



Investigation of thermal aspects of high-speed drilling of bone by theoretical and experimental approaches

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Abstract

Heat generation during bone drilling operations is a serious challenge for the internal fixation surgery of bone fracture. Indeed, the heat generated at the drilling site causes complications including local temperature rise, thermal necrosis, irreversible damages to the bone tissue, and possible failure of orthopedic surgery. High-speed machining is an advanced method which has achieved remarkable results in some cases of reducing the temperature rise of the tool or workpiece. The present research examines high-speed drilling (HSD) of the bone using theoretical (based on Orthogonal Cutting theory and High-Speed Cutting model) and experimental (based on infrared thermography) approaches. The thrust force and temperature changes of the bone and drill bit have been measured at different rotational speeds. The drilling tests have been performed under a constant feed rate of 100 mm min^{-1} , hole depth of 8 mm, and 18 rotational speeds of $1000\text{--}18,000 \text{ r min}^{-1}$ (with 1000 r min^{-1} intervals) on a bovine femur. The results indicated that application of high rotational speeds in most cases caused increased temperature rise of the bone; only the rotational speed of 7000 r min^{-1} (which is associated with dramatic force reduction) and speed of $11,000 \text{ r min}^{-1}$ (which is associated with alteration of the chip formation mechanism and its nature) resulted in the minimum extent of temperature rise in the bone. It was also observed that the High-Speed Cutting model was able to correctly estimate the threshold of high-speed machining range for the bone (5000 r min^{-1}) and was also valid for the bone drilling operation.

Keywords Bone fracture · Internal fixation · Temperature rise · Thermal necrosis · High-speed drilling · Infrared thermography

Introduction

Machining operation constitutes an essential step in bone surgery such as immobilization of the fracture site, osteotomy, and skull base neurosurgery. Drilling operation is one of these processes which is widely used for creating holes to install self-tapping screws and plates in the internal fixation surgery of the bone fracture site. As with other machining operations, during bone drilling, a major part of the energy applied to the tool for chip formation and hole creation is changed into heat. Part of the heat generated during this process is discharged via chips to the outside of the hole. However, a considerable portion of it enters the drill bit and

bone, causing their temperature rise. In case of bone temperature rise and its exceedance beyond the allowable limit, the chance of thermal necrosis and irreversible damage to the bone increases. All these may result in weakened interaction between the screw and bone, failure of the orthopedic surgery, and bone fracture healing in an undesirable direction and angle. The tolerable temperature conditions for the bone to prevent incidence of thermal necrosis is exposure to $47 \text{ }^\circ\text{C}$ (or at most $10 \text{ }^\circ\text{C}$ temperature rise) for 1 min [1–3]. Nevertheless, past research on bone drilling has shown that the extent of temperature rise in conventional drilling method (low-speed drilling) is far higher than the allowable limit ($\Delta T = 10 \text{ }^\circ\text{C}$), which is a serious threat to the success of orthopedic surgery [1–4].

In order to overcome this challenge, some researchers have studied the thermal effects in bone drilling operation and attempted to reduce the extent of temperature rise in the drilling site and prevent incidence of osteonecrosis [5–7]. Since heat generation is indispensable to the drilling

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operation, and as the extent of heat generated during conventional drilling method is high, thus achieving desired process conditions in this method such that it guarantees temperature rise within the allowable range ($\Delta T = 10\text{ }^{\circ}\text{C}$) seems impossible. Accordingly, application of advanced machining methods has been put forward for bone drilling. Some researchers have tried to minimize the extent of bone temperature rise through combining ultrasonic vibration with drilling operation and improving the chip removal conditions as well as reducing machining forces [8–15]. Meanwhile, some others have tried to prevent severe temperature rise using different types of gas or liquid coolants through effective cooling of the drilling site [16–18]. Note that although gas (CO_2 or N_2) and liquid (normal saline or water) coolants have shown some effectiveness in reducing the temperature rise of the drilling site, their wide applications in orthopedic surgery are still doubtful due to requiring special equipment for applying gas coolants as well as the risk of infection caused by the liquid coolant. On the other hand, another study has tested the potential of bone machining with abrasive water jet successfully [19].

Another advanced machining method with industrial applications is high-speed machining (HSM), whose effective performance has been demonstrated for reducing the tool and the workpiece temperature rise in some cases. Generally, in conventional machining operation, it has been found that as the cutting speed increases, so does the heat generation, causing temperature rise (in the tool and workpiece). This temperature rise is so large within a range of the cutting speed that it makes the drilling operation virtually impossible (this range of cutting speed is known as *death valley*). Nevertheless, research performed on large values of the cutting speed has shown that as the cutting speed exceeds the conventional and transition ranges and enters the high-speed cutting range (HSC), the process temperature

declines dramatically (Fig. 1). Regarding the HSC range as well as incidence of drastic fall of temperature rise within that range, several points should be considered:

- The high-speed machining range is different across various workpiece materials; workpieces with a greater mechanical strength enter the HSC range at a lower cutting speed (Fig. 2).
- Several reasons have been propounded for the reduction in the extent of temperature rise of the machining process within the HSC range. They include changes in the plastic behavior of material, changes in the nature of chip and formation of the segmented chip at high cutting speeds, dramatic decline in the machining force, and increased rate of chip evacuation as well as heat transfer to the surroundings.

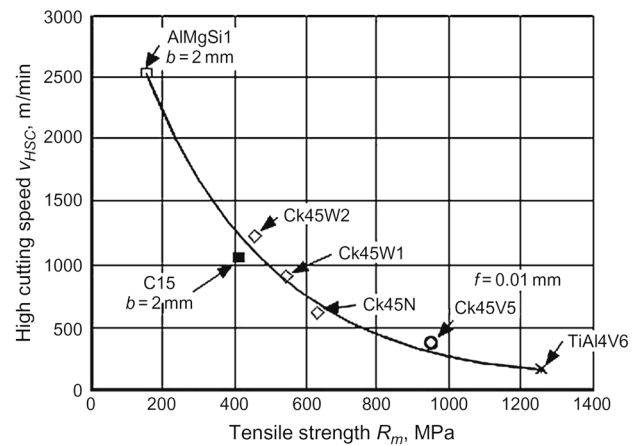
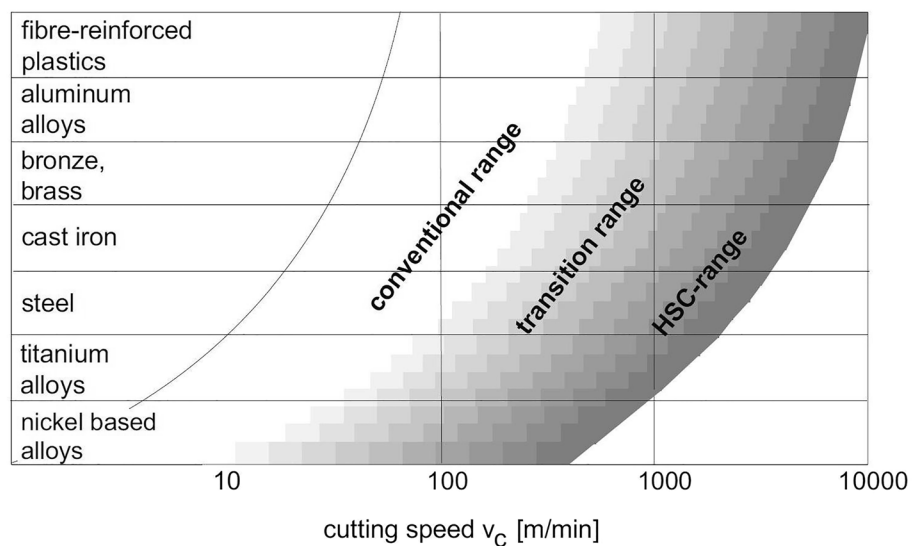


