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Original paper

# Numerical and experimental analyses of drills used in osteosynthesis

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This paper presents the results of numerical analysis and experimental studies of the process of bone drilling using drills applied in osteosynthesis procedures. In the studies, two surgical drills with a diameter $d$ = 4.5 mm and varying in drill point geometry $2\kappa$ were used. Thermal analysis based on FEM allowed determining the distribution of temperatures generated in the bone as a function of rotational speed of the drill. The results indicate that both drill point geometry and rotational speed of the drill have influence on temperatures generated in bone tissue. Additionally, the range was determined for possible values of rotational speed, which does not initiate the process of thermal necrosis of bone. The experimental studies of the process of drilling in a femur model showed the impact of drill point geometry on the values describing the cutting process. It was concluded that the highest values of torques and axial forces during cutting occur in the tools with angle $2\kappa_2 = 120°$.

*Key words*: *surgical drills, finite elements methods, thermal analysis, wear resistance, martensitic steel, bone surgery*

## 1. Introduction

The service life of surgical drills is determined mainly by their correct geometric form and appropriate mechanical properties of metallic material, which guarantees the transfer of loads generated during surgery. The usefulness of the tools in question is evaluated primarily based on their correct drill point geometry. It is assessed mainly by specifying the point angle $2\kappa$ of the drill point. The values of this angle for the drills used in practice are the following: $2\kappa = 90°\div120°$. The normative recommendations do not include specific studies of the required drill point geometry and the criteria for evaluating the degree of wear in drills used in bone surgery. Also, the literature does not pay much attention to this issue, even though these factors substantially affect a proper process of bone drilling. Moreover, there are no literature studies covering biomechanics of this group of tools, and above all, the analysis of their deformation and stress with respect to the functional purpose. This kind of analysis is the basis for the optimization of geometric features (drill point geometry) and the selection of mechanical properties for metallic material.

The papers on the quality of surgical drills present mainly experimental studies of temperature distribution in the bone subjected to drilling [1]–[5]. The results of these studies are inconclusive. For example, such studies were carried out by HILLARY and SHUAIB [3], who determined the temperature distribution in human and bovine bones during drilling, using drill with a diameter $d$ = 3.2 mm for different values of point angle ($2\kappa_1 = 90°$, $2\kappa_2 = 120°$). The study was based on making holes of different depths and at different values of rotational speed of the drill: $n = 400\div2000$ rpm. The study showed that the value of point angle $2\kappa$ had no substantial influence on the temperatures generated in the bone. When evaluating the influence of rotational speed of drills on the tem-

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perature, it was found that the drilling process did not initiate the process of thermal necrosis ($T < 55$ °C) when using rotational speed of $n = 400 \div 1400$ rpm.

AUGUSTIN et al. [4] studied the temperature distribution in porcine femur during the drilling process, using a drill with the diameters $d_1 = 2.5$ mm, $d_2 = 3.2$ mm, $d_3 = 4.5$ mm for different values of point angle ($2\kappa_1 = 90°$, $2\kappa_2 = 100°$, $2\kappa_3 = 120°$). The tests revealed that the value of angle $2\kappa$ affected the temperature distribution. Based on the studies conducted it was concluded that the lowest temperatures were generated by drills with an angle $2\kappa_1 = 90°$, regardless of the analysed diameter. Correct cutting parameters that did not generate critical temperature ($T < 55$ °C) for drills with diameters $d_1 = 2.5$ mm and $d_2 = 3.2$ mm were obtained within the whole range of rotational speed $n$. However, it was observed that drills with a diameter $d_3 = 4.5$ mm should have reached rotational speed $n \leq 460$ rpm during the drilling process.

Another example is provided by the study conducted by NATALI et al. [5]. They studied the temperature distribution in human femur during the drilling process using a drill with a diameter $d = 2.5$ mm and different values of point angle ($2\kappa = 90°$ and $2\kappa = 118°$). Their study was conducted at a constant rotational speed $n = 800$ rpm. The tests showed that the value of point angle affected the temperature distribution. Based on the studies conducted it was concluded that the lowest temperatures were generated by drills with an angle $2\kappa = 118°$.

