Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal 2023, 17(1), 116–123
https://doi.org/10.12913/22998624/156367
ISSN 2299-8624, License CC-BY 4.0

Received: 2022.10.03
Accepted: 2023.01.17
Published: 2023.02.01

Investigation of Infrared Thermography of Cortical Bone Grinding in Neurosurgery

Atul Babbar[1], Vivek Jain[2], Dheeraj Gupta[2], Kapil Kumar Goyal[3], Chander Prakash[4], Kuldeep Kumar Saxena[5], Sandeep Kumar[6], Marian Bartoszuk[7*]

[1] Department of Mechanical Engineering, SGT University, Gurugram (Haryana), 122505, India
[2] Mechanical Engineering Department, Thapar Institute of Engineering and Technology, Patiala, 147003, India
[3] Department of Industrial and Production Engineering, Dr. B.R Ambedkar National Institute of Technology, Jalandhar, 144011, India
[4] School of Mechanical Engineering, Lovely Professional University, Phagwara, Punjab, 144411, India
[5] Division of Research and Development, Lovely Professional University, Phagwara, 144411, India
[6] Division of Research & Innovation, Uttaranchal University, Uttarakhand, 248007, Dehradun, India
[7] Faculty of Mechanical Engineering, Opole University of Technology, ul. Mikołajczyka 5, Opole 45-271, Poland
* Corresponding author's e-mail: m.bartoszuk@po.edu.pl

ABSTRACT
In this work, an effort has been made to determine the effect of different shape surgical burr on the thermogenesis during bone osteotomy. The abrasion during bone grinding leads to heat generation and subsequently rise in the temperature which may have adverse effects such as osteonecrosis, blood coagulation in the carotid artery, damage to sciatic nerves, and even loss of vision. So, mitigating the temperature rise during bone grinding is of paramount importance. Especially, in endoscopic endonasal approach (EEA) in which nasal passage is used for the inserting the grinding burr and reaching the target region. The miniature abrasion can significantly increase the temperature and hence leads to the thermal damage to nerves surrounding the temporal and frontal lobe. These parts of the brain controls movement, problem solving ability, behavior, personality mood, hearing, language, memory, speech, breathing, heart rate, consciousness etc. Furthermore, neurosurgeons rely on their personal surgical experience for estimating the temperature rise during grinding. However, this is much difficult for novice surgeons. Therefore, it becomes critically important to preserve the soft neural tissues and nerves amid bone grinding. To overcome these concerns, infrared thermography technique has been exploited to determine the possibility of thermogenesis during bone grinding by measuring the temperature rise and its distribution using infrared camera. All experiments have been carried at a constant set of process variables. The grinding zone is continuously flooded with the irrigating solution to remove the heat and bone debris away from the grinding site. It has been observed that convex tool shape generated lower maximum temperature i.e. 46.03 °C among all tools. The temperature produced by the convex tool is 12.06% lower than spherical tool, 33.39% lower than cylindrical tool, and 10.55% lower than tree-shape tool. The results showed that convex shape tool could prevent thermal necrosis in the bone as temperature caused (i.e. 46 °C) was less than the threshold limit of osteonecrosis. Thermograms revealed that infrared thermography technique could be implemented for the in-vivo surgical operations for the measurement of temperature during bone grinding.

Keywords: biomimetic; bone grinding; infrared thermography; thermal analysis; surfaces; Burr.

INTRODUCTION

In surgical dissection of brain tumors during brain cancer surgery, bone grinding is an essential process used for removing a part of the skull bone in order to get clearer access to the tumors. Generally, bone grinding is performed using miniature scale diamond burr which rotates at a high speed and removes the bone near carotid artery, cavernous sinus and optic nerve [1]. However, temperature increases during bone grinding which is a serious concern for the experts working in this area as this rise in temperature can cause severe consequences like optic nerve damage, facial muscles control and loss of important functioning of the body [2]. Coagulation of blood, osteonecrosis and blindness is worse concern due to rise in temperature during bone grinding. To protect the surrounding neural tissues, neurosurgeons perform grinding operation manually and they feel certain kind of resistive force which helps them to decide when to stop grinding [3]. It is believed that thermogenesis starts at 43 °C and osteonecrosis at 47 °C [4]. Thermogenesis corresponds to the cell's damage owing to the rise in temperature during bone grinding. This thermogenesis causes damage to the lacunas present within the osteons of the bone matrix which in turn leads to the carbonization of the cells, thereby, failure of the bone's matrix [4]. In this view, controlling the temperature during bone grinding becomes of paramount importance.