Fig. 2 The magnitude of the high cutting speed versus the ultimate tensile strength (UTS) for different work materials [21]

Fig. 1 Definition of high-speed cutting, HSC [20]



The potential of using high cutting speeds for machining operation as well as the possibility of achieving the minimum temperature rise has attracted the attention of industries to the high-speed machining method. It can provide significant advantages such as increased rate of chip removal, reduced machining forces, diminished tool wear rate, reduced machining time and cost, and increased production efficiency for machining processes. These remarkable results have prompted researchers in orthopedic surgery to put forward the idea of high-speed bone machining and try to reduce the temperature rise during bone drilling operation by applying high cutting speeds, and to eventually minimize the chance of occurrence of thermal necrosis. According to the literature, for bone drilling, the rotational speed of 3000 r min⁻¹ is the borderline between high-speed and low-speed bone drilling ranges [22]. One of the first attempts for high-speed bone machining was the research by Abouzgia and James as well as Abouzgia and Symington [23, 24]. These studies revealed the possibility of achieving less temperature rise at high cutting speeds, through their results under some conditions showed a greater temperature rise compared to conventional drilling. Accordingly, it was not possible to definitely conclude the temperature rise reduction at all high rotational speeds. In a research by Udiljak et al., the extent of temperature rise of the drilling site was compared between rotational speeds of 462 and 9900 r min⁻¹. That research observed 19 °C drop in temperature rise at 9900 r min⁻¹ compared to 462 r min⁻¹ [25]. Also, Shakouri et al. found that during high-speed drilling of bone, the temperature rise of the drilling site had a direct relationship with the drill bit's rotational speed; it experienced a significant decline only within the range of 6000–7000 r min⁻¹, after which it continued its ascending trend. Indeed, at very high cutting speeds, the temperature rise was far greater than when using conventional drilling [26]. Also, in a research performed by Shakouri and Mirfallah on bone grinding within the rotational speed range of 45,000–65,000 r min⁻¹, a direct relationship was confirmed between the extent of temperature rise and cutting speed, with the minimum temperature rise gained at 45,000 r min⁻¹ [27].

Having examined the research performed on high-speed drilling of bone, it was observed that some contradictory results were found in some cases. Indeed, application of HSC within some speed ranges not only failed to reduce the temperature rise of the bone and mitigate the rise of thermal necrosis, but it also developed more critical conditions compared to conventional drilling. Another challenge is that it is unclear at what rotational speed the HSC range begins for bone drilling, and at what speed this desired cutting range ends. Precise examination of this issue necessitates studying high-speed bone drilling in terms of HSC principles, Theory of Machining Mechanics, as well as running experimental tests. Accurate determination of rotational speed ranges for

HSM application would significantly contribute to reducing temperature rise of orthopedic surgery and minimizing the risk of incidence of thermal necrosis.

The aim of the present research is to study high-speed bone drilling operations within a wide range of rotational speeds based on theoretical–experimental approaches, to measure changes in the drill bit and bone temperature accurately via infrared thermography; to determine the desired rotational speed to enter the HSC range and its validation against experimental results; and eventually to analyze the results of temperature and force changes based on the Theory of Machining Mechanics and High-Speed Cutting model.

Theory

Calculating the heat generated during bone drilling operation using Theory of Machining Mechanics

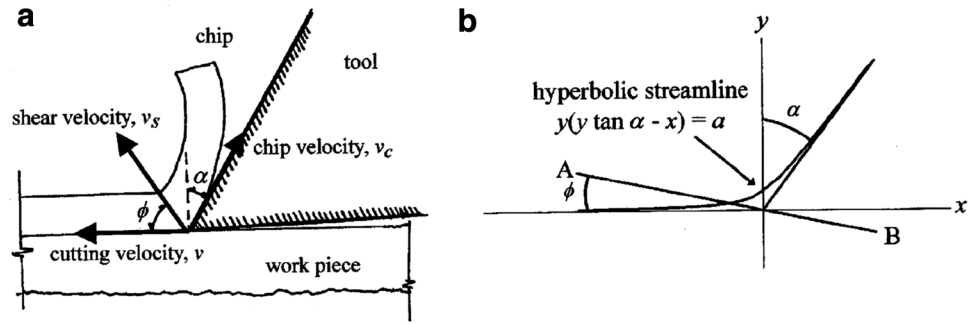
In order to apply the Theory of Machining Mechanics in the present research, it has been assumed that during machining, the bone shows a similar behavior to metals. During metal machining, the cutting parameter is the cause of separation between the chip and workpiece. Although the precise mechanism of chip formation during bone drilling operation is not clear, this research has assumed that its mechanism follows the Orthogonal Cutting principles [28, 29]. This assumption has been made due to the following reasons:

- The aim of this theoretical analysis is to provide a criterion for comparing heat generation during drilling at different rotational speeds, while specifying the precise value of heat generated is not a major goal.
- Although it is clear that the real mechanism of bone chip formation is different from that of metal chip formation, in a research on bone machining in which Orthogonal Cutting theory has been used, acceptable results have been obtained [30].

Although material cutting during drilling operation is more complex in relation to Orthogonal Cutting, the major mechanism of chip formation is the same for both operations, and the Orthogonal Cutting theory can also be used for drilling operation. Figure 3a displays the orthogonal cutting and material removal. The assumptions used for calculating the heat generated in the bone drilling operation are as follows:

- The machining operation has been considered as Orthogonal Cutting.
- The tool's rake angle along the cutting lips of bit has been considered variable.

Fig. 3 **a** A scheme of Orthogonal Cutting and material removal and **b** a scheme of hyperbolic streamline through the primary deformation zone (the shear plane) [30]



- To calculate the shear angle in the shear plane, the *Ernst–Merchant* relationship has been used.
- Although with increase in the hole depth, the bone mineral density (BMD) diminishes, the mechanical properties of the bone have been considered constant.
- The bone behavior has been regarded as non-Newtonian.
- The shear stress has been considered to vary with the strain rate (according to the *Power-law* relationship).
- It has been assumed that the entire energy applied to the system for chip removal changes with heat.

