Journal of Mechanical Engineering *Vol SI 3 (2), 37-47, 2017*

Evaluation of Hole Performance and Force Magnitude on Drilling Parameter for Orthopaedic Surgical Bone Drilling

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ABSTRACT

Internal fixation of bone fractures using immobilization screws and plate is a common procedure in orthopaedic surgery. This surgical procedure involved drilling process into bone and fixative component'sinteraction, which create several problems. Few of the common problems associated in the bone drilling process are hole's accuracy, drill wanders and excessive heat generation, which was directly related to the drilling parameters. This paper investigates the effect of drilling parameter namely spindle speed and feed rate on the cutting force and hole performances namely suraface roughness and surface morphology. Designs of Experiment (DOE) historical data of Response Surface Method (RSM) were adopted to evaluate the correlation between the cutting parameter and the hole's performance. From the conducted investigation, it was found that the most dominant factor that affects the holes performance was spindle speed followed by the feed rate. In addition, the interaction between feed rate and spindle speed also controlled the hole's performances.

ISSN 1823- 5514, eISSN 2550-164X

Received for review: 2016-03-03
Accepted for publication: 2016-03-03
Published: 2017-07-01

Keywords: *Surgical Drill-Bit, Surface Roughness, Cutting Force, Machining, RSM*

Introduction

In orthopedic bone recovery operations, hole making process by means of drilling process are normal procedure for allocation of screw and fixation. The hole performances namely hole accuracy and surface finish are critical for the osseointegration ability [1, 2]. The surface characteristic affects the bone-screw interface strength as well as the cellular response, which is essential for early and healthy bone growth. Various techniques were employed to enhance bone apposition including bioactive coating and surface texturing of fixative components. Apart from that, surface roughness also may affect the healing process [3]. There has been ongoing research associated with implant surface topography. Proper mating between two joining surfaces are necessitated for a stable bone-implant interface in minimizing the trauma due to the drilling forces [4].
Due to the anisotropic properties and complex biological tissue of bones, many problems have been encountered during the bone drilling process such as holes accuracy, drill wander and thermal necrosis which was directly related to the drilling parameter. Thermal necrosis is a common phenomenon during the bone drilling procedure due to the sensitivity of the soft tissue surrounding the bone. Ideally, the generated drilling temperature must be below 47°C in order to avoid thermal necrosis. The magnitudes of the drilling temperature are greatly dependent on the drilling force and should be control. The drilling conditions in the bone drilling process are interrelated by rotational speed and the feed rate which affects the drilling forces and hole qualities [5]. Hence, the understandings of the effects of drilling parameter on the hole performances are necessitated, which will be discovered in this paper.

Experimental Work

Material Specimen

Bovine cortical femur bone was chosen as the work material due to its closeness properties and characteristics with human bone [4]. Table 1 shows the mechanical properties of bovine femur bone. The mid-diaphysis columns were obtained with the average length of 75 mm for the experiments. The average thickness of the cortical wall was 6-8 mm. Periosteum was removed from the drilling surface prior to the experiment to avoid from the chips clogging. The specimens were cuts and mills from bovine femur with a uniform thickness of 4 mm as shown in Figure 1. All experiments were conducted in room temperature without using any coolant or lubricant.

Table 1: Mechanical Properties of Bovine Femur Bone

Mechanical properties	**Value**
Density (kg/m3)	1800
Young's modulus (MPa)	20000
Longitudinal elastic modulus (GPa)	26.1
Transverse elastic modulus (GPa)	10.9
Longitudinal tensile strength (MPa)	140
Transverse tensile strength (MPa)	46
Poisson's ratio	0.36

Figure 1: Sample of material preparation

In this experiment, two flutes with 4.3 mm diameter surgical drill-bit (AISI 420B stainless steel) was used to drill the bovine cortical femur bone. Figure 2 and Table 2 depicted detail's specification of the drill bit. The surgical drill-bit were employed because of its accurate drilling and deliver consistent rotational movement during the process [6]. In addition, a stainless steel drill bit exhibits good corrosion resistance. Besides that, by using stainless steel drill bit, it can minimize the tool wear effect. Totals of 24 holes were drilled with 3 holes replication for each run. To eliminate the apparatus wear impact on the result, the apparatuses were cleaned with a brush and wet tissue before each drilling process.

