Polishing System with Integrated Five Axis Controlled Machine Tools and Cooperative Robots based on Wireless Communication and Acquisition of Servo Information

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***Abstract*—In this study, the concept of polishing using a cooperative robot is explored. A novel system that integrates wireless vibration monitoring technology with servo internal information is presented. In particular, a novel finishing system that utilizes the internal information of the force sensor installed in the base of a cooperative robot was developed. The proposed system can be used to detect human contact and improve the accuracy of machining. In this paper, a blade-shaped workpiece was machined using a Computer Numerical Control (CNC) machine that performs simultaneous 5-axis machining. The surface condition of the machined workpiece was clarified by using a wireless vibration measurement holder and internal servo information. In addition, raw vibration waveforms were observed during the cutting process to investigate the causes of chatter and vibration. The surface condition of the workpiece was examined based on the in-process vibration information, and the efficiency of polishing was improved by limiting the range of rough polishing by the proposed robot system. The prediction of the tool condition during machining and optimization of the polishing operation are discussed in the context of robot polishing. We report on how this method uses data from the previous process to achieve a higher rate in the next process.**

***Index Terms*—5-axis machining, wireless monitoring, polishing monitoring, robotic polishing system**

I. Introduction

In recent years, remote work has become the new norm in the manufacturing industry. Consequently, technological development related to "connected factories" based on the Internet of Things (IoT) has garnered attention from researchers. Highly efficient machining technology based on simultaneous 5-axis machining is gaining popularity. Among the existing machining technologies, highly efficient finishing using barrel tools is the most widely adopted. In a previous study by the authors, an IoT-compatible monitoring system with wireless communication functions for rotary tool holders used in machining centers was presented [1]. Furthermore, the chatter and vibration during the cutting process were monitored by utilizing the internal information of the computer numerical control (CNC) machine tools and monitoring the vibration during the surface finishing of complex curved surfaces by ball end mills. It was observed that the chatter and vibration varied with the tool position and direction of motion owing to machine rigidity and anisotropy of the guideway surface. Furthermore, it was concluded that monitoring the chatter and vibration can effectively improve the finishing process [2].

Industrial robots can perform simple motion control, monitor phenomena through sensing, operate autonomously, and relay data [3]. Recently, cooperative robots that can work with humans and industrial robots without the need for safety fences have been introduced. However, in actual workplaces, many complex tasks, such as the polishing work of complex shapes, are difficult to automate. Therefore, several researchers [4]-[9] have attempted to utilize industrial robots for the polishing work of complex shapes. However, the industrial robots used are not IoT-compatible models equipped with servo internal information and wireless communication functions.

In this study, holder vibration information and machine tool CNC information during the 5-axis machining of a turbine blade-shaped workpiece were acquired. The finished workpiece was polished using the novel robot system proposed in this study. The optimization of the robot polishing motion was conducted based on in-process vibration data during cutting, and the optimal polishing conditions were studied based on in-process data of the

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polishing motion. Thus, the proposed system can be used to realize a "connected factory."

II. IoT-Enabled Sensing Systems and Processing Conditions

A. *Wireless Vibration Measurement Holder and Method of Acquiring CNC Internal Information*

Fig. 1 shows a schematic diagram of the proposed monitoring system for machining. The developed wireless vibration monitoring system (namely, Multi Intelligence®) consists of a BT40 holder with four piezoelectric accelerometers. The piezoelectric accelerometers have sensitivity in one axial direction. In addition, they are equidistant from the center of rotation in the radial direction and equally spaced to ensure sensitivity in the rotational (tangential) direction of the rotational coordinate system. The accelerations ax_1 and ax_2 of each sensor are positive in the direction of the arrow shown in Fig. 1. Therefore, *X*m in the radial direction is obtained using (ax_1-ax_2)/2. The vibration acceleration of *R*m, which represents the direction of rotation, is obtained using (ay_1+ay_2)/2. Thus, it is possible to monitor the vibration acceleration in two directions: the radial direction and rotational direction. The natural frequency of the sensor used in this study was 31 kHz. In addition, an amplifier, an A/D converter, a microcontroller, and a wireless transmitter were used. After the analog processing and information compression by the amplifier, A/D conversion was performed, and the results were transmitted wirelessly to a PC. The PC was connected to the receiver displays and recorded the measurement results in real-time. Two models were prepared for radio transmission: the raw waveform acquisition model, which transmitted raw waveform data at a sampling rate of 44.1 kHz, and the root mean square (RMS) value acquisition model, which calculated and transmitted RMS values at a sampling rate of 50 Hz. The former can determine the cause of vibration by frequency analysis at high sampling rates. The latter can evaluate the presence or absence of abnormal vibration at the machining point by determining the magnitude of the vibration. If the output of the difference or addition operation at any time t is $x(t)$, the RMS operation $a(t)$ of the holder vibration is expressed by the following equation:

