Study on Circular Complex viewed from Environmental Systems – Environmentally-Friendly Cooling Air Drilling Performance –

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(Received September 14, 2007)

In machining processes, cutting fluids are generally used for cooling and lubricating workpieces at the point cutting. However, these fluids frequently include chlorine, sulfur, phosphorus, or other additives. The chemicals not only become a mist affecting the health of workers engaged in the processing but also make the workshop environment worse. In particular, the chlorine becomes one of the causes of global warming by treating waste oil under high temperature conditions. It is furthermore said that huge cost beyond the purchase cost of oil occurs and dioxins (carcinogen) usually exist in the waste oil. Therefore, an environmentally-friendly cooling-air cutting system is required from the standpoint of green manufacturing. This system has been noted as a technique to solve the issues against the environment mentioned above. In the cooling-air cutting processing, the amount of CO₂ emission shows a low value compared with the dry cutting one which uses oil. It is therefore thought that the cooling-air cutting system is a very important processing technique as an environmental countermeasure. At present, in strictly economic and environmental situations, the compatibility of the betterment of production efficiency with the improvement of environment is a subject in the actual spot of a cut processing.

This study deals with the test results of cooling-air drilling performance from the viewpoint of taking green manufacturing into account. The workpiece made of die steel SKD11 was manufactured by the cooling-air drilling performance at a revolution of 840 rpm and a temperature of -20°C with a high-speed steel drill (SKH56). The results were compared with those for the dry cutting performance. The main results obtained in this study are as follows: 1) The tool life for cooling-air drilling performance was about 6 times as long as that for the dry cutting performance. 2) The chip temperature for cooling-air drilling was 220°C lower than that for the dry cutting performance.

Key Words: Green Manufacturing, Circular Complex, Cooling-Air Drilling, Tool Life, Cutting Force

1. INTRODUCTION

Recently, the interest toward environmental issues in the field of cutting processing has been increasing by the legislative regulations such as ISO, and environmental correspondence has been required from the field of the manufacturing¹⁾⁻⁴⁾.

In the manufacturing field, cutting fluids have extensively been used for the improvement of cooling and lubricating effects and the elimination of chip. At present, however, the deterioration of work environment and waste disposal of cutting fluid exist in the processing field using the cutting fluid. Therefore, the improvement of the processing field is an important matter, and it is the center of attention among the engineers.

As one of the solutions for the problem mentioned above, the method of cooling-air drilling (hereafter called "cold drilling") is considered. It is reported that the discharge of CO₂ by using the

cooling-air drilling is less than 50 % of that of the method with cutting fluid (hereafter called "dry drilling")^{5), 6)}.

On the basis of such background, the drilling with cooling air was examined in this study. The cutting characteristics (tool life, cutting force and chip temperature, etc.) between the cold drilling and dry drilling were compared.

2. EXPERIMENTAL METHOD

2.1 DRILLING METHOD

Drilling tests were carried out with an NC machine equipped with a 5.5 kW motor (Model type: FANUC drill-model T). The cooling-air drilling system is shown in **Fig. 1**. The working length of the drill was constantly kept at 60mm for all the tests. The cutting forces (thrust, torque) were measured with a Kistler piezoelectric dynamometer. Compressed air from a compressor enters the mist separator in which fine particles are removed and

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Fig.1 Cooling-air drilling system

then it goes into an air drier so as to reduce its drill point.

Note that the heat exchanger was tentatively used and, due to lack of funds, we had to use the only apparatus available to us at that time. In machining processes, a refrigerating machine is a better alternative.

2.2 DRILL AND WORKPIECE

High speed steel drills manufactured from the same batch were employed in tool life measurements and the drills were all 6mm in diameter. The workpiece materials utilized in this study were made of the Die steel JIS SKD11 (150x300x20) which was produced by the cold dolling, and the average hardness of the steel plates was about 230HB. The surfaces of the workpieces were ground.

