

# Sensor-Equipped Cutting Tools to Visualize the Cutting Process

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The progress of digitalization increases the need for automated and unmanned cutting process. Sensor-equipped cutting tools are expected to be one of the measuring instruments that help visualize and monitor cutting operations because they are positioned closer to the cutting point than conventional measuring instruments, enabling more precise measurement. Sumitomo Electric Industries, Ltd. has promoted research and development on turning tools and milling tools that are equipped with sensors, wireless communication devices, and electric power sources. This paper presents feasibility studies on the monitoring of cutting operations with our sensor-equipped turning tool and milling tool.

Keywords: cutting tool, sensor, Internet of Things (IoT)

## 1. Introduction

Industrial digitization began with the German Industrie 4.0<sup>\*1</sup>. In the machining sector, this trend is toward developing a system that maintains equipment and parts and monitors the production process, by mounting various sensors and communications equipment on machine tools and their peripheral devices and by acquiring and analyzing data. In Japan, the Internet of Things (IoT) and digitization are advancing as Society 5.0<sup>\*2</sup>. Presently, automated and unmanned machining is promoted as digital transformation (DX<sup>\*3</sup>). Moreover, in the recent Covid-19-related confusion, people are having difficulties in traveling. New needs are arising, such as remote monitoring of machining and recording of machining processes.

Cutting tools are positioned closest to the point of cutting. It has been considered that mounting sensors on a cutting tool would enable the machining process to be monitored with high accuracy. Accordingly, various research has been conducted on this.<sup>(1),(2)</sup> However, little of this research has led to commercialization due to the size and cost of sensors and wireless communication devices. Therefore, the aforementioned digitization trend has spread only in the field of machine tools and their peripherals. In recent years, however, research on mounting sensors on a cutting tool has been revitalized along with the sophistication, miniaturization, and cost reduction of sensors.<sup>(3)-(6)</sup> Against this backdrop, Sumitomo Electric Industries, Ltd. conducts research and development of cutting tools on which sensors are mounted. This paper reports on the potential of sensor-equipped cutting tools for the monitoring of cutting and the detection of faulty conditions.

## 2. Machining Digitization Trend

Figure 1 shows a machining center as an example to outline a system that monitors and controls machining processes. A common method of monitoring wear of and damage to a cutting tool has been to measure changes in the electric current of the spindle motor that directly rotates the tool. More specifically, technological developments

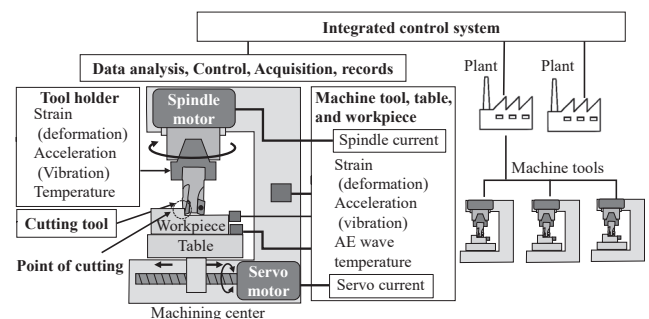


Fig. 1. Monitoring and control system for machining process

include determining tool life when the spindle current exceeds a certain threshold<sup>(7)</sup> and detecting faulty conditions by analyzing the spindle current by means of machine learning.<sup>(8)</sup>

Other ongoing technological developments are the monitoring of the machining process based on the changes in the electric current of the servo motor used to drive the machine tool<sup>(9)</sup> and the monitoring of the machining process based on changes in measurements obtained from a strain or vibration sensor mounted on the machine tool.<sup>(10)</sup> Furthermore, a system that integrates these pieces of information and monitors the machining tool<sup>(11)</sup> and, at a higher level, integrated control systems capable of monitoring plant equipment on a global scale through machine tools<sup>(12)</sup> have also been developed. Additionally, with machining centers, mounting sensors on a tool holder that connects a machining tool to a cutting tool<sup>(13)</sup> has been put into practical use. These arrangements of mounting sensors on a machine tool or its peripheral devices are highly versatile because the arrangement does not depend on the type of the cutting tool. However, placing sensors away from the point of cutting often fails to meet user requirements for abnormality detection due to low sensitivity to the cutting phenomenon occurring at the point of cutting. Specifically, using the electric current of the spindle motor, it is very difficult to monitor the machining process or detect faulty

conditions during turning that involves workpiece rotation. The reason is that the power required to rotate the workpiece is higher than the power used to overcome the cutting resistance produced at the point of cutting. Thus, expectations are high for the mounting of sensors on a cutting tool that is closest to the point of cutting, which enables the machining process to be monitored with high accuracy and sensitivity, albeit declining versatility.

