Tool Temperature in Titanium Drilling

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1 Introduction

Titanium (Ti) and its alloys are lightweight, corrosion resistant, biocompatible, and high-temperature materials that have been widely utilized in aerospace, medical, military, and sports applications. The poor machinability of commercially pure (CP) Ti and Ti alloys has been studied by researchers and summarized in review papers [1–4]. Because of the inherent properties of Ti, particularly the low thermal conductivity, the tool temperature when machining Ti is high and concentrated at the tool tip [1]. High temperature softens the tool material and promotes rapid diffusion wear and severe tool edge chipping [5,6]. This research studies the drill temperature distribution in Ti drilling.

Although Ti drilling has been widely utilized in industry, research publications are still limited. Sakurai et al. [7–9] conducted a series of experiments in drilling of Ti-6Al-4V. Effects of tool surface treatment, cutting speed, and feed on thrust force and torque [7], benefits of the vibratory motion of the drill [8], and the variable feed for chip ejection [9] were studied. Other research in Ti drilling included Arai and Ogawa [10] on the high pressure (7 MPa) cutting fluid-assisted drilling, Dornfeld et al. [11] on the burr formation, and Cantero et al. [12] on the dry drilling tool wear and workpiece subsurface damage. This review indicates that the in-depth research of drill temperature distribution in drilling of Ti is still lacking. In Ti drilling, the tool temperature is high [1–5]. High tool temperature is critical to tool life and has been observed in high throughput drilling of Ti [13]. Detailed thermal modeling and experimental investigation are important to advance the drill design and process parameter selection to increase the tool life for Ti drilling. The goal of this study is to build a thermal finite element model of the spiral point drill, which has demonstrated to be effective in high throughput drilling of Ti [13], to investigate the drill temperature distribution and effect of cutting speed in Ti drilling.

The heat generation rate and drill temperature distribution during Ti drilling are difficult to measure directly. Agapiou and Stephenson [14] have reviewed the analytical modeling of temperature distribution in the drill, which was represented as a semi-infinite body. The empirical force equations from a series of turning (oblique cutting) tests were used to calculate the heat source. A transient heat transfer analysis in the semi-infinite domain was carried out to calculate the heat partition and drill temperature [14]. On the analysis of drill temperature as a finite domain, Saxeena et al. [15] and Watanabe et al. [16] developed the finite difference method. More recently, finite element method has been applied by Fuh et al. [17] and Bono and Ni [18,19] for the drill temperature analysis. These studies showed limitations in accurate prediction of drill temperature. The inverse heat transfer modeling using measured force, torque, and drill temperature as the input is developed to improve the accuracy in predicting the drill temperature distribution for Ti drilling.

By dividing the drill chisel and cutting edges into the elementary cutting tool (ECT) [20] segments, Ke et al. [21] have developed the procedure to extract the force data acting on each ECT, which works like an oblique cutting tool during drilling. At the start of drilling, one ECT after another in the drill chisel and cutting edges gradually engages the cutting action from center of the drill. Using measured thrust force and torque at the start of drilling, cutting forces in each ECT can be calculated. The chip thickness and shear angle associated with each ECT can be measured from the machined chip to estimate the chip speed. Based on this cutting data, the frictional force and heat generation can be determined. A heat partition factor is required to find the amount of heat transferred to the drill for thermal finite element analysis. This heat partition between the drill and chip is recognized as an important, but difficult, parameter to determine. Earlier studies used a constant value for heat partition along the tool-chip interface [14–17]. Variable heat partition factor depending on the cutting speed [22] has later been adopted by Bono and Ni [18] for drilling temperature prediction. More advanced modeling of variable heat partition [23,24] in the sticking and sliding contact regions has been studied for two-dimensional orthogonal cutting. Because of the short length of contact region [1] relative to the characteristic size of finite elements and the lack of basic machining data of Ti to determine the model parameters, the variable heat partition in the contact regions is not used. In this study, the cutting speed-dependent heat partition model [22] is adopted for drill temperature prediction.

