Abstract
Low-frequency vibration drilling can suppress the drilling temperature and extend tool life. In low-frequency vibration drilling, there are drilling times and non-drilling times in each vibration cycle. A past study clarified that the temperature increases during drilling, and the peak temperature in one vibration cycle is nearly equal to a conventional drilling temperature, but the temperature of the drill corner decreases during non-drilling periods. However, the relationship between the amount of temperature increase/decrease during intermittent drilling and the vibration and drilling conditions and temperature change near the cutting edge has not yet been clarified. In this study, to determine the drilling temperature during the drilling and non-drilling periods of low-frequency vibration drilling, the temperature near the cutting edge was measured experimentally by an embedded K-type thermocouple. To identify the optimum conditions for low-frequency vibration drilling without repeating the experiment, the temperature transition of the cutting edge was simulated based on the heat input caused by the cutting energy, calculated from the principal cutting force and speed. To simulate the temperature change of the drill edge, the principal force acting on the cutting edge was calculated from two-dimensional cutting data. A comparison of the experimental and simulated temperatures showed that the simulated temperature transition agreed well qualitatively with the results measured during low-frequency vibration drilling.

Key words: Drilling temperature, Vibration drilling, Titanium alloy, Low-frequency vibration

1. Introduction

In recent years, titanium alloy and carbon fiber composite materials have been used in many products instead of aluminum alloy and steel, due to the light weight and high strength of these materials. In aircraft, where the emphasis is on light weight, these materials have been particularly useful. For example, the B787 and A350WXB, which are new-generation aircraft, use carbon fiber composite materials for about half of their body mass (Boeing Company, 2006; JAXA, 2005). Therefore, assembly of the main structure requires that many holes be drilled in the piled carbon fiber composite materials, titanium alloy, and aluminum alloy in order to attach the body parts and wings. However, the drill temperature becomes very high because the thermal conductivity of titanium alloy is very low (Suzuki, Moriguti, 1995). As a result, there is a risk that the plastic components of the carbon fiber composite materials will soften.

Moreover, titanium alloy chips frequently cause adhesions on the drill cutting edge. Such adhesions could be a factor in cutting edge breakage and could decrease the hole accuracy (Titanium Society, 1992). To address these problems, the step drill method and/or cutting fluid have been used. These, however, increase the drilling time and cleaning costs and decrease the quality of the work environment. On the other hand, several efforts have been made to identify an effective coating for tools to reduce friction and provide heat resistance (Ojima, 1999; Hanyu et al., 2003; Harris et al., 2003). Coated tools are sometimes effective, but are not sufficient to accomplish the dry machining of titanium alloy. Also, a new drilling method incorporating ultrasonic vibration has also been developed (Onikura and Ohnishi, 1998), and its effectiveness for drilling into titanium alloy was reported (Isobe et al., 2015). However, though ultrasonic vibration drilling is suitable for small-hole processing, it is not suitable for big holes.
As another solution, low-frequency vibration drilling (less than 50 Hz) has been proposed. Previous studies established that low-frequency vibration drilling could divide the chips and reduce the thrust force and torque (Toews et al., 1998). Furthermore, it was shown that the accuracy of the inner surface of the hole was improved by low-frequency vibration drilling in deep-hole processing (Mann et al., 2013). Low-frequency vibration drilling can also extend tool life (Arai et al., 1989; Jin and Murakawa, 2000; Nanbu et al., 2012; Sugihara and Enomoto, 2016) with the same drilling times as conventional drilling.

In our past study, measurement of the penetrating temperature at the cap burr indicated that the temperature in low-frequency vibrating drilling was lower than in conventional drilling, and this was considered to help extend the tool life (Okamura et al., 2006). In addition, the drilling temperature of the cutting edge was measured using the tool-work thermocouple method (Okamura et al., 2016). It was shown that with conventional drilling, the drill temperature continued to increase over the drilling period, but with low-frequency vibration drilling, the temperature increased during drilling and decreased during the non-drilling periods. When the conventional feed rate, amplitude, and frequency changed, the drilling time, non-drilling time, and temperature increase/decrease also changed.

