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Experimental Investigation of Delamination Formed by Bone Drilling

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Abstract: Bone drilling is a common method for fixing implants used in bone fractures. Because of the fibre-reinforced composite structure of bone, parameters such as feed rate, spindle speed and drill type affect the hole surface quality. After drilling, the quality of the bore surface, burr formation and delamination at the hole entrance and exit affect the ability of the screw to cause implant failure and fusion problems of the fracture. For this reason, it is very important to conduct drilling with optimum speed and feedrate values. In this study, the effects of processing parameters on hole surface quality and delamination were studied experimentally. In the experiment, bovine bone, which has similar structural properties to human bone, was used. The hole surface quality and delamination formed at the exit of the hole were examined for three different feed rates and spindle speeds. As a result of the experiments, it was seen that the feed rate had more effect on both delamination and hole surface quality than the spindle speed. It was also determined that the cortical part of the bone and the cancellous part of the bone affected the production of heat and drill wear differently.

Keywords: bone drilling; delamination; surface quality

1 INTRODUCTION

Traumatic injuries due to increased human activities often result in bone fractures. Many types of implants are used for internal or external fixation of these fractured bones [1, 2]. Many of these implants require bone drilling during application. After fixation of the fractured bone in the appropriate position with the implants, the most important requirement for the recovery to be timely and properly is the preservation of this broken bone position until the end of the healing process.The loosening of the implant while the healing is in progress leads to the deterioration of the bone reduction, which causes the nonunion or malunion of fractured bone. Delay in the healing process leads to recurrent surgery, limitation of joint mobility and late return to daily activities of the patient.

The fixation of the implant with the help of screws has become routine in clinical practice. Biological and biomechanical complications are encountered, although the screw-implant connection is made with a high success rate [2]. Commonly seen complications are loosening of the screw, infection, nonunion of the fracture and failure of the implant or screw.Screw loosening is an important cause of complications. Rates of screw loosening vary depending on parameters such as excessive or inadequate tightening of the screw, temperature-dependent necrosis during drilling, hole geometric precision and hole surface quality [3]. These problems are encountered mainly because the controllable parameters such as spindle speed and feed rate during drilling are not optimally selected.

In the literature, many studies have been done on the damage-reducing effects of the processing parameters on the bone-healing process.When the studies on the factors affecting the bone screw attachment are examined, Singh G. et al. [4] used the Taguchi optimisation technique to minimise damage during bone drilling. They concluded that damage was minimised at spindle speed 1000 rpm and 50 mm feed rate values. Shakouri E. et al. [5] compared conventional and ultrasound methods in bone drilling. In this study, they found that ultrasound-assisted perforation caused less necrosis formation and bone damage due to less heat formation than in conventional methods. They also found that the surface roughness has lower levels with ultrasound-assisted drilling. Berning et al. [6] reported that necrosis caused by thermal damage decreased bone resistance and caused internal fixation to loosen. Goran et al. [7] studied the effect of drill bit angle, spindle speed and feed rate on bone structure in bone drilling. They reported that high feed rates reduce the increase in bone temperature, which has a positive effect on the structural change of the hole. Alam K. et al. [8] compared the ultrasound-assisted and conventional drilling methods, examining the specimens taken from the entrance and the inner surface of the hole using 3D micro computer tomography. At the end of the study, micro-fractures around the hole in the ultrasound-assisted drilling process occurred less frequently, and this increased the bone-screw attachment ability. Sui et al. [9] have developed a model that calculates the t and the resulting torque in the thrust force drilling process. According to this model, the drill is divided into three zones as cutting edge, end point and gap angle. Thus, it is provided to assist in selecting the appropriate drilling conditions according to the drill bit geometry.

It is noteworthy that the effects of the processing parameters on heat and surface quality are depemd on when the studies on bony puncture are classified (Tab. 1).