Hitherto, the research carried out in the field of bone grinding is as follows: In one of the research [5], temperature rise during the grinding of bone was predicted using pulse-width modulation (PWM) signal. Thermocouples were entrenched in the bone to predict the temperature rise. It was detected that thermal injury can reach up to 3 mm below the grounded surface and 3 mm in traverse direction [3]. Several studies were investigated to explore the temperature effect during orthopedic operation. Shin et al. [6] performed round burr bone milling under various machining conditions and temperature varied from 49-115 °C. During human cortical bone drilling temperature achieved was 40 °C [7]. The effect of mist cooling has also been evaluated for reducing the temperature rise during bone grinding [8]. Furthermore, the type and size of nanoparticles have been studied along with other irrigation methods to mitigate the heat evolved during the removal of bone flaps [9, 10]. Enomoto et al. [11] used different coating materials for depositing the hydrophilic layer over the surface of grinding burr to counter the rising temperature. Furthermore, extensive research has been carried out for drilling of bone [12] but few articles focused on bone grinding [13, 14]. Although the rise in temperature during grinding is a critical concern for neurosurgeons but still, as per author's knowledge, no work has been reported for the effect of different shaped diamond impregnated burrs on the temperature during grinding of porcine bone. So, in present research work, an effort has been made to fulfill this research gap. This paper is organized in the following manner: Initially, bone samples were prepared and then design experimentation has been carried out. Subsequently, the results and conclusion related to grinding temperature of the different shape tools have been consolidated.

MATERIAL AND METHODS

Bone sample preparation

The workpiece used for present investigation is porcine femur bone. The reason for selecting porcine femur bone is that its properties match closely with properties of human bone (refer to Table 1) [15]. Moreover, human bone is not easily available and ethical concerns are associated with it. No animal was forfeited especially for this experimentation. Bones were acquired from the local abattoir and then preserved in the pure formaldehyde solution (33% pure) in a plastic bag to sustain its thermo-mechanical properties as shown in Figure 1. The bone samples were free from any kind of damage and were in the healthy state.

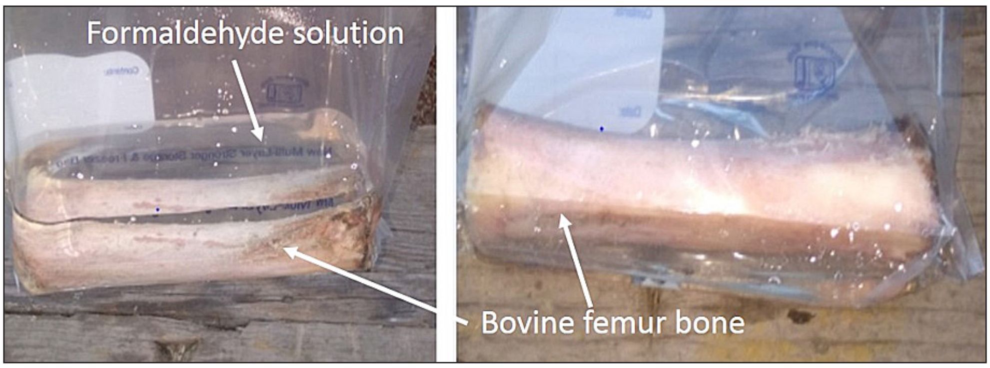

Fig. 1. Porcine bone in formaldehyde solution

Table 1. Comparison of the porcine femur and human bone properties [15–17]

Bone property	Units	Porcine femur bone	Human bone
Thermal conductivity	W/mK	0.1-0.3	0.1-0.43
Specific heat	J/KgK	1300	1330
Shear modulus	MPa	3	3
Young's modulus	GPa	10-22	10-17
Density	Kg/m³	1950-2100	1800-2000
Poisson's ratio	-	0.33	0.4
Tensile strength	MPa	140-250	130-200
Compressive strength	MPa	45-150	40-145

Experimentation

In-vitro experiments have been performed on porcine femur bone with saline irrigation as per clinical standards. The bone grinding has been carried using four different shaped tools to determine the effect on temperature rise. All experiments were carried out on a CNC vertical milling machine with a constant set of process parameters after consulting with neurosurgeons (refer to Table 2).