The chemical compositions and mechanical properties of the workpiece are shown in **Tables 1** and **2**, and **Table 3** shows the drill dimensions and hardness.

2.3 EXPERIMENTAL CONDITIONS

Drilling tests were conducted at a cutting speed (rotational speed of drill) of $14s^{-1}$ and a feed rate of 0.1mm/rev. The cutting condition employed is shown in **Table 4**. Moreover, **Table 5** shows the cooling-air condition for the cold drilling used in the experiment. Cool air ($-20^{\circ}C$) was supplied at a flow rate of 0.6 m^3/min (s.t.p.).

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 COMPARISON OF TOOL LIFE

In **Fig. 2** the tool life for the cold drilling is compared with that for the dry drilling. The results shown in **Fig.2** are the average number of drilled holes for five drills of each type, and the drilling depth was 20 mm. The cutting speed and feed rate were $14s^{-1}$ and 0.1mm/rev, respectively.

The criterion for the termination of tool life was the initiation of violent sound⁷⁾ during the penetration of the drill. The average number of drilled holes before the failure of drill for the cold drilling was 102 and that of the dry drilling was 16. Therefore, the tool life for the cold drilling was about 6 times as long as that for

Table 1 Chemical compositions (mass %)

C	Si	Mn	P	S	Cr	Mo	V	Fe
1.42	0.24	0.41	0.021	0.001	11.78	0.81	0.24	Bal.

Table 2 Mechanical properties

Tensile strength	675 MPa
Elongation	1.25 %
Brinell hardness	230 HB

Table 3 Drill dimensions and hardness

Drill diameter	6 mm
Length	102 mm
Flute length	70 mm
Point angle	118°
Web thickness	$0.87 \text{ mm} \pm 0.07$
Helix angle	$36^{\circ} \pm 1^{\circ}$
Relief angle	$14^{\circ} \pm 1^{\circ}$
Width of margin	0.43 mm
Lip height	0.08 mm
Hardness	1002 Hv

Table 4 Cutting conditions

Drill dia.	6 mm (JIS SKH56)
Feed rate	0.1 mm/rev
Revolution	840 rpm
Drilling depth	20 mm (through)

Table 5 Cooling-air conditions

Temperature	$-20^{\circ}C$
Pressure	0.14 MPa
Flow rate	0.6 Nm^3/min
Nozzle diameter	2 mm
Nozzle angle	45°

the dry drilling.

3.2 COMPARISON OF CUTTING FORCE

Figure 3 shows the relationship between drilling time and cutting force (thrust, torque) for the two types of drillings under

Fig.2 Tool life test result

the same cutting speed and feed rate. The cutting force for the 1st hole is mentioned.

As can be seen in the figure, the thrust for the cold drilling was statically stabilized. However, the thrust for the dry drilling became unstable in proportion to the drilling depth. That is, the thrust for the cold drilling is about 800N without depending on the drilling depth. The thrust for the dry drilling at cutting time of about 18 sec before drill penetration increased with an increase in the drilling depth, and the maximum value was about 1000N. Therefore, the decrease of about 25 % in the thrust for the cold drilling was obtained in comparison with that for the dry drilling.

Against this, a difference between the torque for the cold drilling and that for the dry drilling was small in view of the mean value. However, the dynamic component became greater for the dry drilling than for the cold drilling.

3.3 HEAT QUANTITY

It has turned out that the cutting force for the cold drilling decreases in comparison with that for the dry drilling. Heat quantities were determined on the basis of the experimental results of cutting force in order to clarify the reason why the cutting force was lowered for the cold drilling.

The following equations show the heat quantity per unit time by the torque and that by the thrust, respectively.

$$Q_m = 2\pi \cdot \frac{n}{60} \cdot M \quad (1)$$

$$Q_t = \frac{n}{60} \cdot \frac{F}{1000} \cdot T \quad (2)$$

Here, Q_m ; heat quantity due to torque
 Q_t ; heat quantity due to thrust
 M ; torque (Nm)
 T ; thrust (N)
 n ; revolution (rpm)
 F ; feed rate (mm/rev)

(a) Cold drilling

(b) Dry drilling

Fig.3 Cutting force (1st hole)

By assuming that the energy consumed per unit time is completely converted to heat, the total heat quantity can be determined by the numerical integration of the experimental results of the cutting force shown in Fig.3.