As can be seen, the results of the above studies are different and inconclusive. Therefore, it can be concluded that the issue of optimizing the geometry of the working part of surgical drills and the cutting process parameters in bone has not been fully clarified yet. For this reason, the authors of this paper conducted a numerical and experimental analyses under conditions simulating the process of bone drilling, using surgical drills with different drill point geometries. The study supplements the analysis of deformations and stress in the elements of surgical drill–femur system conducted by the authors using the finite element method [6]–[8].

# 2. Material and methods

## 2.1. Numerical analysis

In order to conduct the analysis based on finite element method, we selected a surgical drill with straight shank and diameter $d = 4.5$ mm. In addition, a femur model was prepared, simulating the hole with a diameter equal to the diameter of cylindrical part of the drill. It reflected the working part (of drill point) for two analysed values of point angle ($2\kappa_1 = 90°$ and $2\kappa_2 = 120°$) – figure 1. Inventor Professional software was used to prepare geometric models.

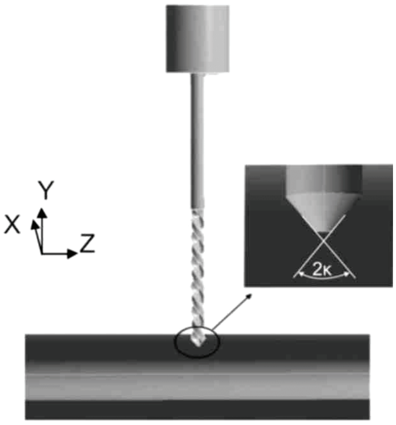

Fig. 1. Geometric model of surgical drill–femur system

The prepared geometric models were accompanied by a grid generated for calculations using the finite element method. SOLID 187 element was used for discretization of the analysed system. The analysis was conducted by modelling the heat flow in transient state.

Transient heat conduction is the initial-boundary value problem. It requires accurate initial and boundary conditions to be properly formulated. The following initial conditions were assumed:

$$T(x, y, z, t)|_{t=0} = T_0, \tag{1}$$

where $T_0$ is an initial temperature ($T_0 = 36.6$ °C).

The second boundary condition (von Neumann's) [9] was used for the modelling of heat propagation. It describes the heat flux density $q$ received by the surface. The heat flux density can be determined according to

$$q = \frac{P_c}{S} \quad (\mathrm{W/m^2}), \tag{2}$$

where:

$P_c$ – total cutting power (W),

$S$ – surface area (m$^2$).

The results of experimental studies presented in the literature [9]–[11] show that 99.5% of cutting work is converted into heat during cutting. In this case, it can be assumed that the amount of heat generated during cutting in time unit is equal to the total cutting power $P_c$, which can be determined as follows:

$$P_c = P_f + P_m, \tag{3}$$

where:

$P_f$ – the power derived from the feed component of cutting power,

$P_M$ – the power derived from cutting torque.

Particular values were determined using the results obtained in experimental studies from the following relations:

$$P_f = V_f \cdot F_{fw} \text{ (W)}, \tag{4}$$

$$P_M = \frac{M_W \cdot n \cdot \pi}{60} \text{ (W)}, \tag{5}$$

where:

$V_f$ – feed motion speed (m/s),

$F_{fw}$ – axial cutting force (N),

$M_w$ – cutting torque (Nm),

$n$ – rotational speed (rpm).

In order to conduct the analysis, appropriate boundary conditions were assumed which reflected the phenomena occurring in the actual system. The following premises and parameters of the cutting process were assumed (figure 2) [1], [3], [4], [12]:

- rotational speed within the range $n$ = 250÷1400 rpm,
- feed motion speed $V_f$ = 100 mm/minute,
- supports were placed to enable movement of the bone along the $X$-, $Y$- and $Z$-axes, and the movement of the sleeve along the $X$- and $Z$-axes,
- heat flux density $q$ was simulated at the point where the tool came into contact with the bone,
- the friction process was stimulated at the points where the drill came into contact with femur (friction coefficient $\mu$ = 0.42),
- the simulations were performed for time $t$ = 5 s, which corresponded to the time needed to drill one hole.

