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Original Article

Effects of Cutting Parameters on Drill Wear during Bone Drilling

Effets des paramètres de coupe sur l'usure du foret pendant le forage osseux

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HIGHLIGHTS OF THE STUDY

What is already known on this topic
A significant increase in heat is generated after several cycles of drilling with the same drill bit. The resulting wear is likely to damage the bone tissue

What question this study addressed
Correlation between the degree of drill wear and the cutting parameters especially the number of drilling cycles.

What this study adds to our knowledge
The drill wear becomes severe after 10 holes, especially at high rotation speeds (300 rpm) with the appearance of large plastic deformations and circular streaks on the cutting edge

How this is relevant to practice, policy or further research.
This study suggests not to exceed 4 reuses of the same bit in the case of non-lubricated drilling.

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Mots-clés : usure, perçage osseux, vitesse de rotation, vitesse d'avance, mèche, microscopie numérique.

ABSTRACT

Introduction. This study focuses on the analysis of the evolution of drill bit wear as a function of the cutting parameters and the number of holes in the case of bone drilling. **Materials and methods.** The holes are made with drill bits 3.2mm in diameter on the tibia bones of a bovine aged about one year. Rotational speeds of 100, 200 and 300 rpm as well as feed rates of 30 and 60 mm/min are adopted during drilling. Drill bits are used to make 2, 4, 6, 8 and 10 holes and the total hole thickness is assessed. The locks are then analyzed by digital microscopy and a new lock serves as a reference. **Results.** The quantitative evaluation of the wear shows that the width of the central edge increases significantly with the number of drill holes and the rotational speed. The feed rate has very little effect on this parameter. The vertex angle, although slightly influenced by the number of holes, remains almost insensitive to the variation of the cutting parameters. Qualitative analysis shows moderate wear after 4 to 6 piercings. This wear becomes severe after 10 holes, especially at high rotation speeds (300 rpm) with the appearance of large plastic deformations and circular streaks on the cutting edge. **Conclusion.** This study suggests not to exceed 4 reuses of the same bit in the case of non-lubricated drilling.

RÉSUMÉ

Introduction. Cette étude porte sur l'analyse de l'évolution de l'usure des mèches en fonction des paramètres de coupe et du nombre de trous durant le perçage osseux. **Matériels et méthodes.** Les trous sont réalisés avec des mèches de 3,2 mm de diamètre sur des tibias d'os bovin âgé d'un an. Des vitesses de rotation de 100, 200 et 300 tr/min ainsi que des vitesses d'avance de 30 et 60 mm/min sont adoptées pour la réalisation des essais. Les mèches sont utilisées pour réaliser 2, 4, 6, 8 et 10 trous et l'épaisseur totale du trou est évaluée. Les mèches sont ensuite analysées par microscopie numérique avec une mèche neuve servant de référence. **Résultats.** L'évaluation quantitative de l'usure montre que la largeur de l'arête centrale augmente considérablement avec le nombre de trous percés et la vitesse de rotation. La vitesse d'avance a très peu d'influence sur ce paramètre. L'angle au sommet, bien que légèrement influencé par le nombre de trous, reste presque insensible à la variation des paramètres de coupe. L'analyse qualitative montre une usure modérée à partir de 4 à 6 perçages. Cette usure devient sévère après 10 trous, surtout à des vitesses de rotation élevées (300 tr/min) avec l'apparition de grandes déformations plastiques et de stries circulaires sur l'arête de coupe. **Conclusion.** Cette étude suggère de ne pas dépasser 4 réutilisations de la même mèche dans le cas d'un perçage non irrigué.

INTRODUCTION

The objective of osteosynthesis is to maintain a mechanical environment proper to good consolidation process. In most cases, the cortical bones are holed to receive screws or pins. As in any material machining process, the drill bit wear out during their use, which can lead to mechanical and thermal damage to the bone. Few studies are specifically dedicated to drill bit wear during bone drilling. High temperatures generated at the tool-bone interface, greatly affect tool lifetime (1-3). They can increase the risk of surface thermal damage to the bone.

Various methods for monitoring the wear of the drill bit or other cutting tools have been proposed (4-7). None of these methods gives complete satisfaction due to the complex nature of the tool wear process. These methods can be classified into direct (optical, radioactive, computer vision, etc.) or indirect (cutting force, current, vibration, acoustic emission, etc.) detection methods depending on the sensors used (8-11). In the laboratory, these methods are often coupled. The advantage of using sensors, mounted on the external power lines, is that they do not interfere with the machining process (12-14). It has been also shown that the bone cannot withstand high temperatures because of the risk of osteonecrosis (4-6). No or very little data are available on bone drilling.

