Cutting Mechanics of Turning with Actively Driven Rotary Tool*

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Abstract
In this paper, turning with actively driven rotary tool method was investigated. The main purpose of the present work is to examine influences of machining conditions especially the tool rotational speed and direction upon the cutting force components, the chip formation and the cutting temperature. Experimental results show that cutting temperature decreases with an increase in the tool rotational speed in a certain speed range. The change in tangential force against the tool rotation in CCW direction exited chatter due to the large radial force.

Key words: Turning with Actively Driven Rotary Tool, Cutting Force, Chip Formation, Cutting Temperature

1. Introduction

The rotary cutting tool[1] has received a considerable attention from many researches during past decades[2)-(8) due to its application in the machining process is possible to decrease the cutting temperature as well as to increase the machining productivity. As the cutting tool rotates and it is cooled during the non-cutting period in one rotation of the tool, it is expected that the temperature of the tool decreases compared with conventional turning. Several types of this method have been developed in the past, which are basically classified into two types namely actively driven[1)-(5) and self-propelled[6)-(8) tools. In the type of self-propelled, the tool rotational speed is depends on machining condition so that it is extremely difficult to optimize the process. On the other hand, in the type of actively driven, the tool rotational speed is controlled by the external power so that it can be changed easily and elevated. Therefore, high machining productivity can be achieved.

Despite those studies have showed the driven rotary tool has a potential, it has not been applied in real production process for several reasons: (1) By the past researchers[1)-(3), the driven rotary tool was only developed on the conventional machine tool, which is lack in stiffness, flexibility and productivity. (2) Machine tools were not available which could enable programmable control of the inclination angle, the offset height, and the tool rotational speed. (3) The state of art of cutting with driven rotary tools is still at pre-matured stage, and it requires systematic researches to apply the technology to actual production.

Recently, the new compound multi-axis machine tool has short cycle time and higher productivity due to faster rapid travel speed, the shorter the tool change time, the larger the depth of cut, and the higher the cutting speed has been developed[9]. Within this machine, B-axis head is used as turning tool holder and its postures such as the inclination angle and
the offset height, also its rotation speed and direction are controlled by the NC programmable, thus enabling the turning with actively driven rotary tool to applied with utilizing this machine.

Therefore, some researchers\(^{(4),(5)}\) have been devoted to the further development of this method in order to make it more applicable to the real production, but they only deal with the effect of inclination angle and the cutting speed on the cutting temperature, while the effect of the tool rotational speed on cutting temperature has not been investigated sufficiently. In contrast to that the present work is to experimentally investigate influences of machining condition especially the tool rotational speed and direction on the magnitude of the cutting force components, the chip formation and the cutting temperature.

2. Experimental procedure

2.1. Experimental equipment and condition

In turning with actively driven rotary tool used in this work could enables two postures of the tool cutting edge relative to the work. The inclination angle \(i\) of the tool holder and offset height \(h\) (offset angle \(\theta\)) are defined as shown in Fig. 1. When the tool rotates from point of large chip thickness to point of small chip thickness, the rotational direction of tool is defined to be counterclockwise. The work velocity \(V_w\), the tool rotational speed \(V_T\), the feed rate \(f\) and the resultant cutting velocity of work and tool rotational speed and its incline angle (that called as the dynamic inclination angle) are shown in Fig. 1. The increase of the tool rotational speed can leads an increase in the dynamic inclination angle. This causes the change of chip flow direction so that the cutting mechanics change from orthogonal to oblique cutting.

Figure 2 shows a photograph of the experimental equipment. In order to measure the cutting force in this equipment, an additional spindle is mounted on the table of a vertical machining center (Hitachi Seiki VM-3) to which the workpiece is attached as shown in Fig. 2. The NT series of integrated Mill Turn machine center, Mori Seiki NT4200 DCG, as driven rotary turning machine that applicable for industry was also utilized in order to measure the cutting temperature.

A 16 mm diameter insert made of PVD Coated Cermet having a relief angle of 11° was used. The work materials employed for the cutting experiment was plain carbon steel JIS:S45C. Cutting forces were measured using the piezoelectric force transducers of the force ring dynamometer. Cutting temperatures were measured utilizing embedded constantan wire-work thermocouple system. The major cutting conditions are summarized in Table 1.
2.2. Cutting force measurement

The three cutting force components of the tangential force $F_Z$, the axial force $F_X$ and the radial force $F_Y$ were measured with the force ring dynamometer as shown in Fig. 3. The force ring is composed of eight piezoelectric force sensors embedded in ring like frame, which it is installed at the fixing point of the main spindle head as shown in Fig. 3. Calibration of the dynamometer was carried out prior to the cutting tests to calibrate the sensitivities of the dynamometer with use of the table-type dynamometer and to compensate the cross talks of the output signals.

