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Effect of Drill Geometry Parameter on Surface Roughness and Hole Morphology in Surgical Bone Drilling

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Abstract

In surgical bone drilling procedure, hole performance namely surface roughness and hole morphology are critical since it will affects the interface strength between the screw and implant which is essential for early and healthy bone growth. The qualities of the hole are greatly dependent with the drill geometry design and the drilling process condition. In this paper, the relationship between both drill geometrical parameter and drilling penetration angle on the hole performance will be identified. Design of Experiment (DOE) historical data of Response Surface Method (RSM) matrix were adopted to evaluate the correlation between the drill geometry parameter and the holes performance (surface roughness and hole morphology). Totals of 51 drills were design and fabricated with different geometry namely point angle, helix angle and web thickness on different condition of penetration angle (0^0, 15^0, and 30^0). From the conducted investigation, it was found that drilling penetration angle was the most significant factor that affect the hole performance followed by the drill point angle. In addition, the interaction between helix angle and web thickness also controlled the hole surface roughness value.

Keywords: Surgical drill, Bone drilling, Surface roughness

INTRODUCTION

In orthopaedic bone surgery, the principal methods for repairing and reconstruction of a bone fracture are achieved by drilling the bone and fixing the separate parts together either by using screws, wires or plates. In most cases, the drilling process create few problems on the hole quality such as holes accuracy, rough surface, micro cracking and drill skiving [1]. The qualities of the hole are related with numbers of factor including the drilling parameter, geometry of the drill bit and drilling condition [2-3]. Many different drill-bit designs and geometries have been suggested over the years each with its own promising results [4-6]. However, most of the studies were performed on ideal normal drilling penetration angle axis which does not represent on the real case. Generally, in normal orthopedic surgery, bone drilling was performed using hand drills and the penetration angles is greatly dependent on the surgeon's manual skill and are normally deviated from the normal axis. Surface roughness in drilling is one of the most important criteria in assessing the drilling quality [10]. In bone drilling application, obtaining a smooth surface roughness on the hole surface are critical since it can affect the interface strength between the screw and implant which is essential for early and healthy bone growth. Therefore, close tolerances and fine surface textures are critical for the osseointegration ability. The qualities of the hole are greatly dependent with the drill geometry design and the drilling process condition which will be the matters that will be discover in this paper. In this paper, the relationship between both drill geometrical parameter and drilling penetration angle on the hole performance will be identified as a groundwork and input for optimizing the drill geometry feature.

EXPERIMENTAL WORK

In this experiment, AISI 420B stainless steel medical grade rod with diameter of 4.3 mm were ground to form the drill bits as shown in Figure 1 with varying angles namely point angle, helix angle and web thickness as depicted in Table 1. Stainless steel drill bit exhibits good corrosion resistance and can minimize the tool wear effects. Totals of 51 holes were drilled with 3 holes replication for each run. To eliminate the apparatus wear impact on the result, the apparatus were cleaned with a brush and wet tissue before each drilling process.

A fresh bovine cortical femur bone was chosen as the work material due to its closeness properties and characteristics with human bone [7-9]. Fresh cortical (compact bone) samples are cuts and mills from bovine femur with a uniform thickness of 4 mm as shown in Figure 2.

Table 1. Drill geometrical parameter design

	Name	Unit	Low	High
A	Web Thickness	%	14	32
B	Point Angle	ºDeg	90	140
C	Helix Angle	ºDeg	16	38
D	Penetration Angle	ºDeg	0	30

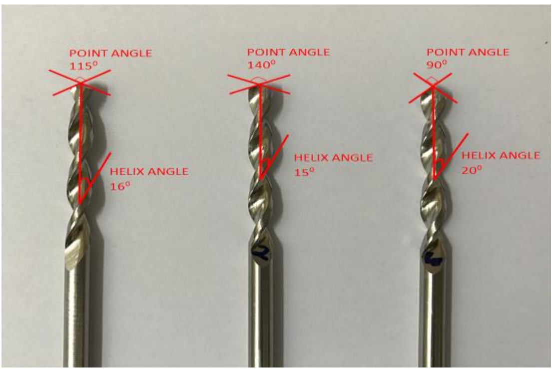

Figure 1: Sample design of the fabricated drill bit

The drilling tests were performed using a DMU60 monoBLOCK DECKEL MAHO CNC 5-Axis machine. The drilling speed of 1000 rpm and 100 mm/min feed rate were employed to represent the actual manual surgical hand drills speed and surgeon penetration feed. Portable surface roughness Mitutoyo SJ-301 model was used to measure the surface roughness value as shown in Figure 3. SEM analysis was performed in order to evaluate the physical damage around the hole surface caused by different drilling penetration angle.

