Smart monitor of tool temperature and vibration in drilling and countersinking processes with a multifunctional wireless communication tool holder system

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Abstract. We developed a novel tool holder equipped with a wireless communication function to monitor the tool temperature and vibrating accelerations in both the radial and rotational directions during a tool rotating operation. In this study, we attempted to measure the inner temperature of a drill tool with a machining center and investigated the influence of cutting speed on it. Based on these results, we developed a smart method to predict the maximum temperature by monitoring the temperature variation during the drill operation and determined the maximum cutting speed from it. Additionally, we attempted to measure the tool vibrations in the rotational and radial directions in a countersinking process. Based these results, we could monitor not only the conventional chatter vibration based on the tool-bending mode but also the high-frequency chatter vibration based on the coupled vibration of the bending and torsion with a developed holder system. Consequently, we demonstrated that the developed smart monitor method with a wireless communication system is effective in estimating the tool temperature in drilling processes and the tool vibration in countersinking processes.

Introduction

Currently, a smart monitoring technology has been attracting particular attention in the factory automation fields regarding the Internet of things (IoT). The real-time monitoring of various physical quantities generated between a tool and a workpiece in machining tools is one of the core technologies. Under the present conditions, the acquisition of processing value by the rotational tool is not sufficient, such as the machining center. We therefore developed an easily reusable tool holder equipped with a wireless communication function to monitor the tool temperature and vibrating accelerations in a manufacturing site. However, in regard to monitoring temperature, we have not started the verification despite it being in demand for deep-hole-drilling that is difficult to monitor by infrared thermography. Otherwise, the example of measured cutting temperature near the tool edge by an un-rotateable tool inserted with a thermocouple at the rotational workpiece (stainless steel or aluminum alloy etc.) in drilling [1]. The absolute value measured by the thermocouple is of high reliability; however, to acquire the thermal electromotive force while securing the signal-to-noise ratio by the slip ring is difficult because most cutting temperatures are measured by the rotating workpiece. For measuring in a rotating drill, measurement methods exist that provide a thermocouple-circuit with a workpiece [2]; it observes the tool edge by a thermometer from the small hole of a workpiece [3]. However, to measure at a manufacturing site is not possible. In regard to monitoring the vibration, we have not started the verification to detect chatter vibrations at high frequencies in the chamfering process.

Regarding vibration monitoring, we have not started the verification to detect chatter vibrations at high frequencies in the chamfering process. There are few management techniques of high quality for processing a surface by the countersink processing. The reports approximately the relationship among cutting condition, cutting force, and processing accuracy are few [4]. Chatter vibrations at high frequencies occur during the countersink processing in a manufacturing site; however, no example exists that verified the phenomenon. Nevertheless, the quality management of the countersink surface necessitating sealing is required. Therefore, an easy method of monitoring the temperature and vibration on a tool edge side is required under the conditions that the drill rotates on the machining center at a manufacturing site.

Herein, we verified the effectiveness of this holder system in the two previously described subjects.

Experimental setup and the basic theory of the processing phenomenon

Measurement of tool internal temperature and cutting condition in drilling. The internal tool temperature of a drill is measured by an inserted thermocouple. Figure 1 shows a schematic diagram of the wireless temperature measurement holder system. The hole for inserting the thermocouple was processed into the tool center by electrodischarge machining (EDM), and the thermocouple was inserted. The hole depth was 2 mm from the chiseled edge. We placed the amplifier, A/D converter, microcontroller, and transmitter in the tool holder. The tool temperature measurement results were wirelessly and continuously transmitted to a computer that is connected to the receiver. The diameter of the thermocouple was 0.5 mm, and of the K type. The transmission frequency was approximately 10 S/s. Figure 2 shows the external appearance of the HSS drill and the electrode for the electric EDM. The length of the drill was 144 mm, and the diameter of electrode was 0.5 mm. Table 1 shows the specifications of the drill and the cutting conditions. The workpiece was S45C of 100 mm × 100 mm × 50 mm. The workpiece was located on the dynamometer (type: 9255B, KISTLER Corporation) on the table of the machining center for simultaneously measuring the temperature and cutting force.

