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INVESTIGATION INTO BONE DRILLING AND THERMAL BONE NECROSIS

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Abstract:
This paper studies the problem and presents the results of different possibilities of avoiding the occurrence of thermal bone necrosis. In fact, in case of fracture of human bones, the best way to better and faster knitting is when a traumatologist fixes the fractured bone ends by drilling and setting the immobilization plates by screws. Because of the drilling process, the surrounding bone tissue is heated and if the temperature around the drilled bone hole exceeds the critical limit, this may result in thermal necrosis, which means the irreversible death of the bone cells exposed to that high temperature.

The paper researches the possibilities of decreasing the value of axial force and temperature of bone drilling process with a proper selection of influencing parameters in drilling. Also, the presents the obtained results of the influence of drill type geometry on the temperature of bone drilling and possibilities of high speed drilling process in thermal bone necrosis avoidance. All researches have been performed at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb.

Key Words: Bone drilling, Thermal necrosis, High-speed drilling

1. INTRODUCTION

The problem of bone fracture in medicine has existed from the times when humans started to treat other people and animals. In case of fracture, it is most important to return the fractured parts into their initial position and to fixate them in the best possible way. In modern medicine there are two basic approaches to fracture: a conventional approach and a direct one.

In the conventional approach, the immobilisation of the fractured parts is done from the outside. The traumatologist treats the fracture by setting it and placing the immobilisation aids from outside. A great disadvantage of this approach lies in the fact that the fractured parts cannot be optimally aligned, and in case of some types of bone fracture the alignment from outside is not possible. Besides, long patient recovery is an additional disadvantage of this approach.

The direct approach, on the other hand, is a more recent method in which the traumatologist drills the bone around the fracture site with classical drills in order to set the immobilization screws and plates and perform bone fixation. When drilling, the traumatologist has to act by pressure force on the drilling tool in order to insure uniform penetration of the drill through the bone. This may result in a temperature increase caused by the plastic deformation of the chips and friction between the drilling tool and the bone. The problem in bone drilling can sometimes be the occurrence of bone necrosis, which means the irreversible death of bone cells [1,2,3,4] in the vicinity of the hole due to the drilling temperature raised over the critical value of 50°C. Thus, the advantage of this method is better and faster knitting of the fractured ends but only if bone necrosis is avoided.

In order to reduce the drilling temperature, the treatment needs to be performed as quickly as possible so that the heat does not penetrate the bone. This is achieved by the increase of the drill axial speed. However, naturally, this speed requires a higher pressure force (axial drilling force). The axial penetration force should not be excessive because in some patients it may even cause further fractures.

As the application of the knowledge from technical sciences, e.g. mechanical engineering, to medicine is growing daily, the interconnection between the two scientific disciplines is stronger. With the development of mechanical engineering technologies, we believe that we can help to solve a lot of problems in medicine. Thus, the study of the drilling parameters and the dependence of the axial drilling force and the bone drilling temperature on these parameters can significantly contribute to the reduction of the bone necrosis occurrence.

2. INFLUENCING PARAMETERS IN BONE DRILLING

A great number of influencing parameters are involved in the axial drilling force and the bone drilling temperature. In technical sciences, multi-factorial orthogonal test plans are mostly used to determine that influence because these plans give maximum information with minimum tests. Despite that, the number of influencing parameters needs to be reduced. In selecting the influencing parameters, the previous research and acquired experience [1,4,5] need to be considered, but in the majority of works that deal with the problems of bone drilling no mathematical model has been established.

In order to determine the relevant mathematical models, an experiment has been carried out on the ALG-100 tool-and-die milling machine. The bone drilling process itself and the measuring of the axial drilling force and the bone drilling temperature are schematically shown in Figure 1.