Table 2: Surgical Drill Bit Geometry Parameter

Drill diameter (mm)	**4.3**
Web thickness (mm)	2.364
Helix angle (°)	19.07
Point angle (°)	96.04
Margin (mm)	0.284
Clearance (mm)	0.358

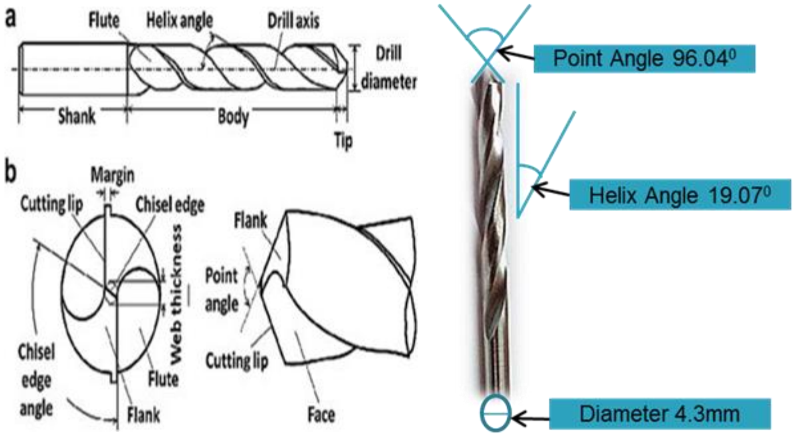
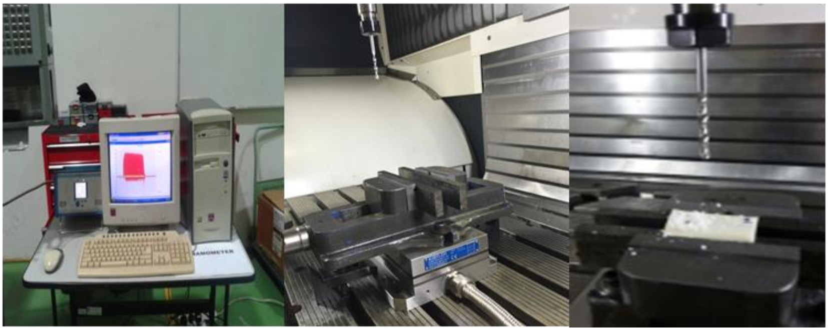


Figure 2: AISI 420B Stainless Steel Surgical Drill Bit

Experimental Equipment

Set of experiments were conducted to investigate the effect of high speed drilling on cutting force and surface roughness. Each test was performed using an HAAS VF-1 CNC Vertical Machine. A Kistler type 9275BA dynamometer was mounted under the work piece fixture to record the thrust force during the process (see Figure 3). Before conducting experiments CNC machine will run without load at least 30 minutes. At the same time, clamping will be checked to ensure that work is neatly sandwiched in the clamped area. This is to prevent that from happening any collision during the machining process. A machining blank expression process will be done on offsets at z axis during the motion and will be ensured fast controlled independent work of earlier machines such as depth and roughness effects of the process of running is free. One of the sizes using the current size parameter is done by using the tool is not counted in the calculation of wear and then found that the actual machining and processing performed each time change cutting parameters.

Dynamometer is used to measure both the torque and the thrust force [7, 8]. During the operation take place the sample of bovine bone is clamped on the worktable of a sensitive drilling dynamometer that are this machine are able to taking 25 mm height and length up to 300 mm. The surface roughness of drilled holes was measured by Mitutoyo Roughness Tester. The bone sample was mounted on the stage of tester, and the stylus was moved over the bone surface at a speed of 10 mm/min. To evaluate hole surface quality, bone debris and hole morphology are observed by SEM (scanning electron microscopy) and optical microscope model EMZ-Meiji.



a) b) c)

Figure 3: Experimental setup for bone drilling a) Kistler type 9275BA dynamometer, b) Kistler amplifier with monitor and c) Drilling Operation.

Experimental Matrix

The experimental matrix and data analysis for this study are conducted by using Design Expert version 6.0 software. Two factors were selected in this experiment. There are spindle speed and feed rate with two levels as shown in Table 3. Then, the process control parameters and their limit were substituted into software. By applying RSM, the planning matrix will contain the value exceeds the (-1) or (+1) range to allow estimation of curvature. The lower limit for low (-1) was added for spindle speed (600 rpm) and feed rate (25 mm/min). While the upper limit for (+1) was added for spindle speed (1500 rpm) and feed rate (85 mm/min). By increasing drill rotational speed (especially at higher speeds range,), drilling thrust force decreases considerably [9, 10].