In this paper, the experimental setup for Ti drilling tests is first introduced. The drill solid modeling, elementary cutting tools, finite element thermal model, oblique cutting mechanics in ECT, calculation of heat generation rate, and inverse heat transfer analysis are discussed in Sec. 3. Experimental results, model validation, and drill-temperature distributions are presented in the following three sections.
2 Experimental Setup

The Ti drilling experiment was conducted in a Mori Seiki TV 30 computer numerical control vertical machining center. Figure 1 shows the experimental setup with the stationary drill and the Ti workpiece driven by a spindle. The drill was stationary so four thermocouples embedded on the flank face could be routed through coolant holes in the drill body to a data acquisition system during drilling [14]. The drill and machine spindle axes were aligned by a test indicator installed in the spindle. The location of the drill was adjusted in the horizontal plane until the eccentricity was less than 10 μm. The tilt of the drill was adjusted so that two planes, which were 5 cm apart in height, both had less than 10 μm eccentricity. Under the drill holder was a Kistler 9272 dynamometer to measure the thrust force and torque.

The workpiece was a 38 mm diam grade two CP Ti bar. The drill was a 9.92 mm diam spiral point drill, Kennametal K285A03906, with a S-shaped chisel edge. Compared to a conventional twist drill, the chisel edge of the spiral point drill had lower negative rake angle. Therefore, the web could participate in cutting, not just indenting like the conventional twist drill. This reduces the thrust force and makes the drill self-centering [25]. The tool material was WC in a 9.5 wt % Co matrix (Kennametal grade K715). The spiral point drill has proven to perform well in high-speed Ti drilling with peripheral speeds over 180 m/min [13]. The chips were collected after drilling and chip thickness was measured to estimate the shear angle of each ECT. The average of three repeated measurements was used to represent the chip thickness.

Figure 2 shows the spiral point drill and locations of four thermocouples on the drill flank surface. The top view of a new drill with two flutes and two coolant-through holes is shown in Fig. 2(a). An XTY coordinate system with the XT-axis parallel to the tangential of the apex of the curved cutting edge is defined. The tips of 0.127 mm dia type-E thermocouples (OMEGA STC-TR-E-36-72) were installed at the edge of hand-ground slots on the drill flank face. Four thermocouples, denoted as TC1, TC2, TC3, and TC4, are arranged at different locations on the flank surface, as shown in Fig. 2(b). The XTY coordinates of the four thermocouples are listed in Fig. 2. The close-up view of TC1 and TC2 is illustrated in Fig. 2(c). TC1 is located close to the cutting edge and away from the drill center. TC2 is placed close to the flute and away from the drill center. TC3 and TC4, as shown in Fig. 2(d), both near the cutting edge, are close to and away from the drill center, respectively. Thermocouples were covered with cement (Omega OB-400) to secure the position and prevent the contact with workpiece.

In this research, three drilling experiments were conducted at three rotational speeds, 780 rpm, 1570 rpm, and 2350 rpm, which corresponded to 24.4 m/min, 48.8 m/min, and 73.2 m/min drill peripheral cutting speeds, respectively. The feed remained fixed at 0.051 mm/rev or 0.025 mm for each tooth of the two-flute drill. All experiments were conducted dry, without cutting fluid.
3 Spiral Point Drill Geometry and Finite Element Thermal Modeling

The thermal finite element model of the drill is established for inverse heat transfer and temperature analysis. The solid modeling of the spiral point drill, elementary cutting tools, thermal finite element modeling of the drill, oblique cutting mechanics in ECT, calculation of heat generation rate, and inverse heat transfer modeling are discussed in Sec. 3.1–3.6.

3.1 Drill Solid Modeling. The spiral point drill has more complex geometry than the conventional twist drill. To develop a three-dimensional (3D) finite element mesh for thermal analysis, the solid model of the drill was established in three steps. First, the drill cross-section profile perpendicular to the axis of the drill was measured using an optical tool-maker microscope. Then, a CAD software, SOLIDWORKS™, was applied to generate the drill body by sweeping the DCSP along a spiral curve with the specified pitch and helix angle. Finally, the trajectory of grinding wheel to generate the spiral drill point with S-shaped chisel edge was simulated to remove unwanted material and create the solid model of drill tip geometry. The drill grinding parameters were provided by Kennametal. The solid model of the spiral point drill is illustrated in Fig. 3. Key parameters of the drill are a 30 deg helix angle, 135 deg point angle, 1.9 mm point length, 1.4 mm coolant hole diameter, 52 deg chisel edge angle, 7 deg clearance angle at cutting corner, 0.43 mm width of margin, 1.4 mm chisel edge radius, and 1.8 mm chisel edge length. The drill was ground using a grinding wheel with 150 mm diam and 1.1 mm corner radius.