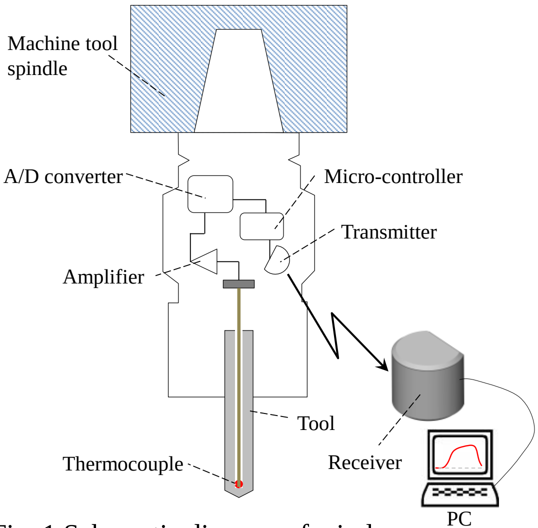

Fig. 1 Schematic diagram of wireless measurement tool holder system to measure temprature

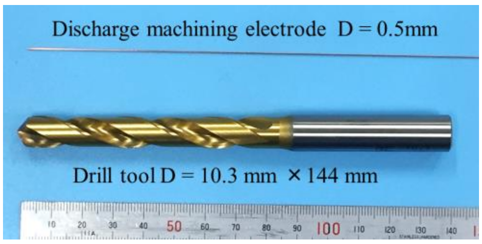

Fig. 2 Discharge machining electrode and drill tool

Table 1 Tool infomation and cutting condition in drilling

Tool information		Cutting condition	
Model num.:	EX-GDR (OSG)	Speed:	25~120 m/min.
Diameter:	10.3 mm	Feed:	0.2 mm/rev.
Length:	144 mm	L/D:	10
Num. of edge:	2	Cutting depth:	50 mm
Tip angle:	130 deg.	Step feed:	non-step
Twist angle:	30 deg.	Coolant:	dry
Cooting:	TiN		

Measurement of vibration and cutting condition in countersink processing. Figure 3 shows the schematic diagram of the wireless vibration measurement holder system. Four piezoelectric acceleration sensors were installed at a position 86 mm from the gauge line and 5.5 mm from the rotational center in the holder system. By implementing this installation configuration, the holder system can better detect vibrations along the rotational axis and the two orthogonal axes. The microcontroller in this holder operates at a voltage that is detectable by the four acceleration sensors. Equations 1–3 are the formulae used to calculate the acceleration in each direction. The accelerations of two orthogonal directions are defined by *Xm* and *Ym*, and the acceleration of the rotational direction by *Rm*.

$$Xm = (ax_1 - ax_2) / 2 \quad (1)$$
$$Ym = (ay_1 - ay_2) / 2 \quad (2)$$
$$Rm = (ax_1 + ax_2) / 2 \quad (3)$$

In addition, the root-mean-square (RMS) of each acceleration value is calculated in accordance with a 0.1 s integral time constant; the resulting value is transmitted to a receiver and stored in a PC. The transmission frequency was approximately 50 S/s. The natural frequency of this acceleration sensor was 20 kHz. Figure 4 shows the external appearance of the chamfering drill and chamfering size. We targeted the M4-thread that countersink for a flat head screw often be required sealing. Therefore, we processed the countersink after creating a hole diameter of 4.5 mm. Figure 5 shows the countersink processing instrument and its corresponding rotating coordinate system. The edge of the countersink drill was positioned in parallel to the Xm axis. The workpiece was S45C of 100 mm × 100 mm × 50 mm. The workpiece was located on the dynamometer (type: 9272, KISTLER Corporation) on the table of the machining center for simultaneously measuring the vibration and cutting force. Table 2 shows the specifications of the countersink drill and cutting conditions.