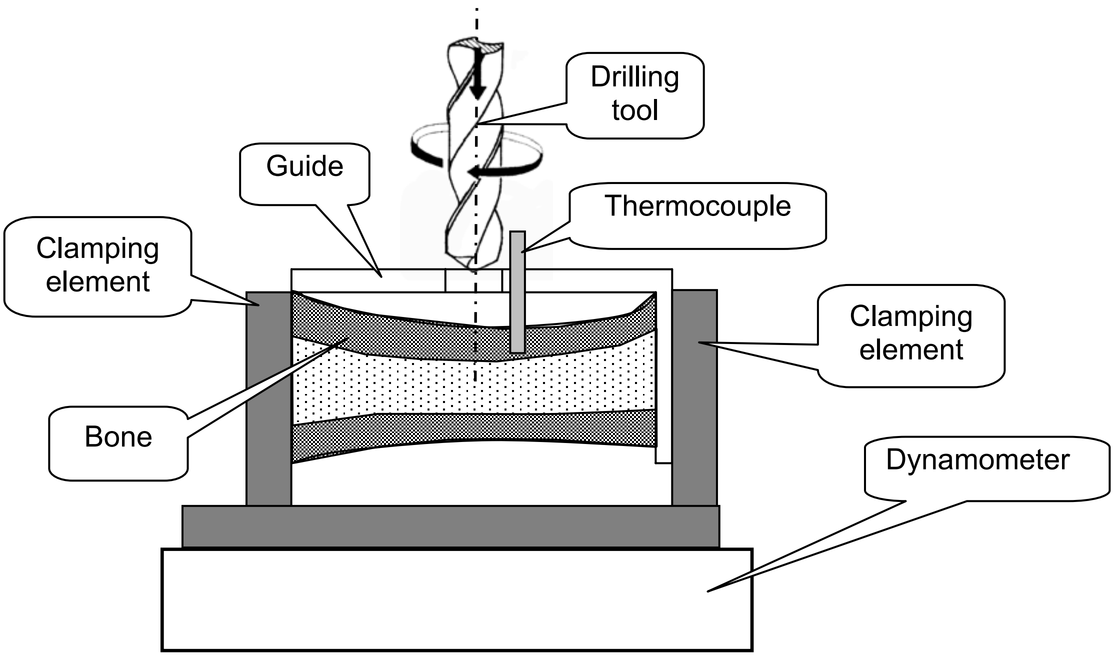

Figure 1: Scheme of the bone drilling process.

According to [6,7] the obtained mathematical models which connect the axial drilling force and the temperature of bone drilling with the axial feed, cutting speed and drill tip angle, as parameters in the drilling process, are as follows:

$$F = p_0 \cdot v_c^{p_1} \cdot f_z^{p_2} \cdot \varepsilon^{p_3} \tag{1}$$

$$T = p_4 \cdot v_c^{p_5} \cdot f_z^{p_6} \cdot \varepsilon^{p_7} \tag{2}$$

where:
F - axial drilling force,
T - bone drilling temperature,
p_0-p_7 - regression coefficients,
v_c - cutting speed,
f_z - feed rate per tooth,
ε - drill tip angle.

A three-component dynamometer Kistler Type 9257B, located under the clamping elements, Figure 1, was used to measure the axial drilling force. The instrument was calibrated before the drilling with the set clamp, guide and bone so as to eliminate their weight. The results were processed in the Dynoware program, installed on a PC. The different values of the drill tip angle have been obtained by grinding the drilling tool of 4.5 mm in diameter on a grinding machine UOZA-3. In order to allow a comparison of the measurement results of bone drilling temperature, the gap between the thermocouple and the drill was set at 0.5 mm, and in all the measurements the thermocouple was set at the depth of 3 mm into the compact bone (corticalis), Figure 1.

Based on the selected experiment plan, the results of measuring the axial drilling force and bone drilling temperature are presented in two right columns of Table I, and the values of input cutting factors are on the left side of the same table.

Table I: Input cutting data and results of axial force and temperature measurement.

