2002 Japan-USA Symposium
on Flexible Automation
Hiroshima, Japan, July 14-19, 2002

SUPPRESSION OF DRILL WEAR BY QUICK RETRACT AT THE HOLE BOTTOM IN INTELLIGENT MACHINE TOOLS

Makoto Fujishima
Soichiro Fukui
Mori Seiki Co. Ltd.
106 Kita-koriyama, Yamato-koriyama,
Nara, 639-1160, Japan

Yoshiaki Kakino
Soichi Ibaraki
Iwao Yamaji
Kyoto University
Yoshida-honmachi, Sakyo-ku,
Kyoto, 606-8501, Japan

Heisaburo Nakagawa
Toshiki Hirogaki
University of Shiga Prefecture
2500 Yasaka,Hikone
Shiga, 522-8533, Japan

ABSTRACT

The influence of the rubbing time on the tool wear of the drilling is studied, and it has been understood that the rubbing time produces a big influence on the tool wear. The system, which shortened the rubbing time with intelligent machine tool by quick retraction at the bottom of the hole, has been developed. By using this system the tool life was increased by 85% from the conventional model

Keywords: machine tools, drilling, intelligent system, rubbing, tool wear

INTRODUCTION

As described in previous our papers, the intelligent machine tool systems currently under development are basically aiming at high speed, high productive machining [1) -3)], For such machining, the tool life is a critical issue.

In this paper the authors address this problem by studying a method for extending tool life and achieving even higher speed and productive by using the sophisticated control functions of an intelligent machine tool to suppress drill wear. Specifically, the authors have analyzed the behavior of the drill at the bottom of hole, and attempted to suppress tool wear by shortening rubbing time, which is one of the causes of wear.

METHOD FOR SUPPRESSING TOOL WEAR AND ANALYSIS OF RUBBING TIME

Method for Suppressing Tool Wear

Tool wear proceeds not only when a normal drilling is carried out (when it is generating chips), but also when it has reached the hole bottom and is no longer cutting (not generating chips), i.e. in the so-called "rubbing" process. Tool wear during cutting is an intrinsic characteristic of the cutting itself and it is therefore difficult to suppress by control, but the tool wear that occurs during the rubbing is thought to be suppressible by control. To be more precise, by retracting the drill rapidly after it has reached the hole bottom, the rubbing time can be shortened and therefore tool wear can be suppressed. Prof. Weck has reported that tool life can be at least doubled by drilling on a machining center with linear motor drives capable of acceleration of 1G rather than a machining center with ball screw drives, which gives acceleration of 0.12G[4)]. Machining test results are shown in Figure 1.

The fact that tool life can be at least doubled by improving the acceleration means that, in normal drilling, tool wear during rubbing process (non chip generating process) is substantially greater than tool wear during cutting process (chip generating process), and therefore the control to shorten the time spent in the rubbing process will considerably extend tool life. The method illustrated in Figure 2, which takes this concept a stage further, is considered effective. Here, the rubbing time is significantly shortened by retracting the drill by applying the maximum torque at slightly higher speed of the servomotor when the tool reaches the hole bottom, which is followed by the normal retraction process. Because intelligent machine tools allow optimization of the servo characteristics (parameters) in machining modes such as drilling, tapping, and end milling, they make this kind of control very simple.

Analysis of Rubbing Time

Figure 2 shows an analysis of the extent to which rubbing time and rubbing distance can be reduced by quick retraction (hereafter called "retraction mode A"). A case where normal retraction is at an acceleration of 1 G (retraction mode B) is compared with a case where the normal retraction is at an acceleration of 0.2 G (retraction mode C) in this analysis.

Figure 3 shows the changes in the command velocity close to the bottom of the hole during drilling. The feedrate decelerates from 1200 mm/min as the tool approaches the bottom of the hole. At the point during this deceleration when the feedrate falls below the level appropriate for cutting, the drill starts rubbing against the material without generating chips: this is the so-called "rubbing" process. Figure 3 shows the status where the in-position check is not executed at the bottom of the hole, which means that the rapid traverse starts immediately after the cutting feed command is completed, rather than when cutting feed is completely finished.

The behavior of the drill at the bottom of the hole is precisely analyzed at this point.