$$a(t) = \left(\frac{1}{T}\int_{t-T}^{t} x(\tau)^2 d\tau\right)^{\frac{1}{2}} \quad (1)$$

Equation (1) is a general RMS formula, and this formula is written into the microcontroller in the wireless holder system. In the microcontroller, the integration time was set to T = 0.1 s, and analog calculations were performed in real time. During the experiment, information on the X, Y, and Z coordinates of the machine tool was obtained simultaneously using *X*m and *R*m. Therefore, for the analysis, a color mapping method that changed the color of the 3D computer-aided design (CAD) space according to the change in magnitude of *X*m and *R*m with time was adopted.

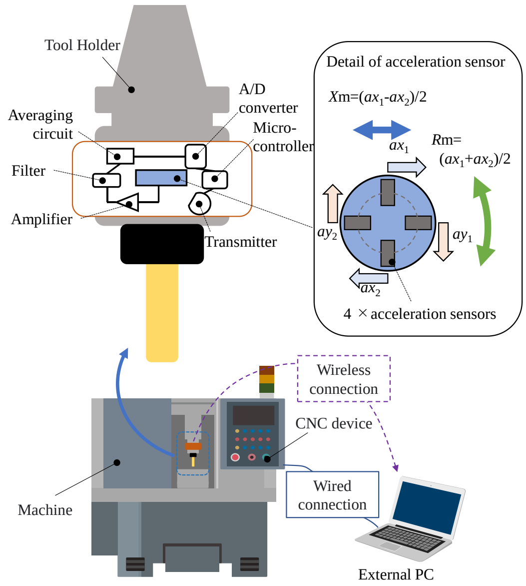


Figure 1. Schematic diagram of a machining monitoring system and wireless holder vibration measurement system.

B. *Cooperative Robot for Polishing Work and Method of Acquiring Internal Information*

Fig. 2 shows a schematic of the robot system used for the polishing process. The robot system was a portable 6-axis cooperative robot (FANUC: CR-7iA/L) and weighed 7 kg. In addition, the robot had a built-in force sensor at the base. The robot performed polishing using an air microgrinder (UHT: MSG-3BSPlus) attached via a jig as an end effector. The force sensor at the base of the robot was used to detect human contact, and the output values of the force sensor were sent to an external PC by obtaining the robot system variables (internal parameters). The sensors used are listed in Table 1. A thermopile-type non-contact temperature sensor (detection wavelength: 8–14 μm, detection distance: 35 mm, spot diameter: 1.5 mm) was used to measure the temperature. The temperature measurement at a given point on the grinding wheel surface during polishing was conducted from one direction. The temperature sensor monitor is used to monitor the grinding workload and detect heat generation that may cause abnormalities in the workpiece and tool. For the measurement of vibration acceleration, we converted from the circuit of the system, namely the Multi Intelligence®, shown in Fig. 1 to wireless vibration monitoring system in Fig.2. Four piezoelectric accelerometers were used for data acquisition. The accelerometers had sensitivity in one axial direction and were placed at equal intervals on the same circumference inside a small case. The X-axis component (Ro*X*m) and Z-axis component (Ro*Z*m) of the vibrations in the robot tool coordinate system were obtained from the difference between the two detected values at 180° opposite circumferences. The component of the vibrations in the rotational direction (Ro*R*m) centered on the Y-axis were obtained from the addition of the two detected values. The calibration of the Ro*X*m and Ro*Z*m values was performed using separately calibrated accelerometers. The calibration of the Ro*R*m values was performed by shaking a wireless tool-holder system of a machine tool with an electronic base attached to the accelerometers mounted on the same axis. Using the RMS value acquisition model, the RMS values were wirelessly transmitted to an external PC. A thermal flow sensor was incorporated near the pneumatic source to measure the airflow rate of the air microgrinder. A system that integrates sensor information and internal robot information was constructed to improve the polishing process.