In low-frequency vibration drilling, cutting heat is generated at the cutting edge during the actual cutting periods, and then the heat generated at the cutting point diffuses to the tool during the non-cutting periods, so the cutting point temperature is subjected to repeated increases and decreases during the vibration cycles in vibration drilling. Also, the drilling time and non-drilling time are greatly affected by the vibration amplitude, the vibration frequency, spindle speed and feed rate.

However, the relationship between the temperature increase/decrease during the drilling and non-drilling periods has not yet been clarified. In this study, to determine the drilling temperature during the drilling and non-drilling periods of low-frequency vibration drilling, we conducted simulations of the temperature of a cutting edge considering the thickness and drilling speed. As a result, the optimum conditions for low-frequency vibration drilling were identified without repeating the experiment.

2. Low-frequency vibration drilling
2.1 Low-frequency vibration drilling machine

Figure 1 is an illustration of the low-frequency vibration drilling machine used in this study. The drilling spindle is mounted on two parallel linear guides. The first is a conventional feed, and the other adds low-frequency vibration. Table 1 lists the specifications of the low-frequency vibration drilling machine.

![Fig. 1 Illustration of low-frequency vibration drilling. The drill spindle driven by a hydraulic servo motor and the feed and vibration directions are shown.](image)

| Table 1 Specifications of the low-frequency vibration drilling machine. |
|---------------------------------------------------------------|
| Travel of axis | mm | 50 |
| Spindle speed | min⁻¹ | 0–10000 |
| Feed rate | mm/min | 0–2000 |
| Vibration amplitude | mm | 0–0.5 |
| Vibration frequency | Hz | 0–100 |
| Mechanical output | kW | 1 |
| Weight | kg | 25 |
2.2 Axial movement in low-frequency vibration drilling

In low-frequency vibration drilling, the relative movement ($X$) distance of the drill and the workpiece are shown by Equation (1).

\[
X = X_F + X_V = F_t + a \sin(2\pi ft) 
\]  

(1)

where $X_F$ is the relative movement induced by the constant feed, $X_V$ is the relative movement induced by low-frequency vibration, $F_t$ is the constant feed rate, $t$ is time, $a$ is the vibration amplitude, and $f$ is the vibration frequency.

As mentioned, low-frequency drilling involves both drilling ($t_{drilling}$) and non-drilling periods ($t_{non-drilling}$); these are shown in Equation (2).

\[
t_{conve} = t_{drilling} + t_{non-drilling} 
\]  

(2)

where $t_{conve}$ is the drilling time of conventional drilling.

This shows that the total duration of low-frequency vibration drilling to create one hole opening is always equal to the drilling time of conventional drilling, and the drilling time of low-frequency vibration drilling is always shorter than that of conventional drilling, as shown in Figure 2. Therefore, the undeformed chip thickness in low-frequency vibration drilling is larger than that in conventional drilling.

For example, Figure 3 shows the undeformed chip thickness in conventional drilling in the case of a rotational speed of 1000 min$^{-1}$ and a feed rate of 40 mm/min with a two-flute drill; the thickness is constant. Figure 4 shows the undeformed chip thickness of low-frequency vibration drilling in the case of a vibration amplitude of 0.6 mm, a vibration frequency of 33.3 Hz, a rotational speed of 1000 min$^{-1}$ and a feed rate of 40 mm/min (the same rotational speed and feed rate as in the case shown in Fig. 3). In this case, the cutting process is continuous even if vibration is added to the tool. Thus, the chip thickness in low-frequency vibration drilling is changed by the rotational speed, feed rate, and amplitude and frequency of the low-frequency vibration. In this study, the undeformed chip thickness can be calculated as follows. As a two-flute drill was used in this study, four trajectories of the cutting edge movement can be drawn during two rotations. Then if we focus on cutting edge A at the third rotation, the difference from the preceding trajectory of cutting edge B at the second rotation represents the variation of the undeformed chip thickness.