Figure 2 presents a common breakdown of cutting costs including tool and personnel expenses. It is generally said that the proportion of cutting tool costs to cutting costs is approximately 4%, although this differs between industrial sectors and individual users, while personnel costs account for approximately 34%.<sup>(14)</sup> Moreover, in actual machining, it is likely that production loss is incurred at a proportion of between 5% and 10%. The causes include discarded defective parts, screening of defective parts, minor machine shutdowns following machining faults, and lowering of processing efficiency intended to avoid defects. Use of sensor-equipped cutting tools would certainly enable the reduction of tool costs owing to extended tool life. However, in view of the overall costs of the cutting process, the effect of tool cost reduction is small. Consequently, if only tool cost reduction is considered, the deployment of sensor-equipped cutting tools is not very cost-effective. Therefore, it is important to take note of other factors: personnel cost cutting through automation, production loss reduction by monitoring the machining process, and machining with high efficiency within a small amount of time while avoiding faulty conditions to reduce personnel expenses and depreciation on equipment. Furthermore, both the size of the working age population and the number of skilled workers are expected to decrease in the future. Given this factor, it is highly probable that the role of sensor-equipped cutting tools will become important from other perspectives such as quantitative evaluation of cutting.

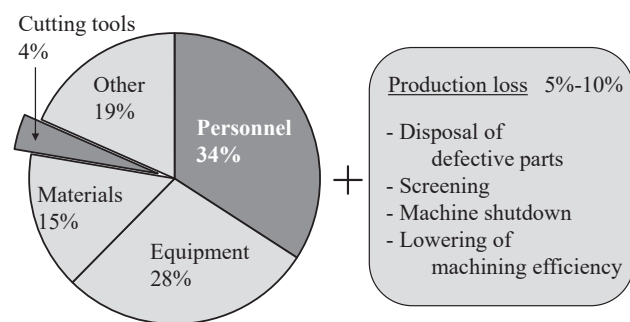


Fig. 2. Breakdown of cutting cost

### 3. Sensor-Equipped Cutting Tools Applied to Turning

Figure 3 illustrates a sensor-equipped turning tool for outside-diameter machining. A strain sensor is mounted close to the edge. A wireless communication device and a power supply are mounted close to the shank's rear end.

The strain sensor measures strain on the body and outputs a value proportional to the cutting resistance. Measurements are transmitted from the sensor-equipped turning tool by radio and collected on a personal computer (PC) connected to a receiver. The sampling frequency is 2 kHz. The receiver is capable of establishing communication off the machine tool and can be installed on a window of the machine tool. This sensor-equipped turning tool, with all required components embedded in its body, offers the feature that it can be mounted directly on the tool rest of a lathe and does not interfere with the workpiece. Accordingly, it enables measurements with ease while cutting an actual part on an actual machine currently in use. Usage examples of a sensor-equipped turning tool are described below.

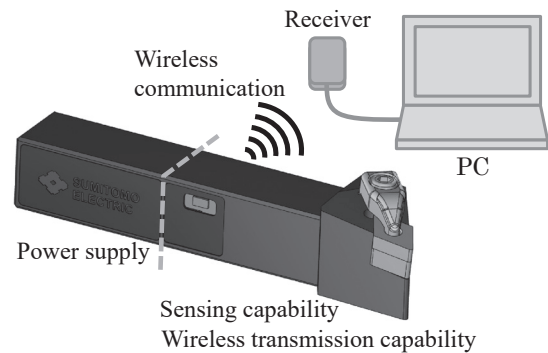


Fig. 3. Sensor-equipped turning tool

A cutting experiment involving interrupted cutting was conducted using a sensor-equipped turning tool to detect edge fracture. Figure 4 and Table 1 show the workpiece and machining conditions.