TABLE I. LIST OF SENSORS FOR THE ROBOTIC SYSTEM

Number	Name	Model	Manufacturer	Position	Remarks
1	Force sensor	CR-7iA/L	FANUC	Inside the robot	System variable：$DCSS_CLLB[1].$FS_FORCE[1]-[3]
2	Multi Intelligence® (Prototype for robots)	-	Yamamoto Metal Technos Co., Ltd	Robot Hand	Under development
3	Infrared temperature sensor	FT-H10	KEYENCE	Robot Hand	Thermopile type
4	Displacement sensor	IL-S100	KEYENCE	Robot Hand	Laser triangulation type
5	Flow sensor	FD-A250	KEYENCE	Near air input	Thermal type

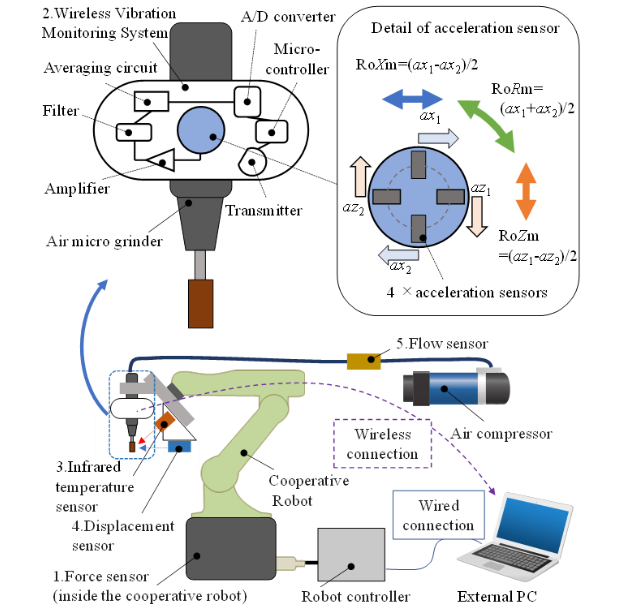


Figure 2. Schematic diagram of a robot monitoring system and wireless vibration measurement system

C. Workpiece Geometry and Cutting and Polishing Conditions

The workpiece had a flat blade shape with a thickness of 2 mm, width of 54 mm, and height of 55 mm. The workpiece material was JIS SUS430.The robot performed the machining of the workpiece surface by acquiring machining information of the following steps: cutting and finishing, rough polishing, and finish polishing.

For the cutting and finishing step, the tool movement direction, holder vibration measurement direction, and the machine atmosphere and sensing direction are shown in Fig. 3. The machining conditions are listed in Table 2. Cutting conditions were set at about half the manufacturer's recommendation in consideration of the protrusion length. The finishing tool was a barrel tool tilted at a 15 °angle from the machined surface, and the contour finishing was performed at a 1 mm pitch. This setting resulted in a theoretical cusp height of about 0.003 mm, which is expected to produce a good cutting surface.

For the rough and finish polishing step, the tool scanning direction and each sensor measurement direction are shown in Fig. 4, and the machining conditions are listed in Table 3. The tool was tilted at a 15 °angle from the machined surface. A #60 grindstone was used for rough polishing, and a #80 rubber grindstone was used for finish polishing.

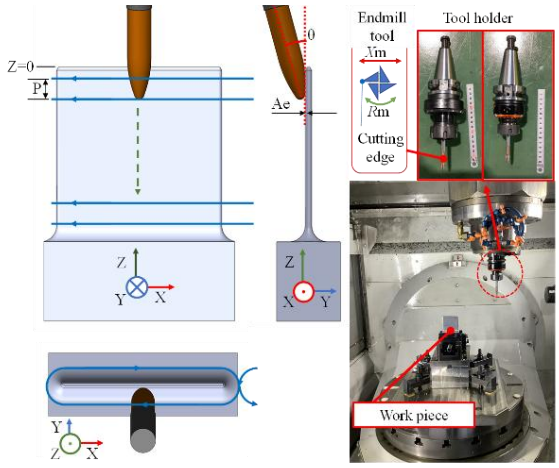


Figure 3. Workpiece machining direction and machining atmosphere.

