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INVESTIGATION OF DRILLING PARAMETERS AFFECTING BOREHOLE CIRCULARITY IN CORTICAL BONE

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ABSTRACT

Cortical bone drilling is a critical step performed prior to implant bolt placement, where drilling parameters play a significant role in the success of the procedure. This study investigates the effects of rotational speed, feed rate, and cooling fluid type on the outcome of the drilling process. A Box-Behnken experimental design was employed, involving 15 samples. Drilling operations were conducted using an SS316L drill bit on a 3-axis CNC machine. Circularity was analyzed using a Mitutoyo PJ3000 profile projector by measuring the x- and y-axis lines of the drill hole shadows under projector illumination. Hardness testing of bone specimens revealed an average microhardness of 45.48 HV with a standard deviation of 1.74, indicating their suitability as a human bone model. The lowest circularity value, 0.00125, was achieved at a rotational speed of 1,500 rpm, a feed rate of 60 mm/min, and in the absence of coolant. ANOVA results show that the feed rate (Vf) significantly affects circularity compared to rotational speed (V) and coolant, with a P-value of 0.0126 and an F-value of 8.86. These findings provide insights for optimizing cortical bone drilling procedures in biomedical applications. Future research should explore temperature distribution across the specimen and drill bit wear resistance resulting from the drilling process.

Keywords: cortical bone drilling; circularity; feed rate; rotational speed; biomedical engineering

ABSTRAK

Pengeboran tulang kortikal adalah langkah penting yang dilakukan sebelum penempatan baut implan, di mana parameter pengeboran memainkan peran penting dalam keberhasilan prosedur. Penelitian ini menyelidiki efek dari kecepatan rotasi, laju pemakanan, dan jenis cairan pendingin terhadap hasil proses pengeboran. Desain eksperimental Box-Behnken digunakan, yang melibatkan 15 sampel. Operasi pengeboran dilakukan dengan menggunakan mata bor SS316L pada mesin CNC 3-sumbu. Lingkaran dianalisis menggunakan proyektor profil Mitutoyo PJ3000 dengan mengukur garis sumbu x dan y dari bayangan lubang bor di bawah pencahayaan proyektor. Pengujian kekerasan spesimen tulang menunjukkan kekerasan mikro rata-rata 45,48 HV dengan deviasi standar 1,74, yang mengindikasikan kesesuaiannya sebagai model tulang manusia. Nilai sirkularitas terendah, 0,00125, dicapai pada kecepatan putar 1.500 rpm, laju pemakanan 60 mm/menit, dan tanpa adanya cairan pendingin. Hasil ANOVA menunjukkan bahwa laju pemakanan (Vf) secara signifikan mempengaruhi sirkularitas dibandingkan dengan kecepatan putar (V) dan cairan pendingin, dengan nilai P-value sebesar 0,0126 dan nilai F sebesar 8,86. Temuan ini memberikan wawasan untuk mengoptimalkan prosedur pengeboran tulang kortikal dalam aplikasi biomedis. Penelitian di masa depan harus mengeksplorasi distribusi temperatur di seluruh spesimen dan ketahanan aus mata bor yang dihasilkan dari proses pengeboran.

***Kata Kunci**: pengeboran tulang kortikal; sirkularitas; laju pemakanan; kecepatan rotasi; teknik biomedis*

1. Introduction

Cortical bone fractures in humans can be experienced due to sports, running, climbing, transportation accidents, work accidents, or even illnesses [1]. Drilling into cortical bone is a necessary procedure in the event of fractures due to accidents and is a primary surgical step before the placement of implant screws [2]. Proper adherence to drilling procedures is crucial to prevent postoperative trauma in patients. Ensuring that the drilling process is conducted correctly and efficiently significantly impacts the success rate of the surgery and the patient's recovery period [3,4].