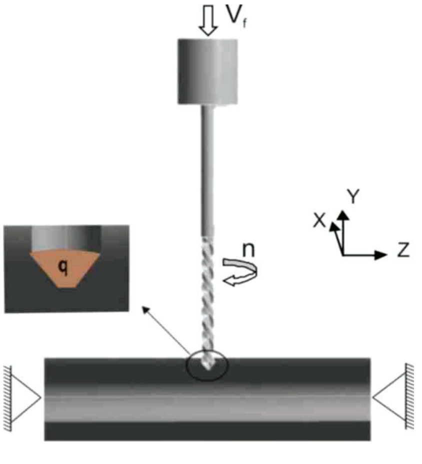

Fig. 2. Calculation model with fixed boundary conditions

The following material parameters were assumed for the prepared model [1], [3], [13]–[15]:

- Surgical drill (X39Cr13 martensitic steel):
  - ○ heat conductivity coefficient $\lambda$ = 47.7 W/m°C,
  - ○ heat capacity $c$ = 490 J/kg°C,
  - ○ density $\rho$ = 8750 kg/m$^3$.
- Cortical tissue of the femur:
  - ○ heat conductivity coefficient $\lambda$ = 0.38 W/m°C,
  - ○ heat capacity $c$ = 1260 J/kg°C,
  - ○ density $\rho$ = 1700 kg/m$^3$.

## 2.2. Wear rate tests for surgical drills

Wear rate tests for surgical drills were conducted in two stages. The first stage involved the determination of the cutting process characteristics. Then they were used to determine average values of axial forces and cutting torques as a function of rotational speed. In evaluations, we used five surgical drills with straight shank of X39Cr13 steel and a diameter $d$ = 4.5 mm ($2\kappa_1 = 90 \pm 1°$ and $2\kappa_2 = 120 \pm 1°$). Five values of rotational speed of the tool, i.e., $n_1$ = 250 rpm, $n_2$ = 365 rpm, $n_3$ = 500 rpm, $n_4$ = 710 rpm and $n_5$ = 1400 rpm, were measured. Feed rate was constant and equal to $V_f$ = 100 mm/minute. In the process of drilling in the area of a single cortical layer, we used the femoral models manufactured by SAWBONES. Measurements were carried out in the Machining Laboratory of Machine Technology Department, Silesian University of Technology in Gliwice, at a stand allowing the values describing the drilling process to be measured and recorded (figure 3). The measuring system of the test stand consists of the following components:

- piezoelectric dynamometer (Kistler 9272A), which enables the measurement of cutting torque and force,
- amplifier (Kistler 5011),
- A/C card: EAGLE USB30, µDAQ series,
- PC equipped with Snap-Master software for data processing.

The second stage involved the measurements of wear land width $VB_B$ on the surface, where the working part of the drill is applied, in relation to the initial position of both cutting edges. The drilling process was carried out by setting a predetermined number of holes at $n_0$ = 20 at a constant rotational speed $n_2$ = 365 rpm and feed rate $V_f$ = 100 mm/minute. The measurements were carried out each time a hole was made. In addition, the values of axial forces and cutting torques during the drilling of each hole were determined. Five drills per each of two analysed values of point angle $2\kappa$ were selected for the study.

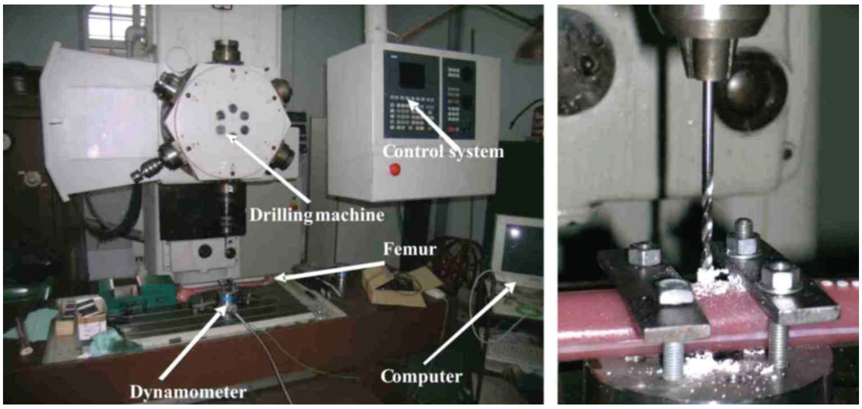

Fig. 3. Stant for testing wear rate of surgical drills

# 3. Results

## 3.1. Results of numerical analysis

The results of the calculations for the analysed drill with different drill point geometries are summarized in the table. The analysis of the results revealed a diversified distribution of temperature generated in femur as a function of rotational speed $n$. It was found that the highest temperatures occur in the tool with the point angle $2\kappa_2$ = 120° at the point of its contact with the processed material, at the maximum rotational speed $n_5$ = 1400 rpm ($T_{max}$ = 88 °C). For the point angle $2\kappa_1$ = 90° the $T_{max}$ value was lower and equal to 82 °C (the table). Due to this analysis an important information is gained – we know the area of bone with a tem-