Then, to simulate the temperature change in the vibration drilling, it is necessary to determine the principal force for different undeformed chip thickness and the amount of heat flowing into the tool.

![Fig. 2 Drilling time and non-drilling time of low-frequency vibration drilling and drilling time of conventional drilling.](image-url)
3. Method of measuring the drill cutting edge temperature with an embedded K-type thermocouple

The cutting edge temperature during cutting was measured using the tool-workpiece thermocouple method in our previous study (Okamura et al., 2016). However, in determining the average electromotive force on all of the tool-workpiece contact surfaces in this method, not only the electromotive force on the cutting point along the cutting edges but also that on the contact point between the drill side edge and the side wall of the machined hole can be measured, and the electromotive force from the contact point between the drill side edge and the side wall of the machined hole, affects to the measured temperature. In addition, during intermittent cutting, the cutting-edge temperature cannot be measured because the cutting edge of the tool and the workpiece have no contact junction in the tool entry period. Thus, the temperature near the cutting edge was measured by a K-type thermocouple embedded near the cutting edge to capture the continuous temperature variation including the temperature during the non-cutting period. Figure 5 shows the drill tip and the embedded K-type thermocouple. Table 2 shows the experimental conditions.
4. Analytical method for predicting the temperature of the drill cutting edge

4.1 Principal force acting on drill cutting edge

The rake angle (αn) of the cutting edge of the drill varies with distance from the center of the drill (y), as shown in Figure 6. In addition, the cutting speed becomes faster as it is farther from the center of drill. For this reason, drilling involves three-dimensional cutting at the cutting edge. However, we assumed that the orthogonal cutting within the plane vertical to the cutting edge can be realized at the main cutting edge of the drill as a first order of approximation. If the cutting edge of the drill is finely divided in its vertical direction, the accumulation of two-dimensional (2D) cutting approximates the actual drill cutting as shown in Figure 7. Then, the principal force during drilling can be obtained from the sum of 2D cutting at each divided edge. Thus, the principal force of the different undeformed chip thickness (th) and the cutting speed and different rake angles were measured for 2D cutting on a lathe. The principal force (F_p), the thrust force (F_t), and the feed force (F_f) in 2D cutting by a lathe were measured using a three-axis dynamometer, and they were recorded in the data logger after being amplified by the charge amplifier.

The measurement conditions during 2D cutting by a lathe are presented in Table 3. Figure 8 is an example of the measured principal force and the moving average.

The results corresponding to each drill cutting edge position are summarized in Figure 9. It can be seen that the principal force increases linearly in proportion to the undeformed chip thickness. In addition, apart from the center of the drill, the rake angle and cutting speed increase, and the principal force decreases. Then, the undeformed chip thickness and the principal force acting on a given position of the drill cutting edge can be derived from these results.

The variation of the undeformed chip thickness affected by the vibrating state of the preceding cutting edge can be calculated as follows. As a two-flute drill was used in this study, the two trajectories of the cutting edges are drawn in the diagram shown in Figure 10. This diagram shows the trajectories of two cutting edges in two rotations in the case of a rotational speed of 1000 min⁻¹, a feed rate of 40 mm/min, a vibration amplitude of 0.6 mm, and a vibration frequency of 12.5 Hz. The painted region is removed as chips, and the difference in each trajectory represents the undeformed chip thickness.

It is possible to obtain the relationships between the undeformed chip thickness and the principal force on each drill.

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Table 2  Experimental conditions of measuring the drill cutting edge temperature with an embedded K-type thermocouple

| Drill type                  | Non-coated straight drill |
|-----------------------------|---------------------------|
| Drill diameter mm           | 6                         |
| Web thinning                | Type S                    |
| Drill material              | CR1 (Cemented carbide Type K) |
| Spindle speed min⁻¹         | 1000                      |
| Feed rate mm/min            | 40                        |
| Condition                   | Non-step                  |
| Vibration amplitude mm      | 0                         |
| Vibration frequency Hz      | 0.8                       |
| Drilling time ratio %       | 100                       |
| Workpiece material          | Ti-6Al-4V                 |
| Workpiece thickness mm      | 3.3                       |
| Cutting fluid               | Dry                       |

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cutting edge point, and they are shown in Fig. 9.