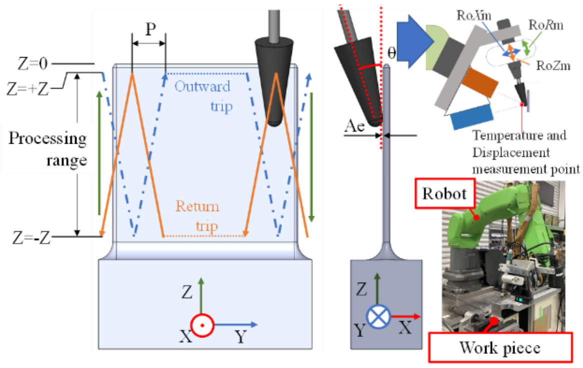
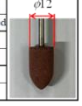


Figure 4. Workpiece machining direction and robot atmosphere.

TABLE II. MACHINE AND CUTTING CONDITIONS USED FOR MACHINING

Machine model	NMV5000 DCG	Image	Cutting model	GS4TN7.5-37.5R-TH3 (MOLDINO)			Image
Manufacturer	DMG moriseiki		Particle size	R37.5 barrel tool			φ7.5 
Max spindle Speed	20000 rpm		Number of tooth	4	Length	52 mm	
Adapter type	BBT40		Diameter	7.5 mm	θ	15 deg	
Number of axes	5		Spindle Speed	4000 rpm	Ap	1.0 mm	
			Feed	800 mm/s	Ae	0.1 mm	
			Coolant	Oil (External lubrication)			

TABLE III. ROUGHING AND FINISHING TOOLS USED FOR POLISHING

Grindstone model	G3511 (Nihon Seimitsu Kikai Kosaku Co.,Ltd.)			Image	Grindstone model	GCMH-125 (Yanase Co., Ltd.)			Image
Particle size	#60 grindstone			φ13 	Particle size	#80 rubber grindstone			φ12 
Number of cycles	2	Shape	Taper cone		Number of cycles	3	Shape	Bullet-shaped	
Diameter	Max 13mm	P	0.1 mm		Diameter	Max 12mm	P	0.4 mm	
Length	30 mm	Ae	0.08 mm		Length	32 mm	Ae	0.2 mm	
Feed	80 mm/s	θ	15 deg		Feed	80 mm/s	θ	15 deg	
Range	14 mm(Z+=-18 / Z-=-32)				Range	48 mm(Z+=4 / Z-=-44)			

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. In-process Measurement During Cutting

Fig. 5(a) shows a photograph of the workpiece after machining. Fig. 5(b) shows a color plot of the effective values of *X*m obtained from the effective value acquisition model and the coordinates of the machining tools. Fig. 5(c) shows the relationship between the height along the Z-axis and the average *X*m value. Barrel tools are prone to chatter and vibration, and the photograph of the workpiece shows that large chatter and vibration occurred in the middle area. From the color-mapped CAD drawing, it can be inferred that large *X*m values were observed at the locations of the chatter and vibration. From the raw waveform acquisition model, it can be inferred that the chatter and vibration during finishing occurred at the same locations under similar cutting conditions. Fig. 6 shows the raw waveform at 0.1 s during machining at areas 1–3 of Fig. 5(a). In addition, the fast Fourier transform (FFT) analysis results of the raw waveform are also shown in Fig. 6. From the raw waveform, it can be inferred that the machining in areas 1 and 3 was stable. However, large oscillations were observed in area 2. Thus, the FFT analysis results at area 2 showed large peaks at 700–800 Hz and 2200–3000 Hz. The natural frequencies of the workpiece based on finite element analysis were 645 Hz for the first-order mode, 1562 Hz for the second-order mode, and 3902 Hz for the third-order mode. In a previous study [10], when the machine was supported at one end by clamp tools and elastically supported at the other end by the rotation machining tool, chatter and vibration were observed at a different frequency than the calculated natural frequency. Therefore, it was assumed that the first-to third-order modes of chatter and vibration were generated owing to a similar phenomenon. The RMS in-process data were plotted on a 3D CAD system to visually represent the multiple modes of chatter and vibration that occurred during cutting at each coordinate.