Table. The results of thermal analysis using the finite element method

| Rotational speed (rpm) | Point angle ($2\kappa$, °) | Temperature in femur ($T_{max}$, °C) |
|---|---|---|
| 250 | 90 | 55 |
| | 120 | 60 |
| 365 | 90 | 58 |
| | 120 | 64 |
| 500 | 90 | 63 |
| | 120 | 72 |
| 710 | 90 | 70 |
| | 120 | 79 |
| 1400 | 90 | 82 |
| | 120 | 88 |

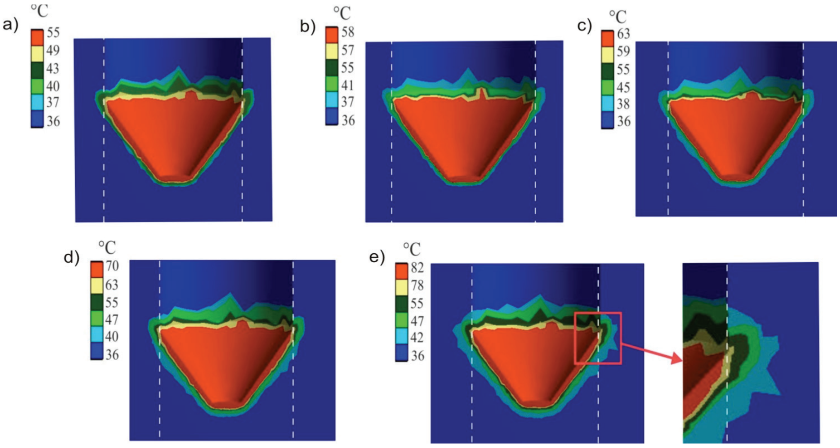

Fig. 4. The temperature distribution in the femur during the process of drilling using a drill with point angle $2\kappa_1$ = 90° for: a) $n_1$ = 250 rpm, b) $n_2$ = 365 rpm, c) $n_3$ = 500 rpm, d) $n_4$ = 710 rpm, e) $n_5$ = 1400 rpm

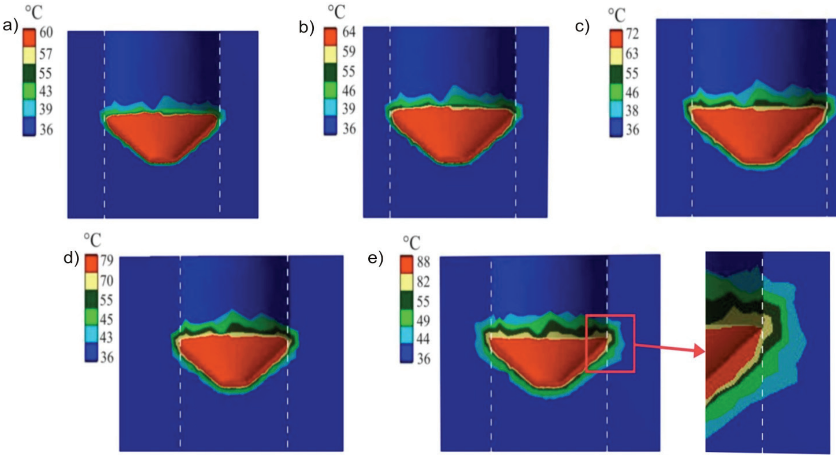

Fig. 5. The temperature distribution in the femur during the process of drilling using a drill with point angle $2\kappa_2 = 120°$ for: a) $n_1 = 250$ rpm, b) $n_2 = 365$ rpm, c) $n_3 = 500$ rpm, d) $n_4 = 710$ rpm, e) $n_5 = 1400$ rpm