Previous research has studied drilling parameters on the effects of the drilling process and results on bone. In their paper, Sui et al. (2020) explain that rotational speed can affect increasing or decreasing workpiece temperature. However, there is still debate whether rotational speed has a direct proportional effect on increasing temperature or vice versa [5]. Other studies have shown a significant correlation between drill hole quality and rotational speed. High revolutions per minute (RPM) will increase drilling efficiency and produce higher roundness. However, high rotational speed will cause vibration and deflection of the drill bit. The vibration will result in poor hole geometry. Likewise, when the rotational speed is low, it will increase dimensional accuracy better, but drilling efficiency will decrease. [6,7]. The speed of the drill into the material or called the feeding rate, also affects the roundness of the drilling results. Too high a feeding rate will increase the pushing force of the drill bit into the material. Too high a pushing force will result in excessive vibrations that have the potential to cause asymmetry of the hole [7,8]. Inappropriate drilling speed and feed rate can cause biological damage to the bone [9]. This vibration will cause the strength of the material to decrease due to the roughness of the drill hole surface. Continuous wear on the drill bit will have fatal consequences for device failure [7,10]. To minimize cellular damage in the bone, cooling at the drilling site is necessary [9-12]. Coolant provides lubrication and irrigation to reduce frictional heat during drilling. Furthermore, this lubrication can affect the roughness and surface integrity of the drilling results [13]. Several types of cooling have been studied for their effects on bone drilling. OpSite fluid has a lower risk of infection so it can be considered in clinical surgery for cooling applications in the cortical bone drilling process [12]. Apart from OpSite, NaCl solution has been shown to reduce more minor temperature changes and more acute osteonecrosis [14].

The shape of the drilling hole that is not cylindrical because the axis of the hole is not parallel to the desired axis can occur because a surgeon carries out the drilling without a guide plate or the help of a robot. The geometry of the drill used also affects the deflection of the hole walls [15]. High rotational speed and feed rate can cause the hole shape, which should be cylindrical or circular, to become oval. The hole diameter is also an important parameter because it directly affects the stability of screw implantation.

As explained, the drilling parameters significantly affect the drilling results, especially circularity. The mismatch of the roundness of the drilling results on the implant will cause tissue damage and harm to the patient. Therefore, this experiment will study the effect of drilling parameters such as rotational speed, feeding rate, and coolant type on the circularity results of the drilling results on bovine cortical bone specimens, in vitro analysis modeled by the Response Surface Method (RSM). The RSM was chosen as a suitable approximation function to predict future responses and determine the values of independent variables (drilling parameters) that optimize the response (circularity values). Statistical measurement in the regression model is used to determine the proportion of the dependent to the independent variable. R-squared (R^2) as a regression function will easily interpret how well the data fits the regression model or its suitability. Identification parameters that significantly affect the circularity of the borehole can be analyzed by Analysis of Variance (ANOVA). With RSM, borehole drilling parameters can be explored, identifying factors that have a critical effect on circularity, and the desired hole quality can be achieved. The results of this study will provide knowledge of the drilling parameters that have the most significant effect on circularity so that the proper selection can be made to minimize the adverse effects of Cortical bone drilling.

2. Methods

This experimental research design was carried out with the help of Design Expert – 13 software. Research parameters based on the box-behnken method with 15 run orders consisting of 3 factors and three levels are shown in Table 1, while the sample numbering is shown in Table 2.

Drilling experiments were carried out on a bovine cortical bone specimen cleaned and soaked in 10% NaCl solution for 24 hours following previous research [12]. Washing using NaCl solution is intended to remove impurities such as fat that are still attached to the cow bones so that the biomaterial is high purity [16]. The bone was then cut to a length of 35 mm, a width of 25 mm and an average thickness of 8 mm, and then the hardness was measured using a microVickers (HV) tool. Drilling was carried out with a 3-axis CNC machine using an SS 316L Orthopedic drillbit with specifications for a diameter of 3.2 mm, a length of 150 mm, and a drill bit angle of 50o. Two types of coolant are NaCl solution, which comes from infusion fluid with an osmolarity of 308 m0sm/l, and Opposite spray Brand: SMITH & NEPHEW SCHW.

Table 1. Parameters design of experiment

No	Factor Name	Level Lowest Value -1	Median Value 0	Highes Value 1
1	Rotational Speed (rpm)	500	1000	1500
2	Feeding Rate (mm/min)	35	65	85
3	Coolant	NaCl	OpSite	Dry

Table 2. Sample run order based on the box-behnken method

No. Sample	Factor 1	Factor 2	Factor 3
	Rotational Speed (rpm)	Feed Rate (mm/min)	Coolant
1	500	60	NaCl
2	1500	60	NaCl
3	1500	60	Dry
4	1500	35	OpSite
5	500	60	Dry
6	1000	35	NaCl
7	500	35	OpSite
8	500	85	OpSite
9	1000	60	OpSite
10	1000	60	OpSite
11	1000	85	Dry
12	1000	60	OpSite
13	1500	85	OpSite
14	1000	35	Dry
15	1000	85	NaCl