Each type of tool has been tested thrice and then their average was taken as final response value. Each trial has been carried for machining time of 20 seconds. All experiments were performed in sequence with cylindrical tool, convex tool, spherical tool and tree-shape tool and correspondingly temperature measurements were made. The complete setup of the bone grinding is shown

Table 2. Constant parameters used during experimentation

No.	Parameter	Level
1	Rotational speed of spindle	5000 rpm
2	Feed rate	20 mm/min
4	Depth of cut	0.5 mm
5	Machining time	20 seconds

below (refer to Figure 2). The infrared camera (U5855A, Keysight technologies, USA) was used to measure the temperature on the surface of bone during bone grinding and results obtained were analyzed using True-IR analysis and reporting tool. An infrared camera was positioned at 1.0 m from the grinding site. The online monitoring of temperature using infrared thermography camera involved 8 frames per second with record interval of 0.125 sec and average was taken as the final value of the temperature. The surface morphology of the grinding burrs before and after grinding has been characterized using surface profilometer and surface electron microscopy (SEM).

RESULT AND DISSUSSION

Infrared thermography

The osteotomy of the bone has been carried to evaluate the possible thermogenesis for brain tumor's dissection surgery. The significant difference was found in the temperature readings of the bone surface due to different shape tools during bone grinding. The temperature readings

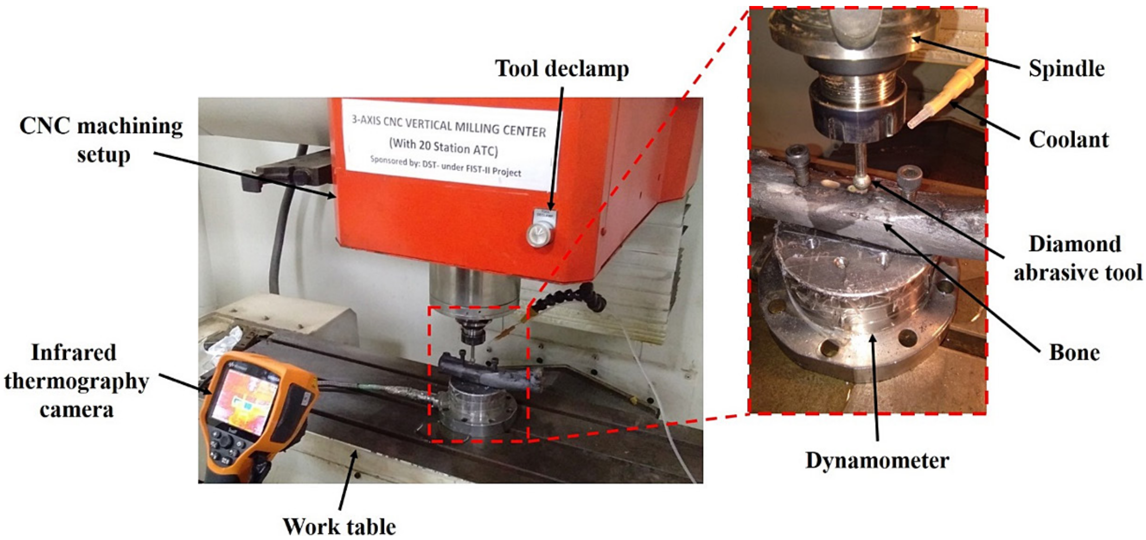

Fig. 2. Experimental setup for bone grinding

measured using infrared camera for each type of tool has been accentuated in the Table 3.