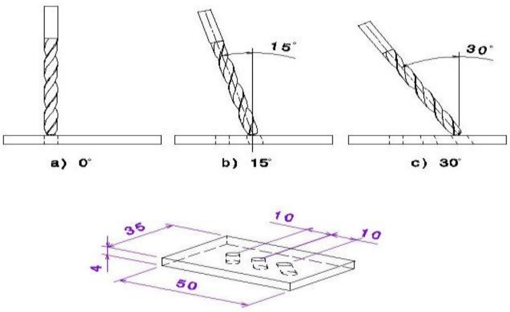

Figure 2. Bone work-pieces with its drilling penetration angle (0^0, 15^0, and 30^0)

Figure 3. Experimental layout

RESULTS AND DISCUSSION

The effects of drill geometries such as point angle, web thickness and helix angle has deep effect on the surface roughness. From the conducted experimental tests, it is evidently shows the variation of surface roughness values on different drills design as well with the variation on penetration angle. Referring to Table 2, the average surface roughness value of bone hole varied from 0.22µm to 1.98µm with overall mean of 0.60µm. From the result it can be observed that the combination of drill bit design for run no. 11 (23% web thickness, 115^0 point angle and 27^0 helix angle) with the 0^0 penetration angle produced the lowest surface roughness with an average value of 0.22µm. The obtained result shows that the optimal combination of drill bit geometry able to produced smooth surface roughness and for this case it provides a better shearing action during the cutting process. Meanwhile, the combination of drill bit design for run no. 51 (32% web thickness, 115^0 point angle and 16^0 helix angle) with the 30^0 penetration angle produced the highest surface roughness with an average value of 1.98µm.

Table 3 shows the statistical analysis of variance (ANOVA) of the predicted response surface model on the influence of web thickness, point angle, helix angle and drilling angle for a confidence level of 95%. Based on the ANOVA, a mathematical quadratic function model of the surface roughness correlated with the drill design parameter was found to be significant with a P-value of less than 0.05. The design geometry parameters with P-values of less than 0.05 indicated that the model terms significantly affected the response in the design space [11-13].

Equation 1 shows the correlation between the surface roughness and the drill design geometry parameters, i.e. web thickness, point angle, helix angle and cutting angle. The prediction model can be denoted by the equation as:

$$\textit{\textbf{Surface Roughness}} = -0.47 - 0.03*A + 0.04*B - 0.09*C - 0.04*D + 3.0 \times 10^{-4} * A*B - 1.48 \times 10^{-3} *A*C + 1.08 \times 10^{-4} *A*D + 2.30 \times 10^{-4} * B*C + 2.33 \times 10^{-4} *B*D + 1.16 \times 10^{-3} *C*D + 8.87 \times 10^{-4} *A^2 - 2.30 \times 10^{-4} *B^2 + 1.59 \times 10^{-3} *C^2 - 1 \times 10^{-4} *D^2 \quad (1)$$

The above mathematical model can be used to predict the values of the surface roughness within the limits of the factors studied. The model's 3D response surface graphical interactions between factors and the surface roughness in the design space are illustrated in Figure 4 to 6. Figure 4(a) shows the interaction of point angle and web thickness to the surface roughness. The contour plot shows in the saddle upside down at which the maximum and minimum point is the combination of extreme value in that range. . It was found that the lower the point angle and web thickness, the lower the value of surface roughness. Meanwhile, Figure 4(b) shows that lower surface roughness value was achieved at the lower web thickness and higher helix angle region.