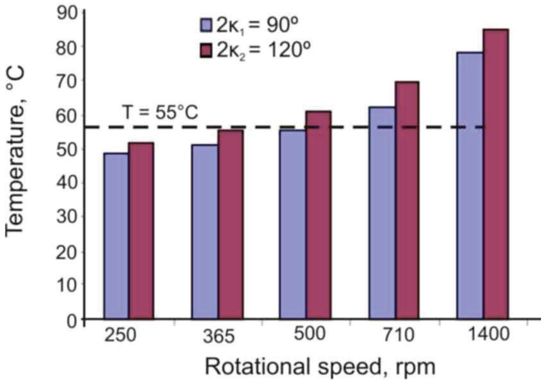

Fig. 6. The temperature distribution at the point of contact of the drill with the femoral bone outside the drilling area

perature $T_{\max} \geq 55$ °C. Exceeding this temperature poses a threat of tissue of destruction, caused by the process of a thermal necrosis of bone. The analysis conducted shows that the maximum rotational speed for the drill with a point angle $2\kappa_2 = 120°$ should be within the range $n_{\max} \leq 365$ rpm. In the case of tools with an angle $2\kappa_1 = 90°$ this value can be higher and should be within the range $n_{\max} \leq 500$ rpm (figures 4–6).

## 3.2. Results of testing wear rate of surgical drills

Based on the study conducted it can be concluded that regardless of the rotational speed applied, the highest values of torques and axial forces during cutting occur in the tools with point angle $2\kappa_2 = 120°$. Among all the variants analysed, the highest values of torque and axial force during cutting were recorded for the above angle at a rotational speed $n_1 = 250$ rpm. These values were as follows: $M_w = 0.57$ Nm and $F_{fw} = 380$ N. In the case of point angle $2\kappa_1 = 90°$, these values were lower and equal to $M_w = 0.50$ Nm and $F_{fw} = 250$ N (figures 7 and 8). The lowest values of torque and axial force during cutting were recorded at a rotational speed $n_5 = 1400$ rpm. These values were: $M_w = 0.18$ Nm and

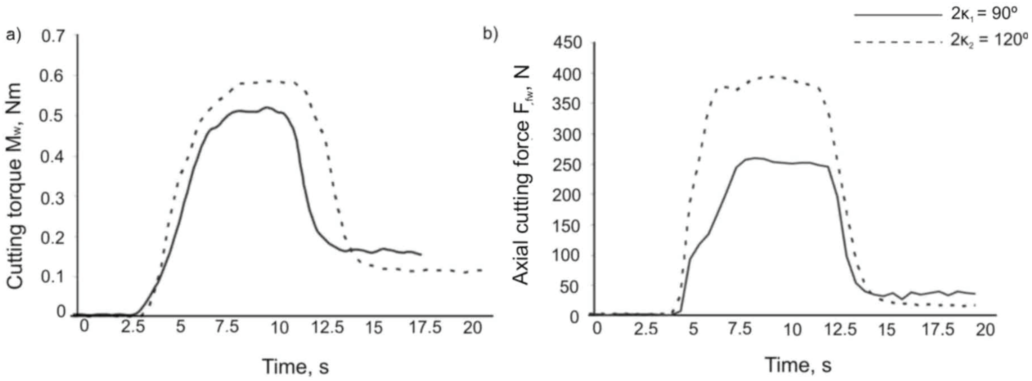

Fig. 7. Features of the cutting process using a drill with a diameter $d = 4.5$ mm for rotational speed $n_1 = 250$ rpm: a) the changes in cutting torque, b) the changes in axial force during cutting

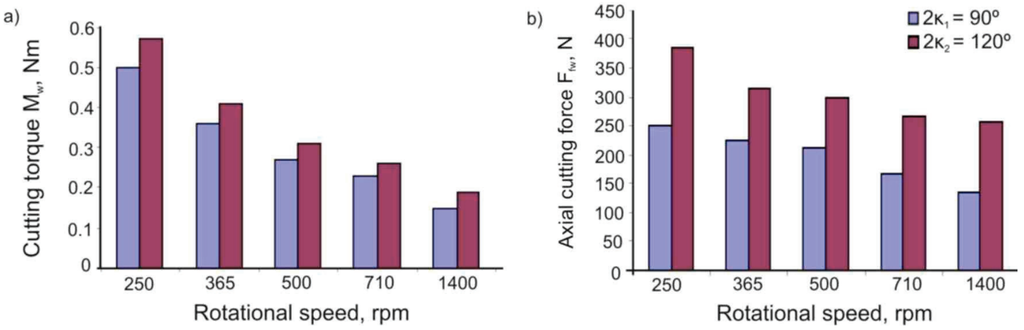

Fig. 8. The impact of rotational speed on cutting resistance during the drilling process at a drill diameter $d = 4.5$ mm: a) the values of cutting torques, b) the values of axial force during cutting

