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A Study on Monitoring Drilling using Torque from Main Spindle Based on PLC in CNC Machine Tools

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PLC 기반 주축 모터의 토크에 의한 드릴링 절삭상태 감시에 관한 연구

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ABSTRACT

Drilling processes require a cutting monitoring function that can be analyzed and gives feedback about strange conditions, tool collision and tool wear in real time. In this study, we proposed a drill monitor using the torque from the main spindle in CNC machine tools and a PROFIBUS network as a PLC-based interface. This paper studied drilling torque changes depending on drill size, the repetition cutting of the drilling and the drill's wear in the same cutting conditions. The material of the drills was high speed steel (HSS) and uncoated. The drills chosen were 2.7 mm, 6.7 mm, and 10.0 mm in diameter. These drills were selected because they had basic holes for their taps.

Key Words : Drilling Monitoring(드릴링 감시), Profibus(프로피버스), CNC Machine Tools(수치제어 공작기계), Torque Monitoring(토크 감시)

1. Introduction

Generally, drilling is one of the most widely used processes, accounting for approximately 30% of all cutting processes. There have long been extensive and continuous studies on drilling performance and monitoring[1-3]. However, existing technologies have not been able to produce standard torque values that can cope with various cutting conditions.

Drilling monitoring performance is largely dependent on the selection of a reliable diagnosis algorithm and appropriate monitoring signals. Currently, various signals such as cutting force, motor current, acoustic emission (AE), vibration, and the number of rotations are used for process monitoring. In this study, a motor torque detected using PROFIBUS (Process Field Bus) communications from the spindle motor drive unit was used as a monitoring signal.

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With the use of PROFIBUS communication, no special sensors for torque extraction are needed and, once it is installed, it can be used permanently. In addition, since it is program logic control (PLC)-based, it has an advantage to take accurate and constant torque always. Furthermore, it has a wide range of technical utilization and application since it can receive feedback rapidly and easily in response to abnormal cutting status[4].

This study aimed to investigate change in cutting torque by drill size with regard to the same materials using PROFIBUS communication based on the PLC, and in particular, analyze how torque changes when a drill size is small. In addition, this study also investigated variability of cutting torque by drill size according to repeated processing. This is because reliability can be achieved when torque size appearing at the same condition should be within a certain level of deviation.

In addition, this study also investigated variability of cutting torque by drill diameter according to drill wear. Tool wear influences torque differently, and this problem can be prevented in the production phase if this change is detected and predicted in advance for tool replacement[5].

2. Drilling processing and wear theories

2.1 Cutting power and torque of drilling

In past decades, a large number of analysis and numerical models have been developed to predict torque and thrust force in drilling. A series of three-dimensional (3D) oblique cutting processes have been used to model drilling processes. More recently, a drilling model using mechanistic or finite element method has been developed. The finite element model can provide a unified approach in drilling and other metal-cutting processes[6].

A drill's cutting power is a sum of rotational power and feed power. The rotational power is a torsion moment (i.e., a power by torque), and feed power is a power by a thrust force. A general method to calculate a torque from the power consumption is presented in Eq. (1).

$$M_c = \frac{P_c \times 30 \times 10^3}{\pi \times n} \ (Nm) \qquad (1)$$

P_c : 소비동력 (kW), n : 회전수 $(rev/\min)$

However, there is another method to calculate torque simply. Eqs. (2) and (3) calculate torque based on experimental results.

$$Md = k \times D^2 \times (0.0631 + 1.686 \times fn) \ (kg \cdot cm) \qquad (2)$$

k : 재료계수, D : 드릴직경 (mm), fn : 이송 (mm/rev)

$$Md = K_1 \times d^2 \times fn^m \qquad (3)$$

K_1, m : 실험데이터특성치, d : 드릴직경 (mm), fn : 이송 (mm/rev)

As described in the above, methods that calculate a drilling torque are known, but torque must be calculated every time drill processing conditions change, such as material characteristics of workpieces, and cutting conditions including transfer rate, tool materials, and machine's performance and specifications, and a calculated value is often different from an actual measured value. To address the above problem, this study selected a method that converts and displays a current value extracted from the spindle motor power in a processing machine into a torque value.

