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Research Paper

Optimization of bone drilling process based on finite element analysis

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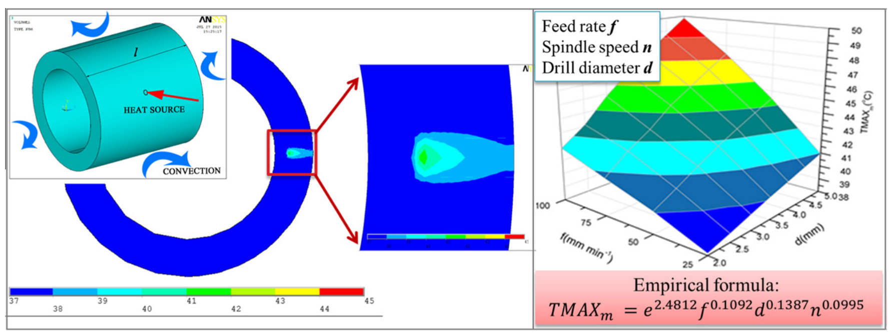
HIGHLIGHTS

- Volumetric heat source is loaded to obtain more accurate simulation results.
- Multiple parameters' synergistic effects on the drilling temperature are studied.
- Empirical formula with sensitivity analysis is proposed to predict the temperature.
- Intermittent feed drilling is demonstrated to reduce the drilling temperature.

GRAPHICAL ABSTRACT



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ABSTRACT

Bone drilling is frequently used in modern surgery operations, especially in fracture treatment. Drilling temperature should be strictly controlled, since when the temperature is 47 °C higher over 60 s, irreversible damages happen to bone. The study investigated the heat transfer of bone drilling by a three-dimensional model based on finite element method. Three principal drilling parameters were studied: feed rate, spindle speed and drill diameter. A parametric study proved that drilling temperature increases once any of three parameters rises. Parameters' effects on drilling temperature are proved synergistic. An empirical formula of maximum drilling temperature depending on three drilling parameters is given with a sensitivity analysis. To a drilling process of surgical operations, this formula could be used for temperature prediction and optimization of parameters respecting drilling temperature. Furthermore, the intermittent feed drilling is proposed and demonstrated to be very efficient to reduce thermal necrosis to bone tissue.

1. Introduction

Bone drilling is a significant part of the internal and external fixation processes in orthopedic surgery. The heat generated during drilling may be partially dissipated by the blood and tissue fluids and partially carried away by the chips formed. However, due to the poor thermal conductivity of fresh cortical bone, which is among 0.38–2.3 $Wm^{-1} K^{-1}$, it's difficult for bone to conduct the rest heat away from the cutting edge. So, the temperature rise at the cutting edge in a deep cortical hole would be extremely high. The phenomenon of bone injury, resulting from the rise of heat during drilling operations, is defined as thermal necrosis. This damage to bone cells would delay the healing process after the surgery and reduce the strength of the fixation. Eriksson and Albrektsson [1] observed that the cortical necrosis and delayed healing occur in living animal bone heated at 47 °C for one minute. Krause [2] states that osteoclasts begin to die when the drilling temperature is higher than 50 °C. According to the study of Augustin [3],

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Nomenclature

$\{\beta\}$	unit outward normal vector
a	intensity coefficient
c	specific heat [J kg^{-1} K^{-1}]
$c1$	first regression coefficient
$c2$	second regression coefficient
$c3$	third regression coefficient
$c4$	fourth regression coefficient
d	diameter of drill [mm]
$[D]$	thermal conductivity matrix
Dep	drilling depth [mm]
D_{in}	inside diameter of bone model [mm]
D_{out}	outside diameter of bone model [mm]
e	constant
f	feed rate of drilling [mm min^{-1}]
h	heat convection coefficient [W m^{-2} K^{-1}]
K_{xx}	elemental thermal conductivity in the direction of x [W m^{-1} K^{-1}]
K_{yy}	elemental thermal conductivity in the direction of y [W m^{-1} K^{-1}]
K_{zz}	elemental thermal conductivity in the direction of z [W m^{-1} K^{-1}]
l	length of bone model [mm]
L	vector operator
n	spindle speed of drill [rpm]
$\dot{q}_{drilling}\,(x, y, z, t)$	volumetric heat generation rate [W m^{-3}]
t	time [s]
$T(x, y, z, t)$	current temperature of the bone [K]
T_∞	ambition temperature [°C]
T_{emp}	empirical value of $TMAX_m$ issued from the regression [°C]
T_{exp}	experimental value of $TMAX_m$ issued from the model [°C]
T_{human}	human body's temperature [°C]
T_S	temperature on the surface S [°C]
$TMAX(t)$	maximum temperature on the bone at moment t (drilling temperature) [°C]
$TMAX_m$	maximum value of $TMAX$ during a drilling process [°C]
V	velocity vector for mass transport of heat [m s^{-1}]
v_c	cutting speed of drill [m s^{-1}]
v_f	feed rate of drilling [m s^{-1}]
ρ	density [kg m^{-3}]