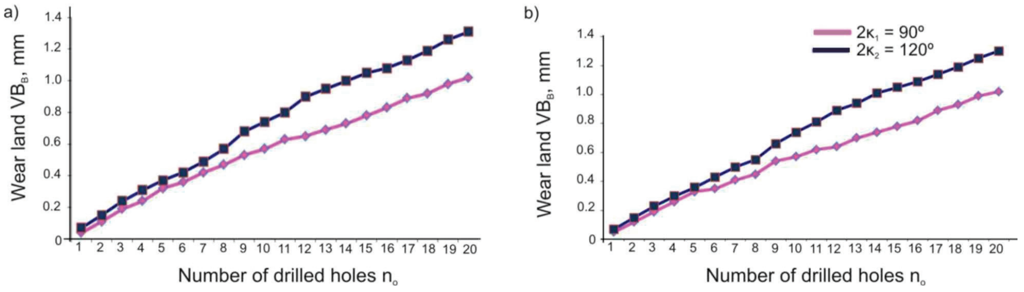

Fig. 9. The results of wear rate tests for surgical drills as a function of the number of drilled holes: a) cutting edge no. 1, b) cutting edge no. 2

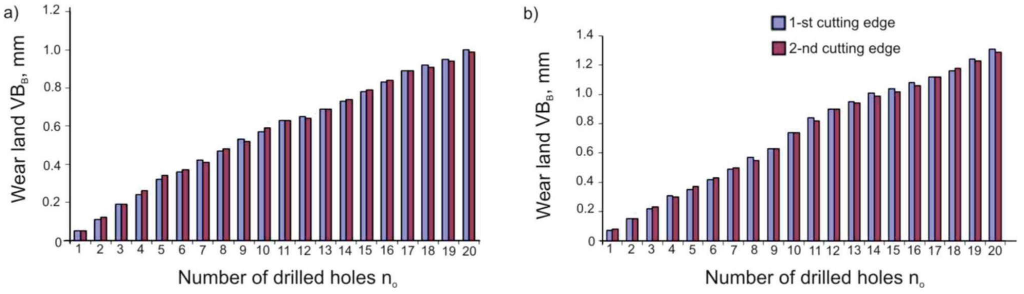

Fig. 10. The results of wear rate tests for surgical drills: a) $2\kappa_1 = 90$°, b) $2\kappa_2 = 120$°

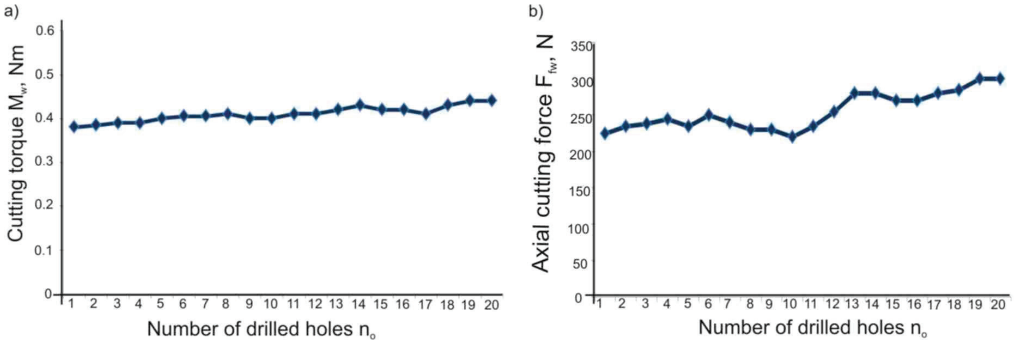

Fig. 11. Cutting resistances as a function of the drill holes for the drill with an angle $2\kappa = 90$°: a) the changes in cutting torque, b) the changes in axial force during cutting

$F_{fw} = 250$ N (for angle $2\kappa_2 = 120°$) and $M_w = 0.15$ Nm and $F_{fw} = 135$ N (for angle $2\kappa_1 = 90°$).