Figure 4 shows the flow chart of procedure to measure the cutting force. In order to measure the cutting force with the current measuring system, the following two problems must be solved. Firstly, error signal was arisen due to the mass inertia of the tool spindle. The typical of error signal of three force components were identified as shown in Fig. 5, which they are synchronized to the spindle rotation and repeatable during idle spindle rotation. In order to compensate the error signals, the force signals are measured during idle rotation of the spindle prior to the cutting tests, and subtracted from the cutting force measured. Secondly, cross talk was influenced the sensed force signal component. In order to solve this problem, the amounts of the cross talks are identified by the calibration and the three force components $F_X$, $F_Y$ and $F_Z$ are estimated by the corresponding three force signals measured, or $V_x$, $V_y$ and $V_z$ based on the following Eq. (1).

$$
\begin{bmatrix}
F_X \\
F_Y \\
F_Z
\end{bmatrix} =
\begin{bmatrix}
0.094 & -0.045 & -0.0035 \\
-0.060 & -0.079 & -0.005 \\
-0.003 & -0.015 & 0.107
\end{bmatrix}
\begin{bmatrix}
V_x \\
V_y \\
V_z
\end{bmatrix}
$$

(1)

where Coefficient’s unit is in N/mV.

![Fig. 3 Built-in type cutting force sensor](image)

Table 1: Major cutting condition

<table>
<thead>
<tr>
<th>Work material</th>
<th>Plain Carbon Steel (JIS:S45C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool: Type Material Geometry</td>
<td>RPMT 1604 MO-BB (Kyocera) PVD Coated Cermet Relief angle $\alpha=11^\circ$, Diameter D=16 mm</td>
</tr>
<tr>
<td>Tool rotational speed $N_r$, min$^{-1}$</td>
<td>0 – 1500</td>
</tr>
<tr>
<td>Work speed $V_w$, m/min</td>
<td>100; 150; 160</td>
</tr>
<tr>
<td>Feed $f$, mm/rev</td>
<td>0.1; 0.143; 0.2</td>
</tr>
<tr>
<td>Depth of cut $a$, mm</td>
<td>0.5; 1</td>
</tr>
<tr>
<td>Inclination angle $i$, deg.</td>
<td>0</td>
</tr>
<tr>
<td>Offset angle $\theta$, deg.</td>
<td>0</td>
</tr>
<tr>
<td>Cutting fluid</td>
<td>Dry</td>
</tr>
<tr>
<td>Direction of the spindle rotation</td>
<td>Tool spindle: CW; CCW</td>
</tr>
</tbody>
</table>
2.3. Cutting temperature measurement

A constantan wire was embedded in the workpiece as shown in Fig. 6. To embed the constantan wire into a workpiece, the workpiece must be cut sliced into two parts, and then a V slot was machined parallel to the central axis of one of parts. The principle of this method is that when the workpiece is cut by the cutting edge, the wire is also machined, and a thermoelectric junction (emf) is formed between the constantan wire and the workpiece at contact area. The work and constantan wire must be electrically isolated from machine tool with using a ceramic coating. To record cutting temperature signals at contact area between the workpiece and tool, the constantan wire and the workpiece wire were connected to a slip ring through a hole at center of the work spindle and then they were connected to an oscilloscope. High sampling frequency of 500kHz was used. By calibration test of the wire-work thermocouple, the correlation between the temperature and the emf generated at the contact area between the constantan wire and the tool was obtained as shown in Eq. (2).

\[ V = 0.0562T \quad (2) \]

where \( V \) is the output voltage in mV, and \( T \) is temperature in °C.

An example of the raw data of output signals detected by embedded constantan wire-work thermocouple technique is shown in Fig. 7. This output signal was obtained periodically that the interval between each signal is equal to frequency in which the cutting edge touches the constantan wire inside the workpiece each one revolution of work. As the output signal was detected during uncutting period, it is seemed that the constantan wire was contacted to the workpiece after the cutting. The temperature increases when the cutting edge near to the constantan wire and continues to increase to its peak of
approximately 500°C (28mV) when the cutting edge cuts the constantan wire in approximately 40µs of time (N_w=500rpm). In view of that, it is great clearly that by using this thermocouple technique, the high local temperature at contact area between the cutting edge and the workpiece can measured accurately.