Some authors found that the temperature increased significantly with drill bit wear in pig mandible, bovine ribs and femoral cortex drilling (15-17). Queiroz et al. (18) concluded that repeated use of the same drill affect cell viability. Therefore, repeated drilling can lead to bone necrosis. Others studies are unanimous that a significant increase in heat is generated after several cycles (approximately 50) of drilling with the same drill bit (19-21). The resulting wear is likely to damage the bone tissue. Considering that the mechanical properties of bone are much weaker than those of steels on the one hand, and taking into account the repeated and unmonitored use of drill bits in the operating room on the other hand, it seems relevant to quantify the wear of the bits used, then to establish correlation between the degree of wear and the number of drilling cycles.

MATERIALS AND METHODS

Preparation of bone specimens

Due to the mechanical characteristics closed to those of human bones, one-year-old cattle tibiae were obtained from butchers, mechanically deperiosteal. Several authors recommend this approach (22-24).

Bone were stored at -20°C. At the time of the experiment, they were immersed in 9/1000 saline and placed in a refrigerator brought to a temperature of 10°C for 4 hours. Samples of cortical bone section 100 mm long and 50 mm wide, along the diaphyseal axis, were taken using a manual saw.

The measurements of the thicknesses of the specimens for the wear analysis were carried out using CT scan. The same scanner was used to measure the entrance diameter of the drilled holes. The thickness of the specimens varied from 5.64 to 14.10 mm ± 0.02.

Drilling process

Each bone specimen was drilled through the center with a 3.2 mm diameter 316 L stainless steel drill bit. These bits are recommended for osteosynthesis of the femoral and tibial diaphysis. Spindle speeds were 100, 200 and 300 rpm, and feed rates were 30 mm/min and 60 mm/min. Other authors have used these same parameters (4,8,22). Table 1 summarizes all the parameters used for the tests.

Table 1: Summary of the drilling parameters used

Variables	Symbols	Values
Rotation speed	N (rpm)	100, 200, 300
Advance speed	V_f (mm/min)	30 & 60
Drill bit diameter	∅ (mm)	3.2
Tool (bit)	O_k	O_1, O_2, O_3
Drilling	E_i	E_1, E_2, E_3
Number of holes	-	02, 04, 06, 08, 10

The number of drills using the same drill bit were 02, 04, 06, 08 and 10 holes. Thus, each drill bit was used for a specific number of drills, under the same bone cutting conditions (rotation speed and advance speed). A total of 180 drill holes were made, according to the breakdown in Table 2. In addition to the 30 drill bits used for drilling, 1 other new drill bit was used as a reference.

Wear assessment by digital microscopy

A Keyence Series VHX-7000® digital microscope (fig. 1) was used to evaluate the wear of the wicks in a room with 260 lux of luminosity. This luminosity is maintained throughout the observation period. The specimen is positioned on the stage and alignment, focus adjustment, illumination, magnification switching, etc., are done automatically. The magnification is then adjusted using the console or the mouse.

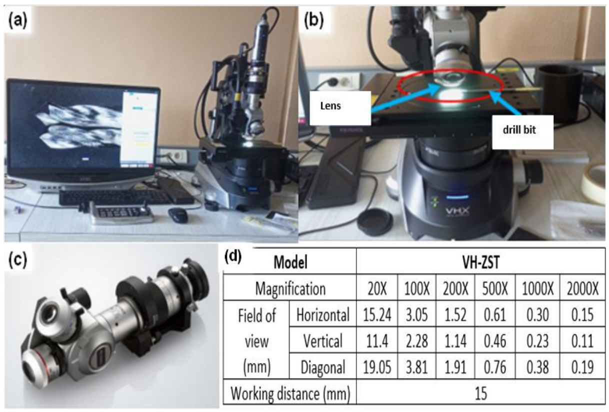

Fig. 1: Digital microscopy analysis device: (a) Keyence® VHX-7000 microscope and monitor (analysis of a new wick), (b) magnification of the objective, (c) double VH-ZST zoom objective, (c) setting parameters

Table 2: Distribution of drill bits according to the number of holes for wear analysis