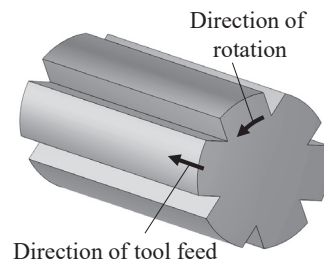


Fig. 4. Workpiece used in the interrupted cutting test

Table 1. Machining conditions

Cutting tool	DCLNL2525M12
Indexable insert	CNGA120412 (BNC300)
Workpiece material	Hardened steel
Cutting speed	100 m/min
Depth of cut	0.2 mm
Feed per revolution	0.1 mm/rev
Cutting fluid	Dry

geometry and machining conditions, respectively. Figure 5 presents the measurement results obtained before and after the occurrence of fracture. Figure 5 (a) provides strain features converted from strain measurements obtained before fracture occurrence. Since interrupted cutting was measured, waveforms representing repeated cutting and non-cutting sections were observed, as shown in Fig. 5 (b). With no fracture on the edge, the strain feature was constant within cutting sections. After fracture occurred, a discontinuous change was observed, as illustrated in Fig. 5 (c). Figure 5 (d) presents a photo of the tool edge after fracture. On actual shop floors, fracture is sometimes discovered by a change in cutting noise. However, when fracture similarly sized to that in Fig. 5 occurs, the operator in many cases fails to discover it because the change in cutting noise is minor compared with the operating noise of the cutting equipment. Use of a sensor-equipped turning tool enables minimal changes to tool edge to be captured.

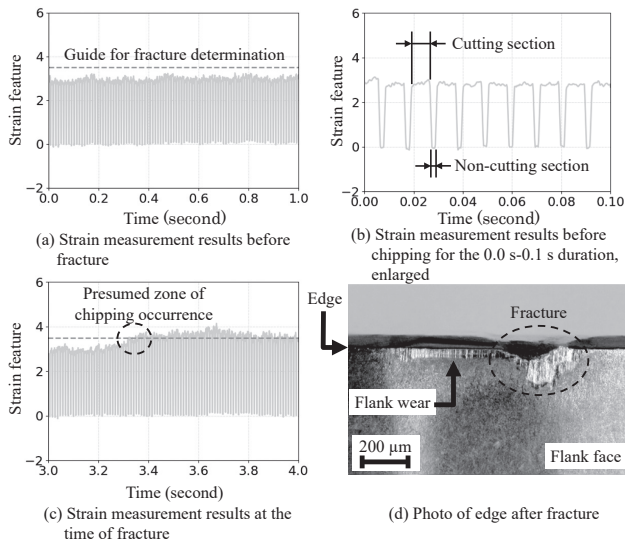


Fig. 5. Measurement results obtained before and after fracture

Figure 6 provides an example of using a sensor-equipped turning tool to machine actual parts. First, the end face was machined, followed by inside diameter, corner, and end face machining. During the corner machining, the strain feature increased momentarily to about three-fold the previous level. Although increasing cutting resistance at a corner is generally assumed when setting a tool path and machining conditions, temporary increases to this level are beyond operators' expectations. The measurement results obtained with the sensor-equipped turning tool led to this finding. By using sensor-equipped cutting tools to visualize machining, it is possible to discover unfavorable machining processes, as described above, and to provide an opportunity for reviewing machining conditions.

It is preferable in many cases to acquire a moderate amount of data, although in some cases new findings are obtained from a set of measurement results, as described in this article. The reason is that, in a process using a sensor-

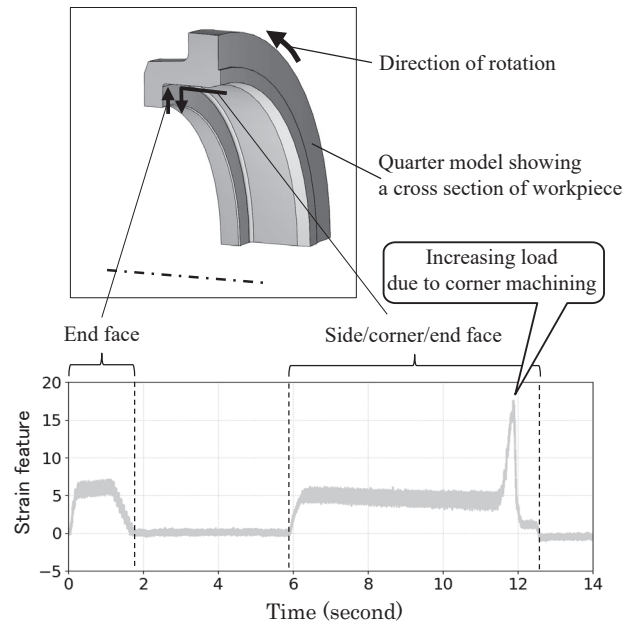


Fig. 6. Strain measurement results for actual part machining

equipped cutting tool, defective products are frequently produced by edge wear and geometrical variation in workpieces. Therefore, it is important to acquire data sets over a modest period length, sufficiently containing changes and variations that resulted in defective products. By analyzing these sets of data in detail, it is highly likely that the causes of defective products can be identified and new findings can be obtained.