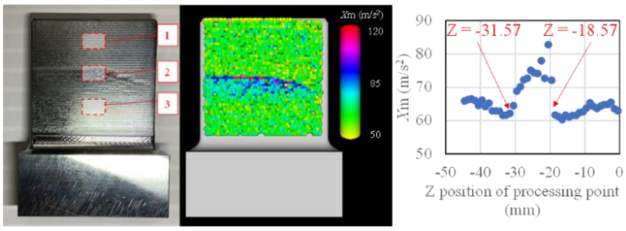


Figure 5. (a) Image of workpiece after cutting. (b) Color plot of RMS value of Xm. (c)Average of the RMS values of Xm for each Z-level

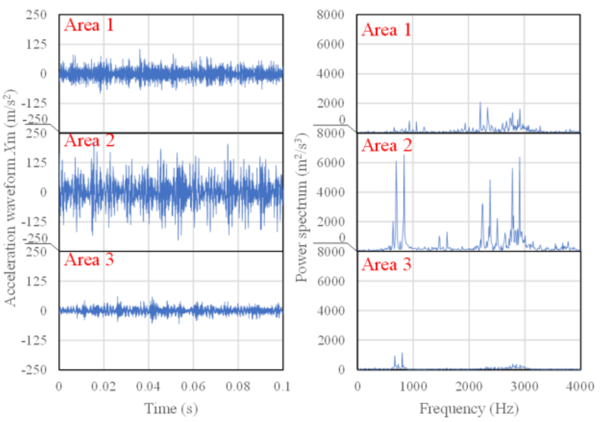


Figure 6. Xm vibration waveform and FFT transform at 0.1 s for areas 1–3.

B. Sensor Monitoring of Polishing Motion

During rough polishing, only surfaces with large chatter and vibrations were polished to reduce the total polishing time. Specifically, the robot performed rough polishing only in the range of Z = -18 to -32 mm, where the vibration values were large, as shown in Fig. 5(c). The average value of the robot force sensor *Fx* (force perpendicular to the workpiece surface), airflow rate, acceleration vibration Ro*X*m, and grinding wheel surface temperature during machining was calculated when the outward and return machining paths were different from the machining coordinate values of the robot; Fig. 7(a) shows these plots for each of the N round-trips during rough polishing. Fig. 7(b) shows the results of the finish polishing. In the case of rough polishing, *Fx* tended to approach 0 as N increased; this indicates that the contact area and contact force decreased owing to tool wear. The airflow rate and Ro*X*m values decreased after N=2.5. A decrease in the airflow rate might have led to a decrease in the tool speed of the air microgrinder; this may have resulted in a decrease in the acceleration vibration. Consequently, the tool surface temperature decreased because of the lower workload on the workpiece caused by tool wear and the lower rotation speed. During the finish polishing, almost the entire surface was polished. The force on the return trip tended to be closer to 0 N than that on the outward trip. The outward cut was an up-cut, and the return cut was a down-cut; this can be attributed to the difference in machining direction, as reported in a previous study [11]. The airflow rate and Ro*X*m decreased for N = 2.5, which can be attributed to the decrease in RPM. Considering the Ro*X*m values, it can be inferred that relatively large RoXm values were observed during idling before and after the changeover between the outward and return paths; however, slightly smaller values were observed when the workpiece was in contact with it during machining. Thus, it can be inferred that for a small *Fx*, the force provided by the finger on the tool decreases, which results in a large vibration owing to tool runout. During roughing, it was observed that the tool surface temperature decreased because of the workload on the workpiece.

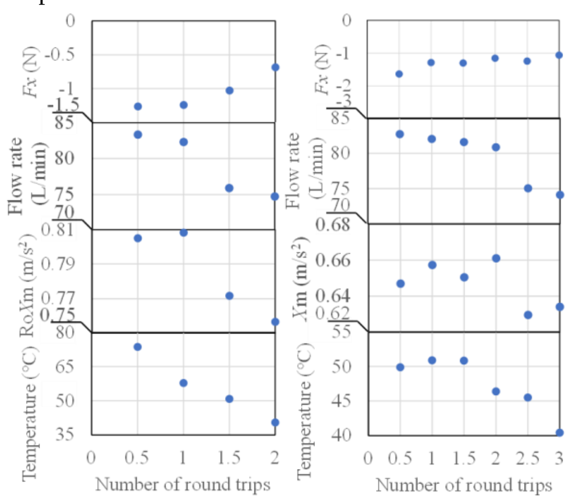


Figure 7. Relationship between the number of round trips, Fx, flow rate, RoXm, and temperature in (a) rough polishing and (b) finish polishing.