2.2 Drill wear

When a cutting load applied to tools during hole machining using a drill becomes large, friction between tool and workpiece is increased. Cutting temperature also rises as processing depth becomes deeper, resulting in degraded hardness of tool and accelerated tool wear. In severe cases, plastic deformation or damage to main cutting edges could occur.

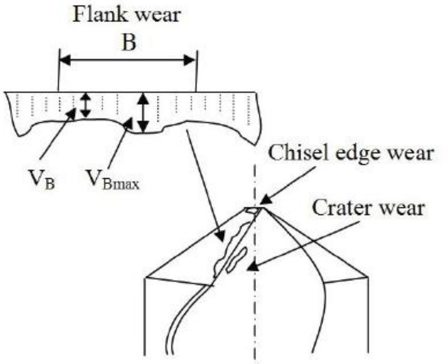

Fig. 1 Schematic illustrations of drill's flank wear

Table 1 Allowable flank wear land for cutting tools in various machining operations

Operation	Allowable flank wear land (mm)	
	High speed steel tools	Carbide tools
Turning	1.5	0.4
Face milling	1.5	0.4
End milling	0.3	0.3
Drilling	0.4	0.4
Reaming	0.15	0.15

There are many wear states in tools. In particular, flank wear is the most commonly occurring, which affects cutting torque significantly as well. In addition, crater wear, notch wear, edge chipping, and built-up edge can occur[5].

Table 1 presents data about allowable limit in flank wear during many types of machining processes, which can be applied as a permissible wear in general[6]. Tests were conducted by changing a drill's flank wear in this study.

3. Technology of interface that collects processing information

In order to collect information generated during a cutting process, a technology of an interface between machine and worker should be provided first, and efficient information collection should be achieved from various production facilities. For proprietary equipment that employs facility interfaces provided by internal application programming interfaces (APIs) such as Cimplicity of FANUC or E-Tower of MAZAK, state information can be easily collected and supplied, but the APIs are only for their own products and have high prices. In addition, the above problems can be resolved by using an open API such as FOCAS1/2 (fanuc open CNC API System 1 or 2) of FANUC when open computer numerical control (CNC) or object linking and embedding (OLE) for process control (OPC) interface, which was a de facto industry standard. However, if open CNC is preferred, methods that collect facility information using open APIs or OPC interface are optimized to distributed environments, which make implementation of facility information collection systems difficult[1].

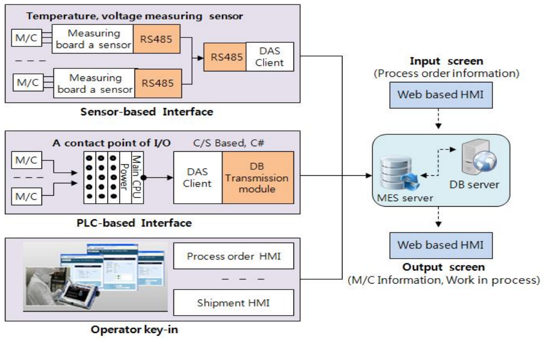

Fig. 2 Configuration of interfacing method for information collect in manufacturing devices

A sensor-based interface module, a programmable logic controller (PLC)-based interface module, and an operator key-in interface module are some of the typical interface modules that can collect information of production facilities. The collected facility information is stored in the production execution system's database, and users can search facility's state or work in process through a web-based human–machine interface (HMI).

4. Test device and method

4.1 Test device interface

This study performed data input/output (I/O) via PROFIBUS communication, which can collect all information contained in CNC machine tools using a PLC-based interface method, which was then combined with drilling monitoring technology.

