The Experimental Investigation of Cutting Forces and Chip Formation on Turning with Actively Driven Rotary Tool

Suryadiwansa Harun[1], Toshiroh Shibasaka[2]

[1]Jurusan Teknik Mesin, Fakultas Teknik, Universitas Lampung, Lampung, Indonesia
[2]Graduate School of Engineering, Kobe University, Kobe, Japan

Abstrak: This paper presents an experimental investigation on chip deformation of the actual turning with actively driven rotary tool. The main purpose of the present work is to make clearly the effect of tool rotational speed and its direction upon the cutting force components, and the chip formation. In order to investigate the effect of tool rotation with a wide range of speed, the cutting tool is driven by the high speed motor of main spindle machine and its rotation is controlled by NC Programmable. The components of cutting force were measured using the piezoelectric force transducers of a force ring dynamometer. Experimental results show that the tool rotational speed can lead an increase in the dynamic inclination angle so that causes the helix angle and the pitch of chip were increased. This indicates the cutting mechanics changed from the orthogonal to the oblique cutting. It was also found that the tool rotational speed has a significant effect on the cutting forces. The resultant and tangential cutting forces decrease with increasing the tool rotational speed to certain value and then constant. The resultant cutting force of rotary tool was approximately 18% lower than the resultant cutting force recorded by the cutting with a non-rotating tool. The axial force increases with an increase in tool rotational speed in a certain speed range and then constant. Interestingly, the constant of the cutting forces as mentioned above along with the increase of the tool rotational speed was obtained at the dynamic inclination angle higher than 45deg. or the velocity ratio higher than 1.
Keywords: Turning with actively driven rotary tool, Tool rotational speed, Cutting forces, and Chip formation.

1. Introduction

High speed cutting has become one of the most promising advanced manufacturing technologies in recent years. The advantages of high speed cutting are high productivity and lower cost. However, as a consequence of high speed cutting, the cutting temperature rises and the life of the cutting tool is shortened. The temperature at the primary shear zone affects the mechanical properties of work material, and high temperature along the tool-chip interface greatly influences the tool wear which leads to drastic reduction of the tool life. When the tool wear progresses, the cutting force, the vibration and the cutting temperature are increased, and hence it causes deterioration in the surface integrity and the dimensional accuracy. Finally the cutting tool reaches to its life, and then the cutting tool must be replaced. Many researches have been carried out to seek for effective methods to overcome the cutting temperature rise when high speed cutting is applied. One of the possible novel methods to decrease the cutting temperature as well as to increase the machining productivity is to apply a rotary cutting tool in turning (Shaw et al., 1952). As the cutting tool rotates and it is cooled during the non-cutting time in one rotation of the tool, it is expected that the temperature of the tool will decrease compared with conventional turning. It is also expected that the rotary cutting tool can be used for high speed cutting of difficult-to-cut materials such as nickel based and titanium based alloys (Lei et al., 2002). However, The state of art of cutting with rotary tools in turning is still at pre-matured stage, and it requires systematic researches before applying the technology to actual production.
The forces acting on the tool are the important aspect of the machining, which is needed for estimating the required power. Also, they have a significant effect on the quality of machined

part. In case of the actual turning with circular cutting edge, the tool-workpiece contact arc is long, thus it can lead to the larger trust radial force (Chou et al., 2004). Therefore, if the structure of the rotary turning tool-holder is lack in stiffness, the deflection of tool could possibly occur. In fact, it is quite often that the occurrence of chatter or poor surface finish can be directly traced to deflection of the tool due to the lack of tool stiffness itself. In order to enhance the stiffness of tool holder system so that the deflection of the tool can be prevented, knowledge about the forces acting on the tool during machining process of the actual turning by circular cutting edge motion is essentially required. Therefore, investigation of cutting force on chip deformation mechanism of the actual turning with rotary tool should be carried out.
This paper presents an experimental investigation on chip deformation of the actual turning with actively driven rotary tool. The main purpose of the present work is to make clearly the effect of tool rotational speed and its direction upon the cutting force components, and the chip formation. In order to investigate the effect of tool rotation with a wide range of speed, the cutting tool is driven by the high speed motor of main spindle machine and its rotation is controlled by NC Programmable.