Table 1 Available literature in drilling on bone

Author vd. and year	Drill diameter	Cooling	Spindle speed	Feed rate	Temperature	Surface roughness	Motor types	Optimizing
Akbar (2018) [10]	+		+	+	+	+		Grey analysis
Singh (2017) [4]	+		+	+	+	+		Taguchi
Shakouri (2015) [5]	+		+	+	+		+	
Pandey (2014) [11]	+		+	+	+	+	+	Fuzzy Logic
Alam (2014) [8]	+		+	+	+	+	+	
Berning (2011) [6]	+		+		+			
Goran (2008) [7]	+	+	+	+	+			

When the studies are examined, most are about reducing the damage caused by the processing parameters in the drilling process and their effects on healing. Many studies have been carried out on the damage caused by perforation of composite materials such as bone. However, there are few studies on damage to the hole entrance and exit of the bones, called delamination. Unlike the other studies in the literature, we studied the effects of feed rate, spindle speed, helical angle and drill diameter on delamination, hole formation and burr formation.

2 DRILLING BONE AND DELAMINATION

There are two methods, surgical and conservative, for the fractured bone to reach the desired anatomical position. In the conservative approach, the fractured bone is reduced by the external plaster cast or plaster splint. Some fractures are easily treated with this method [12]. However, open reduction and implants should be used in cases for which the anatomical reduction is not fully achieved. Screws are often used for the application of implants in open reduction. The bone must be drilled before implant attachment. Due to the advancement of modern medicine, the drilling of bones has become an almost daily procedure in dentistry and orthopaedics. The bone drilling is carried out using tools similar to those used in mechanical methods [1-3]. These methods are generally used in manual, electric and pneumatic drills. These drills have controlled parameters such as spindle speed and feed rate, as in mechanical drilling methods.

There are two types of bone tissue in the bone; cortical bone tissue and spongy bone tissue (Fig. 1). The cortical tissue is a hard and dense tissue, while the spongy tissue shows a perforated, light and honeycomb-like structure.

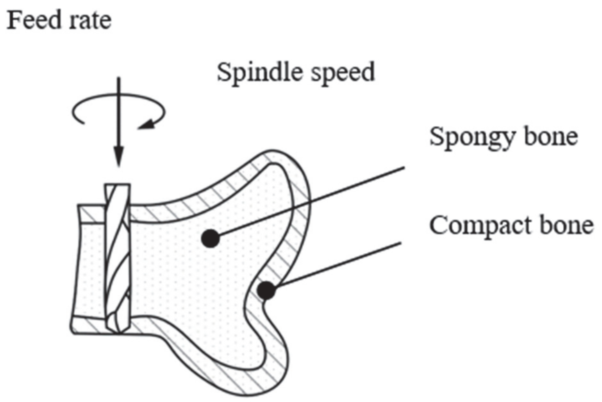


Figure 1 Bone structure and drilling

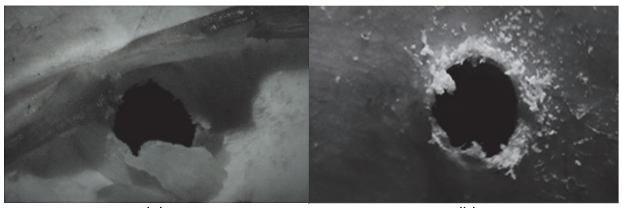
The bone is a non-homogeneous isotropic material and has a bone-fiber-reinforced composite structure at the microscopic level [13]. Most of the bone is composed of inorganic hydroxyapatite and organic collagen. In the case of drilling composite structures, the type of damage called delamination is encountered. In the drilling process, delamination occurs at both the hole entrance and the hole exit [14]. Delamination not only disrupts the bone hole surface quality but also leads to inadequate fixation. Delamination decreases bone-implant holding strength, can adversely affect the healing of the reduced bone and cause further damage. At the same time, if a second hole is to be drilled nearby, it causes the screw clamp in the other hole to be affected and thus loosen [15].

Delamination is one of the major damages that occur in the drilling of layered composites. Delamination occurs at hole inlets and outlets in the drilling of bones, as in all composite materials. In order to determine the amount of delamination formed around the hole, the maximum diameter ($D_{\max}$) in the delamination zone must be found. The delamination factor (Df) is a numerical value proportional to the drill diameter (D) of the maximum damage diameter ($D_{\max}$) occurring in the damage zone during drilling, as can be seen in Fig. 1. The delamination factor is determined by the following formula [16]. This is also named damage zone factor.

$$Df = D_{\max}/D \tag{1}$$

This factor is an important parameter for the assessment of surface damage in the drilling of composite materials such as bone [14]. Surface damage on the perforated bones is an important factor in the evaluation of screw attachment strength [2, 14].