Initially, the temperature of the grinding zone was low but as the grinding continues the temperature of the bone surface starts increasing. Because as the tool comes in contact with the surface of the bone, the heat was generated due to the frictional forces at the interface of tool and bone. In this way, the rotational energy of spindle was converted into the heat via tool which ultimately went into the bone surface due to conduction. Conduction is primarily responsible for raising the temperature of the bone surface, it is clear that highest temperature achieved was 66.11 °C due to the cylindrical tool which may be due to the increase in frictional and shear forces generated at the tool and bone interface which eventually increase the heat evolved during grinding. While convex tool showed maximum temperature of 46.03 °C which is lowest maximum temperature among all tools. It may be due to the fact that convex tool, the effective number of abrasives participated in the grinding were less which leads to less generation of heat during grinding and consequently less rise in temperature. The maximum rise in temperature with spherical and tree-shape tool is 52.34 °C and 51.46 °C respectively. Figure 3 represents the thermograms produced spherical (T1), convex (T2), cylindrical (T3), and tree-shape tool (T4) respectively during bone grinding and maximum average temperature has also been highlighted. Grinding is carried for 20 seconds for each type of tool and coolant is continuously flooded to remove microchips and heat

Table 3. Temperature readings during grinding of bone

Time (sec)	Temperature (℃)			
	Spherical tool (T1)	Convex tool (T2)	Cylindrical tool (T3)	Tree-shape tool (T4)
1	28.71	28.05	28.88	28.63
2	28.83	28.39	28.71	28.93
3	28.94	28.54	28.80	28.59
4	35.01	31.61	30.56	28.69
5	45.01	40.31	52.63	36.19
6	52.34	46.03	69.11	51.46
7	49.25	43.18	59.70	49.16
8	45.09	39.98	56.49	45.73
9	40.46	37.69	50.74	43.65
10	37.45	36.34	42.95	43.08
11	35.41	35.74	38.05	42.74
12	33.93	35.58	35.25	42.39
13	32.96	34.94	33.84	42.24
14	32.39	34.66	33.43	42.00
15	31.90	33.81	32.95	41.85
16	31.45	33.18	32.66	41.84
17	31.24	33.19	32.44	41.89
18	30.79	33.03	32.40	41.79
19	30.79	33.03	32.32	41.73
20	30.39	32.89	32.31	42.25

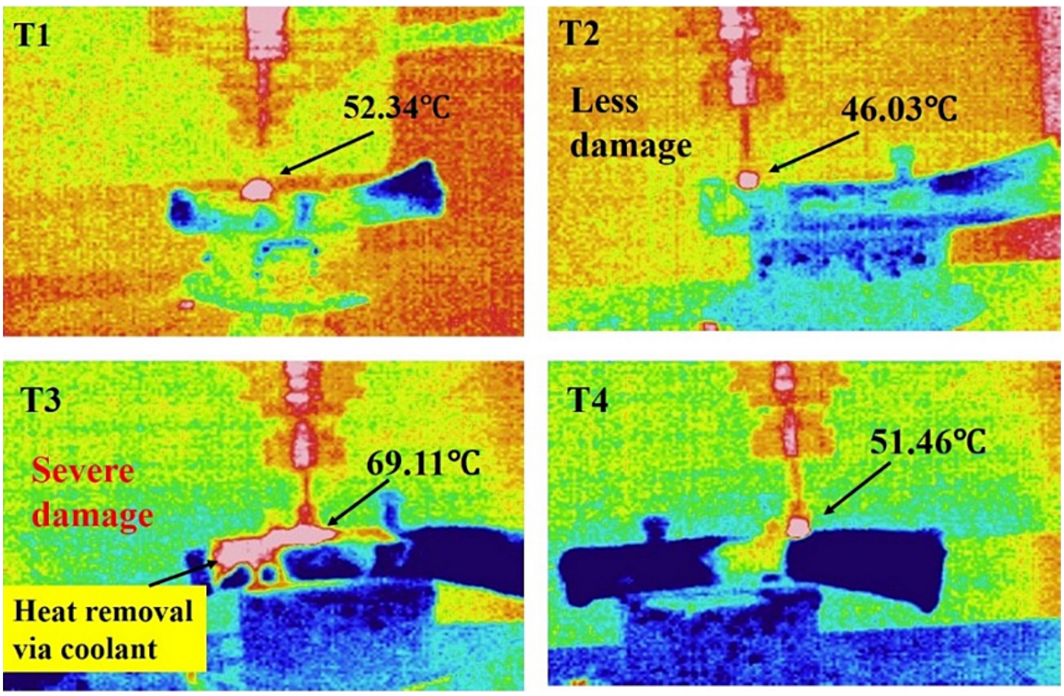

Fig. 3. Thermal images of the cutting zone with visible tool, workpiece material and bone debris