On reaching the bottom of the hole during drilling - at the feedrate indicated in Figure 3 during deceleration of the cutting feedrate - the operation to reverse the direction of feed at the rapid traverse starts.

The feedrate of the rapid traverse with linear acceleration can be described as follows.

$$v = aT \times (t/T - 1 + e^{-t/T}) \qquad (1)$$

Where, v is feedrate (m/s), a is linear acceleration rate in rapid feed (m/s^2), t is the time at which rapid feed starts (s) and T is the servo constant (s),

For the sake of simplicity it is binominal approximation can be obtained by applying the Taylor expansion as follows.

$$v = aT(t/T)^2 / 2 \qquad (2)$$

where, v_r is the velocity at which rubbing commences (m/s). If the rubbing process finishes at the bottom of the hole, the rubbing time, "t_r" (s), can be obtained by:

$$t_r = \sqrt{(2T \cdot v_r / a)} \qquad (3)$$

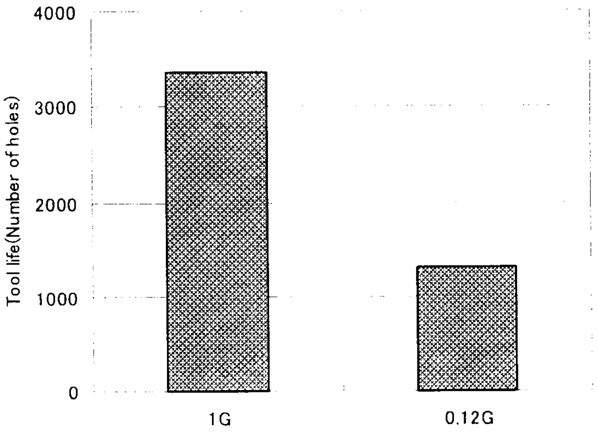

Fig.1 Drill life test effect

(Work piece: GG25. Depth of hole: 24mm.Cutting speed: 215m/min. Feedrate: 3.6m/min. Tool diameter: 8.5mm)

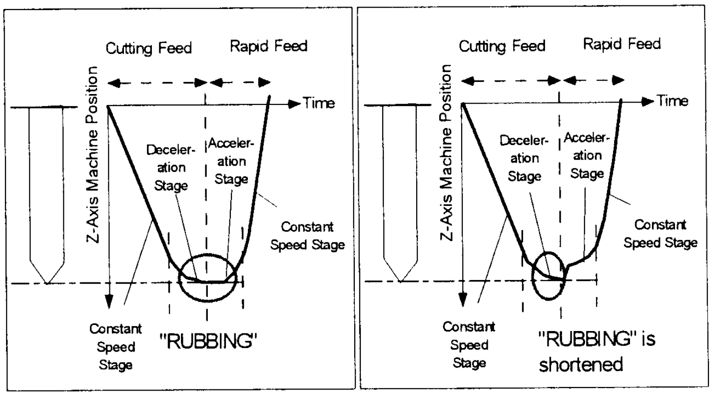

Fig.2 Position change at the bottom of the hole

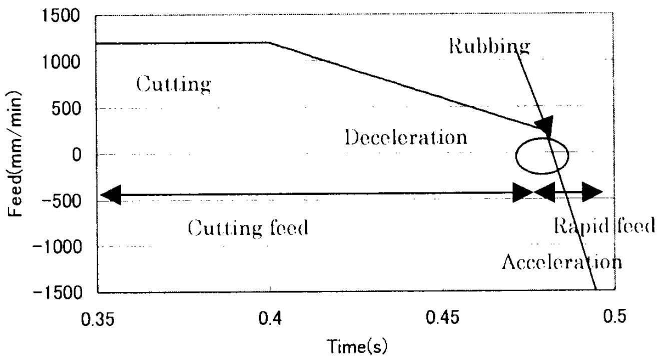

Fig3 Velocity change in drill cycle

(Feed rate:1200mm/min.Cutting time constant:100msec.Rapid accelalation:0.2G)