2. A Feature of Turning With Actively Driven Rotary Tool

Figure 1 shows the basic feature of the turning with actively driven rotary tool process used in this work. Geometrically, this method is characterized by the circular cutting edge, the normal rake angle and the clearance angle. In addition, it is possible to have two positions of the tool cutting edge relative to the work. The inclination angle *i* of the tool holder and offset height *h* (offset angle θ) are defined in Fig. 1. Kinematically, three motions are involved in this method: (1) Cutting motion, work velocity V_W, (2) Feed rate of the tool *f* into workpiece, and (3) The tool rotation speed V_T as the main feature in this method, which causes sidewise motion of tool. It is assumed that when the tool rotates from point of large chip thickness to point of small chip thickness, the rotational direction of the tool is defined to be counterclockwise. Further, the incline angle (that called as the dynamic inclination angle i_d) of the resultant vector of both cutting velocity of work and tool rotational speed was also formed, which it can be expressed as shown in Eq. 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 (Shaw et al., 1952) so that the cutting mechanics change from orthogonal to oblique cutting.

$$\tan i_d = \frac{V_T}{V_w \cdot \cos\theta \cdot \cos i} \qquad (1)$$

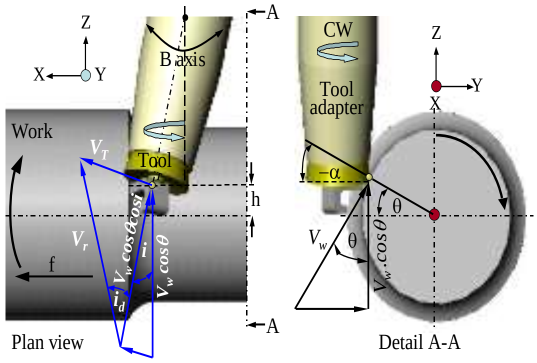


Figure 1. Principle of turning with actively driven rotary tool (Harun, 2008)

3. Experimental Procedure

3.1. Experimental Equipment and Condition

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. A 16 mm diameter insert tool made of PVD Coated Cermet having a normal rake angle of 11^o was used. The insert tool was clamped on the special tool adapter, and then they were fixed on the milling spindle, which is its rotation changed easily and elevated by the programmable control. The work materials employed for the cutting experiment were plain carbon steel JIS:S45C, which were finished prior to the cutting test in the form solid bar of 50 mm diameter and 120 mm length. Cutting forces were measured using the piezoelectric force transducers of a force ring dynamometer. The major cutting conditions are summarized in Table 1.

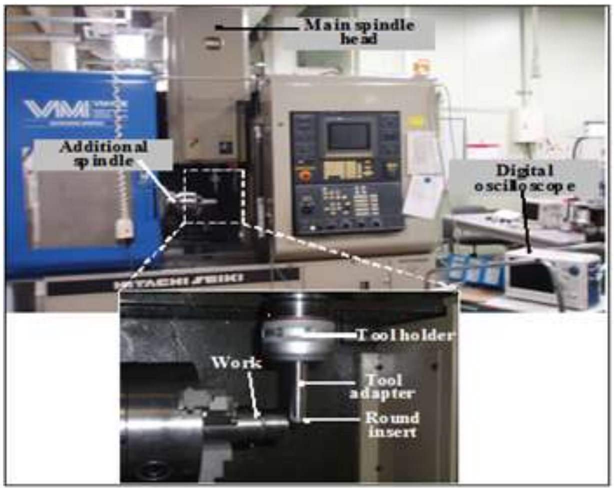


Figure 2. Photograph of experimental equipment of the vertical machine center (Harun, 2011)

3.2. *Cutting Force Measurement*

Figure 3 shows a schematic illustration of the cutting force measurement system in turning with the rotary cutting tool. There are three components of the cutting forces, consist of the tangential force, F_Z, which acts in the tangential direction of the rotating work and represents the resistance to the rotation of the work. The axial fore, F_X is longitudinal force component acting in the direction parallel to the axis of the work rotation. The radial force, F_Y is acting in the radial direction of the work from the centre of rotation. The resultant force, F_R is given by,

$$F_R = \sqrt{(F_X)^2 + (F_Y)^2 + (F_Z)^2} \quad (2)$$

The three cutting force components as mentioned above were measured with the force ring dynamometer as shown in Fig. 3.b. The force ring is composed of eight piezoelectric force sensors embedded in ring like frame, which is installed at the fixing point of the main spindle head as shown in Fig. 3.b. In order to record the output of cutting force signal from those sensors, they should be sent to change amplifiers prior they recorded by using the digital oscilloscope. In order to get an accurate measurement ofthe cutting force components, 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 also the cross talks of the output signals was compensated (Harun, 2011).