Measurement of circularity or deviations that occur after drilling is carried out using a Mitutoyo PJ3000 profile projector type by drawing the x and y-axis lines eight times on the top surface. The drill bit was used once for one hole and replaced with a new one for the next hole to obtain representative measurement results. The circularity of the bone drilling results was observed four times in each drill hole. The results obtained were then analyzed using the RSM-Box Behnken Design method. Design expert-13 software is used to develop matrix design, analyze the significance of drilling parameters, and optimize the roundness process parameters (circularity) in cortical bone drilling. With the help of software, the impact of each parameter on the roundness of cortical bone after drilling can be analyzed. Therefore, to obtain the minimum roundness value, a mathematical model is made for drilling parameters to help determine the appropriate combination of drilling input variables. The optimization module in design expert determines the combination of rotational speed factor levels, feed rate and also the provision of coolant that runs simultaneously to respond to the drill hole's circularity or roundness. Optimization methods with numbers and graphics are used by selecting the desired objectives for each factor (input) and the response (output).

3. Results and Discussion

Micro Hardness of Speciments

The results of measuring the microhardness of bovine cortical bone used in this study are shown in Figure 1.

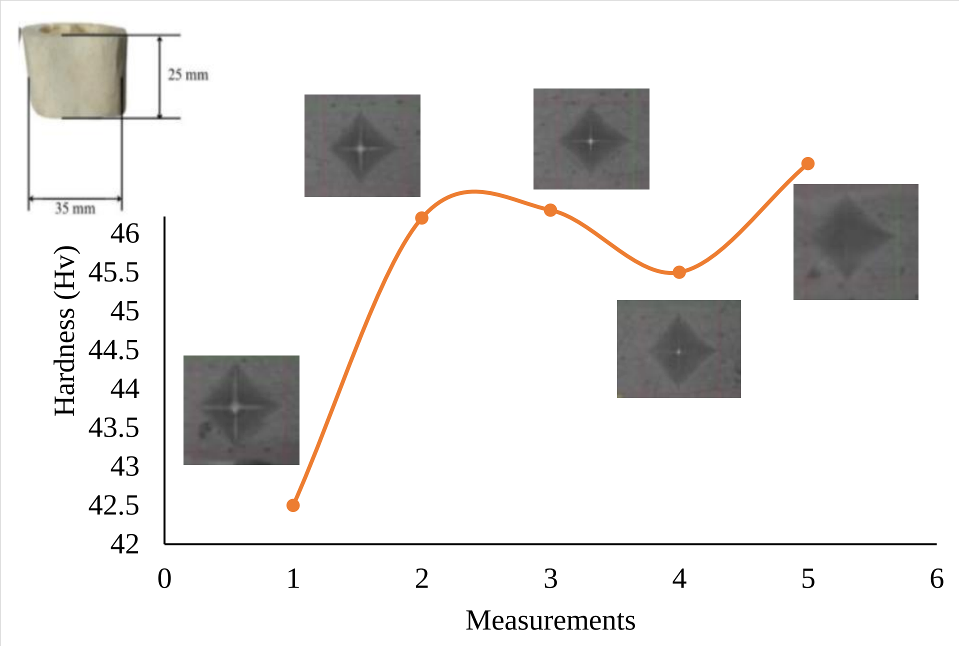


Figure 1. Results of hardness measurements of cortical bone specimens

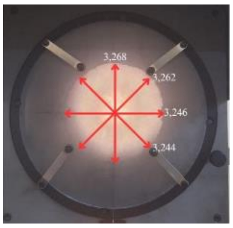
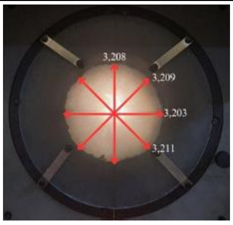
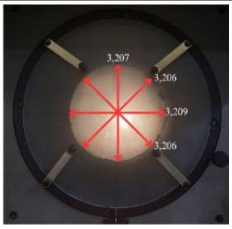
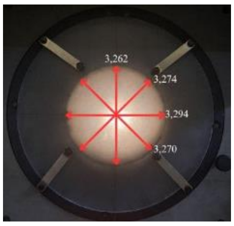
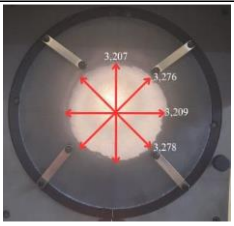
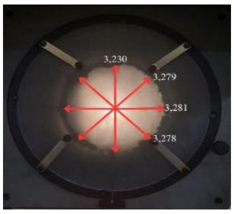
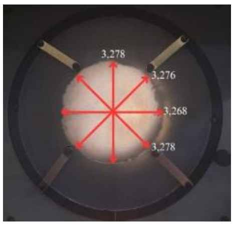
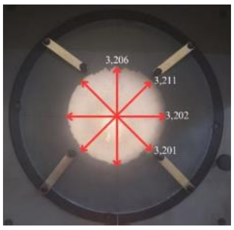
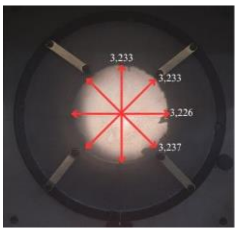
Based on microhardness testing of cortical bone specimens, an average microhardness of 45.48 HV was obtained with a standard deviation of 1.74. The hardness of the specimens used is generally bovine bone hardness values , which have values between 0.41 GPa to 0.89 GPa [17]. When compared with the hardness of human bones for both men and women, which ranges from 24.46 HV (HV = hardness value, kgf/mm^2) for the sacrum to 53.20 HV for the shaft of the tibia, the specimen hardness value is still lower than the hardness of the tibia cortical bone which has a hardness of 51.20 HV [18]. The hardness of a material will significantly affect the performance