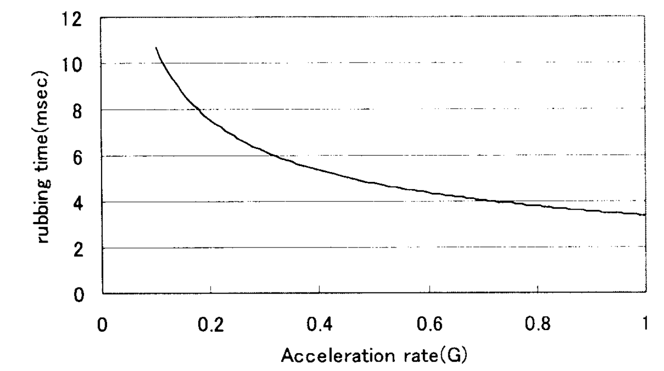

Fig.4 Relationship between acceleration rate and calculated rubbing time

(Cutting speed: 150m/min, Drill diameter: 8.5mm,Servo time constant: 10msec)

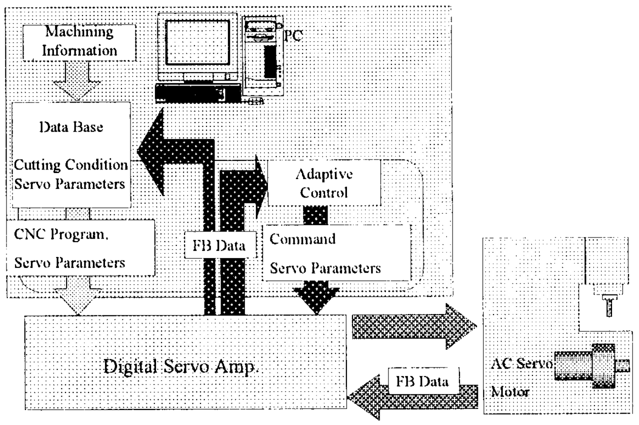

Fig.5 System configuration of intelligent machine tools

Based on this analysis, the rubbing process is established when the feed per revolution of the drill falls below 0.06 mm, and the relationship between the acceleration in rapid feed and rubbing time is shown in Figure 4 where the cutting speed is 150 m/min, the drill diameter is 8.5 mm, and the servo time constant is 10 msec.

Figure 4 shows the rubbing time during the descent of the drill. However it is thought that the rubbing process continues during retraction of the drill where the drill remains in contact with the material, i.e. until there is no more elastic deformation. In addition the result of calculations with theoretical equations has shown that it is very difficult to calculate extremely small motions at the bottom of the hole, therefore the rubbing time must be determined empirically.

EXPERIMENTAL EQUIPMENT AND METHOD

Experimental Equipment

The same equipment as used in previous reports, shown in Figure 5, was used: namely an intelligent machining center with a CNC unit based on an open architecture PC, a high-speed (60m/min) rapid-acceleration (1G) feed system, and a high-speed (20,000 min^{-1}) spindle.

For normal machining, servomotor and spindle motor currents were taken as a measure of cutting forces, but for precise measurement these currents were used in conjunction with a piezoelectric tool dynamometer.

Experimental Method

Cutting experiment. The workpiece material was cast iron FC250 (mean hardness HB220) and the tool used was an 8.5mm (Al - Ti) N-coated carbide drill. Holes of depth 25.5 mm (3D) were machined in the three retraction modes indicated in Figure 2. The cutting speed was 150 m/min (spindle speed = 5620 min-1), the feed per revolution was 0.3 mm, and a soluble type coolant was used with an internal lubrication method (pressure = 7 MPa).

Table 1 The Specification of the machining center

Spindle power (kw)	18.5
Spindle speed (min^{-1})	20,000
Spindle bearing material	Ceramic Ball + Stainless Steel
Spindle diameter (mm)	70
Type of spindle taper	7/24 Taper. No.40
Maximum feed rate (m/min)	60
Feed acceleration (G)	1
Stroke X/Y/Z (mm)	600×430×460
Servo motor output X/Y/Z (kW)	3.5/4.5/4.5
Ball screw diameter/lead (mm)	Φ36 /20
Guide way	Linear roller guide

Measurement of the Z-axis position and thrust close to the bottom of the hole. The actual behavior of the Z-axis close to the bottom of the hole was measured using a displacement gauge in the three modes described earlier. An eddy current sensor was used to measure both the change over time of the relative position of the spindle and table and the change in thrust close to the bottom of the hole in no-load operation. After this measurement, the thrust was measured in cutting experiments for each of the three modes, and the change in thrust close to the bottom of the hole was measured.