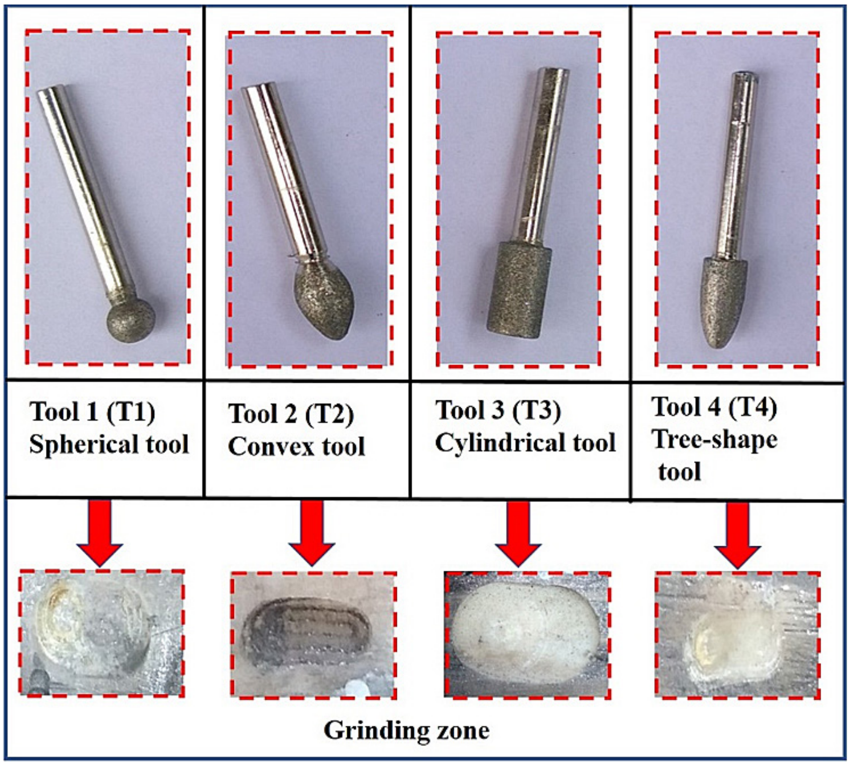

Fig. 4. Bone grinding tools (Grit size #46) and respective grinding zone visible on bone. T1 – cylindrical tool, T2 – convex tool, T3 – spherical tool, T4 – tree-shape tool