Delamination in bone drilling takes place in two different shapes: as a layer separation at the entrance of the drill into the bone (Fig. 2a), and as fraying form on drill output (Fig. 2b). The formation of delamination is considered as a function of the cutting parameters.



(a) (b)

Figure 2 Delamination in the bone. (a) Drill entrance hole; (b) Drill output hole

3 MATERIAL AND METHOD
3.1 Bone Structure

The bone structure contains 30% organic matter, 25% water and 45% mineral. In this study bovine bone, structurally similar to human bone, was used. The mechanical properties of this bone compared to human bone are given in Tab. 2.

Table 2 Comparison for the properties of bovine bone and human bone [2]

Properties	Bone Type	
	Human	Bovine
Density / kg/m^3	1800-2000	2060
Young's modulus / GPa	10-17	10-22
Shear modulus / MPa	3	3
Poisson's ratio	0.4	0.36
Tensile strength / MPa	130-200	140-250
Compressive strength / MPa	45-150	45-150

3.2 Full Factorial Experiment Design

Experimental studies are designed to examine the effects of multiple factors at different levels. The number of experiments according to the *full factorial* method is calculated by the formula $N = n^k$. In this relation, N represents the number of experiments, n represents the number of levels and k represents the number of variables.

The design of full factorial experiments is a multidimensional method; it is advantageous in terms of the investigation of the linearity of functions and the effect of the interactions of factors on the dependent variable and the possibility of making economic evaluation on the system. In this way, it is possible to reduce the costs of the processes and improve the quality.

In addition, *fractional factorial* designs can be used when a high number of interactions is not desired, as in the full factorial design, or when only a low number of interactions are required to examine the main effects and when fewer tests are required [17].

In this study, the factorial design was used. Experiments were performed with a total of $3^4 = 81$ different combinations using 3 levels for drill diameter, 3 levels for helical angle and 3 levels for spindle speed and feed rate.

3.3 Experimental Parameters

The drilling experiments were carried out on the CNC vertical machining bench with equal spacing of 20 mm on the bovine bone (Fig. 3).

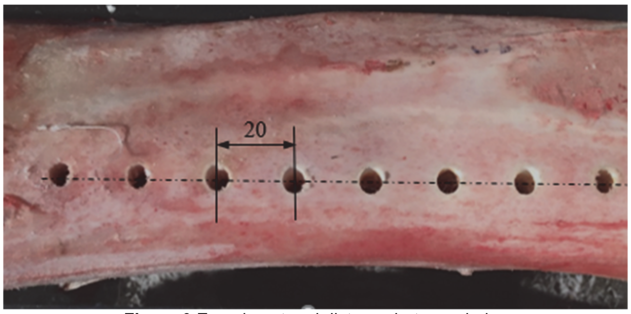


Figure 3 Experiment and distance between holes

Each drilling experiment was carried out using three different feed rates, spindle speeds, drill diameters and helix angles. The parameters used in the experiment are given in Tab. 3. The drill material used in the test is HSS and it is within DIN 338 standard.

Table 3 Machining parameters

Spindle speed / rev/min	Feed rate / mm/rev	Helis angle / °	Diameter / mm
400	0.1	15	4.0
800	0.2	20	4.5
1200	0.3	25	4.8

3.4 Hole Surface Roughness Measurement

For the determination of hole roughness values, measurements were taken from a full section of the bone hole axis after the drilling test. The MITUTOYO SJ-210 instrument with a sensitivity of 0.001 µm was used for this purpose. In the roughness measurement, *Ra* roughness was measured by adjusting the cut off distance of 0.8 mm and probe feed rate of 0.5 mm/s. The drill along the axis of the hole penetrated the cortical bone, spongy and re-cortical bone, respectively (Fig. 4). Since the hardness of the cortical region and the spongy region are different, the surface qualities of these regions differ from each other. Therefore, measurements of cortical regions and measurements of spongy regions were performed separately. In order to increase the accuracy of the measurement, three measurements were made from each region and the roughness values were determined for each [2]. At the same time, it was taken into consideration that the chips were cleaned by using physiological saline and measured with the same sensitivity.

