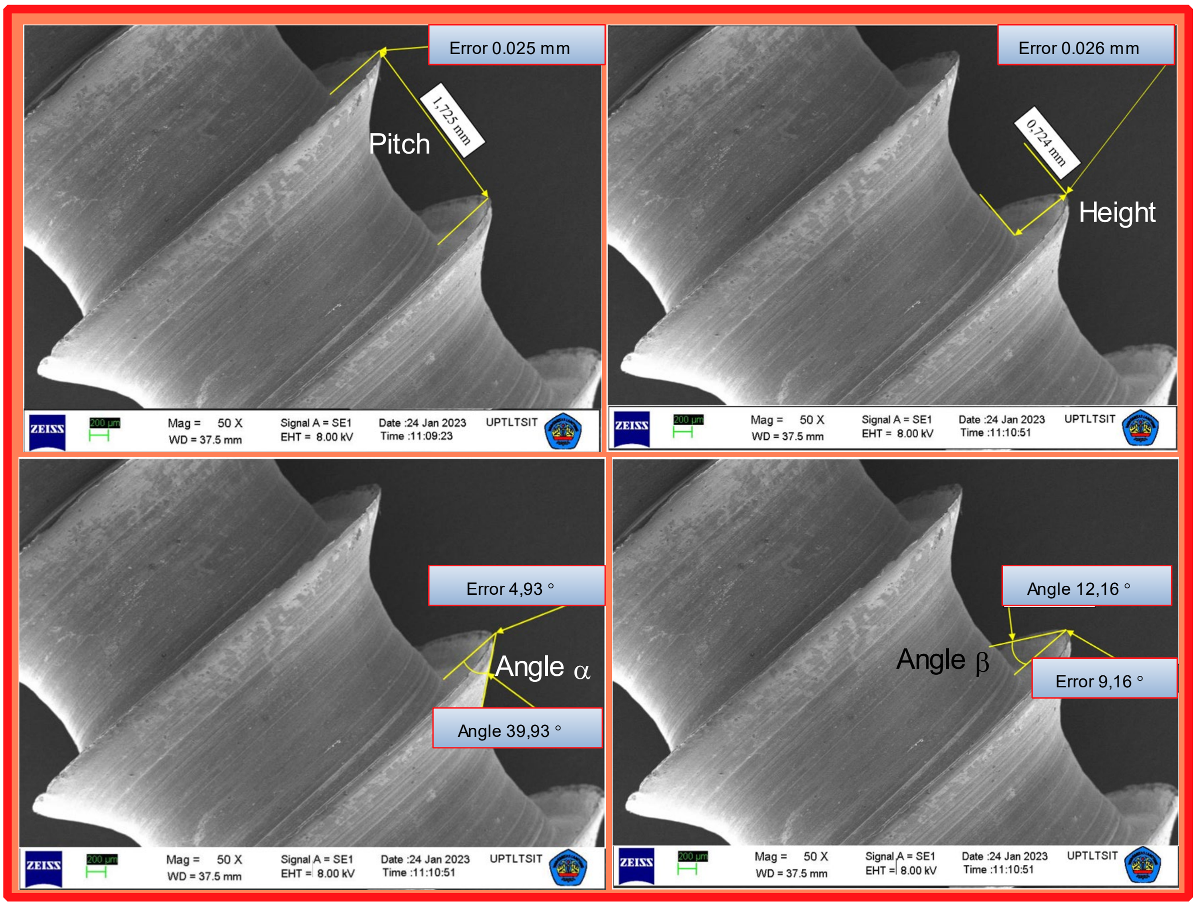

Fig. 7. Pitch error, height error, α angle error and β angle error under scanning electron microscope

3.5 Analysis on Thread Surface Damages

Figure 8 shows various types of damages on the surface of threaded screws at the thread peaks and in the valleys. Damages to the thread peaks include fractures, rough surfaces, non-parallel surfaces and abrasive wear. Damages in the valley areas consist of abrasive wear, adherent material, material build-up and voids. Surface damage occurs as a result of cutting process. Abrasive damage is caused by sharp cutting tool edges or small sharp particles between the cutting tool and the workpiece. Additionally, material build-up occurs as a result of high heat, causing the chip material to adhere. The chips are removed but are still in a high-temperature state, causing them to stick to the threaded screw surface. Several chip materials in the form of small fragments adhere to the surface of the threaded screw. Their damage to machined surfaces can be reduced by lubrication during machining. Minimum Quantity Lubrication (MQL), is one of the lubrication methods to improve the machine surface, because it shows a hardly significant effect on surface roughness [22].

Fig. 8. Surface damages on the machine surface of the thread.

4. Conclusions

Analysis of the SN ratio with Taguchi design experiment provides the best response. The most significant factor that affects the thread pitch error is spindle speed, which has a contribution of 75.75%. The optimal condition to produce minimal thread pitch errors is machining at level one diameter of the tool (A1), level three depth of cut (B3) and level 3 spindle speed (C3). The thread height error is not significantly affected by all parameters tested, with a significant value of more than 5%. Spindle speed has higher contributions than the other factors. The most significant factor that affects the thread angle error is the depth of cut, followed by the diameter of the thread, with contributions of 42.61% and 35%, respectively. The optimal condition to produce low thread angle error is machining at level one diameter of the tool (A1), level three depth of cut (B3) and level three spindle speed (C3). The peak thread distance error is 1.4%, the thread height error is 3.6% and the α angle error is 12.3%. Generally, these errors are a result of heat generated during the cutting process and the worn cutting tool. Damages to the thread peaks include fractures, rough surfaces, non-parallel surfaces and abrasive wear. Meanwhile, damages in the valley areas consist of abrasive wear, adherent material, material build-up and voids.

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