Fig. 6  Rake angle of the cutting edge of the drill

![Diagram](image)

(a) Approximation of drilling  (b) Front view of drilling  (c) Two-dimensional machining

Fig. 7  Procedure to replace the drill cutting edge with 2D cutting.

Table 3  Experimental conditions for measuring the principal cutting force on orthogonal cutting

| Workpiece material | Ti-6Al-4V |
|--------------------|-----------|
| Workpiece diameter | mm        |
| Tool-bit edge material | Cemented carbide K10 |
| Distance from the center of drill | mm | 0.2 | 1.5 | 2.0 | 2.5 |
| Rake angle | Deg. | 10.9 | 30.5 | 33.2 | 35.2 |
| Cutting speed | m/min | 11.3 | 56.5 | 75.4 | 94.2 |
| Feed rate | μm/min | 8.6, 10.3, 14.4, 17.3, 43.3, 51.9, 53.1, 63.7, 72.1, 86.5, 159.2, 191.0, 265.2, 318.3 |

Fig. 8  Example of the measured principal force and its moving average value.
4.2 Amount of heat and flow into tool

Based on the obtained principal force, the amount of cutting energy per unit cutting edge length generated at the radius \( r \) \( (W(r)) \) can be expressed by Equation (3) (Show, 2004).

\[
W(r) = F_p(r) \cdot V(r)
\]  
(3)

where \( F_p(r) \) is the principal force per unit cutting edge length acting at the cutting edge \( r \) mm apart from the drill center, and \( V(r) \) is the cutting speed at radius \( r \).

In this study, one cutting edge was divided into four, as shown in Fig. 9. If one cutting edge was divided into an arbitrary number \( (n) \), the amount of heat inflow from the cutting edges of drill \( (Q) \) can be approximated by the Equation (4).
\[
Q = 2 \cdot W \cdot R_1 \cdot R_2 \cdot R_3 = 2 \cdot F_p \cdot V \cdot l_c \cdot n \cdot R_1 \cdot R_2 \cdot R_3
\] (4)

where \( W \) is the cutting energy at one cutting edge of the drill, \( F_p \) is the principal force of one divided cutting edge, \( V \) is the cutting speed of the divided cutting edge, \( l_c \) is the length of the divided cutting edge, \( R_1 \) is the convert rate to heat from cutting energy, \( R_2 \) is the heat flow rate to the drill and workpiece, and \( R_3 \) is the heat flow rate to the drill from the heat flows to the drill and workpiece combined.

It should be noted that a past study (Ezugwu and Wang, 1997) reported the heat flow ratio due to the combination of materials in workpieces and tools. This study established that the heat flow rate to the chip was 25\%, and there was at least a 75\% inflow to the workpiece and tool, composed of Ti-6Al-4V (workpiece) and cemented carbide (tool). We thus assumed that the cutting energy is completely converted to heat, and the heat flow ratio between the drill and workpiece, changing Equation (5) as follows.

\[
Q = 2 \cdot F_p \cdot V \cdot l_c \cdot n \cdot 100\% \cdot 75\% \cdot 50\% = F_p \cdot V \cdot l_c \cdot n \cdot 75\%
\] (5)

Table 4 presents the details of the analysis conditions. The analysis conditions are the same as the experimental conditions given above. Figure 11 shows the analysis model of the drill used to predict the temperature change. The cutting heat was loaded on the cutting edge of the drill. In the case of low-frequency vibration drilling, the cutting heat loading was changed in accordance with the changes in the undeformed chip thickness. In this study, analysis was carried out using the commercial FEM software Femap with NX Nastran.