Thus, assuming that the amount of heat generated during the machining is equivalent to the amount of work done for material removal, we have:

$$\frac{\partial Q}{\partial t} = F_s v_s, \tag{1}$$

where in the above equation, Q represents the heat generated during the drilling, t is time, F_s shows the shear force, and v_s denotes the velocity in the shear plane. To calculate the velocity in the shear plane, we have:

$$v_s = \frac{v}{\cos(\phi)}, \tag{2}$$

where in this equation, v is the cutting velocity and ϕ shows the shear angle. To calculate the shear angle (ϕ), the *Ernst–Merchant* relationship is used:

$$2\phi + \beta - \alpha = 90^\circ, \tag{3}$$

where β shows the friction angle and α denotes the rake angle. In this equation, the friction angle (β) has been considered 0.644 [30]. Since in the drilling operation, the rake angle is not constant and changes along the cutting lips of bit, thus α should be stated as a function of the distance from the rotational axis (r):

$$\tan(\alpha) = \frac{(2r/D) \tan(\theta)}{\sin(p)}, \tag{4}$$

where r represents the distance from the rotational axis (considered variable between 0 to 0.5D), D is the drill bit

diameter, θ shows the helix angle, and p is half of the drill point angle. The cutting velocity (v) is also variable along the cutting lips of bit, and is obtained from Eq. (5):

$$v = \frac{2\pi r N}{60}, \tag{5}$$

where N is the rotational speed of the drill bit. To calculate the shear force (F_s), the relationship between shear force (F_s), shear stress (τ_s), and area of the shear plane (A_s) is used:

$$F_s = \tau_s A_s. \tag{6}$$

Since the bone behavior has been assumed as non-Newtonian, thus it can be conceived as a viscoelastic material, and its shear stress can be assumed to vary with the strain rate. Accordingly, the strain rate of the material should be determined. Assuming that the material that detaches off the bone through the tool traverses a hyperbolic streamline (Fig. 3b), we have:

$$y^2 \tan(\alpha) - xy = a, \tag{7}$$

where x and y represent the axes of the Cartesian coordinate system. The origin of this coordinate system is assumed to match the tool tip. The constant a in Eq. (7) determines the curvature of a hyperbola, which is obtained from Eq. (8).

$$a = \frac{t_1^2}{16C^2(\sin(\phi))^4[\tan(\alpha) + \cot(\phi)]}. \tag{8}$$

In this equation, t_1 is the undeformed chip thickness. Constant C is also considered as 6 according to other studies [30]. Research in this regard has shown that the amount of heat generated during the machining process is not very sensitive to the changes in C value. Thus, the strain rate, assuming a hyperbolic streamline, is defined as follows:

$$\dot{\gamma}_{AB} = \frac{v}{4\sqrt{a}(\sin(\phi))^2[\tan(\alpha) + \cot(\phi)]^{3/2}}. \tag{9}$$

As mentioned earlier, the relationship between shear stress and strain rate is considered based on *Power-law* relationship. Studies have suggested that the compressive

strength of the cortical bone is in proportion with the strain rate powered by 0.060. Hence, based on *Power-law* relationship, we have:

$$\tau_s \propto (\dot{\gamma})^{0.060}. \quad (10)$$

To find the constant of proportionality (Eq. 10), since the ultimate shear strength value of the bone is around 50.4 ± 14.1 MPa, the constant of proportionality of the equation is considered as 80 MPa [30]:

$$\tau_s = 80(\dot{\gamma})^{0.060}. \quad (11)$$

To determine the area of the shear plane (A_s), we have:

$$A_s = l_s w_s, \quad (12)$$

where l_s is the length of the shear plane and w_s shows the width of the shear plane, which are obtained by the following equations:

$$l_s = \frac{(D - d_0)}{\cos(90 - p)}, \quad (13)$$

$$w_s = \frac{t_1}{\sin(\phi)}, \quad (14)$$

where d_0 is the chisel edge diameter and is negligible. To calculate the undeformed chip thickness (t_1), the following equation is used:

$$t_1 = \frac{f/2}{N/60} \sin(p), \quad (15)$$

where f is the feed rate of the drill bit.

By incorporating the geometric characteristics of the drill bit (including diameter, drill point angle, and helix angle) as well as the parameters of the drilling process (including rotational speed and feed rate) in the set of above equations, eventually the total heat generated during the drilling operation is obtained by Eq. (1). This provides the possibility of calculating the total heat generated in the bone drilling operation for each state of the experimental test, and comparing their results with each other.

Estimating the rotational speed of the HSC range threshold in the bone drilling operation

In the research performed on high-speed machining of various materials, it has been found that there is an exponential relationship between the desired cutting speed to enter the HSC range and the tensile strength of materials (Fig. 2). Accordingly, the High-Speed Cutting model has been developed for various materials, through which the minimum cutting speed required for entering the HSC range can be estimated [21]:

$$v_{HSC} = 56e^{(-R_m/400 \text{ MPa})}, \quad (16)$$

where in this equation, v_{HSC} is the HSC velocity and R_m denotes the ultimate tensile strength of the material. Although this model has been presented for metals and especially materials with the potential for creating continuous chips (Fig. 2), its application is also possible for bone drilling considering the following points:

- The model presented for high-speed cutting is an outcome of numerous experimental tests on high-speed machining process on various materials, and is valid for most materials with an acceptable accuracy.
- The aim of applying this model for bone drilling is merely estimating an initial velocity for the HSC range threshold and its validation against experimental results of changes in the thrust force and in bone temperature.

Accordingly, considering $R_m = 50$ MPa for the ultimate tensile strength of the bone [31] and incorporating it in Eq. (16), $v_{HSC} = 49.42 \text{ m min}^{-1}$ is obtained for the HSC range threshold. Since the aim of the present research has been to examine high-speed bone drilling, and given the use of standard surgical drill bit ($D = 3.2 \text{ mm}$) in experimental tests and considering the relationship between cutting speed and rotational speed of the drill bit ($v = \pi DN$), the minimum rotational speed required for entrance to the HSC range during the bone drilling operation is obtained as $N = 4900 \text{ r min}^{-1} \approx 5000 \text{ r min}^{-1}$.

Hence, in case the High-Speed Cutting model is also valid for bone machining and the rotational speed predicted for entrance to the HSC range matches the actual values, at rotational speeds beyond 5000 r min^{-1} in experimental tests, possibly major changes would occur in the thrust force of drilling or the extent of bone temperature rise, whereby the signs of HSC would become evident.

Materials and methods

Sample preparation

In the present research, drilling tests were performed on the mid-shaft of the bovine femoral diaphysis, which had been removed immediately from its body after slaughter. This selection was due to the great similarity of mechanical characteristics of the bovine femur and human bone as well as the typicality of bovine femur application in other bone machining studies [8, 16, 19, 26]. In order to perform experimental tests of HSD, a pair of bovine femur belonging to an animal was used.

Experimental setup

Since the aim of the present research was to examine the thermal aspects of high-speed bone drilling, infrared thermography was used for measuring temperature changes in the bone and drill bit. The IR thermography technique is a non-contact method of temperature measurement, which is widely applied in research associated with biomedical engineering [32]. Further, to measure the temperature during bone machining operation, IR thermography is preferred over contact thermocouple, since the cortical bone enjoys greater mineral density and mechanical strength, than other parts of the bone, with the maximum extent of temperature rise during machining occurring in its external surface [33–37]. Since the mechanism of temperature measurement of IR camera is contingent upon radiation heat transfer, then, according to *Stefan–Boltzmann* law, the emissivity coefficient of the surface plays a significant role in heat transfer. In the present research, after preparing bone samples, in order to precisely control the emissivity coefficient of the surface and to ensure the accuracy of the temperature measurement method, the surface of the samples was painted using matte black silicon spray. This colored coating was heat resistant up to 600 °C and had an emissivity coefficient of 0.93 [35, 38]. To validate the accuracy of the measured temperature data, all drilling modes in the present research were concurrently monitored using two IR cameras. Note that before running the experimental tests, by comparing the results of IR cameras with the findings obtained by the contact thermometer, the accuracy of IR camera results was ensured. The specifications of the IR cameras used are as follows:

- *FLIR C2*, USA, thermal range – 10 to 150 °C, thermography resolution 4800 pixels, heat sensitivity 0.1 °C, spectral range 7.5–14 μm.
- *TROTEC AC080V*, thermal range – 20 to 350 °C, thermography resolution 160 * 120 pixels, accuracy ± 2 °C, thermal sensitivity ≤ 0.08 °C at 30 °C, spectral range 8–14 μm.

