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FINISH PROCESSING SUPPORT SYSTEM VIA GRINDING FORCE CONTROL BASED ON HAND STIFFNESS ESTIMATION

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ABSTRACT

Compared with machining by automation, handwork is suitable for high-variety low-volume manufacturing, because such manufacturing requires a lower cost and shorter lead time. However, high-concentration machining should be implemented in handwork. Furthermore, any mistake generated by disturbance from tool rotation results in useless products and wasted materials. Our goal was to develop a finish machining support system that can realize high-accuracy machining in the case of tool rotational direction orthogonal to the feed direction without any machining mistakes. Specifically, in this study we developed a fixture-type machining support robot with a parallel link system to achieve good usability and highly accurate machining. We estimate the operator's hand stiffness from the machining force and end effector position during grinding, and then the grinding force is controlled based on estimation of the worker's hand stiffness. As a result, the influence of grinding force on the worker's hand is suppressed, and the problems with machining accuracy in handwork are lessened. Finally, the effectiveness of the proposed method is shown by grinding experiments.

INTRODUCTION

Today, finishing machining of metal parts is carried out by automatic machining using machine tools and handwork. Although automatic machining enables high-accuracy machining on the basis of the shape data of a workpiece, in the case of machining of a high-variety low-volume part, entry of the shape data for each workpiece and tool path definition are needed. Thus, increasing of time and cost become a problem. On the other hand, machining by handwork enables low-cost machining for short periods. However, the machining accuracy decays compared with that with automatic machining because of worker carelessness and the grinding force of tool rotation. As a result, loss of workpieces and products occurs. To overcome these problems, a machining support system that can achieve higher accuracy and more fail-proof machining than that possible by handwork is desired.

Traditional studies intended to improve the accuracy of machining surfaces have been carried out. Nagata et al. proposed a profile controller based on velocity and constructed an industrial robot system using a grinding wheel spindle with a force sensor. [1] [2] [3]. In this study, the tool pressing force is derived from kinetic friction force and viscous friction force, and feedback control using force control based on the impedance model.Because these automatic machining methods require needs to shape data of the workpiece before machining, so isthey are not adequate to for the machining of high-mix low-volume production.

Using these studies as a basis, the authors have developed a support system for hand work. [4] [5]. For example, they developed a machining support system in which the worker grips a tool with a 6-degrees-of-freedom (6-DOF) manipulator. In this method, we achieved a system that estimates the effect of frictional force due to tool rotation during machining by adaptive modeling from measured values of a force sensor and removes so that the worker machines as intended to the tool rotational direction. Moreover, we developed a parallel fixture-type robot with enough stiffness for pressing force. Using this robot, we proposed a method that targets circular machining as typified by a set collar. In this study, we achieved a good machining surface without backlash and undulation by controlling the material removal rate via cutting the volume per second constant [5]. These machining support systems aim at machining in which the tool rotational direction is identical with the feed direction. Therefore, the effect of cutting resistance due to manual condition is not considered. However, in machining of metal parts as typified by a set collar, machining of a slit and grooved part in which the tool rotational direction is orthogonal to the feed direction must be implemented. In this machining, because cutting resistance becomes a strong factor for decay of machining accuracy, a machining support system considering this effect is needed.

Accordingly, in this study, we targeted machining of a part in which the tool rotational direction is orthogonal to the feed direction, and we aimed at the development of a machining support system that can machine with higher accuracy without mistakes as compared with handwork by cooperation between a worker and a parallel fixture-type robot. In this method, we focused on cutting resistance during machining, a control method that suppresses backlash of the machining surface by the grasp of a worker's hand, and control resistance depending on it. We estimate the worker's hand stiffness based on the pressing force and the position of the end effector, and we improve the accuracy of the machining surface by control grinding resistance depending on the worker's hand stiffness.

EXPERIMENTAL DEVICE

In this study, in mind decay of working accuracy resulting from robotic deflection caused by pressing force during machining, we developed a 4-DOF parallel fixture-type robot with a force sensor and a chuck structure at the far tip of the end effector by installing a rotating structure in the end effector of a 3-DOF manipulator. In order to move workpiece to appropriate position and machine a slit part of symmetrical shape part easily for the worker, the device needs at least translational 3DOF and a rotational DOF. Parallel link robot DELTA is able to move the end effector while keeping its posture constant. The parallel link mechanism used in this study should improve the stiffness of the body considerably, thereby suppressing the amount of bend at the end effector by 1.3×10^{-6}m/N. A photograph of this device is shown in Fig. 1.