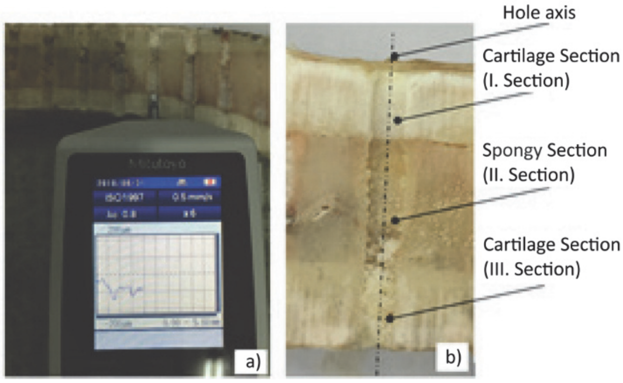


Figure 4 Hole roughness measurement: (a) Type of measurement, (b) Measurement zones

3.5 Delamination Measurement

Delamination (*Df*), known as layer separation formed by drilling of bones, is the ratio of the maximum diameter (D_{max}) formed in the delamination zone to the drill diameter (D) calculated with Eq. (1) [16]. To determine the delamination factor values that vary according to the drilling parameters, images were taken using the Euromex-Nexiuszoom EVO 0.65-5.5 (WF 10X/23MM) brand microscope, and measurements were performed as shown in Fig. 5.

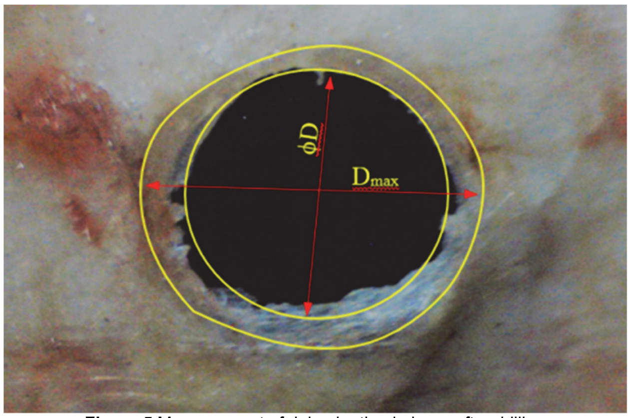


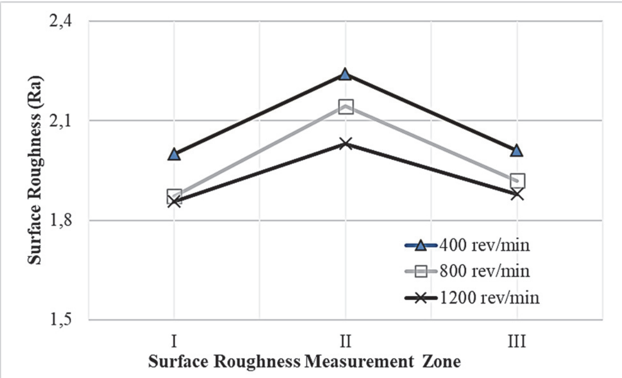
Figure 5 Measurement of delamination in bone after drilling

4 RESULTS AND DISCUSSION

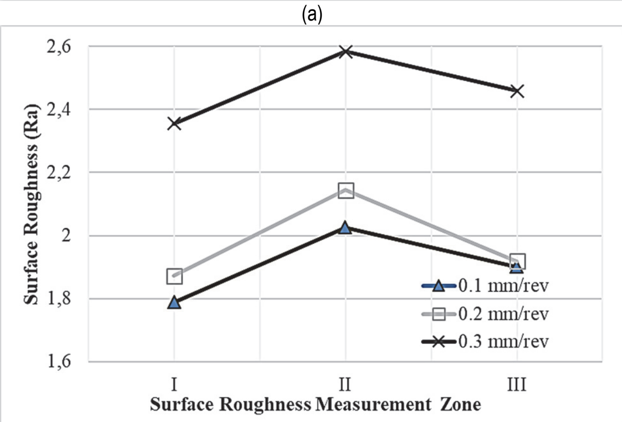
4.1 Surface Roughness

After drilling, a full cross section of the bone was taken, and the graphs were drawn in order to illustrate the effects of the processing parameters on the average surface roughness (*Ra*) in the cortical and spongy regions of the bone (Fig. 6).