3.2 Elementary Cutting Tools (ECT). As shown in Fig. 3(b), two ECTs are used to represent half of the chisel edge (web of the drill) and five ECTs are used to model the cutting edge. The whole drill point is composed of 14 ECTs. Each ECT has a straight cutting edge. The length of cutting edge of the ECT is 0.71 mm and 0.85 mm in the chisel and cutting edge, respectively. Figure 4 shows the rake angle, inclination angle, and angle between drill axis and ECT cutting edge of the seven ECTs. These angles were obtained from the drill solid model since there is no existing formula to calculate these angles of the spiral point drill. The rake angle in the chisel edge is equal to −29 deg and −9 deg for ECTs 1 and 2, respectively. Compared to the conventional twist drill with a 118 deg point angle and −59 deg rake angle [26], the spiral point drill has less negative rake angles.

Oblique cutting mechanics is applied to analyze the cutting forces in each ECT. Cutting forces in each ECT are obtained from experimentally measured thrust force and torque at the onset of drilling, before the full engagement of the drill tip with the workpiece.

3.3 Finite Element Thermal Model. The drill solid model is exported to ABAQUS™, the finite element analysis software used in this study, for mesh generation. Figure 5 shows the finite element mesh of the drill, which is modeled by 68,757 four-node tetrahedral elements. As shown in the top view in Fig. 5(b), 13 nodes are located on the chisel edge and 11 nodes are placed on each cutting edge to achieve reasonable resolution in the analysis of drill temperature distribution in Ti drilling.

The initial condition of finite element analysis is a uniform temperature of 20°C in the drill. Because the drill does not rotate in the experiment, the free convection boundary condition is ap-
\[
\text{Fig. 6 Oblique cutting model of an ECT}
\]

applied to the whole drill inside (fluid hole) and outside surfaces. The heat flux of a vertical wall due to free convection in air is applied on the drill surface [27]

\[ q_{\text{conv}} = B(T - T_{\infty})^{1.25} \]

where \( B = 1.8 \text{ W/m}^2 \text{K}^{1.25} \) and \( T_{\infty} = 20^\circ \text{C} \). The boundary condition on the bottom surface at the end of the drill, opposite from the drill tip, is assumed to be maintained at \( 20^\circ \text{C} \).

The heat generation in drilling is assumed to be maintained at \( 20^\circ \text{C} \). The boundary condition on the bottom surface at the end of the drill, opposite from the drill tip, is assumed to be maintained at \( 20^\circ \text{C} \).

The frictional heat generation is calculated from the ECT 1 at the drill tip, the ECT sequentially engages the workpiece. Assuming the thrust force and torque on each ECT do not change, the thrust force and torque contributed by each ECT can be found by identifying the incremental increase of measured thrust force and torque at the time when an ECT is fully engaged with the workpiece [21].

Figure 6 shows the oblique cutting model of an ECT. Five angles including the inclination angle \( \lambda \), normal rake angle \( \alpha \), angle between the drill axis and ECT cutting edge \( \theta \), chip flow angle \( \eta \), and shear angle \( \phi \) are defined. According to Stabler’s rule [28], the chip flow angle \( \eta \) is assumed to equal to the inclination angle \( \lambda \). The uncut chip thickness and chip thickness are marked as \( a \) and \( a_c \), respectively. An orthogonal coordinate system with the \( X \)-axis in the cutting direction and the \( Z \)-axis perpendicular to the plane determined by the \( X \)-axis and the straight cutting edge is defined for each ECT. The \( Y \)-axis is parallel to the \( X \)- and \( Z \)-axes to form a right-handed coordinate system. The torque, denoted as \( T \), generates a force component \( F_t \) along the \( X \)-axis direction. The \( F_r = T/r \), where \( r \) is the distance from the drill axis to the center of the ECT. The component of resultant force in the \( Y \)-axis is \( F_y \) and in the \( Z \)-axis is \( F_z \). The thrust force, denoted as \( F_{th} \), is parallel to the drill axis and can be decomposed to \( F_t \) and \( F_r \) [18],

\[ F_{th} = F_r \cos \theta - F_t \frac{\cos \lambda - \cos^2 \theta}{\cos \lambda} \cos \theta \sin \phi \cos \theta \]