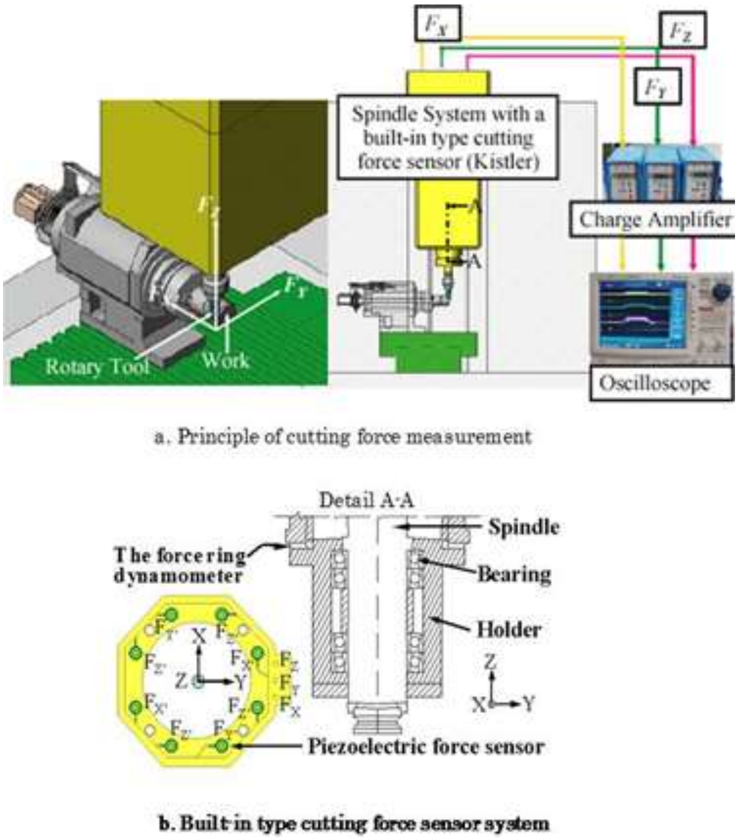
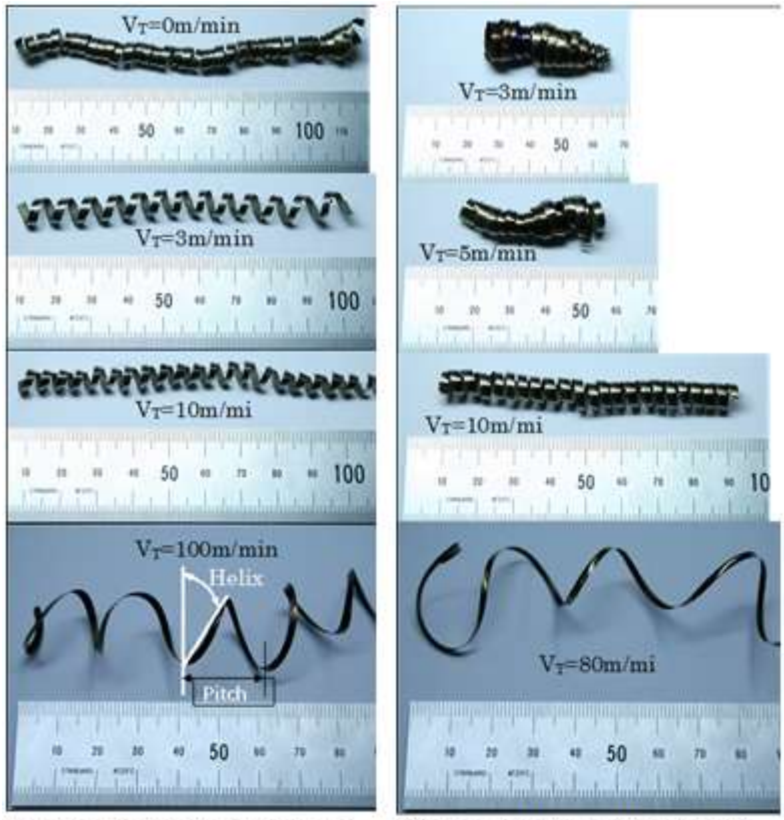


Figure 3. Schematic illustration of cutting force measurement (Harun, 2011)

Table 1. Major cutting condition

Work material	Plain Carbon Steel (JIS:S45C) Diameter=50mm
Tool	Type: RPMT 1604 MO-BB (Kyocera) Material: PVD Coated Cermet Geometry: Normal rake and relief angle $\alpha=11^0$, Diameter D=16 mm
Tool rotational speed N_T, min^{-1}	0 ~ ±4000
Work speed V_W, m/min	60 ~ 160
Feed f, mm/rev	0.1 ~ 0.25
Depth of cut a, mm	0.5; 1
Inclination angle i, deg.	0
Offset angle θ, deg.	0
Cutting fluid	Dry
Direction of the spindle rotation	Tool spindle: CW; CCW