Measurement #	Cutting data			*F, N*	*T, °C*
	v_c	f_z	ε		
	$m\ min^{-1}$	*mm*	*rad*		
1.	6	0.02	1.4 (80^0)	26.8	48.8
2.	16	0.02	1.4	23.1	55
3.	6	0.1	1.4	58.1	45.6
4.	16	0.1	1.4	57.2	50.3
5.	6	0.02	2.1(120^0)	102.1	49.6
6.	16	0.02	2.1	95.6	54.7
7.	6	0.1	2.1	202.4	43.3
8.	16	0.1	2.1	198	46.3
9.	10	0.045	1.57(90^0)	57.8	49
10.	10	0.045	1.57	61.8	53
11.	10	0.045	1.57	61.9	53
12.	10	0.045	1.57	62	52

The input data from Table I have been processed by the software package Statistica 6.0 and the results of the analysis are presented by the mathematical dependence of the axial drilling force on the influencing parameters with the great value of determination coefficient, i.e. $r^2=0.99$:

$$F = 58{,}42 \cdot f_z^{0{,}439} \cdot \varepsilon^{3{,}024} \tag{3}$$

The mathematical model, which analyses the dependence of the bone drilling temperature on the influencing drilling parameters, obtained in the same way, has the determination coefficient $r^2=0.731$ and has the following form:

$$T = 33{,}8 \cdot v_c^{0{,}0964} \cdot f_z^{-0{,}07} \tag{4}$$

On the basis of equations (3) and (4), the response surface of the function is presented in Figures 2 and 3.

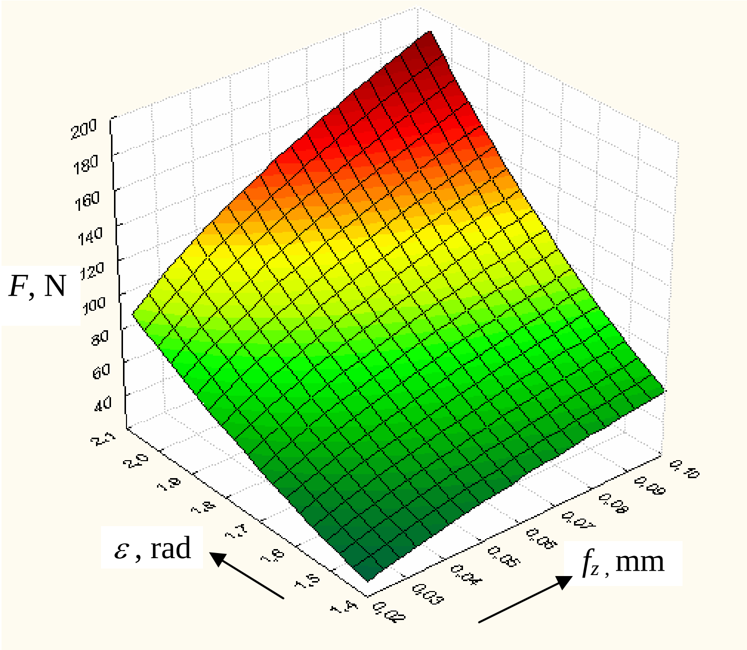

Figure 2: Dependence of the axial drilling force on the influencing drilling parameters.

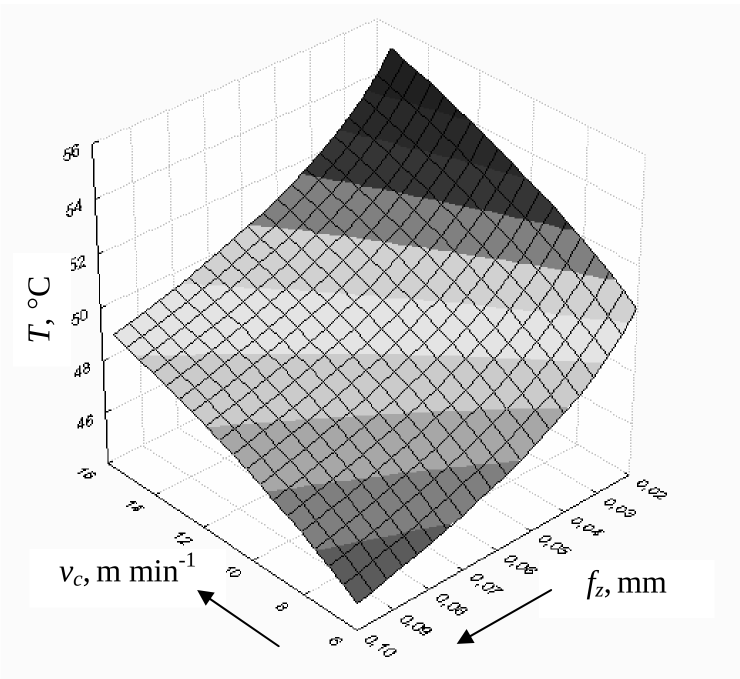

Figure 3: Dependence of the bone drilling temperature on the influencing drilling parameters.