The resultant force on an ECT can also be decomposed to the force components normal and parallel to the rake face, denoted as \( F_n \) and \( F_p \), respectively. \( F_n \) is the friction force in the direction of chip flow on the tool rake face. Because the resultant force lies in the plane defined by \( F_n \) and \( F_p \), \( F_t \) is related to \( F_n \) and \( F_p \) by [29]

\[ F_t = F_p (\sin \lambda \cos \alpha \pm \sin \alpha \tan \eta) - F_n (\cos \lambda \cos \alpha \pm \cos \alpha) \]

\[ F_c, F_p, \text{ and } F_n \] are related with \( F_n \) and \( F_p \) by

\[ \begin{bmatrix} F_n \\ F_p \\ F_t \end{bmatrix} = \begin{bmatrix} \cos \lambda & \sin \lambda & 0 \\ -\sin \lambda & \cos \lambda & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \]

\[ \begin{bmatrix} F_n \\ F_p \\ F_t \end{bmatrix} = \begin{bmatrix} \cos \lambda & \sin \lambda & 0 \\ -\sin \lambda & \cos \lambda & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \]

From Eq. (4), \( F_t \) can be calculated as

\[ F_t = \frac{\cos \alpha \cos \lambda F_n + \sin \alpha F_p}{\cos \lambda \cos \eta + \sin \alpha \sin \eta} \]

\[ F_c \] can be solved by substituting Eq. (2) into (3).

\[ F_c = F_p (\sin \lambda \cos \phi + \cos \alpha \cos \phi) \cos \theta \]

\[ \cos \phi = \frac{a \cos \alpha}{a_c - a \sin \alpha} \]

where \( a = f_d \sin \theta \), in which \( f_d \) is the feed per tooth and \( \theta \) is the angle between the drill axis and ECT cutting edge.

3.5 Heat Generation Rate. On the ECT cutting edge, the friction force and chip velocity are multiplied to calculate the heat generation rate by friction, \( q_f = F_c V_c \). Defining \( K \) to be the heat partition factor determining the ratio of heat transferred to the tool, the heat generation rate on the ECT \( q_{\text{tool}} = K q_f \).

In this study, the cutting speed dependent \( K \) is applied [22]
\[ K = 1 - \left(1 + 0.45 \frac{k_t}{k_w} \sqrt{\frac{\pi d_w}{V_c l}}\right)^{-1} \]  

(9)

where \( k_t \) and \( k_w \) are the thermal conductivities of WC-Co tool and Ti workpiece material, respectively, \( d_w \) is the diffusivity of Ti, and \( l \) is the tool-chip contact length. All thermal properties are temperature dependent. The tool thermal conductivity \( k_t \) is shown in Fig. 7. For CP Ti, \( k_w \) and \( d_w \) are obtained from Ref. [31].

The tool-chip contact length \( l \) was assumed to be twice the chip thickness in previous drill thermal modeling [17]. In this study,

\[ l = s a_c \]  

(10)

where \( s \) is the ratio of the tool-chip contact length to the chip thickness. The value of \( s \) is assumed to be the same across the chisel and cutting edges and is determined by the inverse heat transfer solution.

### 3.6 Inverse Heat Transfer Solution

Inverse heat transfer utilizes the temperature measured by thermocouples TC1 and TC3 embedded on the drill flank surface as the input to predict the heat generation rate at the drill chisel and cutting edges. \( s \) is solved using an optimization method. The flowchart for inverse heat transfer solution is summarized in Fig. 8. By assuming a value for \( s \), the \( l, K \), and \( q_{tool} \) are calculated and applied to nodes on the cutting and chisel edges of ECT. The spatial and temporal temperature distribution of the drill can then be found. The inverse heat transfer method is applied to solve \( s \) by minimizing an objective function determined by the experimentally measured and finite element modeled temperature at specific thermocouple locations, as shown in Fig. 2, on the drill flank face. The discrepancy between the experimentally measured temperature at thermocouple \( j \) at time \( t_i \), \( T_j^{i_{\text{exp}}} \), and finite element estimated temperature at the same thermocouple location and time, \( T_j^{i_{\text{est}}} \), determines the value of the objective function

\[ \text{Obj}(s) = \sum_{i=1}^{n_i} \sum_{j=1}^{n_j} (T_j^{i_{\text{exp}}} - T_j^{i_{\text{est}}})^2 \]  

(11)

where \( n_i \) is the number of time instants during drilling and \( n_j \) is the number of thermocouples selected to estimate the objective function.