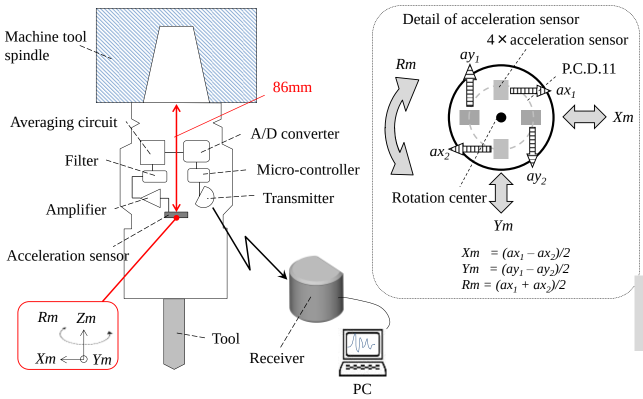

Fig. 3 Schematic diagram of wireless measurement tool holder system to measure vibration.

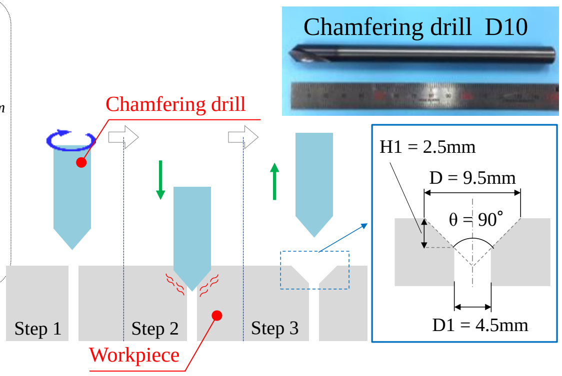

Fig. 4 Illustration of chamfering drill and the schematic diagram of the chamfering process.

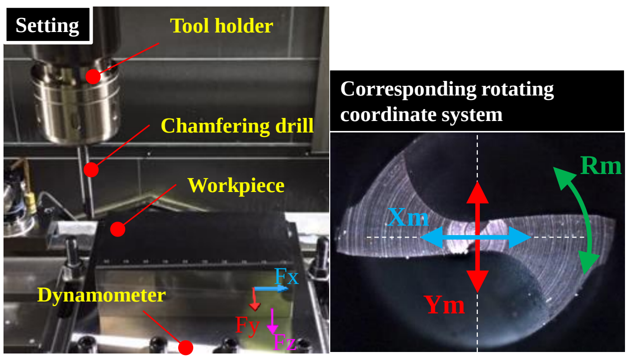

Fig. 5 Picture of corresponding rotating coordinate system.

Table 2 Tool infomation and cutting condition in chamfering

Tool information		Cutting condition	
Model num.:	FX-LS-LDS (OSG)	Speed:	40, 100 m/min.
Diameter:	10 mm	Feed:	0.05 mm/rev.
Length:	150 mm	L/D:	10
Num. of edge:	2	Cutting depth:	9.5 mm
Tip angle:	90 deg.	Step feed:	non-step
Twist angle:	12 deg.	Coolant:	dry
Cooting:	TiAlN		

Result and discussion

Relationship between cutting speed and drill temperature. Figure 6 shows the relationship between time and temperature, where the cutting depth was 50 mm, and the feed amount of one revolution was 0.2 mm/rev. We found that the heat input into the drill per unit time increased with the increase in the cutting speed. The drill was operable until the cutting speed 100 m/min, but was inoperable at the cutting speed 120 m/min because hard adhesion had occurred. In the drill processing of a blind hole, we found that the tool wore out quicker by the increased dwell time at the bottom hole, because the area between the drill and bottom hole increased the effect of rubbing, thus increasing the dwell time [5]. However, the temperature rise of the drill by the rubbing action at the bottom hole is not a sufficient estimate. Figure 7 shows the model regarding the relationship between the drill temperature and time required for the drill to create a blind hole. By setting the process started time to 0, the drill temperature rose at a little behind t_1. In between $t = 0$ and $t = t_1$, the calorific value is small because cutting was performed on only the chiseled edge, and heat transfer time is required from the edge to the central part. Therefore, the dead time t_1 occurred. In addition, considering the rubbing action during the dwell time, the time that the drill feed action decelerated and stopped is defined by t_2 (temperature at that time by T'), the time to retract the drill by t_3, max temperature by T_{max}, and the temperature rise is expressed as T_{max} - T'. Finally, the degree of effects for tool wear is modeled as the difference between T_{max} and T.