As seen in the graph, the increasing rpm converted more energy into heat during cutting, and the resultant temperature facilitates plastic deformation and chip flow, resulting in an improvement in surface quality (Fig. 6a). Roughness values increase with increasing feed rate (Fig. 6b). Increasing feed rate values will lead to an increase in the volume of chips removed per unit time, which in turn will lead to an increase in the cutting forces, thus increasing the roughness values. Throughout the drilling axis, the roughness value in the hole entry and exit area (the cortical part) was lower than the roughness values in the spongy region. The reason for this is that the low hardness in the spongy area affects the stability of drilling and increases the roughness. Also in Zone 3 (the cortical part of the drill exit zone), the accumulation of chip compression in the region where the first deformation leads to the hole outlet is thought to increase the loads on the drill by increasing the vibration. This negatively affects the drill cutting edges and the hole surfaces quality.



(a)



(b)

Figure 6 Bone hole roughness change: (a) Variation of *a* - 0.2 mm/rev, (b) Variation of the revolutions at 800 rpm

Furthermore, as the literature indicates, the progression force and momentum increase as the feed rate increases [18]. Increasing the rate of feed leads to an increase in the volume of chip removed per unit of time. This increases the load on the drill. In fact, it has been seen that the force increases as the feed rate increases in drilling tests using the Kistler 9257 B dynamometer (Fig. 7).

As seen in the figure, the force increased with the contact of the drill to the bone and it was observed that the force tended to decrease due to the temperature increase after passing through half of the hole.

The most important problem in drilling operations is that the chip evacuation due to hole length causes the chip to be trapped inside the hole, and thus the surface quality deteriorates and even the tool is broken [19, 20]. Therefore, the effects of drill diameter and helix angle in Fig. 8 were also investigated.

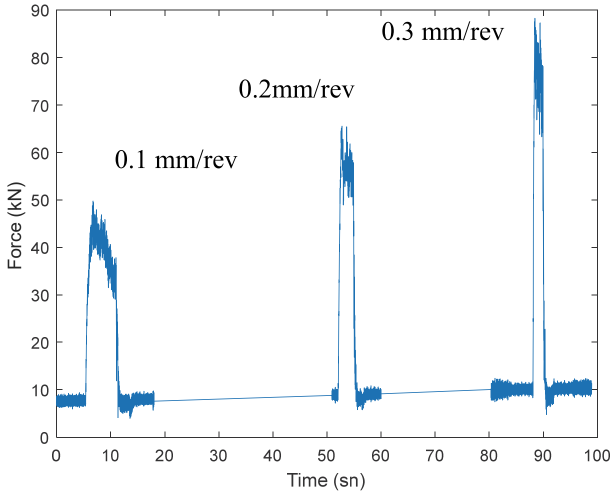


Figure 7 Measurement of force during drilling (⌀4.5-800 rev/min-Helix angle 20°)

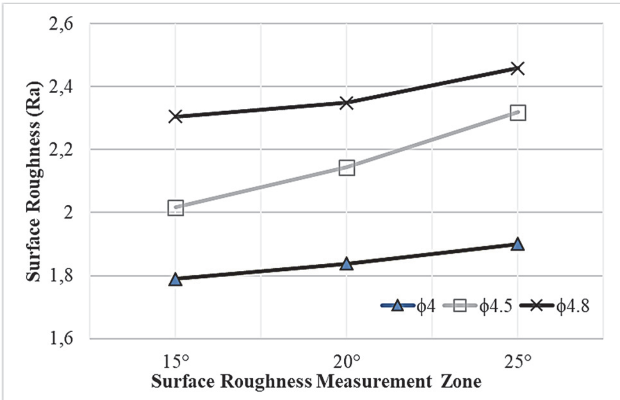


Figure 8 The effect of helix angle and drill diameter on hole roughness

According to the results of the experiment, since the small angle of the helix facilitates the evacuation of the chip, it reduces the amount of chip accumulated in the helix ducts (Fig. 9).