of a drilling process. Softer materials allow drilling to use less power at the same speed as more rigid materials. At the same feeding rate, harder materials require hard work from the drill bit to penetrate the material. Materials with high hardness can cause drill bit wear, reducing stability and service life [19]. This drill bit wear can affect the circularity level of the drilling results. If still used, drill bits that are no longer sharp will result in greater thrust and the hole becoming non-centric.

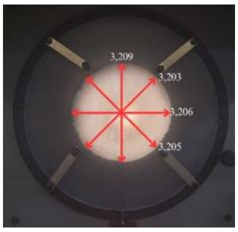
Using animal bones as in vivo modeling has been a commonly used and accepted approach in extrapolating the results obtained to human health. Furthermore, microhardness testing can produce specific mechanical properties for specific computational analyses [20]. In this experiment, cow bone specimens with a hardness close to human bone can be used as a basis for further research. The possibility to obtain specific mechanical properties for each animal bone using microindentation could contribute to making specific computational analyzes of the influence of bone quality on stress distribution possible.

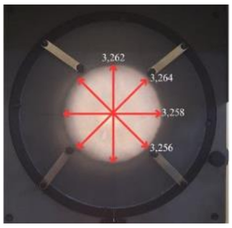
Circularity Meassurement

The results of circularity using a projector profile for 15 specimens are shown in Table 3.

Table 3. Measurement results with projector profile

Run Order	Parameters	Figure and Size	Circularity Value
1	*n* : 500 rpm *f* : 60 mm/min coolant : NaCl	 Average: 3.255	(3.255-3.2) = **0.055 m**
2	*n : 1*500 rpm *f* : 60 mm/min coolant : NaCl	 Average: 3.2045	(3.2045-3.2) = **0.0045 mm**
3	*n : 1*500 rpm *f* : 60 mm/min coolant : Dry	 Average: 3.20125	(3.20125-3.2) =**0.00125 mm**
4	*n : 1*500 rpm *f* : 35 mm/min coolant : OpSite	 Average: 3.21075	(3.21075-3.2) =**0.01075 mm**
5	*n* : 500 rpm *f* : 60 mm/min coolant: Dry	 Average: 3.2075	(3.2075-3.2) = **0.0075 mm**
6	*n* : 1000 rpm *f* : 35 mm/min coolant : NaCl	 Average: 3,2350	(3,2350-3,2) = **0,0350 mm**
7	*n* : 500 rpm *f* : 35 mm/min coolant : OpSite	 Average: 3.2070	(3.2070-3.2) = **0.0070 mm**
8	*n* : 500 rpm *f* : 85 mm/min coolant : OpSite	 Average: 3.2750	(3.2750-3.2) = **0.0750 mm**
9	*n* : 1000 rpm *f* : 60 mm/min coolant : OpSite	 Average: 3.2425	(3.2425-3.2) = **0.0425 mm**
10	*n* : 1000 rpm *f* : 60 mm/min coolant : OpSite	 Average: 3.2670	(3.2670-3.2) = **0.0670 mm**
11	*n* : 1000 rpm *f* : 85 mm/min coolant : Dry	 Average: 3.2750	(3.2750-3.2) = **0.0750 mm**
12	*n* : 1000 rpm *f* : 60 mm/min coolant : OpSite	 Average: 3.2050	(3.2050-3.2) = **0.0050 mm**
13	*n* : *1*500 rpm *f* : 85 mm/min coolant : OpSite	 Average: 3.23225	(3.23225-3.2) =**0.03225 mm**

