Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 55(5) (2023) 115-118
DOI: 10.22060/mej.2023.20586.7273

Determination of convective heat transfer coefficient in human femur bone drilling in the presence of normal saline and evaluation of effective parameters

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ABSTRACT: This research has analyzed the drilling process in the human femur bone to determine the heat transfer coefficient and occurrence or non-occurrence of thermal necrosis. 3D drilling simulation has carried out naturally with air and force convection with normal-saline and the analysis was performed for three feed rates of 50, 100, and 150 millimeters per minute(mm/min) at speeds of 500, 1000, and 2000 rotation per minute(rpm). The results show that in natural cooling, the highest generated heat is equal to 4 Joule at 50mm/min and 500rpm while the lowest value of generated heat is 1.65 Joule at 150mm/min and 2000rpm. The maximum difference of the average heat transfer coefficient with the experimental results is 12.5%, which represents a good accuracy of the present results. The results also show that the average heat transfer coefficient at 100 and 150mm/min is 55% and 29.1% more, respectively, and it is 5% less at 50mm/min compared to the constant value of 20 , which is considered in the previous researches. Also, thermal necrosis occurs under all conditions of natural cooling. In forced cooling, the highest average heat transfer coefficient with normal-saline is 150mm/min at a speed of 2000rpm, which is equal to 3650 , and in all conditions, the bone temperature has not exceeded the temperature limit of thermal necrosis.

Review History:

Received: Sep. 30, 2021
Revised: Jan. 17, 2023
Accepted: Apr. 30 , 2023
Available Online: May, 24, 2023

Keywords:

Bone drilling
femur bone
normal-saline coolant
thermal necrosis
cortical bone

1- Introduction

Bone drilling is very important in orthopedic surgery, dentistry, and bone sampling. Due to the friction between the drill and the bone, heat is generated during the drilling. The inappropriateness of the heat removal mechanism produced during bone drilling causes thermal necrosis and changes the nature of bone alkaline phosphatase. In addition, the loss of the mechanical strength of the drilling place will also cause the loosening of the screws placed in the hole and incorrect welding of the bone. Alam et al.[1] investigated the effective parameters to achieve optimal conditions and their effect in bone surgery and showed that as the drill advances into the bone, the temperature of the cavity increases linearly. Pandey and Panda[2] optimized the parameters of the bone drilling process during the experimental study. Sener et al.[3] showed by drilling on the cow bone that the highest temperature is generated on the surface and depth of the bone hole. Shakouri et al.[4] have studied the theory and experiment of heat generation in the process of bone drilling. The results of this research show that the theoretically calculated generation heat is close to the experimentally measured values in different conditions and it was found that machining theories can predict the amount of heat generation in bone drilling. Also, Karaca et al.[6] studied human bone and observed that increasing rotational speed or decreasing feed rate and applied force in the cortical bone, increased the temperature rising. According to the investigations carried out in the previous theoretical research, the convection heat transfer coefficient is considered to be a fixed value of $20\,\mathrm{w}/\mathrm{m}^2.\mathrm{k}$ which cannot be a correct assumption in the conditions of drilling from the start to the end, and considering that the study of the occurrence of thermal necrosis and its sensitivity. The temperature and duration of keeping the bone at that temperature require a more accurate analysis of the problem in a time-dependent manner, and in addition to the average convective heat transfer coefficient, its instantaneous value also becomes important, so the main goal of the present research is to investigate the average convection heat transfer coefficient more precisely for evaluation occurrence or non-occurrence of thermal necrosis.

2- Governing equations, modeling, and analysis

According to the conditions of the desired problem and the history of its numerical solution, the equations of continuity, mumentum and energy equation along with the equations of the ε-k model were solved for turbulent conditions. The simulation was carried out in two states of natural and forced

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(a)

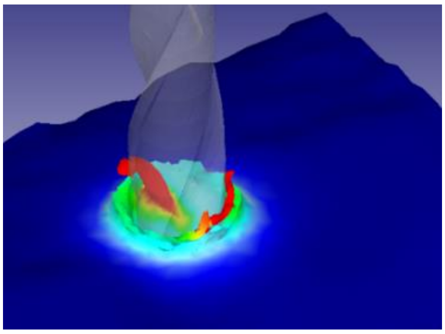

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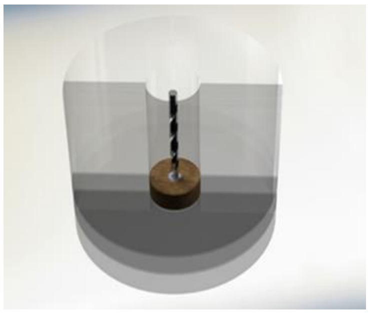
Fig. 1. (a) 3D geometry created in Mimics software based on CT scan images of the human femur bone, (b) An example of the output of Deform software in the analysis of bone perforation



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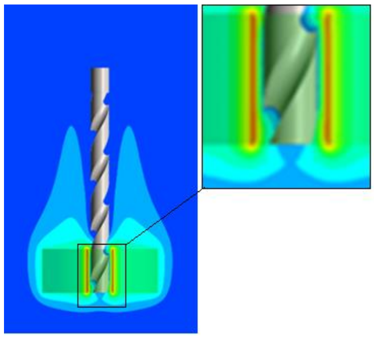


(b)

Fig. 2. a) Geometry contains bone, drill, and fluid, b) Temperature contours in the symmetry plane

cooling in three rotational speeds of 500, 1000, and 2000 rpm and in three feed rates of 50, 100, and 150 mm/min and it was investigated the parameters affecting the heat transfer coefficient. For this purpose, the file of CT scan images of human femur bone was obtained from Ayatollah Mousavi Hospital in Zanjan and created 3D bone geometry by using Mimics software according to Figure 1a for future studies. A part of the 3D model of the bone around the drilling to analyze the heat flux produced as a result of the drilling was determined based on the theory of machining in Deform software, and the heat flux generated was determined. Figure 1b shows an example of this analysis.