Table 4 Analysis conditions.

| Drill type | Non-coated straight drill |
|---|---|
| Drill diameter mm | 6 |
| Web thinning | Type S |
| Thermal conductivity W/(m·K) | 75 |
| Specific heat J/(kg·K) | 290 |
| Density g/cm³ | 14.7 |
| Elem. type | Tetrahedral |
| Elem. propety | Solid |
| Elem. side length mm | 0.3 |
| Elem. number | 38439 |
| Analysis time(step) s(step) | 5 (5000) |
| Spindle speed min⁻¹ | 1000 |
| Feed rate mm/min | 40 |
| Condition | Non-step | Low frequency vibration |
| Vibration amplitude mm | 0 | 0.6 |
| Vibration frequency Hz | 0 | 0.8 | 11.2 | 12.5 |
| Drilling time ratio % | 100 | 36 | 35 | 19 |

Fig. 11 Analysis model and cutting heat loading points.
5. Measurement results of drill cutting edge temperature

Figure 12 shows the measurement results for the drill temperature near the cutting edge. In low-frequency vibration drilling with a vibration amplitude of 0.6 mm and a vibration frequency of 0.8 Hz, the measured temperatures repeatedly rose and fell. This proved that the cutting became intermittent and that the temperature near the cutting edge decreased during the non-drilling time. On the other hand, with a vibration amplitude of 0.6 mm and frequencies of 11.2 Hz and 12.5 Hz, the temperature changes were minute, and no repeated rise and fall of the temperature due to intermittent cutting was observed. When the temperatures of low-frequency vibration drilling and conventional drilling were compared from 0.5 seconds to 3.5 seconds, the temperature was lower in conventional drilling. However, after 3.5 seconds of drilling, the drill temperature in conventional drilling became higher than the temperature in low-frequency vibration drilling in all vibration conditions. This indicates that in cases of low-frequency vibration with frequencies of 11.2 Hz and 12.5 Hz, while the decrease in temperature during the non-drilling period could not be measured, the suppressive effect of intermittent cutting on the drill temperature still occurred. A comparison of the temperatures of the low-frequency vibrating drills showed no difference between the average temperature at a vibration frequency of 0.8 Hz and the temperature at a vibration frequency of 11.2 Hz. However, the temperature at a vibration frequency of 12.5 Hz was lower than that at frequencies of 0.8 Hz and 11.2 Hz. In addition, as shown in Table 2, when comparing the drilling time ratio during one vibration cycle, it was about 35% at the frequencies of 0.8 Hz and 11.2 Hz, but it dropped to about 19% at the frequency of 12.5 Hz. From this finding, it was concluded that the temperature suppression effect of low-frequency vibration drilling can be predicted by the drilling time ratio during one vibration cycle.

![Fig. 12 Measurement results for drill temperature near the cutting edge, measured by embedded K-type thermocouple.](image)

6. Analytical prediction results for the temperature of the drill cutting edge

Figure 13 shows the simulated temperature near the cutting edge (shown in Fig. 11). This was done at the same location as the junction of the thermocouple used to measure the temperature in the experiment. The results showed that the drill temperature in low-frequency drilling repeatedly rises and falls, similar to the measurement results. They also showed that low-frequency vibration drilling results in intermittent cutting. Further, the amounts of increase and decrease in temperature were different for each frequency. The different increments in drill temperature were due to differences in undeformed chip thickness, and the difference decrements in drill temperature were due to differences in the length of the non-drilling period.

Meanwhile, in the case of conventional drilling, the drill temperature constantly increased. From 0.5 seconds to 3 seconds, the drill temperature in conventional drilling was lower than that in low-frequency drilling, as in the measurements results. The undeformed chip thickness in low-frequency vibration drilling was thicker than in conventional drilling, so the principal force was proportional to the undeformed chip thickness, and the heat generated...
on the cutting edge of the low-frequency vibration drill was higher than on the conventional drill.

However, after 3 seconds of drilling, the drill temperature in conventional drilling was higher than that in low-frequency vibration drilling, as in the measurements results. This was because during the non-drilling time, the heat generated on the cutting edge diffused and the temperature of the cutting edge decreased, as shown in Fig. 13. This indicates that low-frequency vibration drilling can suppress drill temperature by intermittent cutting.