Previously, conditions over which PROFIBUS communication technology can be applied have not been available over the PLC-based interface. This was because CNC controllers mounted to machine tools were configured with a closed structure that cannot exchange communication; thus, if all kinds of information collected in the PCL are not provided to the controller manufacturer, communications cannot be possible. However, as the need to communicate has increased compared to five to six year's ago, additional features have been developed for communication users.

A converter module is connected to the port unit for external communication in the PLC module inside the CNC device of the machine, and communication between them can be done via PROFIBUS Decentralized Peripherals (DP). CNC controller suppliers of machine tools also provide communication through PROFINET-PN or Modbus-MD. For communication between converter module and HMI display, TCP/IP was used.

4.2 Module and PROFIBUS interface

First, hardware parts should be linked to connect the monitoring system with the machine's CNC system. Second, the PLC module's program should be modified, and third, various parameter-related

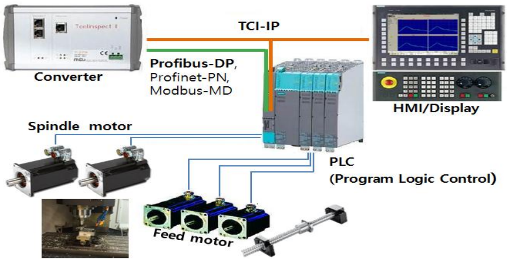

Fig. 3 Configuration of interfacing module

tasks are needed for the connection of PROFIBUS communication in the HMI module.

The interface method of PLC-based PROFIBUS communication between machine and converter module is configured as shown in Fig. 4. The converter module was connected to the port unit for external communication in the PLC module inside the machine's CNC device and communicated via the PROFIBUS-DP. Since the machine tool CNC controller supplier provides PROFINET-PN or Modbus-MD communication modes, communication can also be done with such mode.

The reason for the connection using the above method is to take the current amount in real time. This is because the PLC device recognizes the current amount at the feed motor and spindle motor, which is the machine's constant principal axis motor, when machine is run in the PLC device.

Once the connection between hardware devices is complete, the existing PLC programs inside the machine CNC system should be upgraded to exchange data required for monitoring and abnormal occurrences while monitoring status. That is, a new logic program is added in relation to the monitoring part[3]. The main portion of the new logic is about spindle motor's torque and recognition of the feed

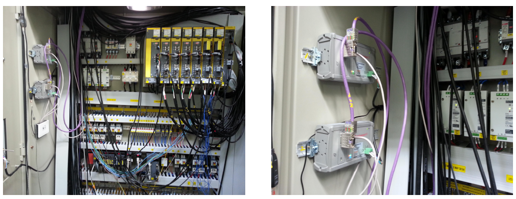

Fig. 4 Connected communication module to PLC of CNC control

shaft's position, and additional PLC programs were developed and applied according to the required functions, such as other tools' detection zones.

4.3 Test method

The material type of the drill for testing used in this study was high-speed steel (HSS) whose surface was not coated and with a point angle of 118°. The drill diameters used were 2.7 mm, 5.0 mm, 6.7 mm, 8.5 mm, and 10.0 mm. These were chosen because they are widely used sizes and basic drills particularly for tapping. The most widely used material, SM45C, was selected as a material for the workpiece for processing.

The machine's specification used in the test was a horizontal machining center whose main spindle size was BT40. FANUC 32i was mounted to the CNC controller, which can support a PROFIBUS communication function. The cutting condition was set to a dry mode, which did not use cutting oil. The cutting depth was 15 mm, and materials of the workpiece used for testing were SM45C, Al, SCM415, and GC25.

The setup order for testing was as follows: a logic program for cutting monitoring was additionally installed to the prepared machine's PLC, as shown in Fig 5, and the PROFIBUS communication port was connected. Then, the workpiece to be tested was fixed, and a processing program was developed to conduct the test work.