### 3.7 Validation

After finding the value of \( s \), the finite element modeling can be applied to calculate temperatures at locations of thermocouples not used for inverse heat transfer analysis. The drill temperature predicted from the finite element modeling at TC2 and TC4 is compared to experimental measurements to validate the accuracy of proposed method.
4 Experimental Results

The experimentally measured chip thickness, thrust force, and torque are applied to calculate the shear angle, ECT cutting forces, frictional heat generation, and heat partition factor.

4.1 Chip Morphology, Thickness, and Shear Angle. The morphology of the Ti chips generated at all three drilling speeds has the same shape, which is an initial spiral cone followed by a folded long ribbon. An example of the chip machined at 73.2 m/min peripheral cutting speed is shown in Fig. 9(a). The spiral cone, as shown in the close-up view in Fig. 9(b), is formed by the gradual engagement of chisel and cutting edges at the drill tip. After the drill tip fully engages the workpiece, the chip morphology changes to the ribbon type. Folding of the ribbon chip is due to the resistance caused by chip ejection [21].

At the end of the spiral cone, a close section of the chip, as marked by the line in Fig. 9(b), determines the variation of chip thickness across the chisel and cutting edges at the moment when the drill tip makes the full engagement with workpiece. The symbol C in Fig. 9(b) represents the center of the drill. A picture of the chip cross section and the corresponding ECT and thickness along the line in Fig. 9(b) are shown in Fig. 9(c). The chip generated by the chisel edge is thicker, due to the negative rake angle. This is consistent with the anticipated rake angle effect on chip thickness.

Measured chip thicknesses $a$, and calculated shear angles $\phi$ at seven ECTs under three peripheral cutting speeds are summarized in Fig. 10. Consistently, the chisel edge generates higher chip thickness and lower shear angle, compared to those of the cutting edge. Along the cutting edge, the chip thickness increases and the shear angle decreases. Under the same cutting speed, the rake angle $\alpha$ and the angle between drill axis and cutting edge $\theta$ of each ECT affect the chip thickness and shear angle. Large $\alpha$ usually decreases the chip thickness and increases the shear angle, whereas large $\theta$ increases the uncut chip thickness as well as the chip thickness. Along the cutting edge, $\alpha$ increases and $\theta$ is about the same (Fig. 4). The combination of these two effects results in a lower chip thickness in the cutting edge, as shown in Fig. 10.

4.2 Thrust Force and Torque on ECT. Figure 11 shows the thrust force and torque measured at three drilling speeds. In the first 1.9 mm of drilling, the force and torque gradually increase until the drill tip makes full engagement with workpiece. Increments in force and torque are assumed to be contributed by the sequential participation of ECTs in cutting. The vertical dash line and the number above it in Fig. 11 represent the drilling depth and the corresponding ECT fully engaged the workpiece, respectively. After the drill tip fully engages the workpiece, the thrust force and torque both reach a more stable level. The speed has a significant effect on the torque and changes the thrust force only slightly after the full engagement of drill tip. High torque at high cutting speed is mainly due to the increasing difficulty in chip ejection [21].

The $F_T$ and $T$ of each ECT, as shown in Fig. 12, are calculated from the incremental increase of thrust force and torque as each ECT engages in drilling (Fig. 11). Although ECTs 1–3 generate high thrust force, their value relative to other ECTs is small in comparison to a conventional twist drill [26]. Similar to a conventional twist drill, the ECTs at the cutting edge of the spiral point drill has a major contribution to the torque.

4.3 Solution of the $s$, $K$, and Heat Generation Rate. The measured temperatures at TC1 and TC3 at three peripheral cutting speeds are shown in Fig. 13. By minimizing Obj($s$) using the measured temperature at TC1 and TC3 as input, the value of $s$ is solved as 6, 6, and 4 for 24.4, 48.8, and 73.2 m/min peripheral cutting speed, respectively. The Golden Section optimization method [32] was used for solution.