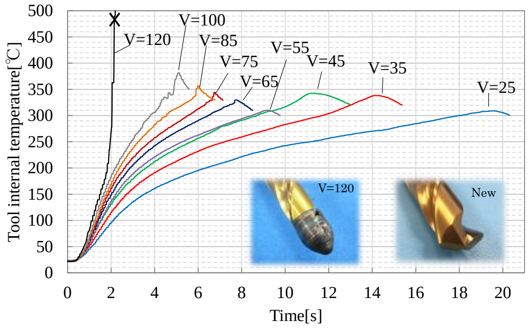

Fig. 6 Drill temperature when drilling under various cutting speed conditions.

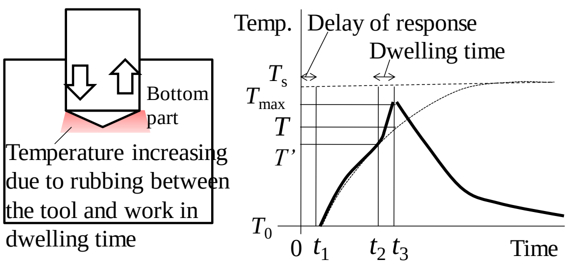

Fig. 7 Model of variation of temperature during drilling process at bottom part

Estimation with drill temperature and adhesion. Figure 8 shows the convergent temperature (T_s) of each cutting speed in Fig. 6 by T and time constant (T_m) at t_3 in Fig. 7. Figure 9 shows the average value of thrust and torque. In Fig. 8, we found that T_s suddenly increased at the cutting speed of 100 m/min. The phenomenon predicted the adhesion at the cutting speed 120 m/min. In Fig. 9, the decreasing of thrust and torque is attributed to the disappearance of the built-up edge at the cutting speed of 55 m/min. However, we found that the adhesion prediction during processing is difficult by only the cutting force, because the variation in the cutting force is unclear. Figure 10 shows the relationship between cutting speed and temperature rise ($T_{max} – T$) by the rubbing action at the bottom hole.

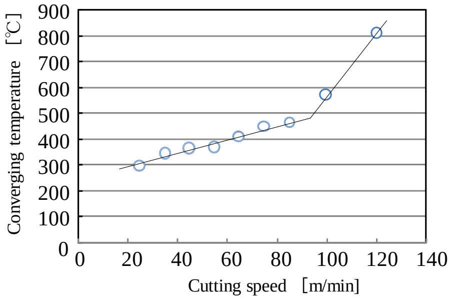

Fig. 8 Relationship Convergent temperature (T_s) and cutting speed.

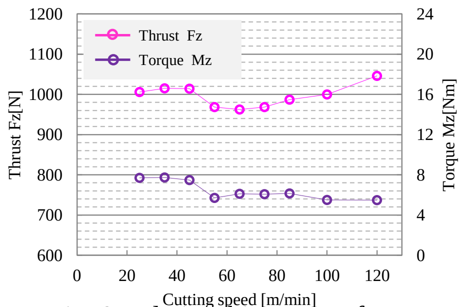

Fig. 9 Relationship cutting force and cutting speed.

