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Experimental investigation and statistical modeling of temperature rise in rotary ultrasonic bone drilling

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Thermal necrosis is one of the major problems associated with the bone drilling process in orthopedic/trauma surgical operations. To overcome this problem a new bone drilling method has been introduced recently. Studies have been carried out with rotary ultrasonic drilling (RUD) on pig bones using diamond coated abrasive hollow tools. In the present work, influence of process parameters (rotational speed, feed rate, drill diameter and vibrational amplitude) on change in the temperature was studied using design of experiment technique i.e., response surface methodology (RSM) and data analysis was carried out using analysis of variance (ANOVA). Temperature was recorded and measured by using embedded thermocouple technique at a distance of 0.5 mm, 1.0 mm, 1.5 mm and 2.0 mm from the drill site. Statistical model was developed to predict the maximum temperature at the drill tool and bone interface. It was observed that temperature increased with increase in the rotational speed, feed rate and drill diameter and decreased with increase in the vibrational amplitude.

1. Introduction

Fracture of bones is a common problem due to age factors, sports injuries, transport and industrial accidents, etc. One of the most common methods to immobilize these fractured parts of bones is to repair and reconstruct by fixing them with metal plate held by screws or locking plate, intramedullary nail, dynamic compression screw-plate etc. Fixing these screws into the bone needs a predrilled hole. Therefore drilling on bone is required in various medical surgeries like orthopedic, dental and trauma surgical operations. In bone drilling process, mechanical work energy is converted into thermal energy [1] which could be the cause of continuous increase in the temperature of bone as well as drill tool. Direct cutting contact between the bone and drill tool bit results in significant amount of heat is produced during the bone drilling process because of material removal and coefficient of friction between the drill bit and bone. It was reported that bones are bad conductors of heat and thermal conductivity is in the range of 0.2–2.27 W/m K [2].

Increase in the temperature near the drilling site during the bone drilling process can cause serious problems like thermal necrosis [3–5], reduced regeneration capacity of protein [4,5] and bone death [6,7]. Permanent death of the bone cells occurred due to rise in temperature beyond a threshold value [3,4] and is known as thermal necrosis or bone necrosis. Researchers have tried to find out the threshold value for the thermal necrosis on animal bones.

Lundskog [3] performed experimental investigation on rabbits and reported that irreversible death of the bone cell occurred if temperature reached 50 °C while cutting a bone for 30 s. In another study, Eriksson et al. [4] reported that, if temperature was raised to 47 °C for 60 s in cutting of bones, the osteonecrosis occurred. Krause [5] reported that bone necrosis was formed, when temperature reached 50 °C. Pandey and Panda [8] concluded that during bone drilling/cutting for 1 min, if temperature rose to 47 °C or beyond then thermal necrosis or irreversible death of the bone cell occurred. Previously reported [8–12] research attempts showed that magnitude of rise in temperature in bone drilling depended upon the various input parameters as shown in Fig. 1.

In the previous published research, researchers tried to control the temperature during bone drilling process by using irrigation technique [7,13–16], designing new drill bits [1,13,15,17,18] and drilling technique [12,19–21]. Using irrigation technique maximum heat generated could be reduced during the bone drilling process, but it could be a further cause of infection near the treated area [22]. Alam and Silberschmidt [19] investigated the effect of ultrasonic vibration parameters (superimposed on conventional drill) on the temperature and compared their findings with the conventional drilling (CD) process. They reported that temperature could be reduced by ultrasonic drilling (UAD) as compared to the CD. Similar kind of experimental results were published by Shakouri et al. [12] and Wang et al. [21]. But still there is a need to

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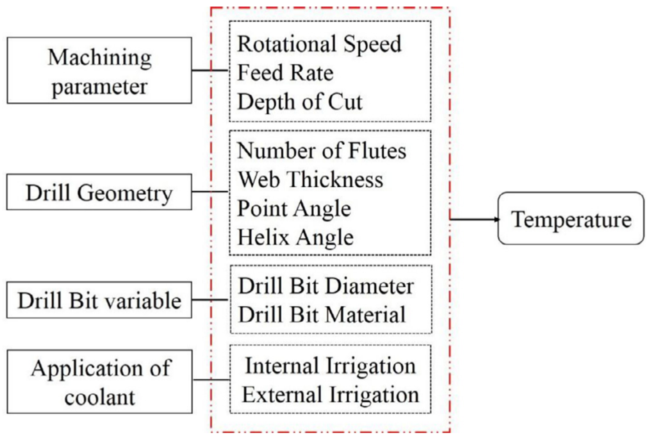

Fig. 1. Parameters influencing the rise in temperature during bone drilling.