In order to provide a wide range of rotational speeds, a high-speed induction motor *Arel TIP: ARFM 1Y-M3* with the maximum rotational speed of 18,000 r min⁻¹ was used. The drilling thrust force was measured by a *Kistler type 9275BA* dynamometer. The drill bits used in the drilling tests were of standard surgical drill bit type made of stainless-steel 316L with a diameter of 3.2 mm, as well as drill point angle and helix angle of 118° and 20° respectively. In order to prevent the influence of the tool wear on the process temperature rise, every drill bit was used for creating at most 10 holes, and then repeated with a new drill bit.

Methodology

References have mentioned the rotational speed of 3000 r min⁻¹ as the borderline between low-speed and high-speed drilling [22]. However, in the present research, it was preferred to initiate the experimental tests from the rotational speed of 1000 r min⁻¹, with the experimental study of temperature changes conducted in both low-speed and high-speed drilling ranges to provide the possibility of comparing the results across a wide range of rotational speeds.

The experimental tests of high-speed bone drilling were performed at rotational speeds of 1000–18,000 r min⁻¹ (with 1000 r min⁻¹) intervals, feed rate of 100 mm min⁻¹, and hole depth of 8 mm. Since other studies have proven that application of feed rates lower than 100 mm min⁻¹ is associated with a dramatic temperature rise, and as the use of feed rates above 100 mm min⁻¹ may lead to the development of further fractures in the bone, thus the present research preferred to conduct the drilling tests at the most suitable feed rate (100 mm min⁻¹) [8, 16, 26, 35]. Accordingly, the high-speed bone drilling tests were performed at 18 drill bit rotational speeds with a constant feed rate and hole depth. In order to ensure the accuracy of the results, the results of every experimental mode were replicated at least three times. Figure 4 reveals the stages of performing HSD tests of the bone and temperature measurement via the IR thermography technique.

Results

After conducting the high-speed drilling tests on the bone samples, the changes in the bone and drill bit temperature were measured along with the thrust force for every rotational speed. Samples of IR thermography images of high-speed drilling have been presented in Fig. 5 (for temperature changes of the bone) and in Fig. 6 (for temperature changes of the drill bit). The complete results of the bone temperature rise, drill bit temperature rise, and thrust force at different rotational speeds are outlined in Table 1.

Bone temperature rise

To more accurately investigate the trend of changes in the bone temperature rise at different rotational speeds, considering the mean temperature rise obtained in each of the HSD test modes, Fig. 7 has been drawn. As can be seen, considering the ascending or descending trend of temperature rise at different rotational speeds, this diagram can be classified into six different regions:

- Region (I) ($N = 1000\text{--}3000$ r min⁻¹): this region, which is considered the range for conventional bone drilling,

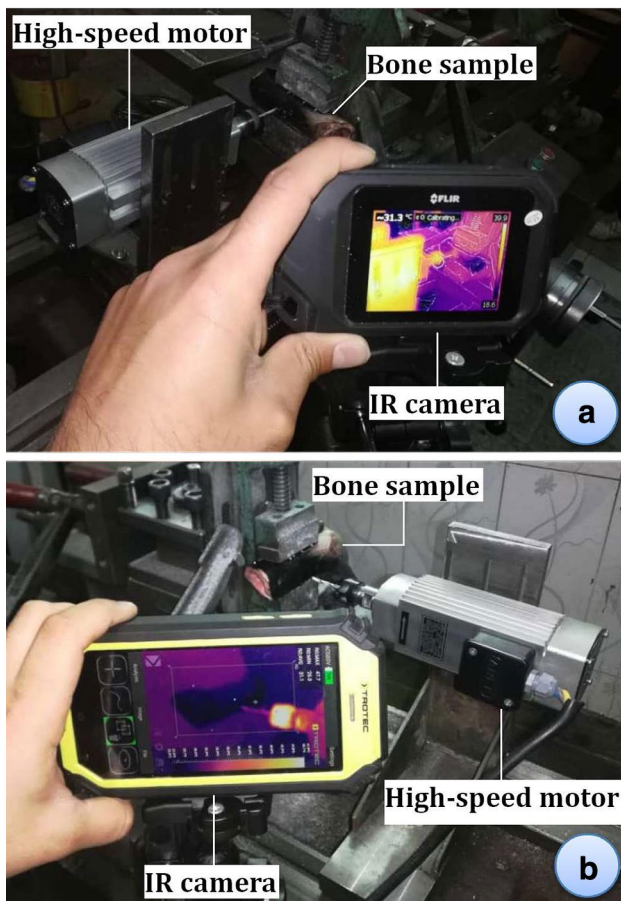


Fig. 4 Experimentations of high-speed drilling of bone: **a** infrared thermography with FLIR C2 IR camera and **b** infrared thermography with TROTEC AC080V IR camera

showed 13 °C reduction in the temperature rise with elevation of the drill bit rotational speed from 1000 to 3000 r min^{-1} . This has also been reported in most studies on conventional bone drilling. Another notable point is that the minimum extent of temperature rise has also occurred in this region as 34.3 °C (at the rotational speed of 3000 r min^{-1}), which is considerably different from the maximum tolerable temperature rise for the bone ($\Delta T = 10$ °C), suggesting inevitability of incidence of thermal necrosis within the conventional drilling range.

- Region (II) ($N = 3000\text{--}5000$ r min^{-1}): in this region, which is considered as the region for transition from low-speed machining to high-speed machining, the increase in the drill bit rotational speed has not been able to reduce the bone temperature rise; rather it witnessed a 2 °C increase in the temperature rise.
- Region (III) ($N = 5000\text{--}7000$ r min^{-1}): in this region, which is considered as the beginning of the HSC range for bone drilling, according to the High-Speed Cutting model estimation, elevation of the rotational speed has

resulted in a considerable decline in the bone temperature rise. Note that the minimum temperature rise of the bone in the present research has been gained in this region at the rotational speed of 7000 r min^{-1} ($\Delta T = 25.7$ °C).

- Region (IV) ($N = 7000\text{--}9000$ r min^{-1}): in this region, changes in the bone temperature rise have found a dramatically ascending trend, and it has grown by around 17 °C.
- Region (V) ($N = 9000\text{--}11,000$ r min^{-1}): in this region, temperature rise has diminished considerably (around 12 °C). It has been the second rotational speed with the minimum temperature rise across all rotational speeds studied in the present research ($\Delta T = 30.3$ °C at $N = 11,000$ r min^{-1}).
- Region (VI) ($N = 11,000\text{--}18,000$ r min^{-1}): in this region, the trend of changes in the bone temperature rise has been ascending, and the increase in the drill bit rotational speed failed to reduce temperature rise; rather it caused more critical results compared to the conventional drilling at beyond 12,000 r min^{-1} . Note that the maximum bone temperature rise in the present research has been gained in this region and at the rotational speed of 18,000 r min^{-1} ($\Delta T = 48.7$ °C).