#### 4. Sensor-Equipped Cutting Tools Applied to Milling

We have also evaluated the performance of milling tools, mounting sensors, a wireless communication device, and a power supply. Sumitomo Electric's sensor-equipped milling tools have the following features.

First, measurements can be obtained in a rotating coordinate system rotating with the cutting tool. For multi-edged tools, measurement results can be separated with respect to each edge.

Second, measurement results are relatively immune to influences other than the cutting phenomenon, because the sensor is close to the point of cutting. Even with the use of a tool holder long in overall length, sensors can be installed closer to the point of cutting than in the instances of installing sensors at the base of a tool holder or on the main spindle. Moreover, the edges and the sensors can be set to constant relative positions in terms not only of distance, but also of phase around the milling tool's axis of rotation.

Third, two types of sensors, strain and acceleration, are mounted to take measurements simultaneously. Strain and acceleration are physical quantities both arising from cutting resistance; however, different factors are involved in their occurrence. Strain sensor measurement results are strongly related to cutting resistance because they are

determined by the cutting resistance at the point of cutting and the rigidity of the milling tool. In contrast, acceleration sensor measurement results are strongly related to unusual vibrations and machining accuracy, because they are affected by the rigidity of the main spindle system comprising the main spindle and tool holder, as well as the rigidity of the discrete milling tool.

In view of the above-described features, we conclude that simultaneous measurements of strain and acceleration in the rotating coordinate system of a cutting tool produce useful data for optimizing cutting and clarifying cutting phenomena.

Figure 7 illustrates a sensor-equipped milling tool, which is an indexable-insert milling tool (Sumitomo Electric part No.: WEZ2500E) with a strain sensor, acceleration sensor, wireless communication device, and power supply mounted. As shown in the figure, measurement results obtained from the strain and acceleration sensors can be converted to four cutting resistance components and four acceleration components in the rotating coordinate system of a cutting tool. Figure 8 presents a system configuration designed for cutting experiments using a sensor-equipped milling tool. The receiver end is configured similarly to the sensor-equipped turning tool. Its sampling frequency is 2 kHz.

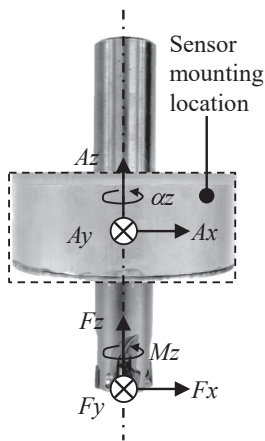


Fig. 7. Sensor-equipped milling tool

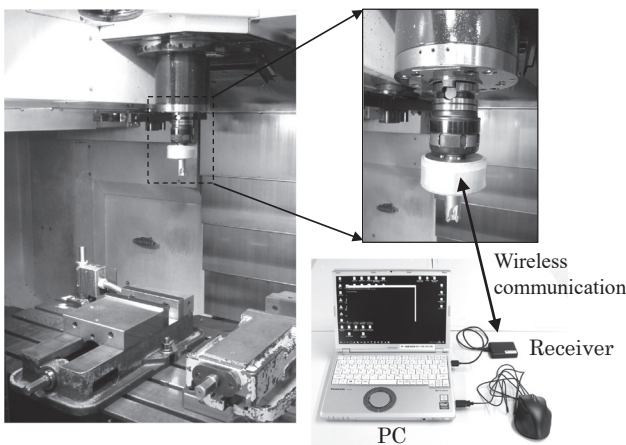


Fig. 8. System configuration for cutting experiments using a sensor-equipped milling tool

Table 2 shows the machining conditions used for the cutting experiment. Figure 9 presents cutting resistances  $F_x$  and  $F_y$  and accelerations  $A_x$  and  $A_y$  measured in the cutting experiment. Figure 9 (a) and (d) plot cutting resistance and acceleration measurement results against time. Figure 9 (b) and (e) are enlarged views of (a) and (d) at around 40 s. According to the measurements conducted in the rotating coordinate system of cutting tool, as shown in Fig. 9 (c) and (f), by plotting  $F_x$  and  $F_y$  or  $A_x$  and  $A_y$  along the x-axis and y-axis, it becomes possible to check cutting resistance and acceleration vectors within a plane perpendicular to the axis of rotation of the milling tool, enabling physical quantities produced on each edge to be separated. Taking note of the measurement results for these four components, the relationships between them and changes occurring at the point of cutting were investigated. The maximum number of edges operating at once was one under the machining conditions used for the current experiment. Therefore, as shown in Fig. 9 (c), cutting resistance vectors produced on each edge are in different directions from each other. The edge numbers shown in the figure were assigned in order of the cutting sequence, cutting from edge 1 to 4. The different magnitudes of the vectors were caused by cutting area fluctuations arising from the relative positions of the edges.