14	*n* : 1000 rpm *f* : 35 mm/min coolant : Dry	 Average: 3.20573	(3.20573-3.2) **=0.00573 mm**

15	*n* : 1000 rpm *f* : 85 mm/min coolant : NaCl	 Average: 3.2600	(3.2600-3.2) **= 0.0600 mm**

The table above presents the results of circularity measurements using a profile projector, where the smallest value occurred at a rotational speed of 1500 rpm, feed rate of 60 mm/min, and without the use of coolant, yielding 0.00125 mm. The most considerable roundness value obtained, 0.075 mm, originated from two different drilling conditions: a rotational speed of 1000 rpm, feed rate of 85 mm/min, without coolant, and a rotational speed of 500 rpm, feed rate of 85 mm/min, using OpSite coolant. Nilai circularity 0.00125 dari hasil pengeboran tulang pada eksperimen ini memiliki nilai yang lebih baik dibandingkan dengan penelitian sebelumnya yang hanya memperoleh nilai 0.018 pada pengeboran paduan magnesium [21].

Analysis of Variance (ANOVA)

The circularity measurement results were then analyzed with RSM using the Design Expert 13 software. The data was analyzed using a 3-model approach, analyzing whether it statistically affected roundness. Likewise, each parameter will be analyzed for its influence on roundness, whether statistically significant or not. Then a mathematical model will be looked for to formulate the influence of each parameter on roundness. Factors that might influence circularity were assessed by examining P values in the analysis of variance (ANOVA). This study observed P values considering a confidence level of (α = 95%. Thus, factors that showed P values less than or equal to 0.05 were considered to have a significant influence on the observed response [22]. The results of the analysis of variance are shown in Table 4.

The ANOVA model in this study shows an F-Model value of 4.12, indicating the significance and adequacy of the model about the accuracy of the signal-to-noise ratio. Based on the P-value can be used as a basis for determining experimental factors that have a significant effect on the desired results [23]. Usually, an experimental factor's significance level is set not to exceed the allowable error. In this research, the desired confidence level is α = 95%, so the P-value with a significant effect cannot be more than 0.05. The P-value in this study is 0.0346, signifying the statistical significance of the model. There is a significant influence from the rotational speed, feed rate, and coolant fluid factors, as well as the linear model, on the circularity of the borehole surface. The Lack of Fit value of 0.3751, more significant than 0.05, indicates that the model inadequately fits the data but does not significantly affect the response.

Table 4. Anova results

Source	Sum of Square	df	Mean Square	F-Value	P-Value	
Model	0.0059	3	0.002	4.12	0.0346	**Significant**
A-Rotational Speed (V)	0.0012	1	0.0012	2.42	0.1483	
B-Feeding Rate (Vf)	0.0042	1	0.0042	8.86	0.0126	
C-Coolant	0.0005	1	0.0005	1.1	0.3168	
Residual	0.0052	11	0.0005			
Lact of Fit	0.0033	9	0.0004	0.3751	0.8768	**Not Significant**
Pure Error	0.002	2	0.001			
Cor Total	0.0111	14				
Std. Dev.	0.0218		R2			0.5294
Mean	0.0322		Adjusted R2			0.401
C.V. %	67.69		Predicted R2			0.1754
			Adeq Precission			

The results of ANOVA in Table 4 show that the P-value of the rotational speed, feeding rate, and cooling type parameters are 0.14, 0.01, and 0.32, respectively. Based on the P-value, the most significant ranking factor is the feeding rate. The axial force during drilling due to the feeding rate causes radial force. At a high feeding rate, a higher radial force will be produced. Furthermore, this radial force affects the deviation of the circular path in the drill hole. In addition, the characteristics of thick and discontinuous chips produced during drilling change when the feeding rate increases, which can cause roughness and worsen the quality of circularity [24]. Compared to rotational speed and coolant type, the feeding speed has a higher impact on the radial force that affects the circularity. While coolant keeps the temperature of the drill bit and workpiece excellent during drilling has a less significant effect. Coolant reduces heat and friction, but does not cause too high a force effect. The significance level of these drilling parameters is also by previous studies.