Using the temperature-dependent material properties, the heat partition factor $K$ varies both spatially and temporally. The $K$ after 1.9 mm depth of drilling, i.e., the stage when the whole cutting edge engages the workpiece, is shown in Fig. 14. The lower $K$ at
higher cutting speed represents that a larger portion of heat generated at the tool-chip interface is carried away by the chip at higher cutting speed. This is a well-known phenomenon at high cutting speed [5]. Because of the cutting speed effect, ECTs at the cutting edge have a higher $K$ than those on the chisel edge.

To compare the heat transfer to each ECT, the $q_{tool}$ is divided by the length of ECT cutting edge to calculate the heat generate rate per unit length of contact, denoted as $q'_{tool}$. Results of $q_{tool}$ after 1.9 mm depth of drilling are shown in Fig. 15. Consistently, due to the higher torque, ECTs at the cutting edge have a much higher $q'_{tool}$ than those at the chisel edge. At 73.2 m/min peripheral cutting speed, the $q'_{tool}$ increases along the cutting edge toward the outside of the drill. This trend is altered at 24.4 m/min and 48.8 m/min cutting speeds at which $q'_{tool}$ at ECT 7 is lower than that at ECTs 5 and 6. This is because the torque of ECT 7 is higher than that of ECTs 5 and 6 at 73.2 m/min cutting speed but lower at 24.4 m/min and 48.8 m/min cutting speed (Fig. 12). At lower peripheral cutting speed, i.e., lower rotational speed, the effect of strain rate hardening at ECT 7 is not high enough to compensate the effect of high rake angle (Fig. 4), which generates lower cutting forces $F_r$.

The peripheral cutting speed has a significant effect on the heat generation rate at the cutting edge. As the cutting speed increases from 24.4 m/min to 73.2 m/min, $q_{tool}$ increases by more than 100% for most of the ECTs on cutting edge.

5 Validation of Drill Temperature Modeling

The finite element prediction of drill temperature is validated by the comparison to experimentally measured temperatures at thermocouples TC2 and TC4. As shown in Fig. 13, a good match of temperature can be seen at TC2 and TC4. The temperature at TC2 is lower and the discrepancy is higher than the other three thermocouples because TC2 is the furthest away from the cutting edge. Generally, the simulation underestimates the temperature at the beginning of drilling. This is likely due to the effect of grooves carved on the drill flank face used to install thermocouples. These grooves were not considered in the finite element modeling.

To quantify the discrepancy between the experimental and modeling results, the root mean square (rms) error $e_{rms}$ [33] and the percentage error $p$ are defined

$$e_{rms} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (T_{j}^{\text{exp}} - T_{j}^{\text{est}})^2}$$

$$p = \frac{e_{rms}}{T_{j}^{\text{peak}}}$$

where $N$ is the number of temperature measurements, $j$ is the thermocouple, and $T_{j}^{\text{peak}}$ is the peak measured temperature. The absolute temperature scale is used to calculate $p$.

The $e_{rms}$ and $p$ at four thermocouples are listed in Table 1. The $e_{rms}$ increases at high cutting speeds due to the high tool temperature at high cutting speed. In general, the $e_{rms}$ and $p$ at TC2 and TC4 are comparable to those of TC1 and TC3. At all three cutting speeds, $p < 5\%$, which is a considerable improvement from the previous drill temperature study [18]. In summary, the low $e_{rms}$ and $p$ and good match of experimentally measured and finite element modeled temperatures at four thermocouples throughout the drilling process validates the proposed method to predict drill temperature.

6 Drill Temperature Distributions

The spatial distribution of temperature near the tip of the spiral point drill after 12.7 mm depth of drilling is shown in Fig. 16. The drilling time was 19.2 s, 9.6 s, and 6.4 s at 24.4 m/min, 48.8 m/min, and 73.2 m/min peripheral cutting speeds, respectively. High temperature is concentrated along the cutting edge at the drill tip. High peripheral cutting speed generates high temperatures in the drill. The peak temperature increases from 480°C to 1060°C when the drill peripheral cutting speed is increased from 24.4 m/min to 73.2 m/min. The peak temperature is located on the cutting edge near the drill margin for all three cutting speeds. This study shows the high drill temperature and cutting speed effect in drilling Ti.