Table 2 Cutting revolution condition (rpm)

Work piece	Drill diameter (mm)				
	2.7	5.0	6.7	8.5	10.0
SM45C	1,900	1,400	900	700	500
SCM415	1,900	1,400	900	700	500
GC25	2,200	1,800	1,400	1,200	800
Al	2,500	2,000	1,600	1,350	900

a) Machine b) Profibus installation

c) Cutting tool d) Test cutting

Fig. 5 Set-up orders for the test

5. Test result and discussion

5.1 Torque by drill sizes

As shown in Fig. 6, SM45C material was used, and torque tests by drill size were conducted. The results showed that torque was larger as the diameter became larger, which was consistent with the prediction results.

However, the test revealed that the 2.7 mm drill, whose diameter was relatively small, produced a torque size around 15 Nm, which was not significantly different from 10 Nm, which was torque size at the time of idle operation. Thus, this result indicated that the difference may be smaller than the above result depending on material characteristics of the workpiece or machine's conditions, which was needed to be studied further.

5.2 Changes in torque by material

Fig. 7 shows the changes in torque by workpiece material with regard to a 2.7-mm diameter drill, which exhibits nearly the same torque regardless of the workpiece material. This indicates that, with the small diameter, no significant effect on torque variation was revealed.

Fig. 8 shows the changes in torque by material with regard to a 6.7-mm diameter drill, in which aluminum (Al) and cast iron (GC25) revealed a lower torque than steel materials SM45C or SCM415, but nearly the same value with those of SM45C and SCM415, which verified that the change in torque was not significantly large according to steel material.

A torque by material with a diameter of 10.0 mm showed a large difference, as shown in Fig. 9. However, SM45C and SCM415 had no significant difference, as also revealed in the case of 6.7-mm diameter.