Previous research has been conducted on borehole circularity using different materials [25]. The feed rate is the significant factor affecting the roundness value in the machining of SKD 11 material, as the high forces involved in the feed rate can lead to workpiece deformation, resulting in inaccuracies in hole circularity [26]. Using alloy materials has been shown to increase the feed rate, which tends to enhance the surface roughness and borehole circularity. Conversely, lower feed rates can prolong drilling time and incur inefficiencies in costs despite yielding satisfactory surface finishes. This study diverges from previous research in terms of the material utilized. Previous studies employed SKD 11 and other alloys with different hardness properties compared to the cortical bone utilized in this investigation. The study conducted by Effatparvar et al. (2020), with the same parameters, the research focuses on bone damage due to temperature rise caused by friction between the drill bit and bone, recommending OpSite fluid as a cooling agent to reduce the rate of temperature increase during drilling [12]. According to the ANOVA data presented above, the B-Feed Rate factor significantly influences the upper and lower circularity of the borehole in the cortical bone drilling process.

Optimization of Drilling Parameters

The optimization method utilizing numerical and graphical approaches was employed by selecting desired objectives for each factor (input) and response (output). The optimized parameters show the target, minimum and maximum limits, and also the order of their importance. In this study, the rotational speed, feed rate, and coolant are optimized at these limits with an importance level of 3 (+++). The response, namely circularity, is optimized with the aim of a minimum value at an importance level of 5 (+++++), shown in Table 5. The optimization parameter table for cortical bone drilling shown in Table 6.

Table 5. Numeric optimization criteria

Variabel Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Rotational Speed	is in range	500	1500	1	1	3
B: Feeding Rate	is in range	35	85	1	1	3
C: Coolant type	is in range	-1	1	1	1	3
Circularity	minimize	0.00125	0.075	1	1	5

Table 6. Optimization of drilling parameters

No	Rotational Speed	Feeding Rate	Coolant	Circularity	Desirability	
1	**1,500.000**	**35.000**	**0.000**	**-0.003**	**1.000**	**Selected**
2	1,391.718	35.198	-0.017	0.000	1.000	
3	1,071.156	35.082	0.811	0.001	1.000	
4	1,000.000	35.000	1.000	0.001	1.000	
5	1,475.463	37.569	0.618	-0.005	1.000	

The software selected the optimal parameter recommendations to achieve the minimum top surface circularity value in cortical bone drilling with a desirability level of 1.000. In this solution, the selected parameters are a rotational speed of 1,500 rpm, a feed rate of 35 mm/min, and a cooling fluid with code (0), OpSite spray solution. Opsite spray's use as a coolant aligns with the research conducted by Evatparvar et al. (2020) [12]. The recommendation of using OpSite solution as an external coolant during drilling has been found effective in preventing temperature rise and reducing the circularity value of the borehole. In this study, the optimum parameter prediction selected by the software obtained the minimum circularity value of -0.003.

4. Conclussion

Drilling parameters, including rotational speed, feeding rate, and coolant type, with three levels of factors each, have been analyzed for their influence on the circularity of the drill results using the RSM-Box Behnken Design method. By knowing the influence of the significance of the parameters on the optimization of drilling parameters, the drilling of implant materials becomes more optimal with the best results to produce circularity so that the implantation process can run well and does not cause side effects due to drilling failure.

The experimental design for measuring the circularity of bone drilling results with an average microhardness of 45.48 HV with a standard deviation of 1.74 has been successfully carried out. The hardness value of this specimen is in the hardness range of human bones for both men and women, so it is suitable for use as a model for human bones. The lowest circularity value of 0.00125 was obtained from drilling results with rotational speed parameters of 1500 rpm, feed rate of 60 mm/min, and without using coolant. Based on ANOVA, the Feeding Rate (Vf) factor has a significant effect compared to Rotational Speed (V) and coolant with a P-value of 0.0126 and an F-value of 8.86. The most optimum combination of drilling parameters to obtain the smallest circularity value can be using a rotational speed of 1,500 rpm, a feed rate of 35 mm/min, and cooling fluid with code (0), namely OpSite. Recommended as the parameter that produces the highest level of roundness compared to other parameters and previous research.

The results of parameter optimization obtained can be used in the bovine bone drilling process to produce the best circularity. Failure of the drilling process can be minimized by using optimal parameters so that the post-bone implant effects can be minimized. Further research can be done by looking at the distribution of specimen temperature and the level of drill bit wear resulting from the drilling process so that repeated drilling can be done to improve the safety and efficiency of drilling for bone implants.

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