Number of holes drilled per bit	N (rpm)						Number of drill bit	Total number of holes
	100		200		300			
	Vf (mm/min)							
	30	60	30	60	30	60		
02	1	1	1	1	1	1	**6**	**12**
04	1	1	1	1	1	1	**6**	**24**
06	1	1	1	1	1	1	**6**	**36**
08	1	1	1	1	1	1	**6**	**48**
10	1	1	1	1	1	1	**6**	**60**
TOTAL							**30**	**180**

Flipping the lens to multiple angles allows for further analysis of the object without having to move it. Automatic capture and measurement allow automatic repeat measurements on identically shaped samples. Thus, for the drill bits studied, the point angle, the width of the central ridge and the geometry of the surface grooves and the lateral ridge were analyzed. Magnification and illumination settings, as well as three-dimensional coordinates, are reproduced automatically. Lighting data is retained even after saving the image. However, the lighting can still be adjusted using the mouse. This option allows you to reproduce the same observation conditions, later and on demand.

By estimating height based on subtle variations in texture, a 3D image is constructed. Areas with a degraded texture are treated as noise, so an accurate 3D image can be captured.

Wear was investigated quantitatively and qualitatively.

Quantitatively, the tip angle was analyzed to highlight wear on the side edges. The width of the ridge at the top is also observed because an increase in this width indicates progressive wear of this ridge at the top (fig. 2).

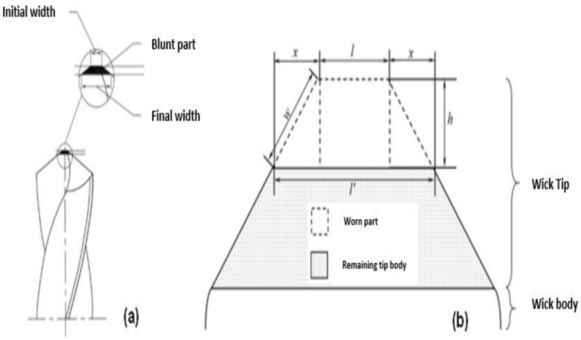

Fig. 2: Tip wear: (a) tip widening by wear, (b) measurement of drill bit wear

The width of the edge at the top l increases progressively according to the degree of wear to reach a value l'. The height h represents the depth (thickness of the worn zone). The total worn area w can be calculated if we consider that the wear process takes place symmetrically on the edge at the top and with respect to the side edges.

From a qualitative point of view, the general profile of the ridge at the top and of the main lateral ridge has been analyzed; in particular the tortuous, blunt, crushed shape with or without removal of the material. These characteristics made it possible to develop a wear scale ranging from 0 to 3.

The concept of crushed edge is close to that of built edge (BUE) essentially found in industrial drilling. However, the weaker and more friable bone material requires further observation at rank to establish a formal equivalence.

The linear manufacturing streaks, their disappearance or their possible replacement by circular streaks of drilling, which testify to the importance of the cycles of rotation of the drill bit, when it rubs on the bone, are also analyzed.

RESULTS

The wear analysis focused on the tip of the bit, and in particular the central edge at the top, the main lateral cutting edges, the surface streaks and the search for deposits of the machined material on the bit. It is therefore an essentially qualitative analysis with some quantitative data. The thicknesses of the drilled parts are also taken into account in the analysis.

Table 3 presents the distribution of the total thickness of the drilled holes.

Drill tip analysis

Figure 3 shows a microscopic image of a new wick. This image is considered the signature of the unworn drill bit.

We can distinguish there, the oblique manufacturing streaks on the cutting face, the face of clearance and the side, the angles and the very sharp edges. The listel has horizontal stripes.