From the performed experiment and the mathematical analysis of the results, it can be concluded that the cutting speed is not statistically significant in the case of the axial drilling force. Contrary, the bone drilling temperature increases with the increase in cutting speed, and according to that, the drill cutting speed should be reduced as much as possible.

When the value of the feed rate per tooth increases, the results show that the axial drilling force also increases, but at the same time, its increase reduces greatly the time of machining. That means a shorter time of friction between the drilling tool and the bone and also a smaller amount of the resulting heat with a consequence of a lower bone drilling temperature. Therefore, it is recommended to use a great value of the feed rate per tooth in bone drilling.

The third influencing parameter in the bone drilling process, the drill tip angle, has a very high influence on the axial force. Its reduction contributes to a great reduction of the axial drilling force but it has no influence on the bone drilling temperature. The conclusion is that with bone drilling it is better to use a smaller value of drill tip angle.

3. DRILLING TOOL GEOMETRY

Although the results show that the drill tip angle value has no influence on the bone drilling temperature, the influence of drilling tool geometry on the bone drilling temperature will be studied in further research. Bone drilling is performed with two different drilling tool geometries, i.e. a classic surgical drill with the 80° drill tip angle value and a two-phase drill (step drill). Both types of drills are shown in Figure 4 and they have a 4.5 mm diameter and the tip of two-phase drill nas 3.4 mm. These two types of drills are made of standard high speed steel and not of surgical steel, but as thermal characteristics of these two types of steel are very similar, this has no influence on the maximal bone drilling temperature.

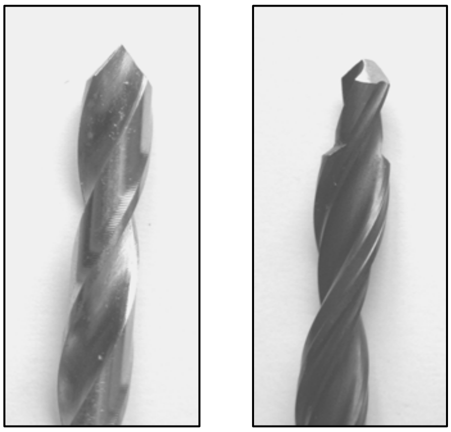

Figure 4: A classic surgical drill and a two-phase drill (step drill).

Twenty-five measurements of bone drilling temperature, with each drilling tool and same constant cutting data as input factors, were made. The cutting speed was 6.53 m/min and the value for the cutting feed rate per tooth was 0.1 mm. The calculated mean values of the measured maximal bone drilling temperature are presented in Figure 5.

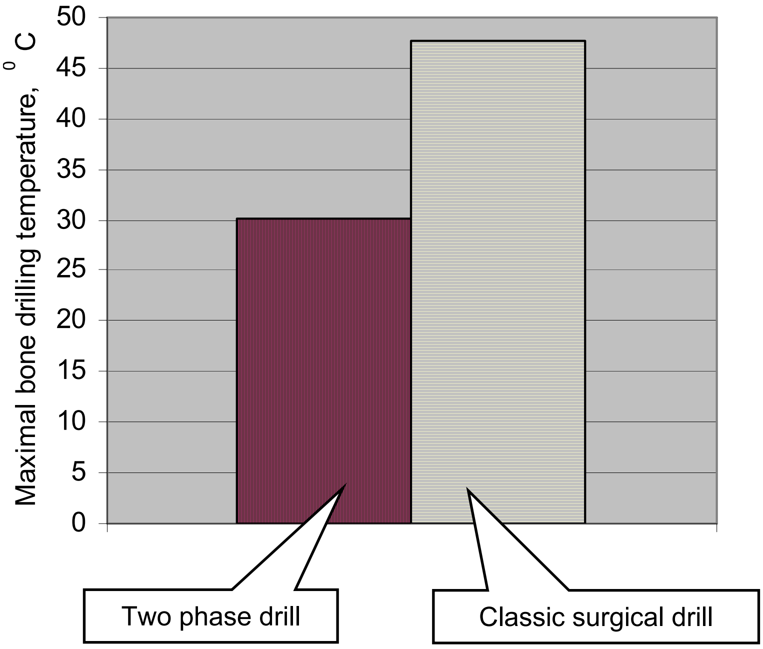

Figure 5: Maximal bone drilling temperature in dependence on the drilling tool geometry.