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Table 2 Surface roughness results

	Factor				Surface Roughness (μm)					Factor				Surface Roughness (μm)			
Run	**A**	**B**	**C**	**D**	**1**	**2**	**3**	**Average**	**Run**	**A**	**B**	**C**	**D**	**1**	**2**	**3**	**Average**
1	23	115	27	0	0.36	0.36	0.35	**0.36**	27	32	90	27	15	0.36	0.35	0.42	**0.38**
2	14	140	27	0	0.39	0.41	0.43	**0.41**	28	23	115	27	15	0.37	0.33	0.35	**0.35**
3	14	90	27	0	0.33	0.25	0.27	**0.28**	29	23	90	38	15	0.33	0.31	0.36	**0.33**
4	23	115	27	0	0.66	0.57	0.6	**0.61**	30	32	115	38	15	0.88	0.8	0.79	**0.82**
5	14	115	16	0	0.43	0.43	0.41	**0.42**	31	23	90	16	15	0.72	0.52	0.44	**0.56**
6	23	115	27	0	0.37	0.22	0.27	**0.29**	32	23	115	27	15	0.42	0.45	0.51	**0.46**
7	14	115	38	0	0.29	0.31	0.29	**0.3**	33	23	140	16	15	0.71	0.8	0.92	**0.81**
8	23	140	38	0	0.26	0.22	0.21	**0.23**	34	32	115	16	15	1.35	1.12	1.19	**1.22**
9	32	140	27	0	0.63	0.62	0.61	**0.62**	35	23	115	27	30	0.32	0.32	0.25	**0.3**
10	32	90	27	0	0.51	0.54	0.53	**0.53**	36	14	140	27	30	0.27	0.33	0.29	**0.3**
11	23	115	27	0	0.24	0.22	0.21	**0.22**	37	14	90	27	30	0.42	0.41	0.38	**0.4**
12	23	90	38	0	0.19	0.19	0.16	**0.18**	38	23	115	27	30	0.64	0.65	0.58	**0.62**
13	32	115	38	0	0.17	0.15	0.18	**0.17**	39	14	115	16	30	0.36	0.33	0.36	**0.35**
14	23	90	16	0	0.5	0.43	0.42	**0.45**	40	23	115	27	30	1.22	1.17	1.15	**1.18**
15	23	115	27	0	0.61	0.66	0.68	**0.65**	41	14	115	38	30	1.61	1.42	1.45	**1.49**
16	23	140	16	0	0.36	0.37	0.33	**0.35**	42	23	140	38	30	1.09	1.13	1.15	**1.12**
17	32	115	16	0	0.62	0.79	0.74	**0.72**	43	32	140	27	30	0.65	0.65	0.66	**0.65**
18	23	115	27	15	0.45	0.42	0.48	**0.45**	44	32	90	27	30	0.32	0.38	0.31	**0.34**
19	14	140	27	15	0.26	0.31	0.27	**0.28**	45	23	115	27	30	0.91	0.62	0.45	**0.66**
20	14	90	27	15	0.43	0.41	0.45	**0.43**	46	23	90	38	30	0.4	0.41	0.37	**0.39**
21	23	115	27	15	0.33	0.22	0.25	**0.27**	47	32	115	38	30	1.51	1.46	1.39	**1.45**
22	14	115	16	15	0.64	0.56	0.45	**0.55**	48	23	90	16	30	0.3	0.22	0.29	**0.27**
23	23	115	27	15	0.63	0.58	0.55	**0.59**	49	23	115	27	30	1.41	1.51	1.45	**1.46**
24	14	115	38	15	0.87	0.75	0.92	**0.85**	50	23	140	16	30	0.85	0.91	0.95	**0.9**
25	23	140	38	15	0.94	1.15	1.21	**1.1**	51	32	115	16	30	2	1.95	1.99	**1.98**
26	32	140	27	15	0.63	0.68	0.63	**0.65**	***A=Web thickness, B=Point angle, C=Helix angle, D=Penetration angle***								

Figure 5(a) show the 3D response of surface roughness against drilling angle and web thickness. The resulting contour shape was in the form of a plane in which the lowest surface roughness was found in the interaction between drilling angle and a lower web thickness. In addition, the highest surface roughness was found to be at the middle point between drilling angle and web thickness. The lowest value of surface roughness occurred at the point when the drilling angle was at 0^0 and web thickness of 14%. This shows that the web thickness and drilling angle provides has less significant effects on surface roughness value. Figure 5(b) shows the 3D response of surface roughness against helix angle and point angle. The produced contour plot tends to followed arch shape or a saddle upside down with extreme curves which indicates the significant of these two factors.