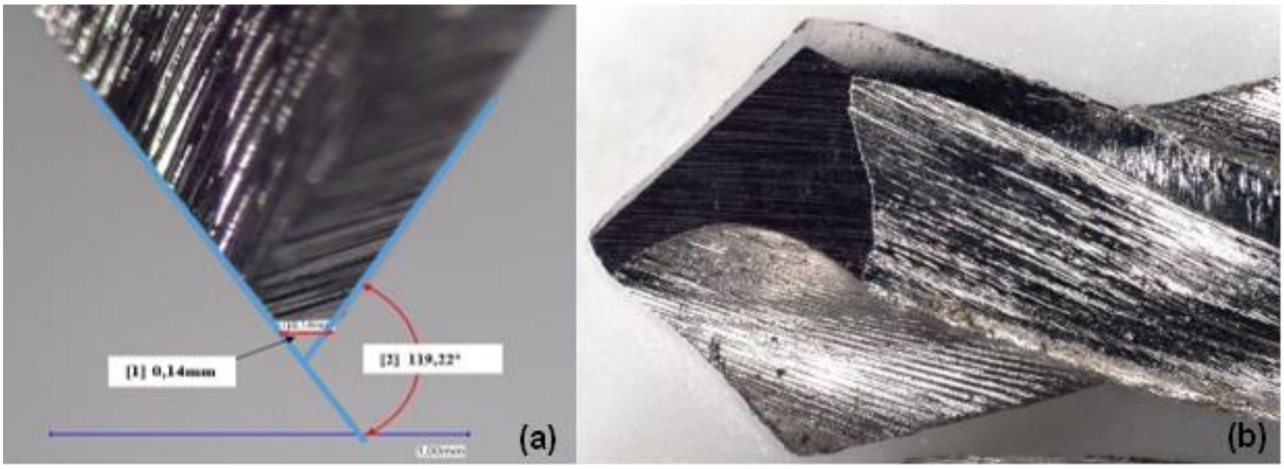

Fig. 3 New drill bit under digital microscopy: (a) tip angle 119°, width of the ridge at the top 0.14mm, (b) different facets of the new drill bit with manufacturing streaks on the surface

Wear from the center edge to the top of the bit

Figure 4 shows anomalies related to the wear of the edge at the top.

The wear of the edge at the top is manifested by a widening and a crushing. The point also has a disappearance of the oblique manufacturing streaks, replaced by circular drilling streaks. The widening of the edge at the top is actually due to wear by removal of the material. Other anomalies are observed, in particular the blunting of the tip by plastic deformation.

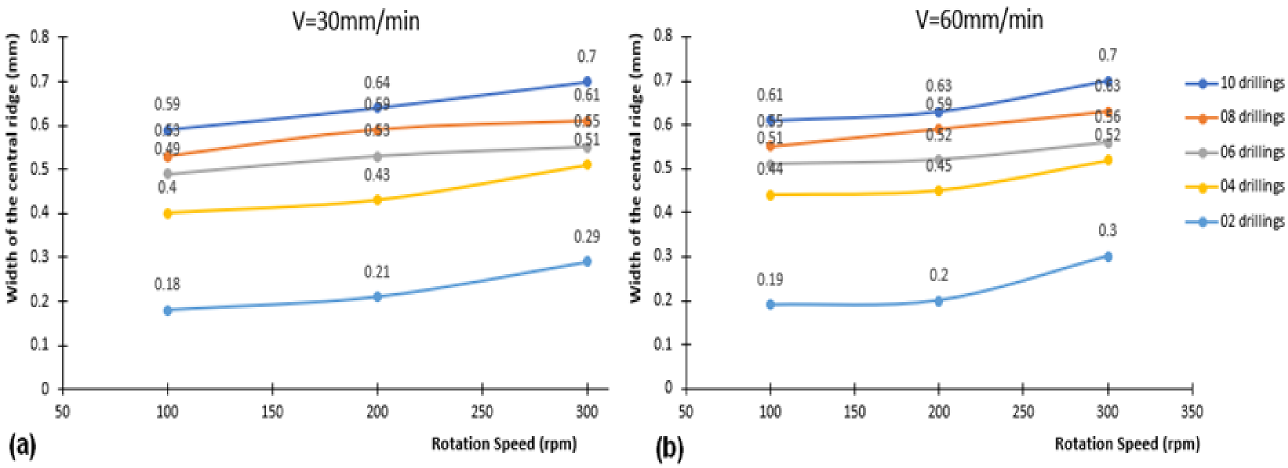

Fig. 4 Evolution of the width of the central edge according to the rotation speed: (a) Vf= 0 mm/min, (b) Vf=60 mm/min

Wear of the main side edge of the drill bit

The main side cutting edge is used to determine the cutting angle. In addition, the modifications of its shape testify to the alterations due to friction. The side cutting edges have anomalies. These anomalies are classified according to their shape: tortuous, blunt, crushed edge (plastic deformation), with or without removal of material.

Table 4 summarizes the distribution of the widths of the point, the point angle as well as the qualitative evaluation of the wear (from 0 to 3) according to the number of holes, the speed of rotation and the advance.