The results from Figure 5 show that the maximal bone drilling temperature value is much lower in the case of drilling bone with a two phase drill than in that of using classic surgical drill. In drilling bone with a classic surgical drill the maximal bone drilling temperature was 47.6°C and in the drilling process with a two phase drill the temperature was 30.12°C. The difference is 17.48°C and that is because at beginning of the drilling process with a two phase drill the bone is pre-drilled with a smaller diameter. Consequently, the maximal bone drilling temperature is much lower.

4. THERMOGRAPHIC MEASUREMENTS IN BONE DRILLING

The previous conclusion that a two-phase drill is the best choice of drilling tool for bone drilling because the bone heating in the drilling process is the least, is confirmed by thermographic measurement of the bone drilling process [8]. The measuring is performed with a thermographic camera, ThermaCAM 695, FLIR Systems, where the heat radiation is focused on a sensor surface matrix (320x240 sensors) of microbolometers. The Infrared (IR) camera thermography enabled the estimation of temperature increase and temperature fields at bone drilling with different types of drill tip geometry. The bone surface was cleaned from tissue rests and covered with a thin graphite layer ($\varepsilon = 0.95$). The IR camera was set at an angle of 60° in relation to the hole axis (drilling direction), and the temperature fields on the bone surface were determined.

The results of the IR camera thermography are images where each temperature isotherm is denoted with a different colour, Figure 6. Such images enable an excellent overview of the temperature distribution in relation to the distance from the drilled hole. Beside a possibility of reading the temperatures, the image enables the determination of bone and drill edges, Figure 6. The reading of maximum temperatures in bone drilling gave the following results:

- highest temperature reached with a classic surgical drill was 97.7°C
- highest temperature reached with a two-phase drill was 78.5°C

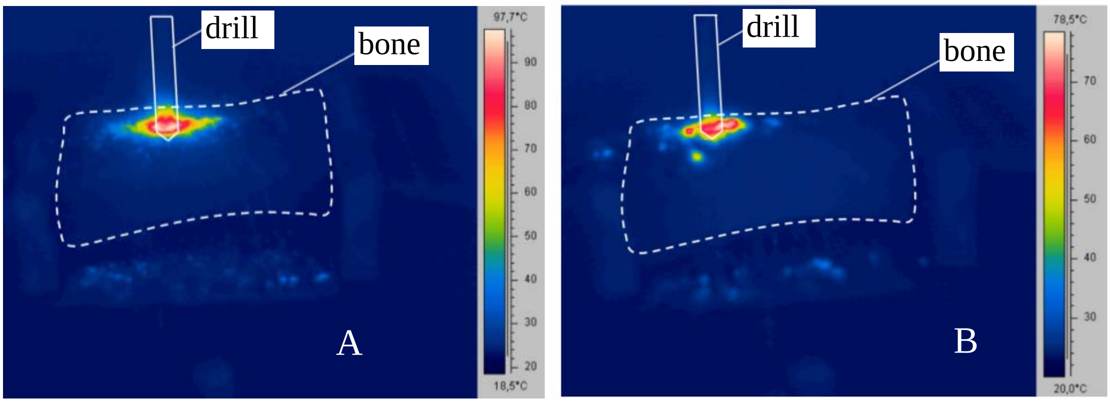

Figure 6: Temperature isotherms in the bone drilling process
A - classic surgical drill , B - two-phase drill.

A comparison of corresponding images and highest temperature values obtained with different drill geometries, Figure 6, established and confirmed that the best results were obtained at drilling with a two-phase drill. In conclusion we recommend a two-phase drill for bone drilling in order to minimize, if not eliminate, the possibility of thermal necrosis. The obtained results also confirmed the previous results in the paper when temperature measurements were performed by applying contact measurements, i.e. the thermopar method.