Table 3: Process control parameters and levels

Factor	Parameter	Limit (-1)	Limit (+1)
A	Spindle speed (rpm)	600	1500
B	Feed rate (mm/min)	25	85

Result and Discussion

From the conducted investigations, it is evident that drilling parameters (spindle speed and feed rate) is important criteria that affect the hole performances namely surface roughness, surface morphology and force magnitude. Experimental results of surface roughness for drilling process are shown in Table 4. From the result, it the minimum of surface roughness is 0.73 μm and the maximum is 3.43 μm. The result of cutting force is 7.46 N and the maximum is 20.15 N.Equation (1) and (2) show the mathematical relationship for correlating the surface roughness and cutting forces considering output responses of drilling parameters, i.e. spindle speed and feed rate. The mathematical model was obtained from using design expert software. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable, which indicates an adequate signal [11]. The prediction model can be denoted by equation as:

$$\textit{Surface Roughness } (\mu m) = 1.006 + 5.692 \times 10^{-4}\,\textit{Speed} - 8.622 \times 10^{-3}\,\textit{Feed rate} \qquad (1)$$

$$\textit{Force } (N) = 5.641 + 2.040 \times 10^{-3}\,\textit{Speed} - 7.28110^{-3}\,\textit{Feed rate} + 9.17910^{-5}\,\textit{Speed*Feed rate} \qquad (2)$$

Table 4: DOE results for surface roughness and cutting force for bone drilling process

Run	Speed (RPM)	Feed (mm/min)	Ra (µm)	Force (N)
1	600	25	0.75	7.46
2	1500	85	0.83	20.15
3	1500	25	1.51	12.1
4	1500	85	1.25	12.9
5	600	85	0.73	11.2
6	1500	25	1.9	11.8
7	600	25	1.39	8.7
8	600	85	3.43	11
9	600	25	0.73	7.49
10	1500	85	0.87	19.94
11	1500	25	1.54	12.8
12	1500	85	1.21	14.12
13	600	85	0.69	10.64
14	1500	25	2.05	11.92
15	600	25	1.38	8.36
16	600	85	3.41	11.88
17	600	25	0.77	7.52
18	1500	85	0.84	19.85
19	1500	25	1.59	11.24
20	1500	85	1.25	13.65
21	600	85	0.78	12.37
22	1500	25	2.11	10.98
23	600	25	1.44	8.98
24	600	85	3.38	12.21

The two factors A and B have large positive effect. Figure 4 shows the interaction factor plot for spindle speed and feed rate towards surface roughness and cutting forces. Surface roughness increases as spindle speed increases but poor when feed rate 25 mm/min. The effect of the primary machining parameters on surface roughness was found to be comparable with that reported by [6, 10]. The interaction graph shows that by increasing the speed the cutting force also increases but the cutting forces more sensitive when feed rate 85 mm/min rather than 25 mm/min. It was indicated by the steep trend of the interaction.

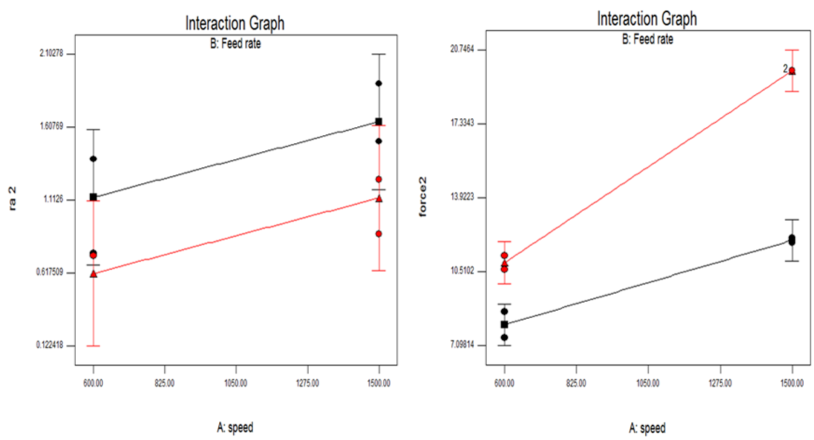


Figure 4: Interaction factor plot for surface roughness and cutting force

Drilling quality includes aperture deviation, migration and gradient along the aperture axis and the changes of surface geometry. During the bone drilling the chips impacted the wall of the holes generating small cracks at the chip surface and causing them to break when the critical strain is reached. The small particles such as debris, smearing, and feed mark were appeared because drilling into the bone. Due to the friction and thermal effects its can cause microfracture as shown in Figure 5. Hole quality in drilling is evaluated in terms of hole diameter and cylindricity, surface roughness, and burr. It is clear from the images that the hole produced is circular from the top but with burr as shown in Table 5.