Influence of the speed of rotation according to the number of holes on the width of the central edge at the top

Further analysis shows that this increase in the width of the central edge is also influenced by the rotational speed regardless of the number of drill holes. Thus, at the 6th drilling at 100 rpm the width of the central edge is 0.49 mm. After 8 holes, this width is 0.53 mm at 100 rpm. And at 10 holes, this width is 0.59 mm. However, at 6 holes, this width goes from 0.49, 0.53 and 0.55 mm at 100, 200 and 300 rpm respectively. This shows the influence of rotational speed on tip abrasion. This influence is less marked than the number of holes (fig. 4).

The width of the ridge at the top increases as a function of the speed of rotation, but moderately in relation to the number of holes.

Table 3: Distribution of the thicknesses crossed by the drill bits

	Drill bit	Bone	Thick 1	Thick 2	Thick 3	Thick 4	Thick 5	Thick 6	Thick 7	Thick 8	Thick 9	Thick 10	TOTAL
02 HOLES	50	E3	8.20	10.90									19.10
	51	E6	10.80	12.70									23.50
	52	E1	7.80	9.90									17.70
	53	E5	7.10	10.40									17.50
	54	E2	5.90	10.40									16.30
	55	E4	7.40	10.90									18.30
04 HOLES	40	D6	11.80	11.90	12.10	13.80							49.60
	41	D1	6.40	6.80	7.10	10.30							30.60
	42	D4	9.60	9.80	10.10	10.30							39.80
	43	D3	13.10	13.20	13.50	13.80							53.60
	44	D5	5.40	5.80	5.90	6.60							23.70
	45	D2	6.50	6.70	7.20	9.50							29.90
06 HOLES	35	C1	7.30	7.50	7.90	8.10	8.70	11.70					51.20
	33	C2	6.40	6.70	7.10	7.50	8.10	10.20					46.00
	30	C5	9.70	9.70	9.81	9.95	9.99	10.60					59.75
	31	C4	9.00	9.10	9.40	9.90	10.30	12.10					59.80
	32	C3	13.60	13.70	13.90	13.90	14.00	14.10					83.20
	34	C6	10.90	10.99	11.01	11.70	12.04	13.20					69.84
	Drill bit	Bone	Thick 1	Thick 2	Thick 3	Thick 4	Thick 5	Thick 6	Thick 7	Thick 8	Thick 9	Thick 10	TOTAL
08 HOLES	20	B3	8.30	8.40	8.45	8.70	8.80	8.90	9.20	12.30			73.05
	21	B4	8.60	8.80	8.90	9.20	9.90	10.10	11.50	13.50			80.50
	22	B1	8.40	8.42	8.43	8.43	8.51	8.55	8.58	8.60			67.92
	23	B5	9.10	9.20	9.30	9.30	9.43	9.45	9.49	9.50			74.77
	24	B6	8.00	8.12	8.21	8.22	8.25	8.35	8.45	8.60			66.20
	25	B2	10.30	10.31	10.39	10.40	10.45	10.51	10.60	10.70			83.66
10 HOLES	10	A2	9.70	9.80	10.00	10.30	10.60	10.90	11.20	11.50	11.70	12.00	107.70
	11	A1	6.60	6.70	6.90	7.00	7.20	7.60	7.90	8.10	8.60	9.80	76.40
	12	A4	9.60	9.61	9.63	9.64	9.65	9.66	9.68	9.68	9.69	9.70	96.54
	13	A3	8.20	8.70	8.90	9.00	9.20	9.50	9.80	10.00	10.60	12.00	95.90
	14	A5	8.00	8.10	8.40	8.60	8.70	9.00	9.20	9.50	9.70	10.30	89.50
	15	A6	7.10	7.70	7.90	8.00	8.50	8.90	9.00	9.50	10.00	12.80	89.40

Table 4: Summary of the evaluation of the wear parameters according to the cutting parameters

	V_f =30			V_f =60			Number of holes
	Grade of anomaly	Tip angle	Width	Grade of anomaly	Tip angle	Width	
N=100	0	119	0.18	0	119	0.19	02
	2	117	0.40	2	117	0.44	04
	2	116	0.49	2	116	0.51	06
	2	114	0.53	2	114	0.55	08
	2	114	0.59	3	114	0.61	10
N=200	0	119	0.21	0	119	0.20	02
	1	117	0.43	1	117	0.45	04
	2	116	0.53	2	116	0.52	06
	2	114	0.59	2	114	0.59	08
	3	114	0.64	3	114	0.63	10
N=300	0	119	0.29	0	119	0.30	02
	1	117	0.51	1	117	0.52	04
	2	116	0.55	2	116	0.56	06
	2	114	0.61	2	114	0.63	08
	3	114	0.70	3	114	0.70	10