Measurement of tool wear. In order to measure the tool life in each mode, a large number of holes of depth 25.5 mm (3D) were machined successively in the three retraction modes indicated in Figure 1. Additionally, a large number of holes of depth 8.5 mm (1D) were machined in retraction mode B. This was done in order to investigate the effects on tool wear of extending the cutting distance and the number of rubbings (rubbing time).

The cutting force during drilling was measured by taking the spindle motor current as a guide, and the tool life was measured on the basis of changes in this current.

The cutting conditions used in the experiments were as follows:

Material: FC250 (cast iron) Cutting speed: 150 m/min
Tool: Cemented carbide drill with (Al, Ti) N coating
Feed: 0.3-mm/rev. Hole diameter: 8.5mm
Coolant: soluble type, 11.2 L/min

EXPERIMENTAL RESULTS AND EXAMINATION

Differences in Tool Life According to Retraction Mode

The relationship between the number of holes and mean cutting force (torque determined on the basis of spindle motor current) in high-speed drilling of FC250 cast iron in the three retraction modes described previously is indicated in Figure 6. When the tool is not worn, there is hardly any recognizable difference in the cutting force in the three modes, but as the number of machined holes increases, there is a relative increase in cutting force in modes with longer rubbing times (i.e. in the order C → B → A). The results of determining the tool wear coefficient W_f, defined in the reference (1), are shown in Figure 7. Since it has been confirmed that W_f has a good correspondence with the width of peripheral wear, Vc, we can see in Figure7 that peripheral wear progresses more quickly in modes with a longer rubbing time.

In Figure 7, if the point is taken where W_f= 0.25 to mark the tool life, the tool life in mode A is 3800 holes, in mode B it is 2700 holes, and in mode C it is 2000 holes. It is apparent that the shorter the rubbing time in the mode, the greater is the number of machined holes, and the longer is the tool life.

Differences in Rubbing Time, *Rt*, According to Retraction Mode

Figure 8 shows the profiles of Z-axis position from the time when the drilling starts, to the time when the retraction starts after the drill reaches the bottom of the hole, and the profiles of cutting force, measured by the method described in Section 3.2.2 in the three retraction modes. Note that since it is difficult to measure the Z-axis position during cutting with an eddy current sensor, the data in Figure 8 was obtained by measurement during air cutting. The temporary rise in the cutting force during deceleration that can be seen in the range 0.59 s to 0.6 s in the figure is due to speed fluctuation as the feed mode changes from cutting feed to rapid feed.

For the purposes of investigating the change in thrust in each mode close to the bottom of the hole in detail, overlaid position and cutting force data are shown on the magnified time axis in Figure 9.

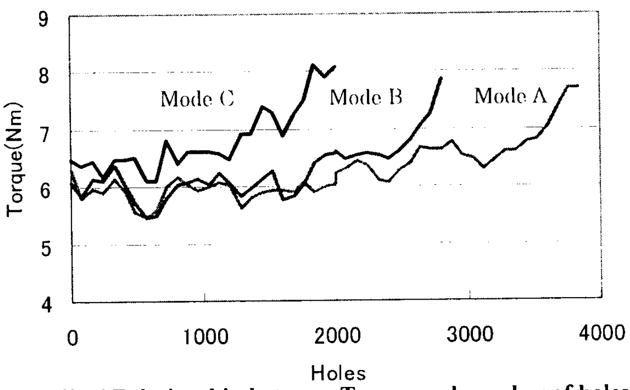

Fig.6 Relationship between Torque and number of holes

(Workpiece:F250,Tool: ϕ 8.5 (Al,Ti) N coated sintered carbide. Cutting speed: 150m/min. Feed:0.3mm/min)