Table 2. Machining condition

Cutting tool	WEZ2025E
Tool diameter	25 mm
Number of teeth	4
Indexable insert	AOMT11T308PEER-G (ACK3000)
Workpiece material	S50C (JIS)
Cutting speed	47.1 m/min
Axial depth of cut	2 mm
Radial depth of cut	5 mm
Feed per tooth	0.1 mm/t
Cutting fluid	Dry

Cutting continued under the aforementioned machining conditions. The relationships between edge fracture and measurement results were investigated. Tool edges were observed, suspending cutting at cutting length intervals of 0.3 m. Fracture occurred first on edge 1, which was followed by edge 3. Edges 2 and 4 remained free of fracture. Figure 10 provides the measurement results and photos of the edges. Figure 10 (a) and (d) plot measurement results obtained in a state free of fracture. Figure 10 (b) and (e) present measurement results obtained with fracture only on edge 1. Figure 10 (c) and (f) show measurement results obtained with edge 1 in an advanced state of fracture plus additional fracture on edge 3. Figure 10 (a) and (b) reveal that fracture on edge 1 resulted in a reduced cutting area on edge 1, with the cutting resistance decreasing from approximately 522 N to approximately 442 N. Meanwhile, the decrease in the cutting area on edge 1 led to an increasing cutting area on edge 2, with cutting resistance increasing from approximately 520 N to approximately 608 N. Figure 10 (d) and (e) revealed no noticeable

change in comparison with the strain measurement results. According to Fig. 10 (b) and (c), fracture on edge 3 resulted in a decrease in the cutting resistance of edge 3 from approximately 864 N to approximately 645 N, and an increase in the cutting resistance of edge 4 from approximately 705 N to approximately 866 N. Additionally, Fig. 10 (e) and (f) reveal that the accelerations along edges 2 and 4 increased, while the accelerations along edges 1

and 3 decreased. No substantial change in acceleration was observed when fracture occurred on edge 1, while a major change in acceleration occurred when the additional fracture occurred on edge 3. The reason for this is that, as revealed by Fig. 9 (b) and (e), since acceleration is determined through second-order differentiation with respect to displacement, acceleration vectors are produced in opposite directions (off by 180°) around the axis of rotation. In the