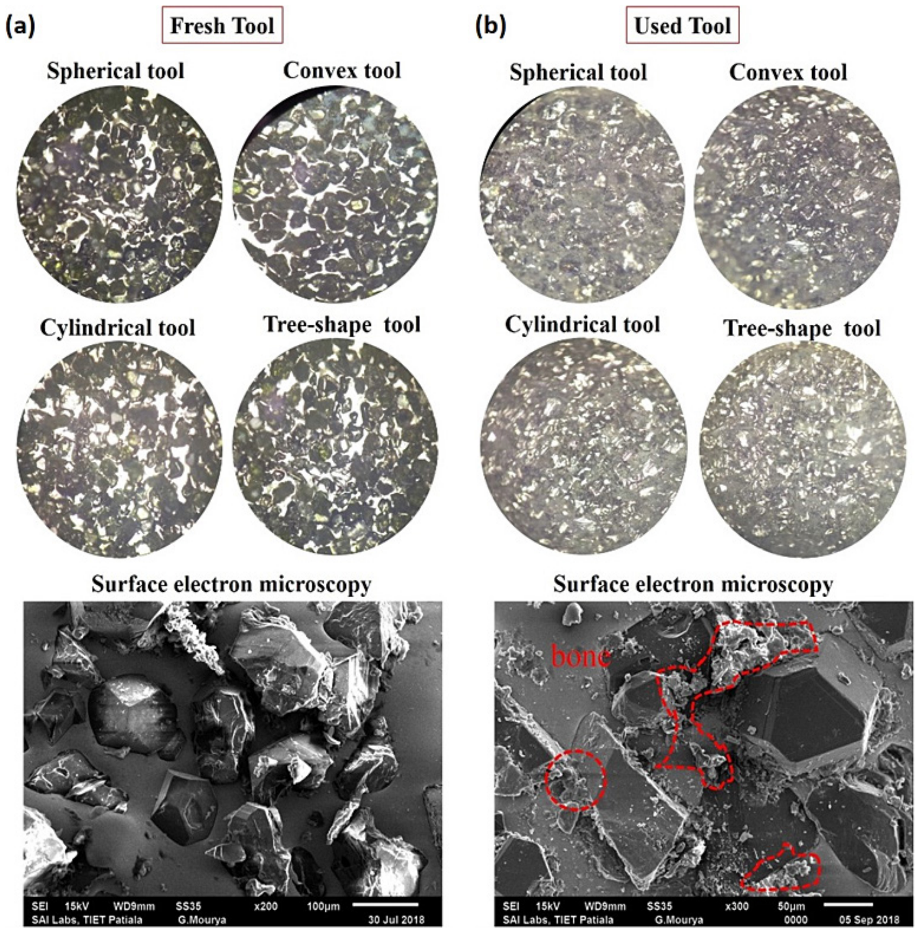

Fig. 5. Surface morphology of the grinding burr before and after bone grinding

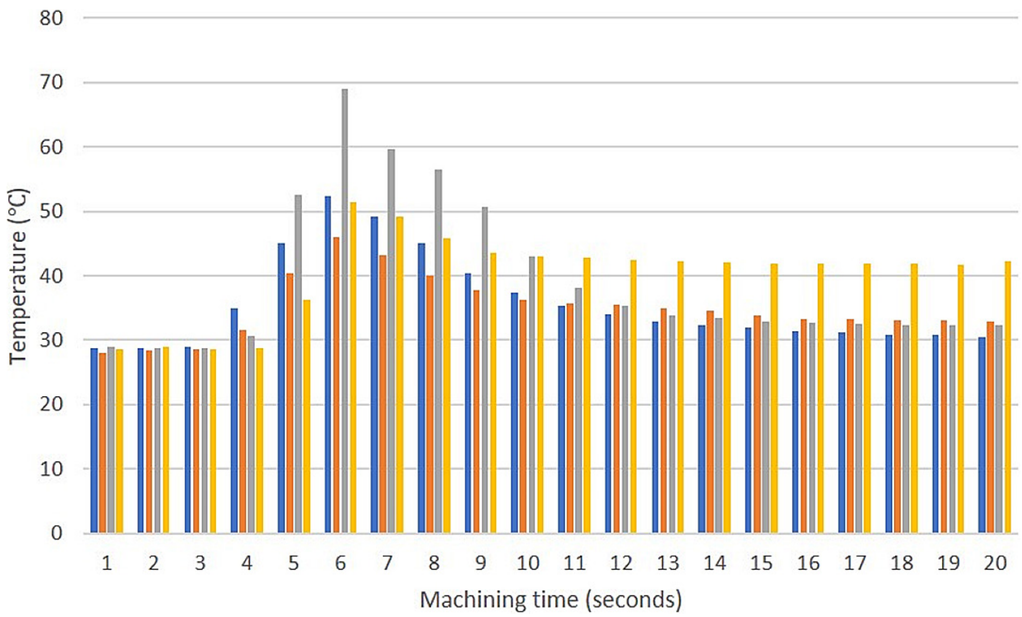

Fig. 6. A graphical plot of temperature vs Machining time using different shaped grinding burrs

evolved during osteotomy. The surface of the bone after grinding with different tools has been shown in Figure 4.

Subsequently, the surface of the tool has been characterized for loading in terms of the bone debris settled in the adjacent vacant spaces between the abrasives. The burr loading has been studied at two stages i.e. fresh tool and used tool. The surface electron microscopy images shown in the Figure 5a, clearly shows the vacant spaces in between the successive diamond abrasive grains. After grinding, the bone chips evacuated from the grinding sit gets settled in the empty location on the end and lateral face of the burr, as evidently in Figure 5b.