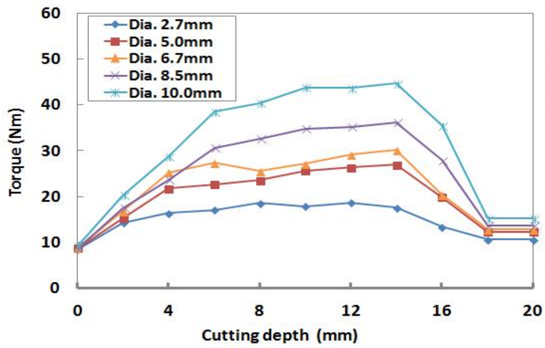

Fig. 6 Torque curve of drilling according to drill size at SM45C material

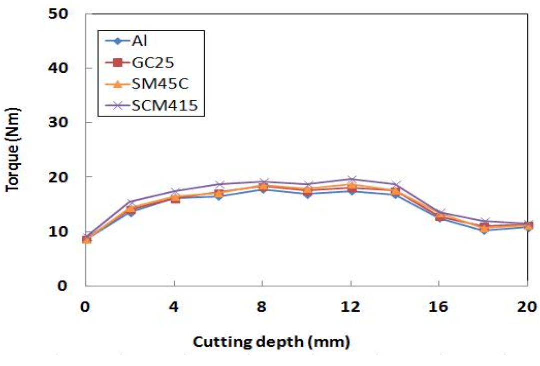

Fig. 7 Torque curve of drilling at Dia. 2.7mm drill

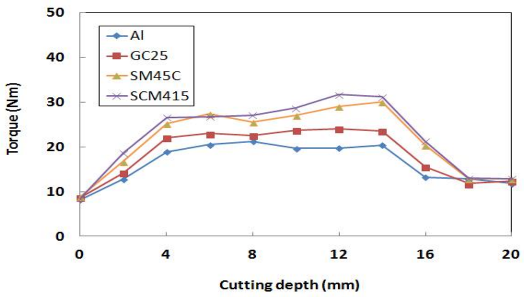

Fig. 8 Torque curve of drilling at Dia. 6.7mm drill

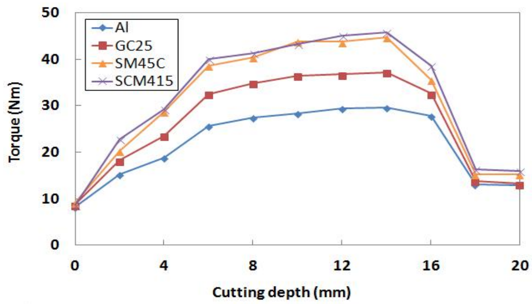

Fig. 9 Torque curve of drilling at Dia. 10.0mm drill

5.3 Repeatability by drill sizes

The repeatability test by drill size was conducted five times. The ratios of maximum and minimum values compared to the mean value were displayed. In Fig. 10, ±7% error was measured at the entry of drill processing with a 2.7-mm diameter drill, and the range of error was gradually decreased as the processing depth increased.

In addition, ±5% error was revealed at the entry of processing with a 6.7-mm diameter drill in Fig. 11, but the error was decreased compared to that of a 2.7-mm diameter drill overall. In Fig. 12, ±5% error was exhibited in the 10.0-mm drill, but the error due to processing depth was rarely found.

5.4 Wear by drill sizes

The test results of changes in torque at the time of drill wear occurrence showed no significant changes regardless of wear amount in the case of a

2.7-mm diameter drill in Fig. 13. This result indicated that the wear condition did not affect the torque size due to the small diameter size.

However, a change in torque was verified at the wear condition according to drill depth in the case of diameters sizes 6.7 mm and 10.0 mm in Figs. 14 and 15. In particular, the reason for the large change in torque around a cutting depth of 15 mm was because a deeper move (typical minimum drill diameter or deeper) than a normal cutting depth had to be done for complete penetration as a result of the depth in the tip due to the point angle with the cutting length (depth) of 15 mm of the workpiece.

The definitions of the drills used in this test were as follows: the normal state of the drills in this paper refers to a state of newly purchased, unused drills. A little wear state refers to 0.4 mm or smaller on the basis of flank wear, and a lots of wear state refers to 0.4 mm or higher on the basis of flank wear.