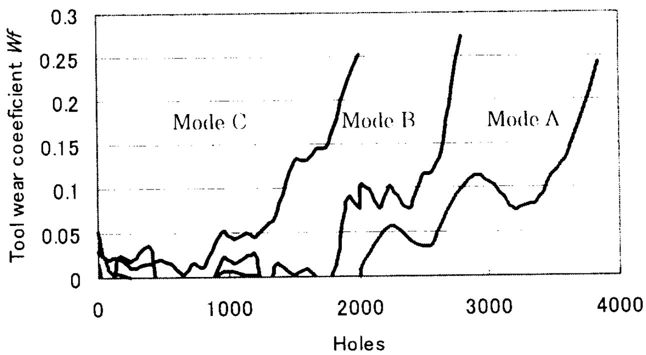

Fig.7 Relationship between tool wear coefficient and number of holes

(Cutting conditions: same as shown in Fig.6)

From this figure, the rubbing time Rt based on the assumption made in the theoretical analysis in Section 2.2 - i.e. that rubbing starts when the feed falls below 0.03mm per tooth, meaning 0.06mm/rev. (at a cutting speed of 150 m/min, this corresponds to a feedrate of 337mm/min, indicated by a black dot in the figure) - is found to be 6ms in mode A, 8ms in mode B, and 13ms in mode C. By multiplying it by the drill speed of 93.7 rotations per second, the number of revolutions that rubbing continues is calculated as 0.56 revolutions in mode A, 0.75 revolutions in mode B, and 1.22 revolutions in mode C.

Differences in Tool Wear According to Depth of Machined Hole

Figure 10 shows the relationship between the number of holes drilled and the mean cutting force (torque determined on the basis of spindle motor current) when holes are machined at depths of 1D and 3D. Despite the fact that there is a threefold difference in the cutting distance between the hole depths of 1D and 3D, hardly any change in spindle torque is observed as machining progresses.

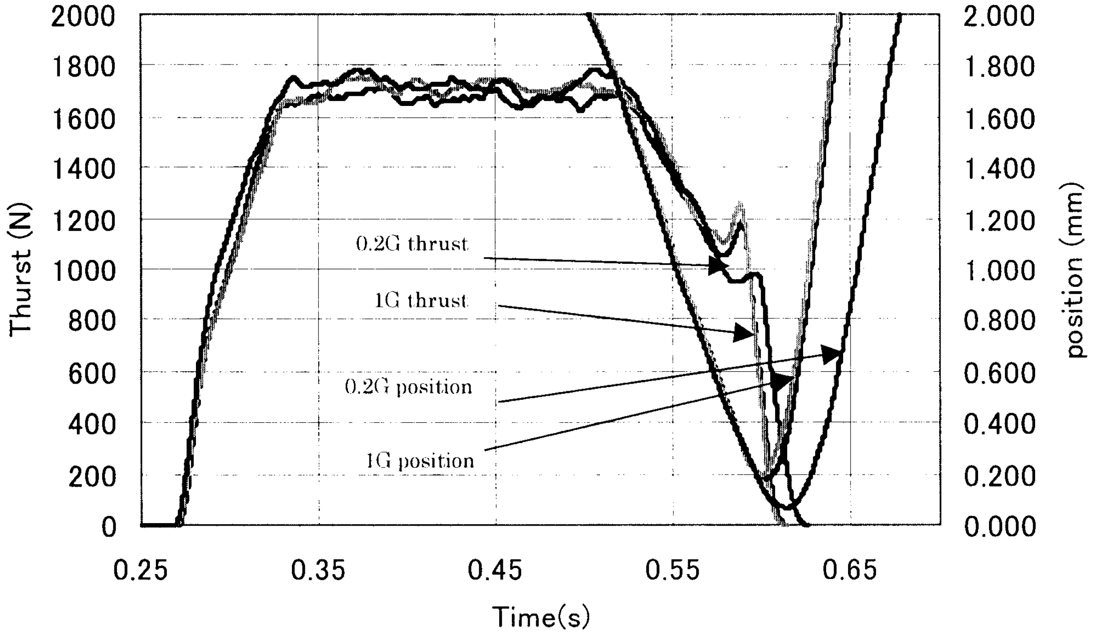

Fig8.Thrust and position change in a drill cycle at different modes (1cycle)