Although the highest temperature values far exceed the critical temperature of 50°C, the second parameter that must be considered is the time the temperature remained at the highest level. If the duration of temperature above critical value is less than 1 minute, there will be no thermal necrosis. That fact leads us to a high speed drilling process, because strictly following the cutting theory and according to [9,10], basic features of the high speed machining process are at least 4-5 times higher cutting speeds than those in standard drilling processes, and considerably lesser heating of the workpiece. In the case of a bone workpiece it is to be expected that the majority of generated heat would be passed to chips, and not to the tool or the bone. At the same time, high speed drilling would reduce the drilling time [11,12,13]. Therefore, the application of high speed drilling of bones should be the subject of further research.

5. HIGH SPEED BONE DRILLING

The research on high speed bone drilling was carried out in the Machine Tool Laboratory at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb. A three-axis vertical NC milling machine Flexmatic FA 530 S was used in the experiment. The speeds of the main spindle of this NC milling machine were between 3000 and 24000 revolutions per minute.

The increase in bone temperature during high-speed drilling was measured by a digital thermometer BEHA unitest Therm 100, capable of measuring temperatures up to 200°C and with a resolution of 0.1°C.

A classic surgical drill and a two-phase drill were used in the experiment, and both drilling tools had the same diameter of 4.5 mm. This high speed drilling experiment was carried out also on pig bones whose medium part had the thickness of corticalis of approximately 4 to 6 mm. All other measuring conditions were the same as in the previously obtained standard drilling processes. The cutting feed rate per tooth in the high speed drilling process was constant and it was 0.1 mm, and each result was obtained on the basis of 25 measurements. Figure 7 gives the mean value of the bone temperature increase during high speed drilling with a classic surgical drill and a two-phase drill vs. cutting speed.

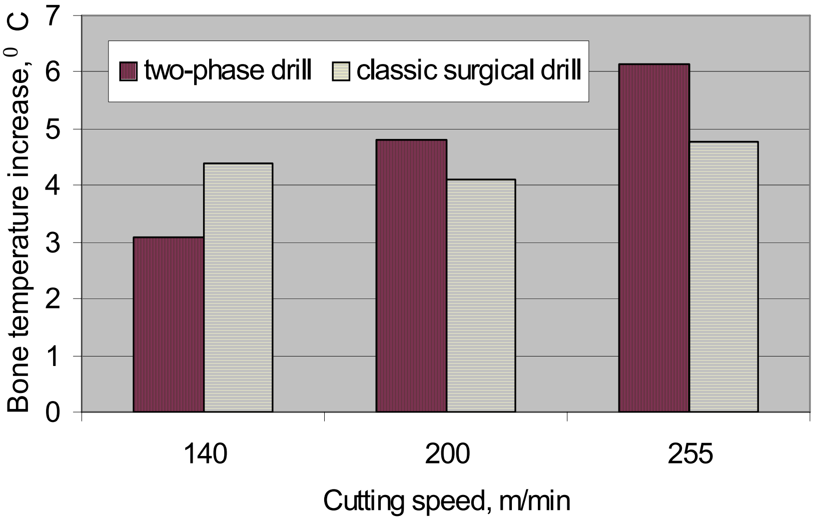

Figure 7: Bone temperature increase during high speed drilling with a classic surgical drill and a two-phase drill vs. cutting speed.

From Figure 7 one can see that the bone temperature increase during the high speed drilling also depends on the drilling tool geometry. The best result, i.e. the smallest bone temperature increase of 3.095°C, was obtained with a two-phase drill at the cutting speed of 140 m/min. It can also be noted that with a classic surgical drill the bone temperature almost does not change with the increase in the cutting speed. On the other hand, with a two-phase drill, the increase in cutting speed causes the rise in the bone temperature increase. The results of the high speed bone drilling procedure obtained in the tested range of cutting speeds between 140 m/min and 255 m/min lead us to a conclusion that it makes no sense to increase the cutting speed above 140 m/min.