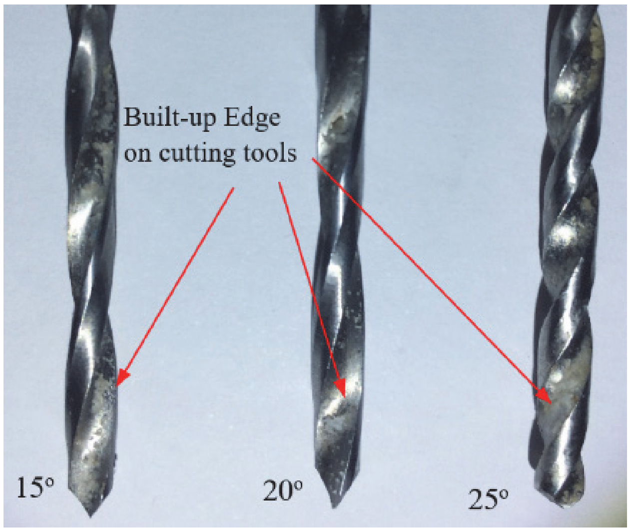


Figure 9 Built-up Edge to the cutting tool

It is reported in the literature that the increase in helical angle worsens the chip removal as the helical flute increases the helical length [21]. In this case, as shown in Fig. 10, increasing the roughness of the helix caused an increase in surface roughness. When the helical angle was

15° to 20°, this tendency was low and increased at 25°. The reason for this is that depending on the increase in the helical length, the chip is in contact with the hole surface for longer periods during evacuation.

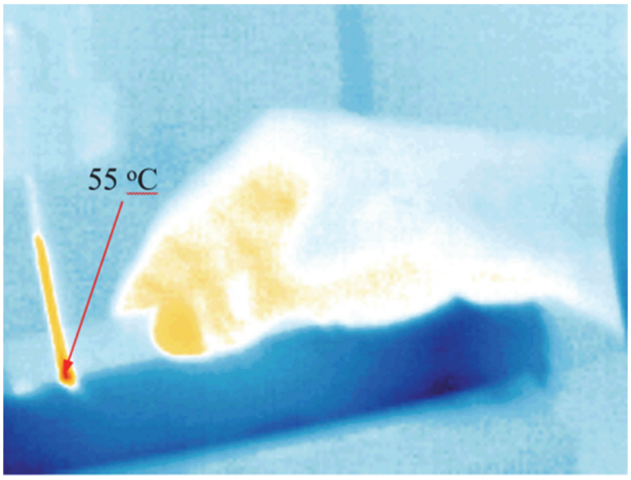


Figure 10 Exceeding the temperature of necrosis during drilling (1200 rev/min-0.1 mm/rev)

In this case the hole roughness increased. Similarly, the surface roughness increased with the increase in diameter. This can be attributed to a much more noticeable increase in chip load and energy, as in the adversity of progress and helix angle.

In addition, Fig. 9 shows an increase in temperature due to chip bulk and progression. Particularly in Zone 1 and Zone 3, increasing of temperature is higher in these regions because of the higher bone stiffness compared to Zone 2. This is evidenced by the Testo 875 brand infrared thermal imager during drilling (Fig. 11).