Surface streaks

The manufacturing streaks observed on the new pins are all oblique, in particular on the cutting and clearance faces, the web and the side. A section highlights the sinuosity of these streaks and makes it possible to establish the total profile and the roughness profile. The two profiles are similar, which shows an absence of wear. The total profile and the roughness profile are identical on the new bit, whereas a difference is observed between the total profile and the roughness profile on the bit after 10 drillings. In other words, the wear of the bit also results in the presence and accentuation of the surface roughness.

As the number of holes increases, the manufacturing grooves tend to disappear on the surface and are replaced by very marked circular drilling grooves after 08 or 10 holes. At 04 holes, we observe that the manufacturing grooves are less pronounced and interspersed with circular drilling grooves, forming a kind of mesh, especially on the relief face.

DISCUSSION

Bones do not have the same thickness. The distribution of the thicknesses is random. However, the observed measurements correlate with known anatomical data from bovine bones (25,26). The total thickness of the drilled holes represents the sum of the thicknesses of each cortex crossed by the same drill bit during drilling. This total thickness changes naturally with the number of holes. With 02 holes, the total thickness ranges from 16.3 to 23.5 mm. With 04 holes, it varies from 23.7 to 51.6 mm. With 06 holes, it varies from 46.0 to 83.2 mm. At 08 holes, it varies from 66.2 to 83.66. Finally with 10 holes, it varies from 76.40 mm to 107.70 mm. The variation of these measurements confirms the relative uncertainty on the bone thickness actually traversed by the drill bit during drilling. The number of holes should therefore also be correlated with the total thickness through which the drill bit passes. It is nevertheless useful to remember that friction is not only a function of the total thickness, but also of the number and duration of each hole. The longer the drilling lasts, the more the tool will rub on the walls and the wear will be substantial. The results of the measured thicknesses agree with those of the literature. The average thickness of the beef tibia is about 10.14 mm, greater than that of the human tibia measured at 4.33 mm. The difference in thickness is obvious. It reflects a much longer friction time, from one number of holes to another. Following on from this, we can validly put forward the hypothesis that at the same feed rate, wear is a function of the number of holes. It is no variation of the total thickness as a function of rotation speed or feed rate. The distribution was therefore purely random.

There is a variation in the width of the cutting edge at the top depending on the number of holes. If we consider for example the speed of rotation of 100 rpm and the feed rate of 30 mm/min, the width of the edge at the top which is 0.14 mm for the new drill bit, goes to 0.18 mm, 0.40 mm, 0.49 mm, 0.53 mm then 0.59 mm for 02, 04, 06, 08 and 10 holes respectively. It is therefore a gradual increase in width from the central edge to the top, influenced by the number of holes. This reflects progressive wear.

The pattern of this wear cannot be easily predicted. It depends on the resistance of the bone, the thickness crossed, the previous drillings, etc. This wear evaluation criterion is not found in the classical literature. We recognize another mirror criterion under the names flank wear (VB) and crater wear (KT). A factor is associated with it: the reduction in the length of the main edge. In reality, the decrease in the length of the main lateral edge corresponds (in mirror) to the increase in the width of the edge at the top (27).

The measured tip angle varies from 114 to 119°. This angle seems to decrease with the number of holes. This decrease may be related to the elimination of material by friction. However, it is not significant, probably due to the small number of piercings performed. Marciniak et al. (28) found a decrease in the tip angle after almost 1000 drillings, the speed of rotation seeming to be one of the determining factors. These results show that, up to 02 holes, these edges are normal. At 04 holes, they begin to present sinuosity and become tortuous. At 06 holes, they become blunt for the most part up to 08 holes. At 10 holes, several microscopic images show signs of crushing. The central edge deteriorates with the number of holes. For bits having made a given number of holes, the abrasion from the central edge to the top does not vary enough.

The critical zone of wear by removal of material at the level of the central edge is represented by the points with the highest number of holes and the highest rotation speed. Feed speed do not appear to significantly influence side edge wear. The ridge at the top also presents other qualitative anomalies (tortuous, blunt, crushed, etc.). These anomalies are best described on the main lateral cutting edge.