To determine the convective heat transfer coefficient, a cylindrical model according to Figure 2a was selected from the diaphysis part of the bone and analyzed using Ansys Fluent software. In addition, for the analysis, the independence of the grid was carried out and the number of 1405584 elements was selected.

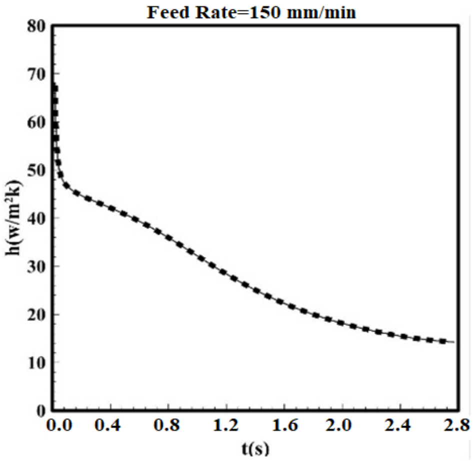
2- 1- Natural Cooling

The desired problem was analyzed for the natural cooling mode in three feed rates of 50, 100, and 150 mm/min and three rotational speeds of 500, 1000, and 2000 rpm. Figure 2b shows an example of temperature contours in the bone in the symmetry plane of the hole.

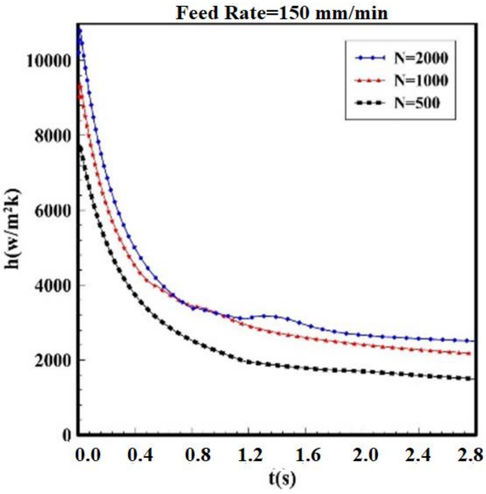
To investigate the changes in convection heat transfer coefficient, the problem has been analyzed in three feed rates of 50, 100, and 150 mm/min for rotational speeds of 500, 1000, and 2000 rpm. For example, the convection heat transfer coefficient versus time from the start of drilling in feed rate 150 mm/min, the rotational speed of 2000 rpm is shown in Figure 4a.

2- 2- Force Cooling

Also, the desired problem for the forced cooling mode has been analyzed by changing the type of boundary conditions for this condition, in three feed rates of 50, 100, and 150 mm/min and three rotational speeds of 500, 1000, and 2000 rpm. Figure 3b shows the changes of the convection heat transfer coefficient in terms of time from the start of drilling with normal saline cooling fluid for different rotational speeds at the feed rate of 150 mm/min. Also, Table 1 shows the average convection heat transfer coefficient during the entire drilling time for normal saline cooling fluid in the forced cooling condition, obtained from mathematical calculations for different conditions.



(a)



(b)

Fig. 3. Variations of convection heat transfer coefficient versus start drilling time of cortical bone, a) Natural cooling, b) Force cooling

Table 1. Average Convective heat transfer coefficient during drilling time for force cooling

	Feed rate [mm/min]		
	50	100	150
Rotational speed [rpm]	$\bar{h}\left[\frac{w}{m^2.k}\right]$	$\bar{h}\left[\frac{w}{m^2.k}\right]$	$\bar{h}\left[\frac{w}{m^2.k}\right]$
500	1670	1936	2481
1000	1921	1987	3350
2000	1813	2574	3653

3- Conclusion

The review of available numerical research shows that the convective heat transfer coefficient was considered a constant value, which will not be correct due to the type of cooling fluid and other conditions such as drill rotation speed, and feed rate. Therefore, this research investigates the heat transfer coefficient for instantaneous and the average in two states of natural and forced displacement in drilling the human femur bone to investigate the occurrence or non-occurrence of thermal necrosis more precisely. The results show that in all drilling conditions investigated in the natural convection state, the bone temperature exceeds the limit defined for thermal necrosis and its occurrence will be certain. Also, the results, in this case, show that the average convection heat transfer coefficient is higher by 55% and 29.1% at feed rates of 100 and 150 mm/min, respectively, and by 5% less than at feed rates of 50 mm/min of the constant value, 20 $w/m^2.k$, which has been considered in previous theoretical and numerical researches. In the case of forced cooling, which was analyzed with normal saline fluid, the results show that the cooling capacity decreases with the increase in drilling time. In drilling with normal saline fluid, as the depth of drilling increases, heat penetration into the bone and also the cavity has been more. Forced cooling has caused a lower temperature of the bone surface compared to natural cooling so that the maximum temperature drop in the forced convection state compared to the natural convection state will be equal to 20 degrees Celsius. Besides, in the case of forced convection with normal saline, the bone temperature did not exceed the permissible limit in any of the drilling conditions and thermal necrosis did not occur.

4- Acknowledgment

Finally, we would like to express our gratitude to the management of Ayatollah Mousavi Hospital in Zanjan, as well as Dr. Mehran Setare, who provided the necessary cooperation in conducting this research.

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HOW TO CITE THIS ARTICLE

Sh. Sadri, J. Ghasemi, Determination of convective heat transfer coefficient in human femur bone drilling in the presence of normal saline and evaluation of effective parameters, Amirkabir J. Mech Eng., 55(5) (2023) 115-118.

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