Drill bit temperature rise

The results of the drill bit temperature rise at different rotational speeds are shown in Fig. 8. Since the drill bit temperature rise at various cutting speeds has found both ascending and descending trend at times, the diagram in Fig. 8 can be classified into six different regions:

- Region (I) ($N = 1000\text{--}3000$ r min^{-1}): in this region, it can be observed that elevation of the cutting speed has resulted in diminished drill bit temperature rise. This region of the drill bit rotational speed is important in two aspects: (1) the minimum drill bit temperature rise across all speeds examined in the present research has been found in this region at the rotational speed of 3000 r min^{-1} ; (2) this region is the only region of the rotational speed within which the extent of temperature rise of the drill bit is less than that of the bone; at rotational speeds beyond 4000 r min^{-1} , due to enhanced heat generation as well as the increased share of the heat entering the drill bit, its temperature rise substantially exceeds that of the bone.
- Region (II) ($N = 3000\text{--}6000$ r min^{-1}): in this region, with the increase in the drill bit rotational speed, its extent of temperature rise has also grown.
- Region (III) ($N = 6000\text{--}7000$ r min^{-1}): similar to the trend of changes in the bone temperature rise within 6000–7000 r min^{-1} , the drill bit temperature rise has also diminished in this region.

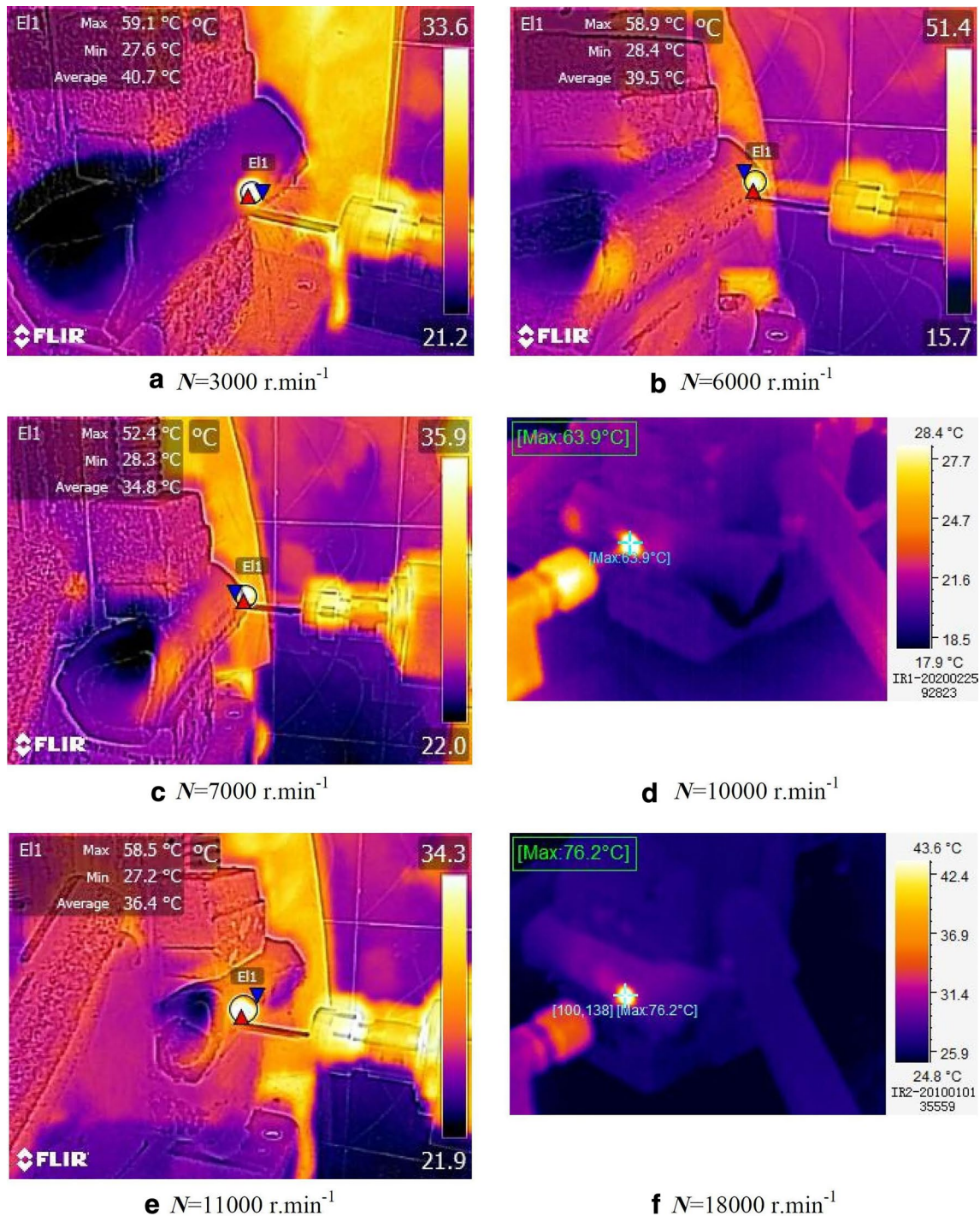


Fig. 5 Thermographic images during high-speed drilling in various rotational speeds

- Region (IV) ($N = 7000\text{--}9000 \text{ r min}^{-1}$): in this region, the drill bit temperature rise has grown considerably. The result obtained for the drill bit temperature rise at the rotational speed of 9000 r min^{-1} ($\Delta T = 68.1 \text{ °C}$) is so different from the findings of other speeds that the drill bit does not experience such a temperature rise within the rotational speed range of $9000\text{--}17,000 \text{ r min}^{-1}$.
- Region (V) ($N = 9000\text{--}11,000 \text{ r min}^{-1}$): similar to Fig. 7 (for changes in the bone temperature), the drill bit temperature rise in this region has dropped. The minimum temperature rise observed in this region