The answer to the question whether high speed drilling can produce a smaller temperature increase in bone drilling can be found in a comparison of the obtained results when the bone drilling is carried out at the standard cutting speed of 6.53 m/min and feed rate per tooth of 0.1 mm [6], and the previous results obtained at a cutting speed of 140 m/min and the same value of feed rate per tooth. The comparison is presented in Figure 8.

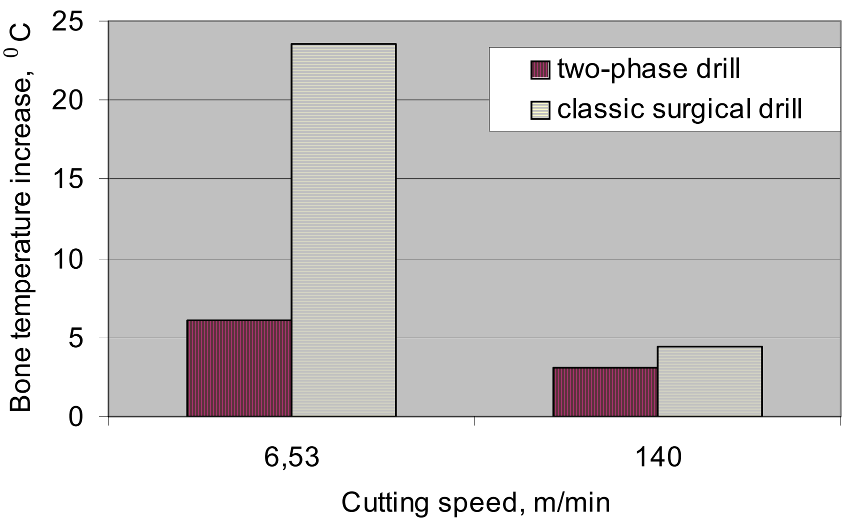

Figure 8: Comparison of the bone temperature increase during a classic and a high speed drilling process.

Figure 8 shows that the high speed bone drilling (cutting speed of 140m/min) with a two-phase drill produces almost twice lower bone temperature increase than in the classic drilling (cutting speed of 6.53 m/min), but the difference is only approximately 3°C. The high speed bone drilling with a classic surgical drill produces almost six times lower bone temperature. The difference in this case is much higher, approximately 19°C. The answer to the question put in the previous paragraph is affirmative, i.e. it can be concluded that the high speed drilling significantly decreases the bone temperature increase if compared to the drilling at the standard cutting speed.

6. CONCLUSION

According to the obtained results it is possible to conclude that the cutting speed, as an influencing factor, statistically has no effect on axial drilling force, but affects proportionally the maximal temperature of bone drilling. The increase in the drill cutting speed in drilling with a classic surgical drill results in the increase of the bone drilling temperature. Therefore, in classic drilling, the drill cutting speed should be reduced as much as possible.

The drill feed rate, as the second influencing factor, acts proportionally on the axial drilling force and is inversely proportional to the rise in the bone drilling temperature. Therefore, the feed rate in classic bone drilling should be as high as possible.

The drill tip angle has a very high influence on the axial drilling force. Its reduction influences to a great extent the reduction of the axial drilling force but drill tip angle values do not affect the bone drilling temperature.

Comparing the results for different drilling tool geometries, it can be concluded that the best choice of a drilling tool for classic bone drilling is certainly a two-phase drill because its use causes the least increase in bone temperature.

Results in Figure 7 show that the bone temperature increases during the high-speed drilling process when using a two-phase drill. In high-speed drilling with a classic surgical drill, the bone temperature almost does not change with the increase in the cutting speed. In both drill type geometries the best result was obtained at the value of the cutting speed of 140 m/min.

A comparison of the bone temperature increase during a classic and high speed drilling process, Figure 8, leads to a conclusion that the high speed drilling significantly decreases the bone temperature increase in both drill types. In addition, even better results, i.e. much lower bone temperature increase, are obtained by high speed bone drilling when a classic surgical drill is used instead of a two-phase drill. The high speed bone drilling is also preferable because the duration of the drilling process is definitely shorter and consequently, the generated high temperature affects the bone for a shorter period of time; hence, the bone necrosis is less likely to occur.

Suggestions for further researches are to carry out experiments with drilling at even higher cutting speeds using a classic surgical drill and to try to use the drills with inside cooling.

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