Figure 17 shows cutting speed effect on distributions of temperature along the chisel and cutting edges after 12.7 mm depth of drilling. At three peripheral cutting speeds, the pattern of temperature distribution is the same: low at the chisel edge and high near the margin. As the cutting speed increases, the location of peak temperature moves outside toward the drill margin.

At the highest peripheral cutting speed, 73.2 m/min, after drilling for 0.2 s, 0.5 s, 0.8 s, 1.0 s, 6.4 s, 20 s, and 50 s, the temperature distributions along the chisel and cutting edges of the drill are shown in Fig. 18. The location of peak temperature on the drill cutting edges is moving with respect to the time of drilling. In this
case using the spiral point drill for Ti, the location of peak temperature gradually moves from the drill center toward the drill margin. But, even at long drilling time, the peak temperature does not occur at the outmost point of the cutting edge (drill margin). The temporal analysis of drill temperature shows the steady state was not achieved. The drill temperature keeps rising with the increase of the drilling depth. The peak temperature reaches 1750°C at 50 s drilling time, which corresponds to a 102 mm depth of drilling. The rate of increase in drill temperature gradually drops at higher drilling depth.

7 Concluding Remarks

This study quantified the level of high temperature and effects of cutting speed and cutting time on drill temperature distributions in dry drilling of Ti. The complete temporal and spatial distributions of the drill temperature can be analyzed accurately and validated experimentally. This was based on the work of many researchers in drilling study in the past years. A finite element thermal model combined with inverse heat transfer analysis, which used experimentally measured thrust force, torque, chip thickness, and temperature as inputs, was validated with reasonably good agreement. An accuracy of <5% discrepancy between experimentally measured and numerically predicted drill temperature was achieved. This study showed that the cutting edge had a lower heat partition factor and higher heat generation rate per length than the chisel edge. The peak temperature of the drill increased from 480°C to 1060°C as the peripheral cutting speed increased from 24.4 m/min to 73.2 m/min after 12.7 mm depth of drilling. The location of peak temperature moved outside toward the drill margin as the peripheral cutting speed increased. The modeling results also showed the drill temperature did not reach the steady state after a long, 50 s, drilling time.

The research in Ti drilling is ongoing on several fronts. The proposed method can be expanded to the drilling condition with the supply of cutting fluid, which is important for the high throughput drilling of Ti. Using the predicted drill temperature

<table>
<thead>
<tr>
<th>Peripheral cutting speed (m/min)</th>
<th>TC1</th>
<th>TC2</th>
<th>TC3</th>
<th>TC4</th>
</tr>
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<tr>
<td>24.4</td>
<td>10.8</td>
<td>9.5</td>
<td>15.3</td>
<td>12.9</td>
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<tr>
<td>e_{\text{rms}} (°C)</td>
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<td>2.9</td>
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<td>p(%)</td>
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<td>11.8</td>
<td>22.1</td>
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<td>2.9</td>
<td>2.2</td>
<td>3.5</td>
<td>2.8</td>
</tr>
<tr>
<td>e_{\text{rms}} (°C)</td>
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<td>27.2</td>
<td>23.6</td>
<td></td>
</tr>
<tr>
<td>p(%)</td>
<td>3.6</td>
<td>4.8</td>
<td>3.9</td>
<td>3.4</td>
</tr>
</tbody>
</table>

![Fig. 13](image1.png) Comparison of the measured and modeled temperature at four thermocouple locations

![Fig. 14](image2.png) Heat partition factor $K$ at seven ECTs after 1.9 mm depth of drilling

![Fig. 15](image3.png) Heat generation rate per unit length $q_{\text{tool}}$ at seven ECTs after 1.9 mm depth of drilling

Table 1 Root mean square (rms) and percentage errors
distribution and cutting forces, the coupled thermal and mechanical stress analysis of the deformation and stress distributions of the drill can be performed. This study can also be expanded for the drill selection, drill geometry design, and optimization of drilling process parameters to further enhance the productivity of drilling Ti and other advanced engineering materials.

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