![Simulated temperature near the cutting edge.](image)

Fig. 13 Simulated temperature near the cutting edge.
(Analytical conditions are the same as the experimental conditions shown in Table 2).

7. Comparisons of experimental and prediction results

Comparing the results of the analysis with the experimental results in the case of low-frequency vibration drilling with a vibration amplitude of 0.6 mm and a vibration frequency of 0.8 Hz, a significant effect of intermittent cutting can be seen.

Figure 14 shows the results of the analysis and the experiment. The difference in the drilling temperature was about 23.5 °C at the peak at 0.5 seconds of the initial drilling stage. This is because during the initial drilling, only the chisel performs as the cutting edge, and in the analysis, the chisel has no cutting speed and there is no principal force; therefore from Eq. (5), the chisel does not create cutting heat. However, in practice, heat is generated by friction between the chisel and workpiece and the heat form the plastic deformation of the workpiece. The difference at the time of initial cutting was reduced to 13.8 °C in 1.2 seconds, but this difference was also a factor in the temperature difference observed later.

The drill temperature rise gradient during drilling was almost the same in the analysis and in the experiment. This shows that the heat flow into the cutting edge during the drilling time in the analysis well simulated the experiment. On the other hand, the drill temperature drop gradient during the non-drilling time in the analysis was significantly different from that in the experiment. This was because the calculation of the heat inflow of the drill in the analysis considers only the heat generated on the cutting edge, but in the experiment there are other heat flows, such as the frictional heat between the drill side and the inner surface of the hole, and the inflow from the high-temperature chips in the flute. From the heat flow of the frictional heat and high temperature chips, the temperature of the drill in the experiment will be higher than that in the analysis. For this reason, the heat near the cutting edge in the analysis easily spreads around the cutting edge, while it was difficult for the heat near the cutting edge in the experiment to spread around the cutting edge. The difference between the analysis and the experiment in conventional drilling was also considered to be due to the same reason. Furthermore, the chips in the conventional drilling are not divided and stay longer in the drill flutes than in the low-frequency vibration drilling. Therefore, the heat inflow from the chips in the flute becomes larger, and the difference between the analysis and experiment becomes larger for conventional drilling than for low-frequency vibration drilling.

This is also why the drill temperature cannot be seen to fall in the non-drilling period in the experiment in the case of the low-frequency vibration drilling with a vibration amplitude of 0.6 mm and frequencies of 11.2 Hz and 12.5 Hz.
The above implies that, to improve the accuracy of the calculation of the drill temperature, it is necessary to consider other heat flows, such as the frictional heat between the drill side and inner surface of the hole, and the inflow from high temperature chips in the flute.

6. Conclusion

In this study, the temperature was measured by a K-type thermocouple embedded near the cutting edge in order to determine the temperature increase/decrease that occurs during intermittent drilling and the vibration and drilling conditions and temperature change near the cutting edge. A simulator was developed to predict the cutting edge temperature during low-frequency vibration drilling based on the cutting energy.

The following conclusions were derived.

1) From 0.5 seconds to 3.5 seconds, the drill temperature in conventional drilling was lower than that in low-frequency drilling. However, after 3.5 seconds of drilling, the drill temperature in conventional drilling was higher than that in low-frequency vibration drilling.

2) The simulated drilling temperature in low-frequency drilling showed repeated rises and falls, and the increase and decrease in temperature were different for each vibration frequency. These differences were due to differences in undeformed chip thickness; the difference in the decrement of the drill temperature during the non-drilling period was due to differences in the length of the non-drilling time.

3) The simulated drill temperature rising gradient during drilling agreed well with that observed in the experiments. The drill temperature dropping gradient during the non-drilling time was significantly different, however. This was because the simulator did not consider the frictional heat between the drill side and the inner surface of the hole nor the inflow from high-temperature chips piled up in the drill flute.

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