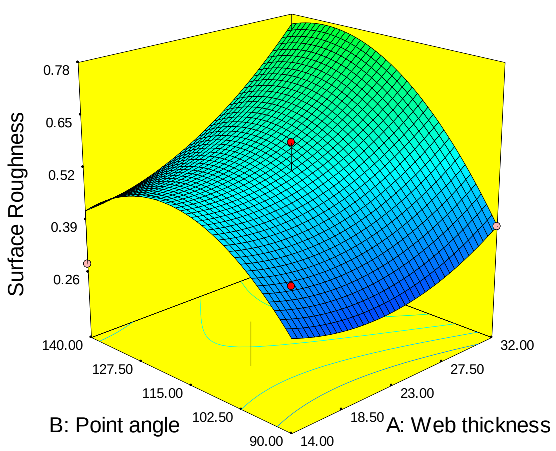
Figure 6(a) shows the 3D response of surface roughness against drilling angle and point angle. The resulting shape is in the form of a plane in which the low surface roughness is found to be at lower interaction drilling angle and a lower point angle, while the high surface roughness occurred at the point when both drilling angle and point angle at the highest values. Meanwhile Figure 6(b) shows the 3D response of surface roughness against drilling angle and helix angle. The contour plot shows arch shape is like a saddle upside down with extreme curves show the interaction of these two factors is also significant.

Hole Surface

SEM analysis was performed in order to evaluate the physical damage caused by various drill bit design and penetration angle. Drilling quality includes aperture deviation, migration and gradient of the aperture axis and the changes of surface geometry [9]. In this study the quality of the holes surfaces were observed to evaluate the effect of drill geometry design with different penetration angle. Figure 7 shows the sample of SEM micrograph for three different penetration angles 0^0, 15^0 and 30^0. It can be observed that penetration angle of 0^0 and 15^0 produced the smooth holes surfaces compared to 30^0 for all the drills design. From the observation, when the drill bit penetrates into the bone, it forms a burr around the developing hole. The best results are for 0^0 degree penetration angle (i.e. straight hole) because the drill axis was perpendicular to the bone surface, which preclude the drill from skidding across the bone surface upon commencement of the drilling operation.

Table 3. ANOVA result

Source	Mean Square	F Value	Prob>F	
Model	0.22	3.89	0.0006	Sig.
A-Web thickness	0.23	3.99	0.0539	
B-Point Angle	0.35	6.03	0.0193	
C-Helix Angle	0.030	0.53	0.4717	
D-Drilling angle	0.75	13.00	0.0010	
AB	0.055	0.95	0.3360	
AC	0.22	3.92	0.0560	
AD	3.048E-003	0.053	0.8192	
BC	0.048	0.84	0.3663	
BD	0.12	2.13	0.1533	
CD	0.53	9.21	0.0046	
A^2	0.062	1.08	0.3057	
B^2	0.25	4.28	0.0462	
C^2	0.44	7.73	0.0088	
D^2	0.018	0.31	0.5833	
Residual	0.057			
Lack of fit	0.058	1.06	0.4827	Not sig.
Pure Error	0.055			