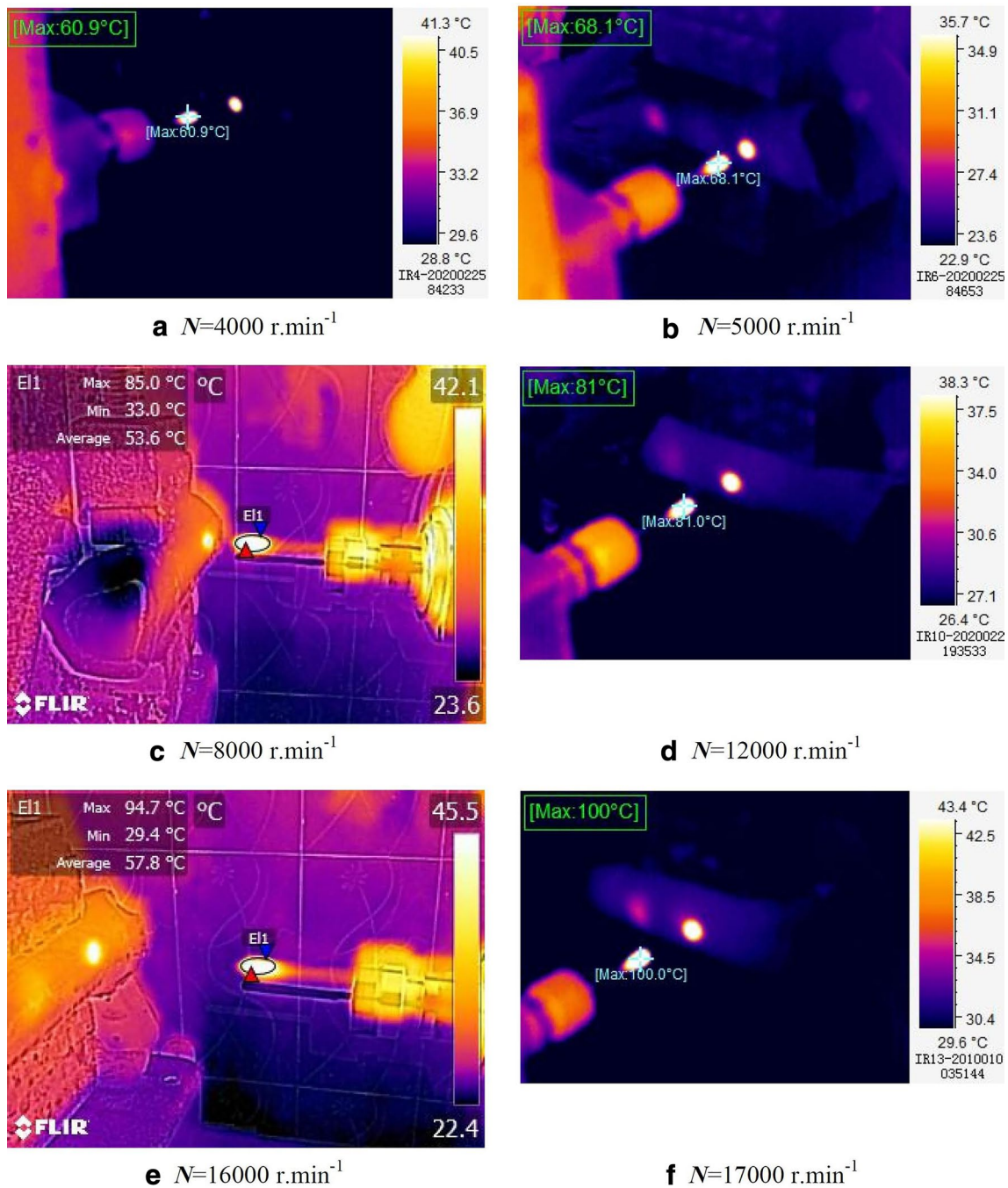


Fig. 6 Thermographic images after drill removal in various rotational speeds

belongs to the speed of $11,000 \text{ r min}^{-1}$, standing the third following 3000 and 7000 r min^{-1} , regarding the development of the minimum extent of drill bit temperature rise.

- Region (VI) ($N = 11,000\text{--}18,000 \text{ r min}^{-1}$): in this region, the drill bit temperature rise has been ascending, such that from $11,000$ to $18,000 \text{ r min}^{-1}$, ΔT has grown by around 36°C . Note that the maximum

drill bit temperature rise in the present research has been found at the rotational speed of $18,000 \text{ r min}^{-1}$ ($\Delta T = 82.5^\circ\text{C}$).

Table 1 Experimental results of high speed drilling of bone (bone temperature rise, drill bit temperature rise, thrust force)

Rotational speed, N ($r \text{ min}^{-1}$)	Bone temperature rise, ΔT ($^{\circ}\text{C}$)	Drill bit temperature rise, ΔT ($^{\circ}\text{C}$)	Thrust force, F (N)
1000	47.2 ± 0.6	38.9 ± 1.3	34.07 ± 5.16
2000	38.5 ± 0.8	31.4 ± 0.7	31.24 ± 1.26
3000	34.3 ± 0.2	30.7 ± 1.6	22.91 ± 0.59
4000	34.7 ± 0.7	35.1 ± 0.2	21.78 ± 0.55
5000	36.3 ± 0.8	42.8 ± 1.7	21.08 ± 0.37
6000	33 ± 0.1	47.7 ± 1.2	2.69 ± 0.01
7000	25.7 ± 1.3	44.3 ± 2.1	2.48 ± 0.09
8000	40.9 ± 1.1	54.1 ± 0.1	2.34 ± 0.04
9000	42.6 ± 2	68.1 ± 2.1	2.31 ± 0.2
10,000	35.4 ± 0.5	48.2 ± 0.1	2.19 ± 0.02
11,000	30.3 ± 0.2	46.7 ± 1.1	2.09 ± 0.02
12,000	37 ± 2.2	54 ± 1	2.04 ± 0.01
13,000	38.6 ± 0.5	58.4 ± 1.4	2.29 ± 0.07
14,000	42.4 ± 2.1	58.6 ± 0.7	1.7 ± 0.01
15,000	42.8 ± 2.2	62 ± 1.2	1.67 ± 0.22
16,000	42.8 ± 0.3	63.4 ± 0.7	1.7 ± 0.02
17,000	46.3 ± 1.5	73.9 ± 2.9	1.73 ± 0.02
18,000	48.7 ± 1.2	82.5 ± 1.5	1.6 ± 0.03

Discussion

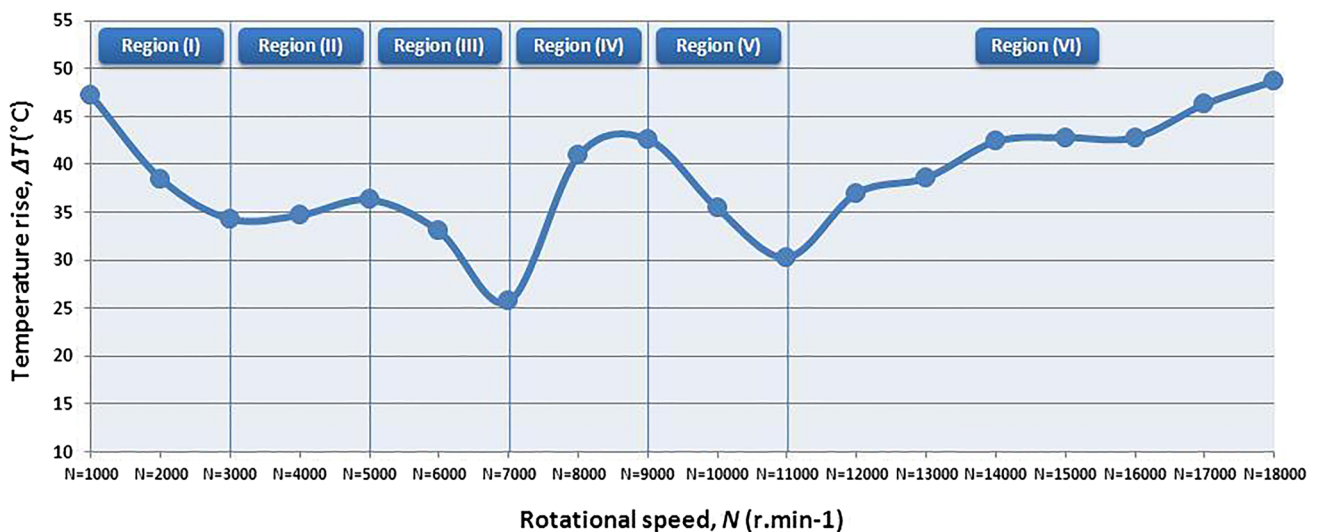
Based on the results obtained from bone temperature changes during high-speed drilling operation, it was found that with the increase in the drill bit rotational speed, the bone temperature rise did not follow a uniform trend, i.e. it decreased and increased from time to time considerably.