In the second stage of experimental studies, the measurements were carried out using only the rotational speed $n_2 = 365$ rpm. They reveal that the highest values of wear land width $VB_B$ on the surface were observed in the case of tools with the point angle $2\kappa = 120$° (figures 9 and 10). For the tools with such a value of point angle $2\kappa$, the average value of wear land width after drilling 20 holes was $VB_B = 1.30$ mm. In the case of angle $2\kappa_1 = 90^\circ$, the value was lower and equal to $VB_B = 0.98$ mm. The measurements proved that the process of wearing surgical drills was similar in both cutting edges analysed. In addition, the values of axial force and cutting torque as a function of the number of drilled holes were determined. It was found that with an increase in the number of holes, the values of axial force and cutting torque were increased for both analysed valus of point angle $2\kappa$ (figure 11).

## 4. Discussion and conclusions

The numerical and experimental analyses presented in this paper can be seen as a natural continuation of the studies conducted by the authors, whose aim is to develop a methodology for determining the functional properties of the drills used in osteosynthesis. The preliminary tests of the tools used in clinical practice, characterized by different diameters $d$ and drill point geometries ($2\kappa_1 = 90^\circ$ and $2\kappa_2 = 120^\circ$), were designed to carry out a numerical analysis of the surgical drill–femur system under conditions simulating the cutting process, using the finite element method [6]–[8]. The analyses show that, regardless of the value of drill diameter $d$ and axial force $F$, the highest values of deformations and reduced stresses occur in the tools with point angle $2\kappa_2 = 120^\circ$. Therefore, it can be assumed that the wear rate of surgical drills with such a point geometry will be faster.

In order to verify the results of numerical analysis, an experimental study of the drilling process in a femur model was conducted. It revealed that, regardless of the rotational speed $n$, the highest values of torques and axial forces during cutting occurred in the tools with a point angle $2\kappa_2 = 120^\circ$ (figures 7 and 8). These results correlate well with those obtained in the numerical analysis of surgical drill–femur system and confirm the correctness of the assumptions. Furthermore, it was found that with increased rotational speed $n$ the values of axial force and cutting torque were reduced.

Optimal selection of cutting parameters in the bone should also minimize the cutting resistance. In this case, the positive influence of increasing the values of rotational speeds must also reflect the intensity of thermal phenomena occurring during the drilling process. Too high a rotational speed of the drill may cause thermal necrosis of bone tissue. According to the literature data, bone cells are destroyed at the temperature of about 55 °C. The problem of selecting the correct parameters for cutting in the bone has not been well described in the literature yet. Therefore, this study attempts to determine the acceptable rotational speed of the surgical drill analysed, using the finite element method.

The influence of both drill point geometry and rotational speed $n$ on the temperature generated in the drilling process was assessed based on the thermal analysis conducted. This confirms the results of experimental studies carried out by AUGUSTIN et al. [4]. The analysis of the results obtained showed that the highest temperatures occur in the tool with point angle $2\kappa_2 = 120^\circ$ at the point of its contact with the processed material (the table). The temperature rises with an increase in rotational speed of drills. Therefore, this part of the study also determines the range of acceptable rotational speeds $n$, for which the value of temperature at the point of the contact of the drill and the femoral bone outside the drilling area does not exceed $T_{\max} \leq 55$ °C. The analysis conducted showed that the maximum rotational speed for the drill with the point angle $2\kappa_2 = 120^\circ$ should be equal to $n_{\max} \leq 365$ rpm. In the case of tools with point angle $2\kappa_1 = 90^\circ$, the value can be higher and equal to $n_{\max} \leq 500$ rpm (figures 4–6). The ranges of acceptable values of the speed $n$ are similar to those obtained by Augustin.

Considering the results of thermal analysis, the measurements of wear land width on the surface where both cutting edges are applied as a function of the number of drilled holes were conducted only at the speed $n_2 = 365$ rpm. The selection of such a rotational speed was intentional. This allowed a comparative analysis using the rotational speed adequate for both types of drills. The measurements showed that the highest values of wear land width $VB_B$ were observed in the case of tools with point angle $2\kappa_2 = 120^\circ$ (figure 9).

To sum up, it can be concluded that the conducted experimental studies of the bone drilling process confirm the results of the numerical analysis of a surgical drill–femur system carried out by the authors, and presented in this paper [6]–[8]. The results of the numerical analysis and experimental studies indicate that among the drills tested, the most preferable solution is to use the tools with an angle $2\kappa_1 = 90^\circ$. The tools with such a drill point geometry allow higher cutting speeds to be reached, resulting in a reduction in cutting resistance. Consequently, this ensures a lower intensity of wear rate of the drills used in surgical procedures.

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