Figure 6 depicts the maximum temperature produced by the tool T1, T2, T3 and T4 during grinding of porcine bone. The values of temperature have been plotted against the machining time. The results revealed that convex shaped tool generated temperature lower than the threshold value (47 °C) to cause necrosis of bone so it could be used for surgical operations to prevent osteonecrosis.

Different shaped grinding burrs influence the temperature generation owing to their contact areas or first contact with the workpiece. In the case of a pin-pointed grinding burr, for instance, the effective contact area is concentrated only on a single point over the workpiece, and the impact of the tool tip striking the specimen causes a sharp increase in stresses over the tool face. As a result, each tool has a unique grinding path and effective contact area, which affect tool wear and the related temperature. The T4 tool is pointed than the T2 tool in this instance i.e., T2 has a larger radius of curvature than T4. Therefore, when grinding bones with the T2 tool, a lower temperature is generated. Table 4 shows the comparison for obtained results with similar investigations in the field and present study. The average temperature reported in the present study is less than those reported by the other investigators which clearly establishes the adequacy of the proposed methodology.

CONCLUSIONS

The effect of the four different shape tools has been investigated in terms of thermogenesis

Table 4. Comparison of the temperature results as reported by past researchers and present study of bone grinding

Researcher (Year)	Bone	Cooling method	Temperature	Reference
Zhang et al. (2013)	Bovine femur	Saline mist	<40 °C	[14]
Enomoto et al. (2014)	Bovine femur	Pure water	≥ 100 °C	[18]
Yang et al. (2017)	Bovine femur	Dry	41.6 ±1.95 °C	[10]
Mizutani et al. (2019)	Bovine femur	Saline	≤ 100 °C	[11]
Shakouri et al. (2019)	Bovine femur	–	53.2 °C (ΔT)	[19]
Present study (2022)	Porcine femur	Saline	T1: 35.61 °C T2: 35.00 °C T3: 39.21 °C T4: 40.24 °C	–

and burr loading during osteotomy of the porcine bone. The distribution of the temperature on the bone has been characterized using infrared thermography and corresponding burr loading with microscopic images. It has been observed that convex tool shape generated lower maximum temperature i.e. 46.03 °C among all tools. The temperature produced by the convex tool is 12.06% lower than spherical tool, 33.39% lower than cylindrical tool, and 10.55% lower than tree-shape tool. Thermograms revealed that infrared thermography technique could be implemented for the in-vivo surgical operations for the measurement of temperature during bone grinding. SEM images revealed that significant loading may occur on the burr during grinding due to the settlement of the bone chips in the successive empty position in between the diamond abrasives. It has been observed that convex shape tool could be used to mitigate thermogenesis during neurosurgical operation such as brain tumor's dissection. The authors, seeing further possibilities to reduce the harmful effect of temperature, want to analyze the issues of the kinematics of the process in further works. The tools shown in the article are special grinding wheels. Parallel to them, drills are tested and their thermal effects on the cutting zone. Therefore, further work will focus on optimizing the kinematics of the process and the shape of the tools.