Fig.4 Experimental equipment for measurement of chip temperature

$$\int_0^t (Q_m + Q_t) dt \quad (3)$$

The measured values of the total heat quantity for the cold drilling and dry drilling were 258.2J and 287.5J, respectively. Consequently, the total heat quantity for the cold drilling brings about a reduction of about 10 % in comparison with the dry drilling.

3.4 COMPARISON OF CHIP TEMPERATURE

Next, the influence of the lowering of heat quantity on the temperature of chip discharging from the drill groove was investigated. **Figure 4** shows the manufactured simple apparatus for measuring the chip temperature⁷⁾. The chip temperature was estimated from the water temperature in the container into which the chip dropped. This measuring method⁸⁾ of cutting temperature which was estimated from the water temperature has not been reported yet. Under present situation, we have examined the water temperature during the cold drilling by using a simple apparatus.

After plotting the rising temperature of water, the chip temperature was approximated by a linear equation. **Figure 5** shows the measured values of the water temperature.

Figure 6 shows the relationship between the chip temperature and water temperature for estimating cutting temperature of drill point. The chip temperature for the cold drilling was about 280 °C as shown in the figure, while it was about 500°C in the dry drilling. Therefore, it is recognized that the chip temperature for the cold drilling brings about a decrease of about 220°C in comparison with the dry drilling.

The color of the chip for the dry drilling has changed from gray into violet due to the heat effect, whereas the color of the chip for

Fig.5 Measured values of water temperature

Fig.6 Relationship between chip temperature and water temperature with the cold drilling

the cold drilling scarcely changed.

It can be concluded that the reason why the tool life for the cold drilling increases is attributable to the lowering of the chip temperature.

3.5 CUTTING TEMPERATURE OF DRILL POINT

A method for measuring the cutting temperature of drill point is shown in **Fig.7**. The diameter of the drill which brazed a sheathed thermocouple was 10 mm. The drill was fixed by a chuck and a workpiece was rotated in the measurement. That is, the cutting temperature at the rake face of drill was measured by using the one of 10 mm diameter. **Figure 8** shows the measurement position of drill point.

Figure 9 shows the measurement results of the rake face temperature. The temperature of the drill point both for the cold drilling and the dry drilling increased with the drilling time. It was, on the whole, understood that the temperature of drill point for the cold drilling became lower compared with that for the dry drilling. The temperature of drill point for the cold drilling was about 200 °C and that for the dry drilling was about 330 °C. The difference was about 130 °C. It can be explained from the result that the drill life can be increased by using the cold processing.

Fig.7 Block diagram for measurement of cutting temperature of drill point

4. CONCLUSIONS

The conclusions of this study can be summarized as follows:

- 1) The cutting force (thrust) with the cooling-air drilling was 25 % lower than that for the dry drilling.
- 2) The tool life for cooling-air drilling was found to be about 6 times as long as that for the dry drilling.
- 3) The chip temperature for cooling-air drilling was 220°C lower than that for the dry drilling.
- 4) The cutting temperature of drill point for the cooling-air drilling became low with 130°C compared with that for the dry drilling.
- 5) Total heat value of cooling-air drilling brings about the lowering of about 10 % in comparison with the dry drilling.

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Fig.8 Measurement position of drill point
($a = 1.7$ mm, $b = 2.2$ mm, $r = 3.5$ mm)

Drill dia. $\phi 10$ mm Revolution 9.1 s⁻¹
Feed rate 0.1 mm/rev Depth 20 mm (Blind hole)

Fig.9 Comparison of cutting temperature of drill point

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