(Workpiece:F250,Tool: ϕ 8.5 (Al,Ti) N coated sintered carbide,

Cutting speed: 150m/min, Feed:0.3mm/min)

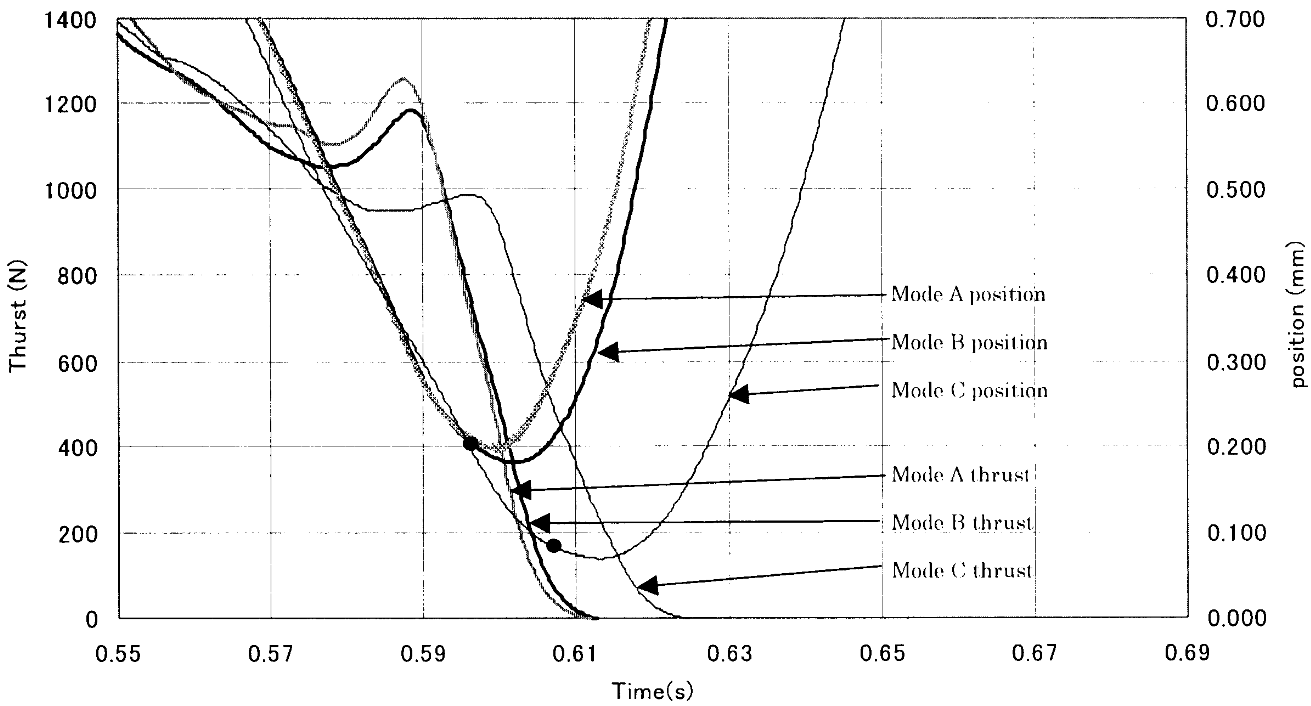

Fig.9 Thrust and position change in drill cycle at different modes (at the bottom of the hole)

(Cutting conditions: same as shown in Fig.8)

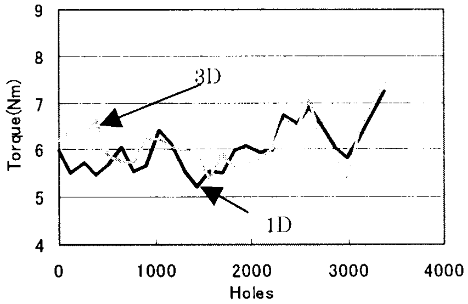

Fig.10 Relationship between cutting torque and number of holes at different depth of hole

(Workpiece:F250,Tool: ϕ 8.5 (Al,Ti) N coated sintered carbide, Cutting speed: 150m/min, Feed:0.3mm/min)

Verification of Experimental Results

We have seen that tool wear comprises wear at the bottom of the hole and wear during cutting. Tool wear is affected by chipping and chip blockages, the progress of it is extremely complex and very difficult to represent using a numerical model. However the tool wear coefficient *Wf* can be represented as following simple model.

$$Wf = n * (\alpha + \beta) \qquad (4)$$

In this equation, α is the coefficient for tool wear due to cutting for one hole, and β is the coefficient for tool wear due to rubbing for one hole.