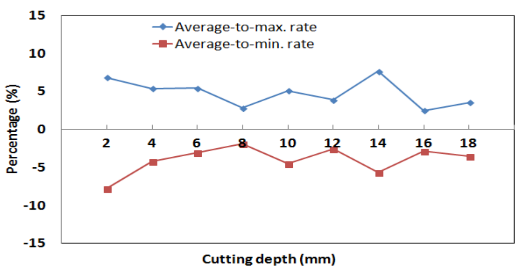

Fig. 10 Repetitive test of drilling torque at Dia. 2.7 mm drill

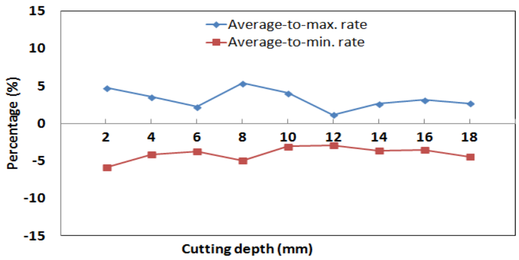

Fig. 11 Repetitive test of drilling torque at Dia. 6.7 mm drill

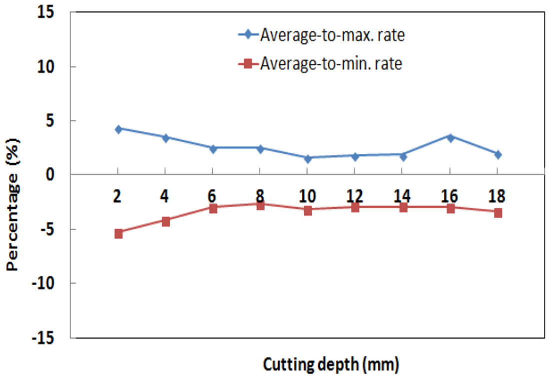

Fig. 12 Repetitive test of drilling torque at Dia. 10.0 mm drill

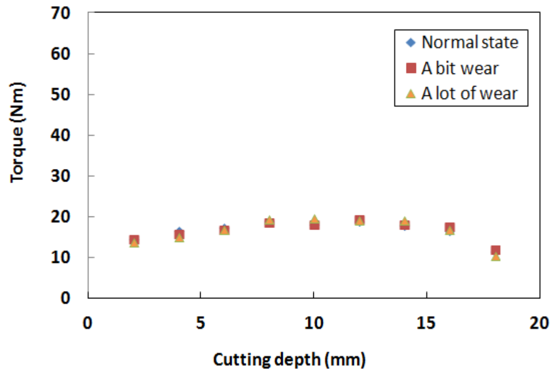

Fig. 13 Torque variation by wear at Dia. 2.7 mm drill

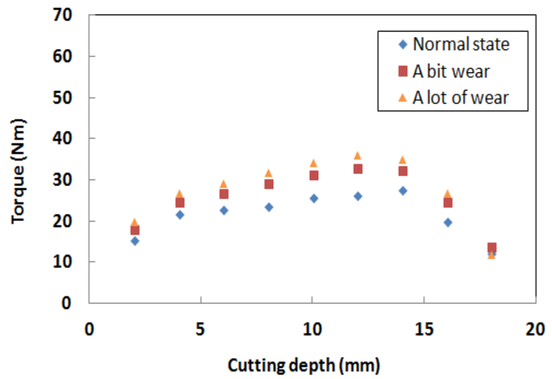

Fig. 14 Torque variation by wear at Dia. 6.7 mm drill

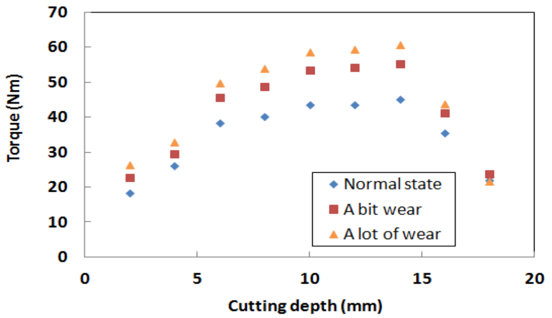

Fig. 15 Torque variation by wear at Dia. 10.0 mm drill

6. Conclusion

Torque was directly extracted from the main spindle of the test machine in a test environment where the PROFIBUS communication was able to test a change in torque according to materials of workpieces and drill sizes. The test results on changes in torque due to wear and the repeatability tests according to drill size are summarized as follows:

1. Difference in torque value was within a range of 2–3 Nm according to a material of workpiece for the case of small-diameter (2.7 mm) drill, which showed no significant effect of materials. Thus, it was difficult to distinguish normal and abnormal states, and change in torque was minimal when a diameter was small. This phenomenon will be studied further continuously through additional studies in the future.
2. SM45C and SCM415 materials exhibited a similar torque value regardless of drill diameter, and their torque sizes were larger than those of aluminum and cast iron materials. That is, aluminum and cast iron were materials with a good cutting property so that they showed a small cutting resistance.
3. The repeatability test by drill diameter showed that a variation was revealed within around 8% when a drill's diameter was 2.7 mm, and within 5% when a drill's diameter was 10.0 mm. This result indicated that repeatability is more stable as diameter is larger, but that a smaller-diameter drill had a larger change in torque compared to a mean torque size at the same condition than that of a larger-diameter drill.
4. The wear test showed that a smaller-diameter drill had no significant change in torque according to wear amount, and torque size varied significantly according to a wear amount if diameter was larger. Thus, since a change in torque according to a wear amount can be a good factor for determining replacement time of tools, it can be helpful to derive test data that can determine replacement time considering materials of workpieces, cutting condition, and other devices and jig effects.

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