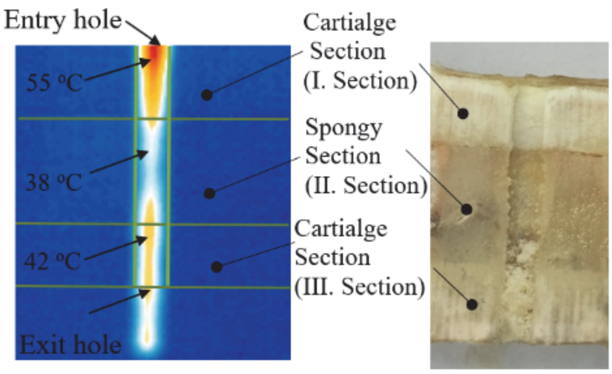


Figure 11 Temperature change by region in bone drilling

As seen from the picture, when the color change of the drill in the hole entrance zone and the spongy area is examined, it is seen that the redness is higher in the entrance region. Bone drilling (chip removal) is a thermo-mechanical process. In this process, heat is generated as a result of friction and plastic deformation along the tool-burrs and tool-bone interfaces [22]. Since the heat conduction coefficient of the bone is too low from the drill material, a large part of the heat is discharged through the cutting tool. The temperature of the cutting tool increases to 47 °C, which is the critical temperature for necrosis formation. It was observed that this temperature especially increased in the drilling at 1200 rpm (Fig. 12). The shear energy increases as a function of both the spindle speed and the feed rate.

4.2 Bone Drilling and Formation of Delamination

One of the most common problems encountered in perforating composite materials such as bone is delamination at the entrance and exit of the hole [16-18]. This delamination can be prevented or reduced by the selection of appropriate cutting tools, drilling parameters and operations [22]. In this study, which investigated the delamination factor in perforation of bones, delamination at the outlet of the hole was observed to deteriorate the quality of the hole (Fig. 12).

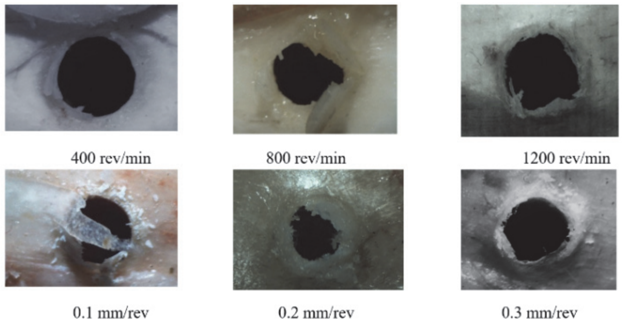


Figure 12 Variation of bone delamination according to processing parameters

After the drilling test, the delamination measurements around the hole were performed as shown in Figure 4. The percentage of delamination was calculated using the following equation to determine the effects of the processing parameters, and the graph in Fig. 13 was plotted.

$$Percentage\ of\ delamination = \left(\frac{D_{\max} - D}{D}\right) \times 100 \quad (2)$$

As seen in the graphs, the increase of the processing parameters increased the percentage of delamination (Fig. 10). According to the measurements obtained, the feed rate was found to be more influential than the spindle speed on delamination. This is due to an increase in the area of deformation in one cycle without increasing the progress. Increased feeding rate also increased the thrust forces feeding, leading to an increase in the area of deformation at the outlet of the hole [23].

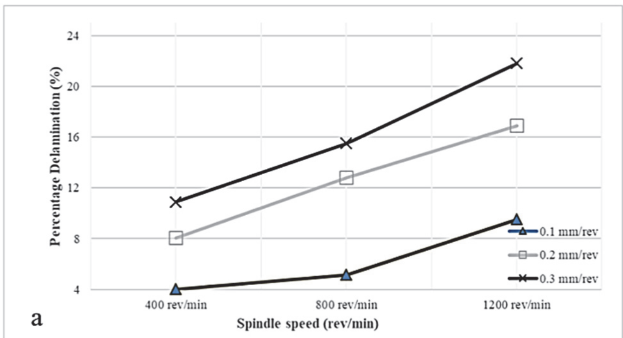


Figure 13 Variation of the delamination according to the processing parameters

This resulted in delamination and mass and burr formation around the hole (Fig. 14). The increase in the speed of the drill reduced the contact time of the drill with the bone, but it led to an increase in the temperature and caused an increase in the area of damage at the outlet of the hole. The increase in drill diameter and helix angle also caused the adhesion of bone chips in the helix ducts and caused the increase of cutting forces and increased delamination.