ISBN 978 979 8510 61 8



(a) Tool rotational direction of clockwise, CW (b) Tool rotational direction of counterclockwise, CCW

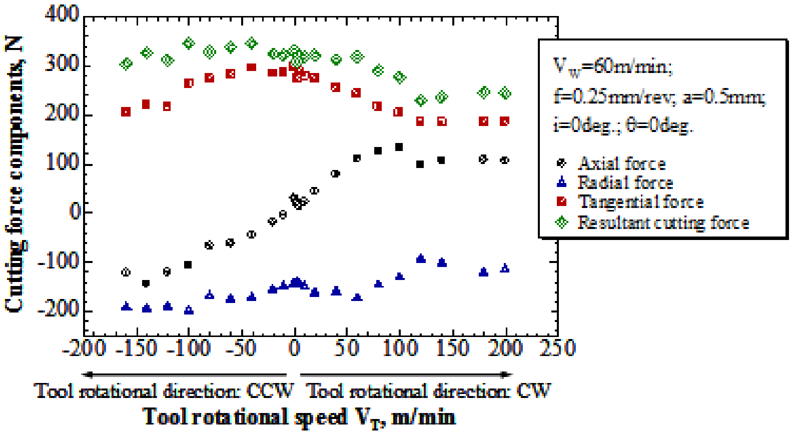
Figure 4. Photographs of chip obtained during machining with various tool rotational speed (cutting conditions: V_W=60m/min; a=0.5mm; i=0deg.; θ=0deg.)

4. Result and Discussion

4.1. Chip formation

Figure 4 shows the photograph of chips obtained during machining with various tool rotational speeds and in either direction ofthe clockwise (CW) and the counterclockwise (CCW). In case ofthe tool was rotated in CW direction, see Fig. 4.a, with increasing the tool rotational speed, the helix angle of chips and the pitch of chip were increased, and 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.

Interestingly, the chip produced during machining when the tool was rotated in CCWis somew hat different as compared to the opposite direction as shown in Fig. 4.b. As observed in this fi gure, it was rather broken especially at the low tool speeds (3 and 5 m/min). It is further obser ved that its helix angle and its pitch were smaller as compared to the case of the tool rotate in opposite direction. This caused by the chip stacked on the work surface so that the chip flow b ecomes not smooth.



a. Case of VW = 60m/min

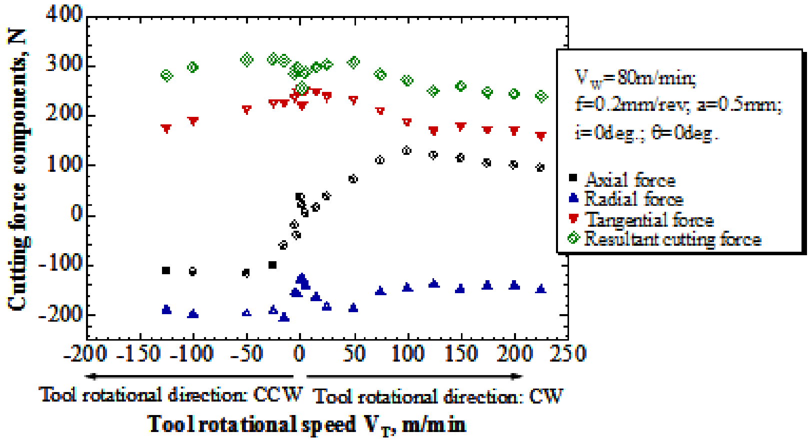


Figure 5. Effect of tool rotational speed on cutting forces

4.2. Cutting Force

Figure 5 shows the effect of the tool rotational speed on cutting forces when the tool was rotated in either direction of CW and CCW. In case of the cutting speed V_W of 60 m/min, the tangential force decreases with increasing the tool rotational speed in either tool rotation direction of CCW and CW, see Fig. 5.a. This can be attributed to reduced amount of work done in chip deformation of turning with actively driven rotary tool. According to Eq.1, the increase of tool rotational speed can lead an increase in the dynamic inclination angle so that causes the helix angle and the chip pitch increased. This indicates an increase in chip flow angle, and then leads the effective rake and shear angle was increased. These factors cause the cutting force decreases along with the increase of tool rotational speed. Interestingly, the decrease of the tangential force with an increase in clockwise tool rotational speed was effective to a speed limit of approximately 100 m/min or the velocity ratio is higher than 1 (calculated from Eq.1) and then constant. It means that the decrease of that cutting force based on the increase of tool rotational speed already reaches the saturation state. In others word, the effect of effective rake and shear angle to decrease the cutting force was limited by the increase of tool speed cutting itself. Furthermore, it is interested that the variation of tangential force along with the increase of counterclockwise tool rotational speed was almost constant in a speed range from 0 to -40 m/min. This seems caused by the chip stacked on the work surface so that the chip flow becomes not smooth.