In addition, another important parameter is the cooling time of workpiece as shown in Fig. 7, which is defined as amount of time that needed when the high temperature at the contact point area at the workpiece surface gradually reduced to the ambient temperature of approximately 25°C (1.4mV) due to heat dissipated into workpiece and heat loses by convection and radiation.

3. Result and discussion

Figure 8 shows the effect of the tool rotational speed on cutting forces when the tool was rotated in both the clockwise (CW) and the counterclockwise (CCW) directions. The tangential and radial forces decrease with increasing the tool rotational speed in a speed range from 60m/min (CCW) to 45m/min (CW). However, the change of tangential force against the tool rotational speed is not so large as the change in radial force. The axial force increases with an increase in clockwise tool rotational speed. When the tool is rotated in CW direction, the tangential velocity of the tool has the same direction with feed direction.
That results in large axial direction velocity, which is the sum of the tangential velocity of tool and feed speed. This factor increases the axial force component with an increase in the tool rotational speed. As consequently of magnitude all cutting force component, the resultant cutting force decreases with an increase of tool rotational speed. The change of resultant cutting force against the tool rotational speed is also not so large in experimental range of the tool rotational speed.

However, the chip surface that produced during machining for both tool rotational direction of CCW and CW is rather different as shown in Fig. 9. The chatter mark was observed on the chip surface during machining with tool rotational direction of CCW, while the smooth chips surface was observed when the tool rotated in the opposite direction. It was seemed that the unstable cutting or chatter occurred during machining with tool rotational directions of CCW due to the large radial force.

Figure 10 shows the photograph of chips obtained during machining with various tool rotational speeds. With the increase of tool rotational speed, the helix angle of chips was increased, then it seems that the chip flow becomes smooth, also its flow direction was changed. This indicates the cutting mechanics change from the orthogonal to the oblique cutting. This leads to an increase in the effective rake and shear angle. It is understood that the increase of these angles cause the decrease of the cutting force with an increase in the tool rotational speed.

In addition, the chips formed at the non rotating tool are colored in the dark-bluish that caused by oxidation, also the dark-bluish of chip color was obtained for case of a tool rotational speed of 25 m/min, but its color did not dominant in bluish. This means that those chips were formed at higher temperature as compared with those formed at the tool rotational speed of 50 and 75 m/min, which are colored in brownish-purple.
Figure 11 shows the effect of the tool rotational speed on the cutting temperature signal and cooling time under a fixed cutting speed of 150 m/min. It can be seen from this figure that tool rotational speed has a significant effect on the cutting temperature. The cutting temperature decreases with increasing tool rotational speed in a speed range from 0 to 75 m/min. It is seemed that the decrease of the cutting force leads a decrease in the cutting energy, and then resulting a decrease in the cutting temperature.

In addition, when the tool rotational speed increases, the cooling time became short because of the fall of the cutting temperature. To understand the characteristic of cooling abilities of driven rotary tool, definition of the cooling time is determined as described in the sub section 2.3. However, it was assumed that the effect of cooling at the ambient temperature is the same to both the tool and the workpiece. In case of the tool rotational speed of 75 m/min (1500 rpm), the tool cutting edge needs time of 40 ms for entering to cutting zone. As compared with the cooling time of 23 ms at this condition as shown in Fig. 11, it is seemed that the cutting edge was cooled down before entering the cutting zone. However, if the tool rotational speed is higher than 75 m/min, the cutting temperature of cutting edge may be continue to rise due to the heat accumulation. This means that the cooling of the tool edge includes the upper limit.

![Fig. 11 Effect of tool rotational speed on cutting temperature](image)
4. Conclusions

Turning with actively driven rotary tool method with programmable control the tool rotational speed was carried out. The influence of machining conditions especially the tool rotational speed and direction upon the cutting force and temperature was experimentally examined. Major experimental conclusions are as follows:
1. The change in tangential and resultant cutting force against the tool rotational speed is not so large as compared with that of radial and axial force.
2. The radial forces decreases with an increase in tool rotational speed, while the axial force increases with an increase in tool rotational speed.
3. Chatter marks were observed when the tool rotational speed with tool rotational direction of CCW increased.
4. The cutting temperature decreases with the increase of tool rotation speed in a certain speed range.

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