This has also been mentioned in other studies [23–26]. In order to analyze the results of the present research and further examine the factors affecting the bone temperature rise during high-speed drilling operation, the concurrent effect of all of the following parameters should be taken into account [20, 21, 26, 35]:

- Heat generation during the material removal;
- Changes in the thrust force at various rotational speeds;
- High-Speed Cutting model;
- Chip formation mechanism and chip nature.

By calculating the heat generated at various rotational speeds (1000–18,000 $r \text{ min}^{-1}$), using Eqs. (1)–(15) and calculating the heat rise percentage of each mode in relation to the heat generated at 1000 $r \text{ min}^{-1}$, the diagram of changes in the heat generated at various rotational speeds has been found (Fig. 9). Based on the above figure, it is observed that generally, the increase in the drill bit rotational speed has led to augmented heat in the machining process. This increase in the heat generation at high rotational speeds continues such that the heat generated at the rotational speed of 18,000 $r \text{ min}^{-1}$ is around 41% greater than the heat resulting from the speed of 1000 $r \text{ min}^{-1}$. Thus, regarding the Machining Mechanics and the Orthogonal Cutting theory, application of high rotational speeds leads to further bone and drill bit temperature rise (similar to results of [30]).

Another factor affecting the temperature rise of the high-speed bone drilling operation is machining forces. Based on the results of measuring the thrust force (Fig. 10), it can be seen that with the increase in the drill bit rotational speed from 1000 to 3000 $r \text{ min}^{-1}$, the thrust force has diminished due to reduced undeformed chip thickness and

**Fig. 7** Thermal changes of bone during high-speed drilling (in various rotational speeds)

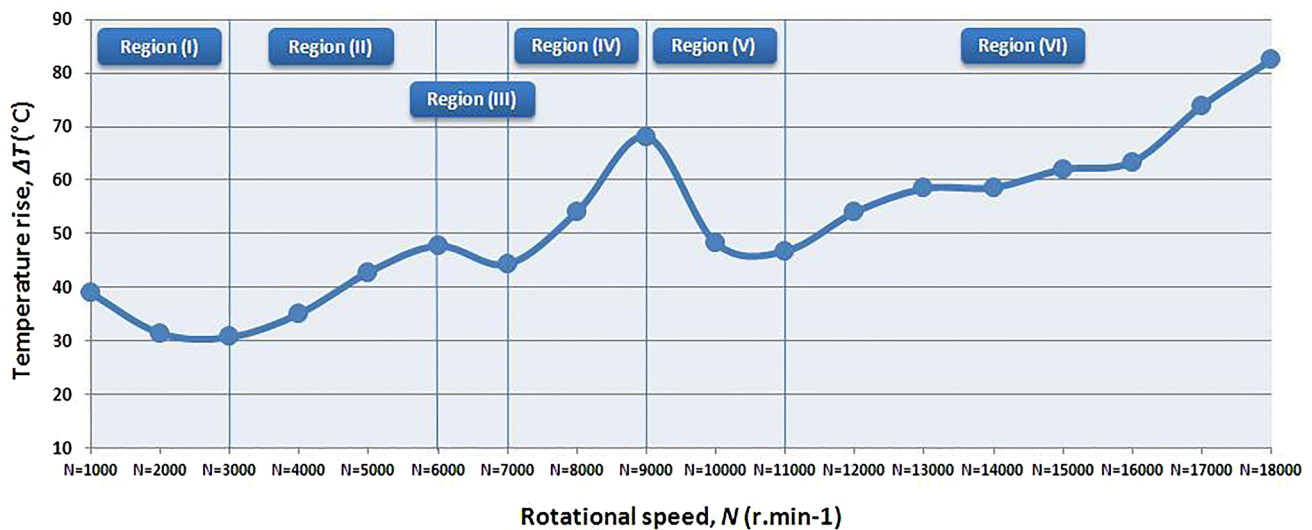


Fig. 8 Thermal changes of drill bit after drill removal (in various rotational speeds)

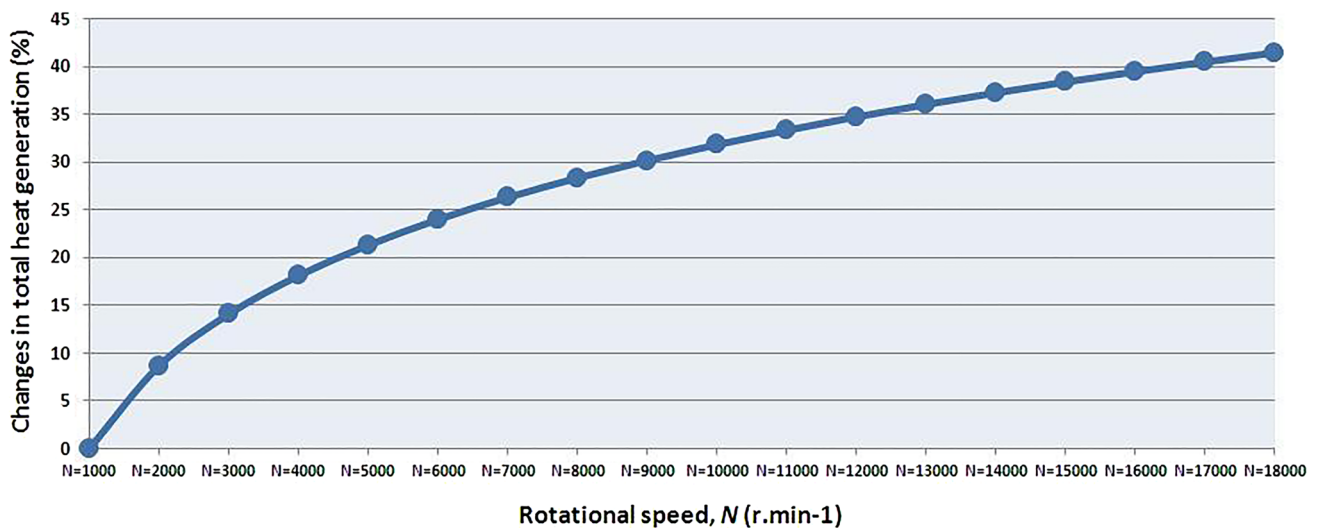


Fig. 9 The change in heat generation at different rotational speeds compared to the heat generated at initial rotational speed (1000 r min^{-1})

thus decreased force required for chip formation, as well as less chip accumulation in drill flutes and hence reduced pressure force required for chip removal. The outcome of these factors was reduced bone temperature rise in the above region. Within $3000\text{--}5000 \text{ r min}^{-1}$, considering no significant decline in the force as well as increased heat generated in response to elevated cutting speed (Fig. 9), the bone temperature rise has increased slightly. However, from 5000 r min^{-1} onwards (up to 7000 r min^{-1}), as predicted by the High-Speed Cutting model, the evidence of entering the HSC range was observed, whereby dramatic decline in the thrust force occurred. This diminished force can arise from the change in the plastic behavior of the material and

facilitated chip formation conditions [39]. Figure 7 demonstrates that this considerable reduction of force has resulted in a dramatic decline in the bone temperature rise at 7000 r min^{-1} and the minimum temperature rise throughout the entire range of rotational speeds. Further, considering the dramatic reduction of thrust force and the substantial fall of temperature rise from 5000 r min^{-1} , it can be inferred that estimation of the High-Speed Cutting model regarding 5000 r min^{-1} as the threshold for the HSC range for bone drilling has matched the experimental realities to an acceptable level, and the above model is valid for bone drilling.