In contrast to those cutting forces, the axial force increases with an increase in clockwise tool rotational speed and then constant as shown in Fig. 5.a. 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 (Harun, 2008). However, the change of axial force with increasing the tool rotational speed was almost constant in a speed range is higher than approximately 60 m/min, which is the equal to the dynamic inclination angle of 45deg (case of V_w= 60 m/min) or the velocity ratio of 1 as calculated from Eq.1. When the tool rotational speed is higher than the work cutting speed V_W (the dynamic inclination angle is higher than 45deg.), the chip will sliding on the rake face of the tool. It is seemed that the sticking region at chip-tool interface is eliminated, and this tends to reduce of the frictional drag. The drop in the frictional drag was invoked to explain the observed constant change in the magnitude axial cutting force at the velocity ratio range is higher than 1.
The radial force decreases slightly as increasing tool rotational speed in clockwise tool rotation direction, while it was almost constant as increasing tool rotational speed in opposite direction. As consequence of magnitude all cutting force components, the resultant cutting force also decreases along with the increase of tool rotational speed in experimental range of the tool rotational speed.
In addition, the resultant cutting force of rotary tool was found to be smaller, which was approximately 18% lower than the resultant cutting force recorded by the cutting with a non-rotating tool. The similar trend was also observed at the case of the cutting speed was changed from 60 to 80 m/min as shown in Fig. 5.b. It is importantly noted that the results as mentioned above were not reported by the past researchers.

5. Conclusion

In this paper, an experimental examination of the effects of the tool rotational speed and direction upon the chip formation and the cutting forces during turning with the actively driven rotary tools were carried out. The following remarks are concluded in this paper from the experiments.

1. It was found that the increase of the tool rotational speed can lead an increase in the dynamic inclination angle so that causes the helix angle and the pitch of chip were increased.
2. It was further found that the tool rotational speed has a significant effect on the cutting forces. The resultant and tangential cutting forces decrease with increasing the tool rotational speed to certain value and then constant. The resultant cutting force of rotary tool was approximately 18% lower than the resultant cutting force recorded by the cutting with a non-rotating tool.
3. The axial force increases with an increase in tool rotational speed in a certain speed range and then constant.
4. Interestingly, the constant of the cutting forces as mentioned above along with the increase of the tool rotational speed was obtained at the dynamic inclination angle higher than 45deg. or the velocity ratio higher than 1.
5. However, the radial force decreases slightly as increasing tool rotational speed in clockwise tool rotation direction, while it was almost constant as increasing tool rotational speed in opposite direction.

6. References

Shaw, M.C., Smith, P.A., and Cook, N.H., the Rotary Cutting Tool, Transactions of the ASME.1952:74:1065-1076.

Lei, S.T. and Liu, W.J., High-speed Machining of Titanium Alloys Using the Driven Rotary Tool, International Journal of Machine Tools and Manufacture. 2002:42:653-661.

Chou, Y. K. and. Song, H., Tool nose radius effects on finish hard turning, Journal of Materials Processing Technology. 2004:148(2):259-268.

Harun, S., Shibasaka, T., and Moriwaki, T., Cutting Mechanics of Turning with Actively Driven Rotary Tool. The Journal of Advanced Mechanical Design, System, and Manufacturing. 2008:2(4):579-586.

Harun, S., Evaluasi dan Aplikasi Dinamometer Force Ring untuk Mengukur Gaya Pemotongan pada Pemesinan Bubut dengan Sistem Pahat Berputar, Jurnal Teknik Mesin FTI ITS. 2011:11(3):173-257.

Acknowledgement

The Experiment presented in this paper is done in the Lab. CIM Kobe University in the frame work of Hibah Penelitian Strategis Nasional with the Title "Rancang Bangun Sistem Pahat Put ar Modular (*Modular Rotary Tool System*) Untuk Pemesinan Material Alat Kesehatan Ortoped ik (*Titanium Alloy*)”. I would like to thank Prof. Toshiroh Shibasaka who contributed to the su ccess of this research project. Also the authors would like to thanks for the Direktorat Litabma s DIKTI for their financial support under 582/UN26/8/PL/2013 Grants.