We found that the temperature rise by the rubbing action increased while increasing the cutting speed. Figure 11 shows the microphotograph of the drill margin part. At the cutting speeds of 25 m/min and 55 m/min, we found that built-up edges occurred, but almost no damages were observed. At the cutting speed of 75 m/min, the tool wear or mark like high-temperature oxide film occurred. Furthermore, at the cutting speed of 100 m/min, the situation became worse. This phenomenon is the predicted adhesion. Therefore, initially, we identified the time constant (*Tm*) of the tool system in the safe cutting speed. Subsequently, we presumed the convergent temperature (T_s) between *t* and *T* when gradually increasing the cutting speed in the safe range; thus, we can set up a standard of optimization for the cutting speed by searching the condition that T_s suddenly increases against the cutting speed.

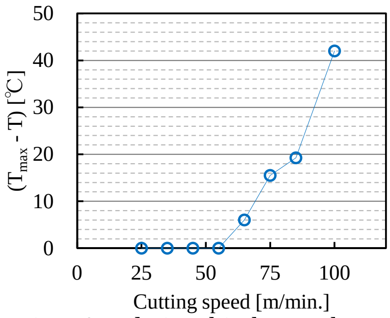

Fig. 10 Relationship betweeb cutting speed and temperature rise.

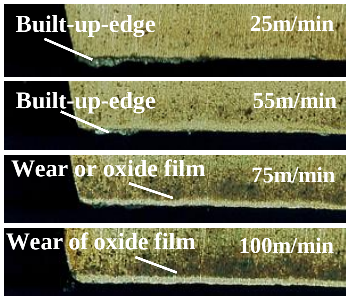

Fig. 11 Microphotograph of drill margin part.

Cutting force and vibration of tool system. Figure 12 shows the relationship among the cutting force of the workpiece side, the vibration acceleration of the tool side, the road meter of the spindle, and the Z-axis position with the conditions that the cutting speed was 150 m/min, the feed amount was 0.1 mm/rev, and the dwell time was equivalent to 40 revolutions. We found that the decrease in thrust by slowing down the feed speed of the Z-axis around 0.3 s, increases the variation component of the torque in dwell time at the bottom hole around 0.4 – 0.9 s. For the dwell time of the bottom hole, *Xm*, *Ym* increased and *Rm* clearly increased. Meanwhile, the dynamometer and this holder system could detect the vibration at the bottom hole, but the road meter of the spindle could not. Figure 13 shows the microphotograph and the profile curve measured along a circumferential direction on the processing countersink surface. The quality of the countersink surface was deteriorated by the occurrence of the chatter mark. Figure 14 shows the FFT result of the torque around 1 s in Fig. 12. Whether or not prepared hole in drill processing, to occur a coupling bending natural frequency of a beam with fixed-free or support is known [6]. To model a chamfering tool for the countersink in a beam with fixed-free conditions, the bending natural frequency with fixed-support conditions of this tool is 2200 Hz, that with fixed-free conditions is 1050 Hz, and the torsional natural frequency with fixed-free conditions of the holder is 4411 Hz. In Fig. 14, in addition to the bending natural frequency of a beam with fixed-support conditions, the bending of tool and the torsional of the holder natural frequency of a beam with fixed-free conditions is suspected. Therefore, this holder system is effective for monitoring chatter-vibration-coupled bending and torsion above 4 kHz.