RERERENCES

1. Shih, A.J., Tai, B.L., Zhang, L., Sullivan, S., Malkin, S. Prediction of Bone Grinding Temperature in Skull Base Neurosurgery. CIRP Ann Manuf Technol. 2012; 61: 307–310. DOI: 10.1016/j.cirp.2012.03.078
2. Wang, G., Zhang, L., Wang, X., Tai, B.L. An Inverse Method to Reconstruct the Heat Flux Produced by Bone Grinding Tools. International Journal of Thermal Sciences. 2016; 101: 85–92. DOI: 10.1016/j.ijthermalsci.2015.10.021
3. Zhang, L., Tai, B.L., Wang, G., Zhang, K., Sullivan, S., Shih, A.J. Thermal Model to Investigate the Temperature in Bone Grinding for Skull Base Neurosurgery. Med Eng Phys. 2013; 35: 1391–1398. DOI: 10.1016/j.medengphy.2013.03.023
4. Babbar, A., Jain, V., Gupta, D., Agrawal, D. Histological Evaluation of Thermal Damage to Osteocytes: A Comparative Study of Conventional and Ultrasonic-Assisted Bone Grinding. Med Eng Phys. 2021; 90: 1–8. DOI: 10.1016/j.medengphy.2021.01.009
5. Tai, B.L., Zhang, L., Wang, A.C., Sullivan, S., Wang, G., Shih, A.J. Temperature Prediction in High Speed Bone Grinding Using Motor PWM Signal. Med Eng Phys. 2013; 35: 1545–1549, doi:10.1016/j.medengphy.2013.05.011
6. Shin, H.C., Yoon, Y.S. Bone Temperature Estimation during Orthopaedic Round Bur Milling Operations. J Biomech. 2006; 39: 33–39. DOI: 10.1016/j.jbiomech.2004.11.004
7. Matthews, L.S., Hirsch, C. Temperatures Measured in Human Cortical Bone When Drilling. J Bone Joint Surg Am. 1972; 54: 297–308. DOI: 10.2106/00004623-197254020-00008
8. Zhang, L., Tai, B.L., Wang, A.C., Shih, A.J. Mist Cooling in Neurosurgical Bone Grinding. CIRP Annals. 2013; 62: 367–370. DOI: 10.1016/j.cirp.2013.03.125
9. Yang, M., Li, C., Zhang, Y., Jia, D., Zhang, X., Hou, Y., Shen, B., Li, R. Microscale Bone Grinding Temperature by Dynamic Heat Flux in Nanoparticle Jet Mist Cooling with Different Particle Sizes. Materials and Manufacturing Processes. 2018; 33: 58–68. DOI: 10.1080/10426914.2016.1244846
10. Yang, M., Li, C., Zhang, Y., Wang, Y., Li, B., Hou, Y. Experimental Research on Microscale Grinding Temperature under Different Nanoparticle Jet Minimum Quantity Cooling. Materials and Manufacturing Processes. 2017; 32: 589–597. DOI: 10.1080/10426914.2016.1176198
11. Mizutani, T., Satake, U., Enomoto, T. Surgical Diamond Wheels for Minimally Invasive Surgery in Bone Resection under Small Quantity of Coolant Supply. Precis Eng. 2019; 56: 80–86. DOI: 10.1016/j.precisioneng.2018.09.015
12. Kumar, R., Panda, S.S. Drilling of Bone : A Comprehensive Review. J Clin Orthop Trauma. 2013; 4: 15–30. DOI: 10.1016/j.jcot.2013.01.002
13. Shakouri, E., Mirfallah, P. Infrared Thermography of High-Speed Grinding of Bone in Skull Base Neurosurgery. Proc Inst Mech Eng H. 2019; 233: 648–656. DOI: 10.1177/0954411919845730
14. Zhang, L., Tai, B.L., Wang, A.C., Shih, A.J. Mist Cooling in Neurosurgical Bone Grinding. CIRP Ann Manuf Technol. 2013; 62: 367–370. DOI: 10.1016/j.cirp.2013.03.125
15. Singh, G., Jain, V., Gupta, D. Multi-Objective Performance Investigation of Orthopaedic Bone Drilling Using Taguchi Membership Function. Proc Inst Mech Eng H. 2017; 231: 1133–1139. DOI: 10.1177/0954411917735129
16. Gupta, V., Pandey, P.M. In-Situ Tool Wear Monitoring and Its Effects on the Performance of Porcine Cortical Bone Drilling: A Comparative in-Vitro Investigation. Mech Adv Mater Mod Process. 2017; 3(2). DOI: 10.1186/s40759-017-0019-z

17. Gupta, V., Pandey, P.M. Experimental Investigation and Statistical Modeling of Temperature Rise in Rotary Ultrasonic Bone Drilling. Med Eng Phys. 2016; 38: 1330–1338. DOI: 10.1016/j.medengphy.2016.08.012
18. Enomoto, T., Shigeta, H., Sugihara, T., Satake, U. A New Surgical Grinding Wheel for Suppressing Grinding Heat Generation in Bone Resection. CIRP Annals. 2014; 63: 305–308. DOI: 10.1016/j.cirp.2014.03.026
19. Shakouri, E., Mirfallah, P. Infrared Thermography of High-Speed Grinding of Bone in Skull Base Neurosurgery. Proc Inst Mech Eng H. 2019; 233: 648–656. DOI: 10.1177/0954411919845730