Meanwhile, considering the lack of significant changes in the thrust force from the rotational speed of 7000 r min^{-1}

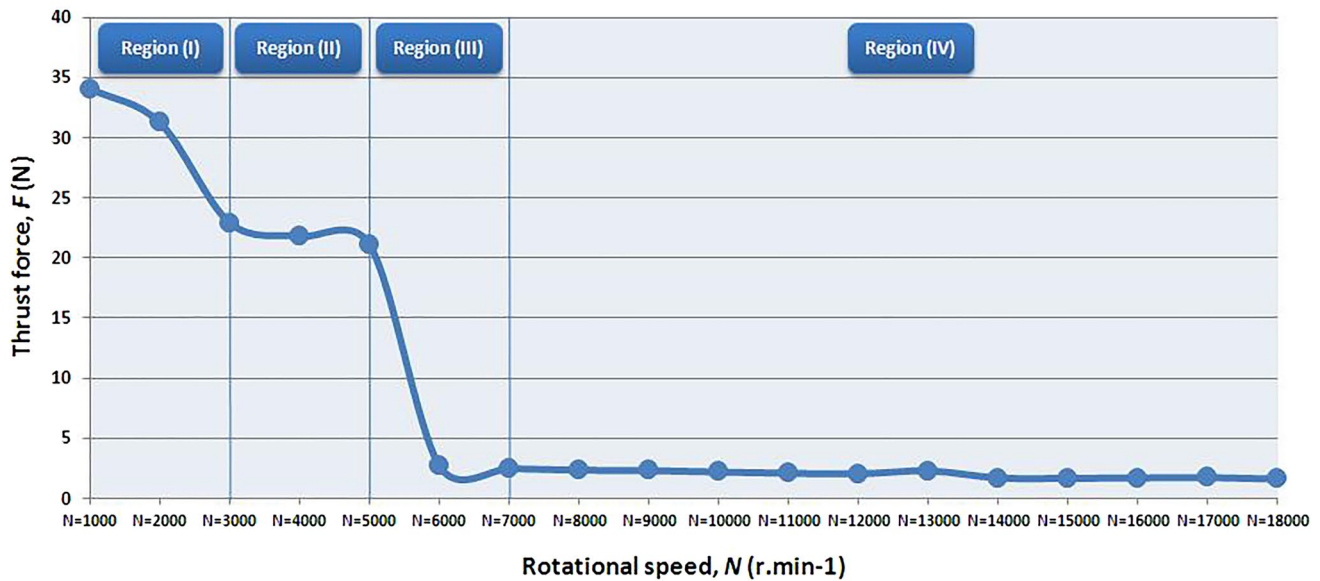


Fig. 10 Thrust force versus drill rotational speed (high-speed drilling of bone)

onwards (Fig. 10), as well as the ascending heat generation with the increase in the rotational speed (Fig. 9), the bone temperature rise from 7000 to 9000 r min^{-1} can be justified. In spite of no tangible changes in the thrust force and the increasing heat generation with the elevation in the rotational speed, a substantial drop can be seen in Fig. 7 regarding the bone temperature rise within 9000–11,000 r min^{-1} . The considerable fall of temperature within this range is attributed to the substantial changes in the chip formation mechanism, chip nature, and chip evacuation rate. Indeed, during experimental tests, from 10,000 r min^{-1} onwards, it was observed the chip size diminished significantly, and the bone chips were practically discharged in the form of powder-shaped particles to the outside of the hole [40]. Note that since the formation and removal of powder-shaped chips are far easier than those of discontinuous chips, thus the factor of chip-hole wall friction is attenuated to a great extent, causing diminished temperature rise in the above region. However, from 11,000 r min^{-1} onwards (up to 18,000 r min^{-1} in the present research), due to lack of changes in the thrust force, chip formation mechanism, and chip nature, as well as increased heat generation with elevation of the rotational speed, the bone temperature rise has found an ascending trend [4, 26], within condition becoming even more critical compared to conventional drilling range.

Eventually, it can be concluded that application of high-speed drilling for orthopedic surgery at the rotational speed of 7000 r min^{-1} would lead to a significant reduction in the temperature rise (around 9 °C compared to the best outcome using conventional drilling) and in turn diminished risk of thermal necrosis. Also, application of HSC for bone drilling is contingent upon identifying proper rotational speeds and

implementing their operation in those ranges. Otherwise, far more critical results may be obtained even compared to conventional drilling, thus increasing the chance of thermal necrosis. Another notable point is that although in the present research the High-Speed Cutting model was used considering several assumptions for high-speed bone drilling, the value estimated by the model for the HSC threshold range speed showed an acceptable consistency with the trend of changes in the force as well as variations of bone temperature rise. This highlights the potential of this model for high-speed drilling of bone.

Conclusion

The present research examined the thermal aspects of high-speed bone drilling of a bovine femur using IR thermography. The aim was to test the potential of the HSD method for reducing bone drilling temperature rise and in turn the risk of thermal necrosis through examining the changes in the bone temperature rise at various rotational speeds. The results indicated that the High-Speed Cutting model was successfully able to estimate the HSC range threshold speed for bone drilling (rotational speed 5000 r min^{-1} for the drill bit with a diameter of 3.2 mm). Through inducing a substantial reduction in the force within this range, it yielded the minimum temperature rise of $\Delta T = 25.7$ °C at the rotational speed of 7000 r min^{-1} (the first recommendable rotational speed for application in orthopedic surgery). Further, the changes in the mechanism of chip formation and chip nature at 11,000 r min^{-1} offered the second most suitable speed regarding development of the minimum temperature rise (following 7000 r min^{-1}). Finally, note that in bone drilling

operation, application of rotational speeds beyond $12,000 \text{ r min}^{-1}$ should be absolutely avoided due to significant temperature rise (even more critical than the outcomes obtained through conventional drilling).

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Compliance with ethical standards

Conflict of interest The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent Informed consent was obtained from all individual participants included in the study.

Appendix

Notation

A_s	Shear plane area
C	Shear rate material constant
D	Drill diameter
F	Thrust force
F_s	Shear force
N	Drill rotational speed
Q	Heat generated during drilling
R_m	Ultimate tensile strength
$T, \Delta T$	Temperature, temperature changes
A	Chip material streamline curvature
d_0	Chisel edge diameter
F	Feed rate
l_s	Length of the shear plane
p	Drill point half-angle
r	Distance from rotational axis
t	Time
t_1	Undeformed chip thickness
v	Cutting velocity
v_s	Shear velocity
v_{HSC}	High-speed cutting velocity
w_s	Width of the shear plane
x, y	Cartesian co-ordinates
α	Rake angle
β	Friction angle
ϕ	Shear angle
γ	Strain rate
θ	Helix angle
τ_s	Ultimate shear stress

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