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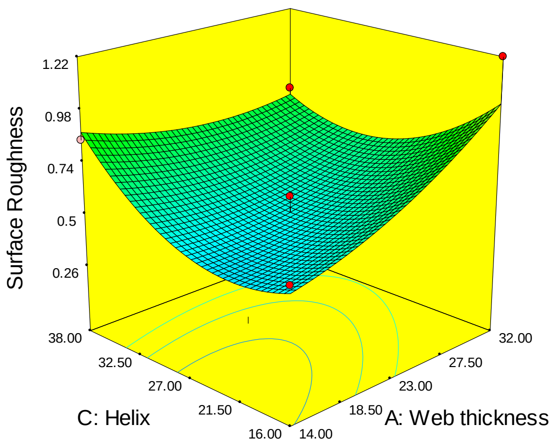
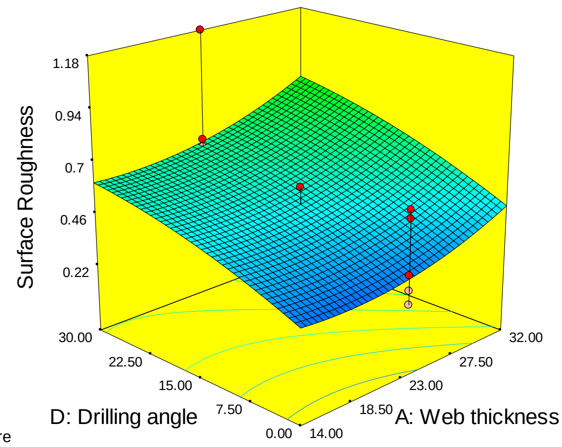


(b)

Figure 4. 3D response surface of surface roughness on a) Point angle and web thickness b) Helix angle and web thickness



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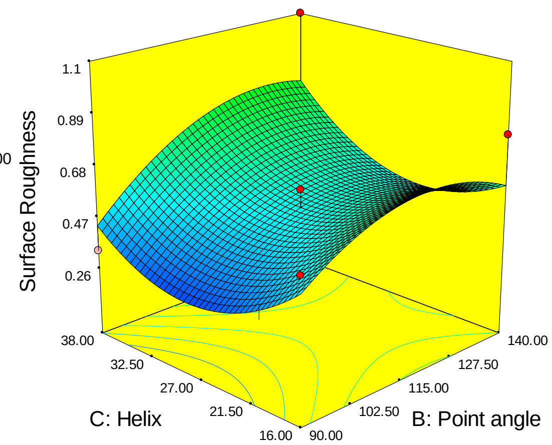
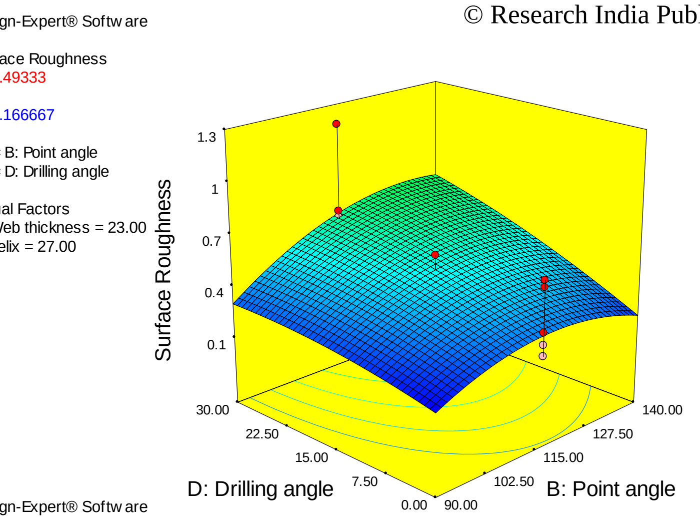
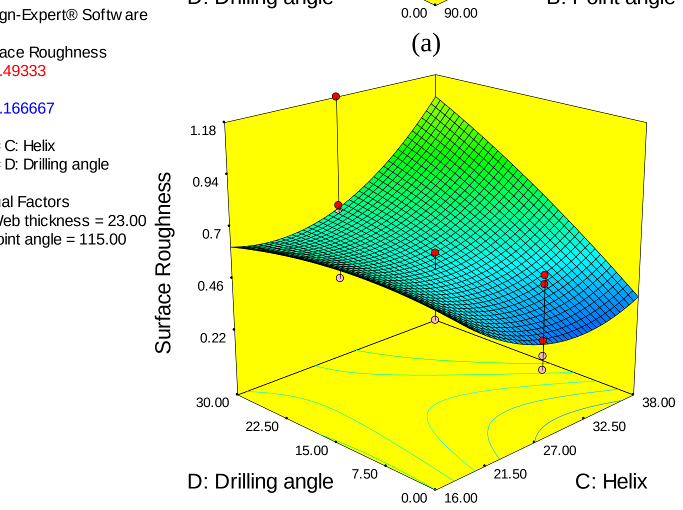