thermal damage was caused to the bone while temperature was between 47 °C and 50 °C. The thermal damage on bone tissue during orthopedic sawing was also investigated and the threshold temperature found was about 55 °C [4].

In order to minimize the damage caused by the high temperature (above 47 °C) in bone drilling operations, it is necessary to optimize the drilling parameters. Many researches have been conducted to find out effects of different drilling parameters on multiple quality characteristics of bone drilling. Drilling parameters such as spindle speed, feed rate, drilling depth, drill tip angle, drilling force and drill diameter were experimentally studied [5–7]. Pandey and Panda [8] used the analysis of variance (ANOVA) to determine the effect of each drilling parameter on drilling temperature. Beside, drilling experiments on bovine bone with spindle speeds from 800 rpm to 3800 rpm were performed by Lee et al. [9], and it is concluded that the drilling temperature rises with increase in spindle speed. Other methods like drilling experiments on bone-like material Poly Methyl Methacrylate (PMMA) were also used for prediction [10]. Previous researches were mainly aimed to investigate the effect of individual drilling parameter on the bone drilling temperature. This paper studies multiple parameters' synergistic effects on drilling temperature with a three-dimensional model. The objective is to build an instruction for classic bone drilling operation in form of a general empirical formula that is concise and simple for using.

Recently the numerical simulation based on finite element method is a possible substitute for high-cost and complex experimental work, especially as a useful tool for verification of analytical results and prediction. ANSYS is powerful and practical FEM-based numerical simulation software for analyzing complicated structure. ANSYS Mechanical is capable to analyze the thermal response of structures to heat transfer effects, involving conduction, convection, and radiation heat transfer [11]. It is widely used for modeling heat transfer problem owing to its excellent performance in solving problem of different modes including steady, transient, linear and nonlinear. Thiagarajan, King et al. [12] investigated a steady-state heat transfer simulation in ANSYS to quantify thermal losses of the pool boiling. Zhou et al. [13] simulated oxygen cutting, similar with procedure of drilling, using a composites heat source model to predict the cutting temperature in ANSYS.

The Finite Element Method (FEM) presents effective performance not only in virtually all areas of engineering but also in applied science like medical science. The FEM could avoid the high-cost in term of expense and time of experimental study in medical science. For example, ANSYS is used for the simulation of biomaterials like bone and dent to investigate their mechanical and thermal properties. This paper analyzes the temperature's change during cortical bone drilling with different parameters, including drill spindle speed n, feed rate f and drill diameter d via ANSYS. Specifically, with customizing ANSYS by APDL (ANSYS Parametric Design Language) script, a three-dimensional heat transfer model of bone was built and verified. In addition, a volumetric heating source was used in this model. Li et al. [14] compared volumetric and surface heating sources in the modeling of laser melting of ceramic materials and concluded that the simulation result with volumetric heating source is more accurate and stable.

Other applications of finite element method were also used to investigate the mechanism of cutting process and to predict drilling temperature. Tu et al. [15] used a three-dimensional finite element model to show that lowering the initial temperature of Kirschner pin can decrease the temperature rise as well as the size of the thermally damaged zone. Mokhtar and Fawad [16] worked out a complete theory for bone drilling modeling to obtain the heat flux. A new thermal model has been worked out by Lee et al. [17] for bone drilling with a sensitivity analysis and a single parametric study was also investigated for this model. Sezek et al. [18] worked with a FEM-based model for bone drilling and found a safety zone for drilling parameters.

To date, most studies of bone drilling modeling proposed a new model or a new theory without further practical research of the drilling temperature by exploring the model or the theory. This paper presents a detailed investigation from the foundation to the validation of the three-dimensional model, followed by results of different levels. Hundreds of simulations were completed in ANSYS with values that correspond with the real drilling procedure. The influence on drilling temperature is studied separately with single parameter and double parameters. The effects of multiple parameters on drilling temperature were proved synergistic. In order to generalize the numerical results, an empirical formula