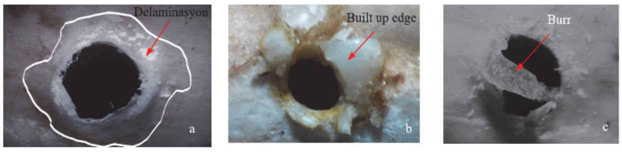


Figure 14 Types of damage at the hole exit: (a) Delamination; (b) Built up edge, c) Burr formation

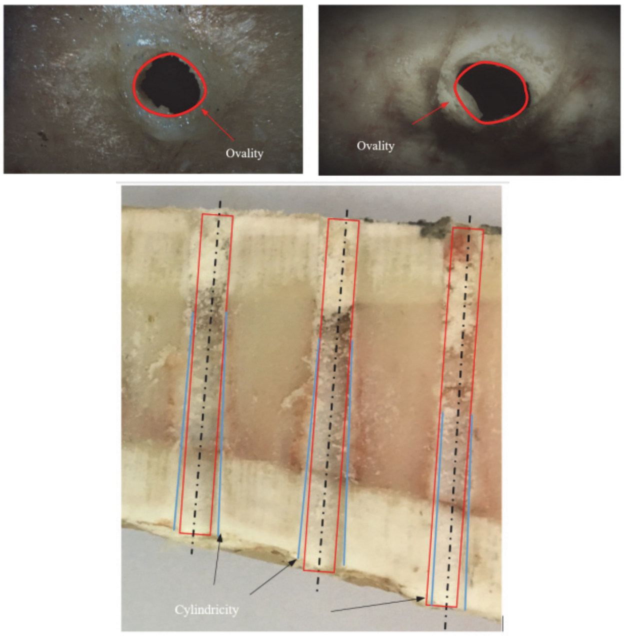


Figure 15 Determination of hole errors. (a, b) Ovality; (c) Cylindricity

In addition, the incremental spindle speed and feed rate values caused the cylindrical and circular hole shapes to deteriorate and the hole became oval (Fig. 15).

Table 4 Effects of machining parameters on burr

Diameter / mm	Deviation amount / $\times 10^{-4}$ m^2	Helix angle / °	Deviation amount / $\times 10^{-4}$ m^2
4	112.664	15	102.540
4.5	173.387	20	114.560
4.8	210.547	25	140.587
Feed rate / mm/rev		Spindle speed / rev/min	
0.1	105.225	400	95.457
0.2	109.254	800	102.604
0.3	148.158	1200	129.355

* Because of the large number of experiments, only the values where the change was observed clearly were given.

The effects of the processing parameters on the cylindrical values are calculated according to the deviation from the standard area and given in Tab. 4. According to the results of the experiment, drill diameter, progression, helix angle and number of revolutions were found to affect the geometric sensitivity.

5 CONCLUSION

For the reposition and stability of the fractured bone, the application of implants by opening holes on the bone is one of the most used methods in orthopaedic surgery. According to the results of the experiment, it was determined that the processing parameters were influential in delamination, surface quality and hole geometry and this affected the holding strength of screws. Accordingly, the results obtained from this study can be listed as follows:

- Delamination is increased when spindle speed, feed rate and drill helix angle are increased. The main reason for this is the increase of the feeding forces. Drill diameter, feed rate and spindle speed were found to be influential on delamination, respectively.
- As the helix angle increased, it was observed that the bone particles adhered to helix ducts and made the evacuation of the burrs more difficult.
- Roughness values in the cortical region of the bone were measured to be lower than in the spongy region. It was determined that with the increase of spindle speed, the roughness decreased, and it increased with the increase of feed rate.
- Since the heat conduction coefficient of bone was lower than that of the cutting tool, it was found that 80% of the heat transfer was on the cutting tool and bone chips, and the rest was on the bone.
- It was determined that delamination, bone particle mass and chips were formed in the hole outlet area.
- Increased spindle speed increased the deviation from the circular and cylindrical hole shape.
- When all factors are considered, the change of the machining parameters affects the surface and size quality of the holes, which will affect the holding strength of the screws.

When all factors are considered, the change of the machining parameters affects the surface and size quality of the holes, which will affect the holding strength of the screws at the same standards.

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