Based on the values of *Fz*, Fig. 8(a) and Fig. 8(b) show color-mapped 3D CAD diagrams of machining for increasing and decreasing Z-coordinate values at N=0.5. For decreasing Z-coordinate values, *Fz* changed in a wavy pattern. In contrast, for increasing Z-coordinate values, *Fz* was relatively stable; this indicates that the quality and tool wear may be more stable for increasing Z-coordinate values.

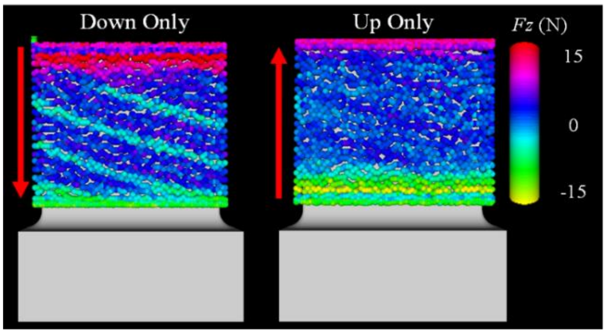


Figure 8. Color plot of Fz in finish polishing for N=0.5. (a) Down only. (b) Up only.

C. Evaluation of Workpieces after Machining

Fig. 9 shows a photograph of the workpiece surface after machining in each process. The positions at a distance of 10, 25, and 40 mm from the surface at Z=0 were termed positions 1, 2, and 3, respectively. The gloss values were evaluated using a gloss checker (Horiba, Ltd.: IG-331). At the end of machining, the gloss value was approximately 150 at positions 1 and 3. However, the gloss value was 19 at position 2, where stronger chatter vibration was observed, as shown in Fig. 5(c); this indicates that the gloss value can be predicted from the vibration value *Xm*.

Rough polishing was performed only in position 2, and the gloss increased to 47 after rough polishing. Subsequently, full surface finish polishing was performed, and it was ensured that all surfaces were uniformly finished with a gloss value of 140–150; this indicates that a uniform polished surface can be obtained by optimizing the robot polishing process using the in-process vibration information. Thus, the effectiveness of the proposed method in providing in-process information during machining and the polishing process was validated.

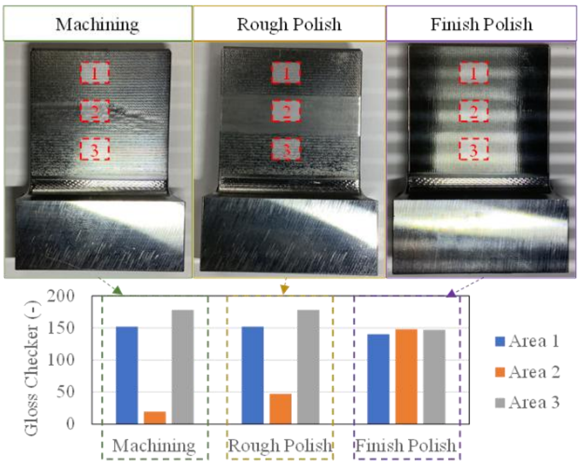


Figure 9. Surface image of workpiece and gloss value for surface position.

IV. Summary

In this study, polishing was performed using in-process vibration information on the machine tools and a sensing system based on a cooperative robot. The following conclusions can be drawn:

- The wireless vibration measurement holder was able to obtain the chatter and vibration data on the machining process of thin workpiece geometries using barrel tools and simultaneous 5-axis machining. In addition, the raw waveform measurement model was able to predict the cause of the chatter and vibration.
- It was found that the state of the machined surface can be predicted by plotting the vibration information on machining and CNC internal information on a 3D CAD system.
- To improve the efficiency of machining and the machining time, the operating range of rough polishing and finish polishing can be optimized based on in-process information.
- It was found that the wear condition of the tools and the condition of the air grinder can be determined from the information on the polishing process by the robot. Additionally, it was confirmed that stable machining can be ensured by monitoring *Fz* values based on internal information on the recognition sensor of the cooperative robot for detecting human contact.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Takamasa Yamamoto conducted the research, analyzed the data and wrote the paper; all authors had approved the final version.

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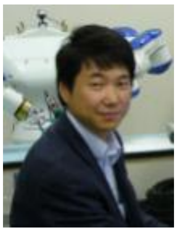

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