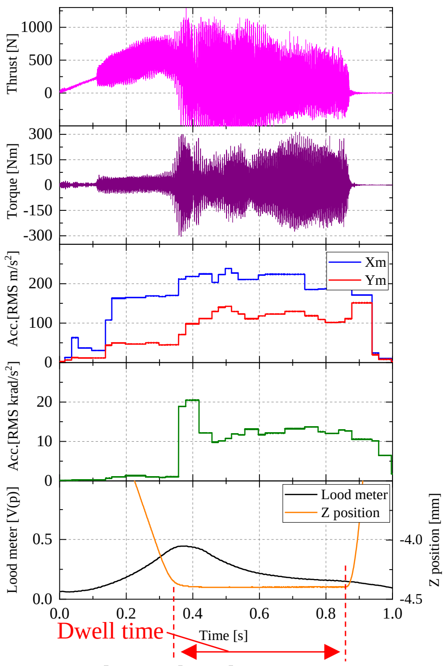

Fig. 12 Relationship that processing phenomenon by each sensors

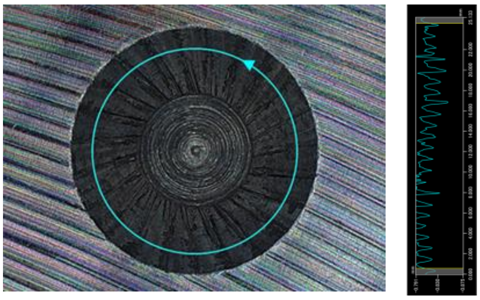

Fig.13 Microphotograph and profile curve of processing countersink surface.

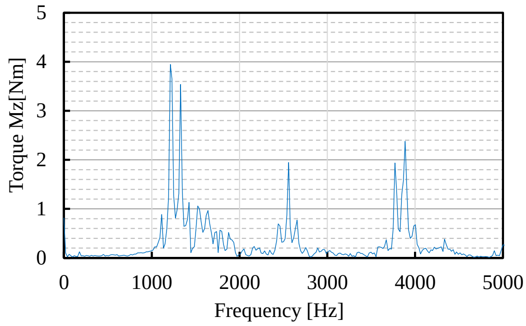

Fig.14 FFT result of measured torque during chatter vibration.

Summary

1) In setting of the cutting speed when drill processing, the method predicted the convergent temperature *Ts* based on monitoring the tool internal temperature at each condition is effective for setting up a standard adhesion.
2) In monitoring the tool internal temperature, by focusing on the temperature rise by the rubbing action at the bottom hole when processing a blind hole, some possibility of predicting a limited cutting speed in the safe range exist.
3) In addition, the natural frequency of a beam with fixed-free conditions also affects the natural frequency of a beam with fixed-support conditions; the chatter vibration that occurred in the countersink processing proved that the coupled vibration affected the torsional natural frequency of the holder.
4) Regarding the chatter vibration that occurred in the countersink processing, the detected function of the torsional vibration with this holder system is an effective method for detecting high frequencies, e.g., beyond 4 kHz chatter vibration in dwell time at the bottom hole.

References

[1] Adachi, K., Ogawa, K., Arai, N. and Igaki, H., Measurement of cutting temperature of drill point and cutting characteristics during low frequency vibratory drilling of aluminum, Journal of Japan Institute of Light Metals, Vol. 40, No. 3 (1990), pp. 171-175 (in Japanese).

[2] Rahim, E.A. and Sasahara, H, A study of the effect of palm oil as MQL lubricant on high speed drilling of titanium alloys, Tribology International Vol. 44(2011), pp. 309-317.

[3] Ueda, T., Nozaki, R. and Hosokawa. A., Temperature measurement of cutting edge in drilling (Effect of oil mist), Annals of the CIRP, Vol. 56(2007), pp. 93-96.

[4] Zaima, S., Yuki, A. and Horiuchi, O., A study on the countersinking of aluminum sheet (1^{st} report) On the relation between the geometry of countersink and the chisel edge angle of drill, Journal of Japan Institute of Light Metals, Vol. 15, No. 4 (1965), pp. 209-217 (in Japanese).

[5] Fujishima, M., Fukui, S., Kakino, Y., Ibraki, S., Yamaji, I., Nakagawa, H. and Hirogaki, T., Supprssion of drill wear by quick retract at the hole bottom in intelligent machine tools, Proceedings of Japan-US Flexible Automation, (2002), pp. 251-256.

[6] Fuji, H, Marui, E. and Ema, S., Generating mechanism of drill chatter, Transactions of the Japan Society of Mechanical Engineers, Series C, Vol. 51, No. 462 (1985), pp. 436-445.