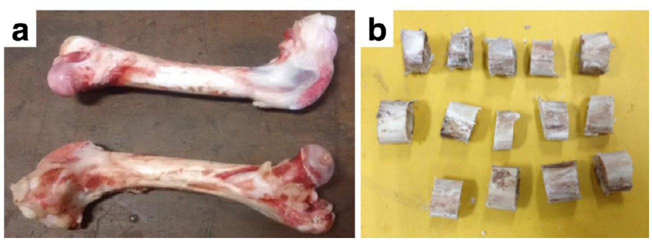

Fig. 2. (a) Pig bone samples (b) samples of bone after slicing.

minimize the rise in temperature during surgical bone drilling process for more efficient and successful orthopedic and trauma surgery.

The main objective of the present study is to reduce the rise in temperature and heat generated during bone drilling with a RUD technique using a hollow tool coated with diamond abrasive particles. This is similar to the rotary ultrasonic machining (RUM) process where a cylindrical rod was generated after the drilling, due to the hollow profile of the tools. In this process, the rotating hollow tool with diamond bonded abrasive particles was ultrasonically vibrated in the downward direction (Z-axis) at a given feed. Material was removed by the cutting action of the diamond bonded abrasive particles on the tool and hammering action of the ultrasonic vibration. Whereas in CD process material was removed by the flutes of the drill bit and no ultrasonic vibration was given.

2. Material and experimental method

2.1. Material

Experimental investigations were carried on the male pig bones i.e., 11–12 months old as shown in Fig. 2 because of its close resemblance to human bones [23–26]. Bone samples were obtained from the local butcher shop and experiments were performed within 2 h after the obtained the bone samples. No animal was killed for the study and experiments were performed only on those bones which are used by the food industry. Experimental studies were conducted on the mid diaphysis part of the bone after the thin and soft thin periosteum layers were removed. The mid diaphysis part was further sliced using diamond coated hacksaw to perform the experiments as shown in Fig. 2(b). Thickness of bone of more than 5 mm and below 4.5 mm were not included in this study.

2.2. Experimental procedure

In order to perform the experimental investigations to find out change in temperature with RUD using diamond coated hollow tool on bone, rotary ultrasonic tool assembly was designed and fabricated as shown in Fig. 3(a). Diamond abrasives of mesh size 80–100 were electroplated on the hollow shank as shown in Fig. 3(b) with areal average abrasive density as 15 *abrasive*/ mm^2. Conventional drill bit which was used to perform CD has been shown in Fig. 3(c).

The designed assembly consisted of an ultrasonic transducer of 800 W with frequency of 20 kHz, which was connected to one side of the housing and diamond coated hollow tool was attached with nut and collet locknut on the other side of the transducer. Computer numerical control (CNC) machine collet was coupled with the housing from another end. Slip rings were provided on the housing for electrical signal input. The designed and build assembly was clamped on the CNC milling machine head as shown in Fig. 4. Rotational motion of the assembly, table motion along the x–y axis and feed rate was varied from the machine controller unit and amplitude was varied from the ultrasonic controller unit.

Temperature was recorded from a drill site at a distance of 0.5 mm, 1.0 mm, 1.5 mm, 2.0 mm with K-type thermocouples as shown in Fig. 5. For accurate measurement of temperature, parallel predrilled holes were prepared on the sliced pieces of bone with respect to the main drilled hole to insert thermocouples. Before measuring the value of temperature all the thermocouples were checked and calibrated properly. Initial (T_i) and final (T_f) temperatures were recorded with each thermocouple and change in the temperature (Δt) was considered to optimize the process parameters. Experiments were performed at room temperature without any cooling method.

2.3. Design of experiments and selection of process parameters

Pilot study was performed to compare the RUD and CD of bone. Effect of external cooling method on RUD of bone was also studied. Normal saline water was used as the coolant and the drilling studies were performed on the same bone in order to maintain the uniformity. Comparative results are listed in the Table 1. Vibrational amplitude (16 µm) and vibrational frequency (20 kHz) was used only for RUD process. Results showed that RUD generated a lower temperature with respect to the CD even without the irrigation. Therefore it was believed that RUD of bone had been a potential process and could be further explode as an option for orthopedic drilling.

Response surface design of experiment methodology (RSM) was used to evaluate the relationship of independent process variables on the output response. RSM was chosen because it gives the interactions of the independent response variables, true response of the surface curvature, generates a second degree order statistical model and is useful for optimization of process parameters [27]. General equation [28] which is used in RSM is represented in the following form of Eq. (1).

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum \sum_{i<j} \beta_{ij} X_i X_j + \varepsilon \qquad (1)$$

In the equation, Y is expected response variable, β_i's are the constant coefficient terms, X_i is the coded input process variable, ij denotes the interaction between the two independent variables and ε is the random experimental measurement error.

In the present work, four input process parameters were selected with five levels of each parameter that has been listed in Table 2. Most of the previous reported research was focused on the low speed bone drilling i.e., below 3000 rpm [11]. Alam et