The sum of the tool wear coefficients per hole ($\alpha + \beta$) is $6.8*10^{-5}$ in mode A, it is $9.3*10^{-5}$ in mode B, and it is $12.5*10^{-5}$ in mode C. The ratio among modes A, B, and C is 1: 1.38: 1.85.

The rubbing time described previously is 6 ms in mode A, 8 ms in mode B, and 13 ms in mode C, and similarly the ratio among the three modes is 1: 1.33: 2.16. These results are shown 11 and Table 2.

As shown in Figure 11, in each mode the wear coefficient due to rubbing for one hole shows a very good proportional relationship with rubbing time. It also appears that β is large in comparison with α. The value of α can be estimated about $2.5*10^{-5}$.

This can be confirmed in the experiment in Section 4.3, and in drilling at a depth of around 3D where chip blockage is minimal, it can be said that the effects of wear due to rubbing close to the bottom of the hole are greater than the effects of wear during cutting.

As is apparent, the rubbing time is shortest with a quick retraction at an acceleration of 1 G, and the progress of tool wear due to rubbing is suppressed under this condition. This is considered to be the reason that the tool life was longest with a quick retraction of 1G in Section 4.1.

This same reason is considered to explain why tool life is longer with a normal retraction at an acceleration of 1G than with an acceleration of 0.2 G. From the above, it is understood that under cutting conditions where wear is a dominant factor, drill life can be extended considerably by using the quick retraction operation with a high acceleration.

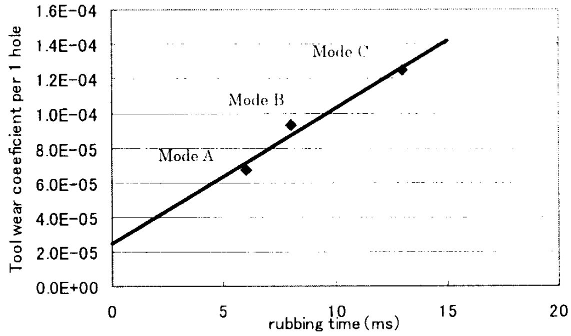

Fig.11 Relationship between tool wear coefficient and rubbing time

Table.2 Relation between rubbing time and tool wear

	Mode A	Mode B	Mode C
Acceleration (G)	1	1	0.2
Retract type	Quick	Normal	Normal
Tool life (Holes)	3800	2700	2000
Tool wear coefficient per 1 hole	$6.8*10^{-5}$	$9.3*10^{-5}$	$12.5*10^{-5}$
Rubbing time (ms)	6	8	13

CONCLUSION

As a result of research into a method of suppressing tool wear in machining of cast iron by shortening the rubbing time at the bottom of the hole during drilling, the following conclusion are made:

1) The tool is worn very quickly during rubbing, rather than during the period when chips are being generated.
2) The quick retraction mode, in which the rubbing time is restricted, is extremely effective in suppressing tool wear.

Due to 1) and 2), the mode in which only acceleration is increased (mode B) gives a 35% increase in tool life, and quick retraction mode A gives an 85% increase in tool life, when compared with the normal retraction mode C.

REFERENCES

(1) M.Fujishima et al. Integration of Adaptive Control Functions for Drilling in Intelligent Machine Tools, International Conference on Automation Technology 2000 Vol.1 pp.531-.535.

(2) Y. Kakino et al. High speed and High Productive Drilling by Intelligent Machine Tools, 1998 JAPAN-U.S.A. Symposium on Flexible Automation. Vol. 1, pp.285-289

(3) M. Fujishima et al. Study on Advanced Drilling by Intelligent Machine Tools (1st report) JSPE, Vol.66, No11, 2000, pp.1792-1796

(4) M.Weck et al. Next Generation High Speed Machine Tool Proc. of the 8th International Machine Tool Engineers Conference (1998) p.180