It is observed in the case of a new drill bit that there is no deformation of the edge at the top, straight lateral cutting edge, straight manufacturing streaks. Few anomalies are visible after 02 drillings. After 04 drillings, there is no deformation from the edge to the top, the lateral cutting edge is tortuous, the manufacturing streaks are less pronounced and interspersed with circular drilling streaks. After 06 holes, we observe the beginning of plastic deformation (crushing) of the edge at the top, tortuous lateral cutting edge, absence of manufacturing streaks on the clearance face. Observation of the drill bit after 08 drillings shows plastic deformations (crushing) from the edge to the top, crushed lateral cutting edge, circular drilling streaks on the clearance face. After 10 drillings, a degree of plastic deformation (crushing) of the edge at the top is observed, the lateral cutting edge is crushed and the circular drilling streaks are observable on all the faces. It should be noted that the oblique manufacturing streaks, although less pronounced, are nevertheless present at 06 or even 08 holes, whereas they are completely absent from the draft face and the sides.

Bone shavings, invisible in macroscopy, are observed, and larger in size depending on the number of holes. The observation of a drill bit after 10 drillings, shows the blunting of the tip, a tip angle within normal limits, some disintegration of the material on the left side edge and a decrease clear of machining grooves on the cut face. The oblique machining streaks remain partially visible on the flute, on the side of the clearance face. Abrasion of the material is occasionally observed on the tip or on the side edge. These observations are essentially qualitative. It was only a question of looking for anomalies that could be related to the wear of the wicks. Some quantitative measurements were made. The results demonstrate the influence of the number of drill holes on drill bit wear in bone surgery. The number of drillings performed was relatively low, but under extreme conditions, without pre-drilling and without irrigation. These conditions probably explain the fact that signs of wear are detected from the 4th hole. The use of a very high-definition camera also explains the ability to detect unrecognized signs of wear that are little described. The study of the profile of the main edge requires that we linger over it since anomalies are detected from the 4th drilling. A more in-depth study of these anomalies will certainly make it possible to find a classification according to the severity of the wear. It should nevertheless be noted that the rise in temperature appears very early before the signs of wear. While from 200 rpm and from the 3rd row of holes, the temperatures are well above 55°C, the signs of wear are only very slight on the 4th hole. Even at the 6th hole, the surface anomalies are less. Therefore, the absence of signs of wear does not guarantee drilling without the risk of thermal

complications. Some authors reach the same conclusion (17-18).
The qualitative wear parameters we presented are not also discussed in the current literature. In the absence of an objective quantitative tool for measuring wear, it is possible to assess it by observing the shape of the bit tip. Other modeling criteria and observation of the wick tip are necessary to guarantee the repeatability of the results. Some studies nevertheless find that despite a lower resistance of the bone, compared to steels and alloys, the bit is subjected to significant frictional forces (especially in the absence of irrigation or lubrication). These forces lead to overall wear of the point which affects the thickness of the edges, their shapes, the presence or absence of deposits on the sides, the flutes or even the edges. These authors have also shown that this wear is correlated with the number of times the drill bits are used (16-18,28,29).
The study mainly focused on the analysis of the wear of the drill bit according to the machining parameters and the number of holes. It has been shown that surface anomalies can be detected significantly by digital microscopy. Some quantitative analyzes of the width of the ridge at the top have been carried out. This study demonstrates that the width of the central edge increases significantly with the number of drill holes.
It was fresh bone, but without external irrigation. It was a question of studying the possibility of reusing the wicks in extreme conditions in order to determine a field of use in complete safety. Despite its macroscopic appearance, the bit already shows significant signs of wear on the 10th hole.
The results obtained encourage continued research into bone drilling under more favorable conditions with irrigation, without damaging the electronic measurement equipment. In industry, water irrigation seems rather to compromise the quality of the surface roughness. This phenomenon has not yet been studied during bone drilling. It is therefore useful to reconsider the number of drillings in bone surgery because of a deterioration that is noted very early from the 4th drilling.

Authors' contributions

Jean Gustave Tsiagadigui, Marie-Ange Ngo Yamben, Paul William Mejouyo Huisken, Marc Leroy Guifo, Loïc Fonkoue, Handy Eone, Jean Bahebeck, Ebenezer Njeugna, Maurice Aurélien SOSSO: Design of the experiments; Conduct of the experiments; Analysis and interpretation of the data; Contribution of the experimental material, Exploitation of the data analysis tools; Drafting of the article.

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