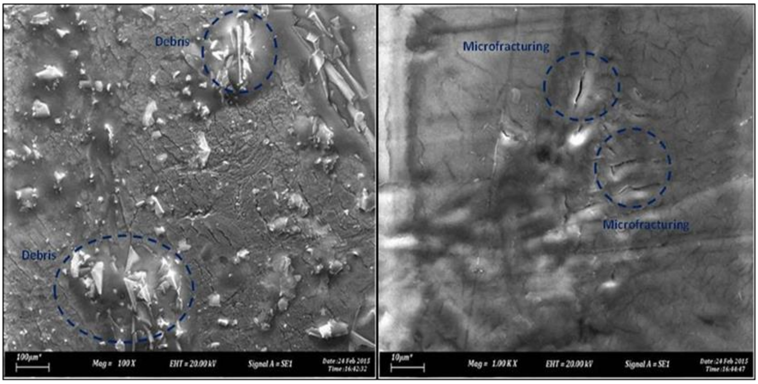
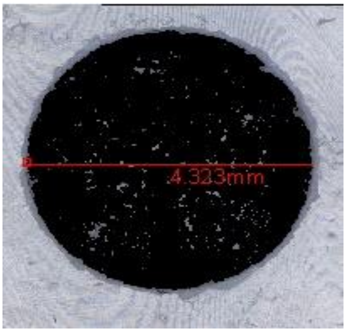
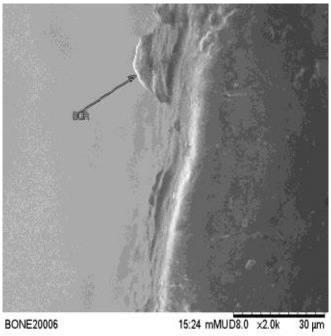


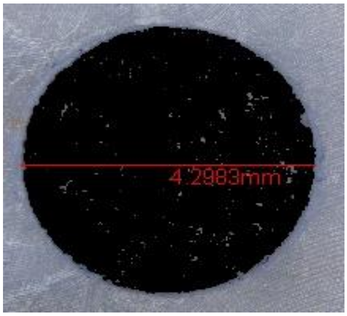
Figure 5: SEM 100µm view of drill hole surface

When the drilling speed was increased from 600 rpm to 1500 rpm, the hole morphology became well-defined, and the chips appeared as small fragments as shown in Table 5. In general, the higher the drilling speed was, the smaller the debris. From the investigation when the drilling speed increased, the amount of bones extracted per unit of time decreased, and the bone debris curled from up to aside. In addition, the length of the debris decreased, bone debris breakage accelerated, and the hole morphology improved, resulting in excellent drilling quality.

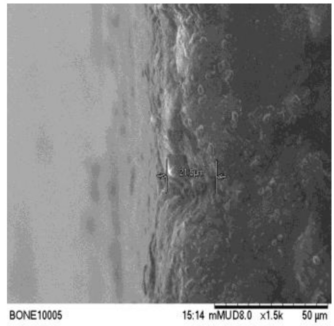
Table 5: Effect hole morphology with drilling speed

Drilling Speed	**Hole Morphology**	**Bone Effect**
600 RPM	 Diameter : 4.323 mm	

1500 RPM



Diameter : 4.298 mm



Conclusion

Investigations of high performance surgical drill-bit bone analysis using Response Surface Method (RSM) historical data were studied. Surface roughness, surface morphology and cutting force were measured for each experimental state. The following conclusion can be drawn:

- This study demonstrated the interaction effect of drilling parameters on surface roughness and cutting force of drilling hole of the femur bovine bone using RSM. The interaction between the feed rate and the spindle speed significantly affected the surface roughness and the cutting force.
- From the result, the minimum of surface roughness is 0.736 µm and the maximum is 3.43 µm. The result of cutting force is 7.459 N and the maximum is 19.785 N. By increasing drill spindle speed (at higher speeds range, especially), drilling cutting force increases considerably.
- Spindle speed and feed rate had a significant influence on drilling force, bone debris and hole morphology. By increasing spindle speed, the drilling quality was improved and the surface roughness increases gradually up to a specific cutting speed due to the rise in friction between the two surfaces (drill-bit and bone)[12]-[15].

To conclude, the results from the conducted experiments can provide reference for force control and selection of rotational speed and feed rate in bone surgeries.

Acknowledgement

The authors wish to thanks Universiti Teknikal Malaysia Melaka, Universiti Kebangsaan Malaysia, Hospital Angkatan Tentera Kem Terendak Melaka and the Government of Malaysia for the technical and financial support for the experiment under HLP scholarship.

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