(b)

Figure 5. 3D response surface of surface roughness on a) Drilling angle and web thickness b) Helix angle and point angle



(a)



(b)

Figure 6. 3D response surface of surface roughness on a) Drilling angle and point angle b) Helix angle and drilling angle

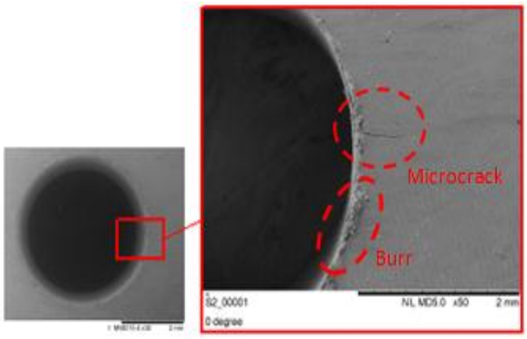
During the bone drilling process, the produced chips impact the wall of the holes generating small cracks on the chip surface and causing them to break when the critical strain are reached. In addition, due to the deviated angle at the beginning of contact point causing a deformation around the hole surface. The combination from both friction and thermal effects increase the micro-fracturing effect as the penetration angle increased. Figure 7 shows the defects cause due to the different penetration angle. Results of the study revealed that insertion angle is the unique factor determining the passage of a drill bit to the bone surface. According to these results, standard drill bit geometry could perforate and pass cortices when inserted at ≤ 30° penetration angle.

CONCLUSIONS

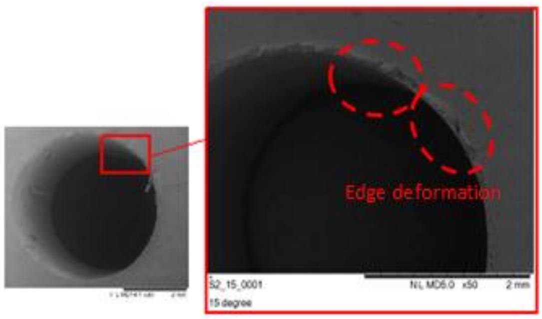
A practical investigations on the effects of drilling quality (surface roughness and hole surface) with different drill geometry parameters were studied. The following conclusion can be drawn as follows:

- This study demonstrated the interaction on the effects of drill-bit design geometry parameters with surface roughness for different drilling penetration angle conditions. The interaction between the design geometry parameter and the drilling penetration angle significantly affect the surface roughness and hole surface quality of bone.
- From the conducted investigation, the most significant parameter that affects the surface roughness and holes surface quality were penetration angle followed by the point angle. In addition, helix angle and web thickness give less significant effect on the hole performance.

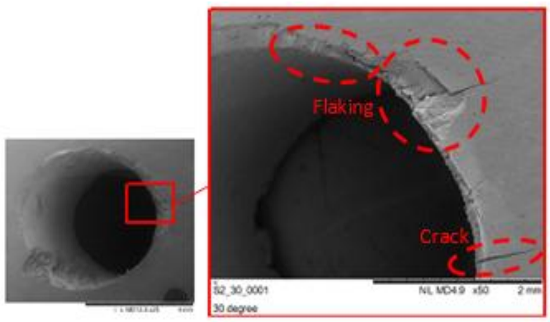
To conclude, the results from the conducted experiments provide the reference values for the development of high performance surgical drill design in orthopedic bone surgeries application.



(a) Drill design no 2 at 0^0 penetration angle



(b) Drill design no 2 at 15^0 penetration angle



(c) Drill design no 2 at 30^0 penetration angle

Figure 7. SEM views of hole surface sample for drill design 2 at varied penetration angle of 0^0, 15^0 and 30^0

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