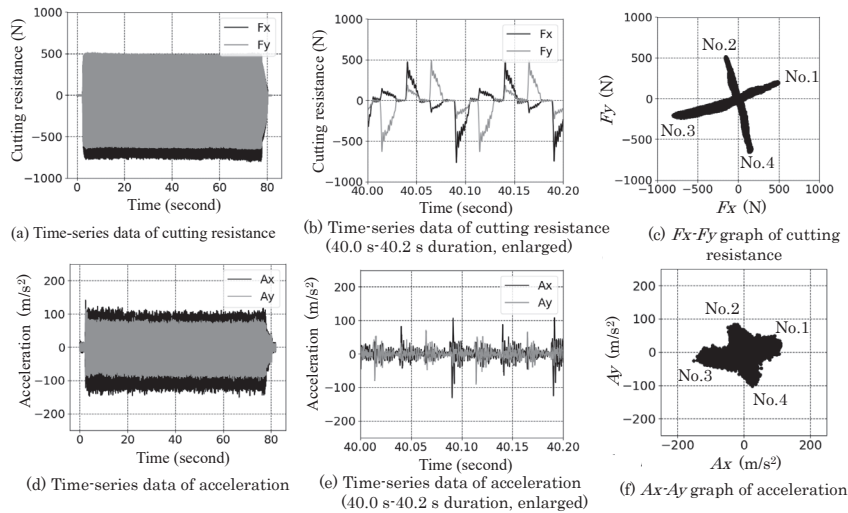


Fig. 9. Measurement results obtained with sensor-equipped milling tool

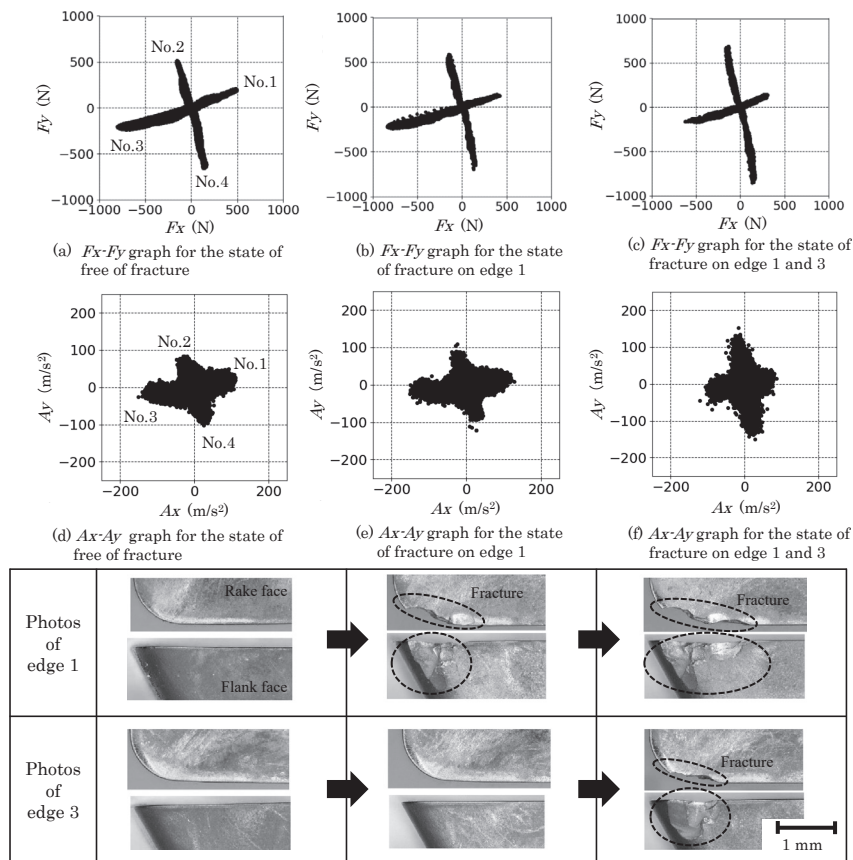


Fig. 10. Relationships between fracture and measurement results for sensor-equipped milling tool

current measurements, although the cutting resistance of edge 1 decreased after fracture, no change was observed, because the cutting resistance vector of edge 3 located in the opposite position was greater than that of edge 1 and, in Fig. 10 (e), the acceleration vector of edge 1 was overridden by the acceleration vector of edge 3. It is likely that, when the additional fracture occurred on edge 3, both cutting resistance vectors of edges 1 and 3 were found to have decreased in comparison with the state of free of fracture, as shown in Fig. 10 (f), with the change between before and after the fracture being also observed with respect to acceleration.

This section described that strain and acceleration measurement results obtained from cutting using a four-edged milling tool could identify not only the occurrence of fracture, but also on which edges fracture occurred. Going forward, we intend to investigate the relationships between strain and acceleration measurement results and wear on edges and other cutting phenomena.

## 5. Conclusion

This article described: development of sensor-equipped cutting tools with sensors, a wireless communication device, and a power supply mounted on them for turning and milling applications; monitoring of machining processes; and a finding that the measurement results enabled determination of unusual changes in cutting force during cutting and fracture on tools.

Future tasks include exploring the possibilities of automated machining and production loss reduction using these sensor-equipped cutting tools, and making ideal machining possible by visualizing complex and ununderstood cutting phenomena.

### Technical Terms

- \*1 Industrie 4.0: This term means the Fourth Industrial Revolution, in which manufacturing processes become smoother than before, with humans, machines, and other corporate resources mutually communicating with each other to share information such as each product's state of manufacturing and customer data. Moreover, Industrie 4.0 also sets goals such as reshaping the existing value chains and developing new business models.
- \*2 Society 5.0: A human-centered society that balances economic advancement with the resolution of social problems by a system that highly integrates cyberspace and physical space.
- \*3 DX: An abbreviation for digital transformation. DX is to transform products, services, and business models through the use of data and digital technology based on customer and social needs and to establish a competitive advantage by reshaping business operations, organizations, processes, and corporate culture/climate.

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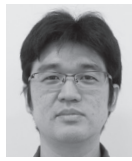
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