A rotary actuator made by Harmonic Drive Systems Co., Ltd., FHA-11C-100-E200 is used for a parallel link manipulator and the end effector with a rotating structure. A rotary actuator made by Harmonic Drive Systems Co., Ltd., FHA-8C-100-E200

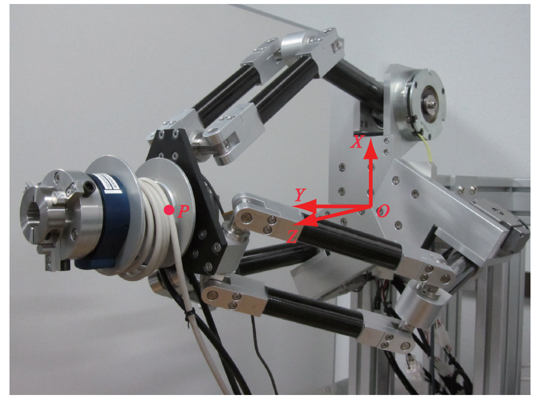

FIGURE 1. Machining support system with parallel link mechanism

is used for a rotating structure in the end effector. The force sensor made by Nitta Co., Ltd. ISF-67M25A50-I40-ANA is a 6-DOF force sensor. Specs of the motors are shown in Table. 1. The tool is a Minitor Co., Ltd., V11HS drill, which is a wheel spindle (CA3207) of 6 [mm] in diameter. The rotational speed of the drill is 5000～50000rpm, and the maximum torque is 23 [Nm]. If the maximum torque is exceeded, the drill automatically stops. The digital micro scoop made by Harmonic Drive Systems Co., Ltd., is used for evaluation of the machining surface. This 3D measuring equipment has a measuring accuracy of 1.0×10^{-5}m.

TABLE 1. Motor specifications

Axis	1 axis to 3 axis	4 axis
Motor model	HFA-11C	HFA-8C
Motor driver	HA-655-1-200	HA-655-1-200
Gear reduction ratio	100	100
Maximum torque	11N·m	4.8N·m
Maximum revolution	60.0r/min	60.0r/min
Rotor inertia	0.067kg/m^2	0.029kg/m^2
Motor mass	0.62kg	0.40kg
Driver mass	1.70kg	1.70kg
Encorder resolution	800000p/rev	800000p/rev

In this study we referred to Zeghloul's method for solving kinematics with the DELTA parallel link manipulator. The kinematic parameters of arm ($j = 1$) of the DELTA parallel link robot are set as shown in Fig. 2. Coordinates of arm ($j = 2$) and arm ($j = 3$) are rotated $\frac{2}{3}\pi$, $\frac{4}{3}\pi$, respectively, about the Z axis.

The whole robot, features of the arm ($j = 1$) and modeling are shown in Fig. 2. Here, L_1 is the length of link1, L_2 is the length of link2, r_A is the distance from the center of the base to the joint and r_B is the distance from the center of the end effector to the joint. In this device, $L_1 = 2.0 \times 10^{-1}$m, $L_2 = 2.0 \times 10^{-1}$m, $r_A = 1.3 \times 10^{-1}$m and $r_B = 6.0 \times 10^{-1}$m. The joint angles of the links are ϕ_{1j},ϕ_{2j} and ϕ_{3j}($j = 1, 2, 3$).

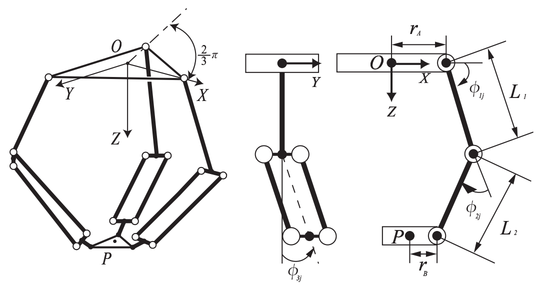

FIGURE 2. Kinematic parameters of DELTA

CONTROL SYSTEM
Controller Design

In this study, the worker's hand model is estimated as hand stiffness during machining. We propose a method in which the grinding force is controlled depending on the hand stiffness estimate. The control system in this study is shown in Fig. 3.

In each work, the force control is implemented to achieve machining at pressing force according to the work. We use the impedance force control based on the velocity command for force control. We set each parameter of force control as follows: Force feedback gain K_f is 0.20. Desired inertia coefficient M_d is 1.0N$\cdot s^2$/m, and desired damping coefficient B_d is 6.0×10^{-3}N$\cdot$s/m. Sampling time Δt is 0.001 s

Because the robot and the worker's hand move for force control, the worker's hand becomes unstable, which is likely to be affected by the grinding force. We estimate the worker's hand stiffness from pressing force and robotic manual position during force control, which controls destabilization of the worker's hand and reduces grinding width error. Using a machining model in this study, by control of the tool rotation of the grinder depending on the hand stiffness estimate based on the grinding theoretical formula, we control the grinding force. In this way we suppress destabilization of the worker's hand, and prevent backlash of the grinding width.

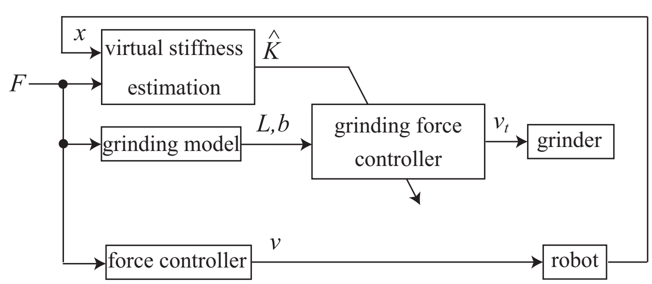

FIGURE 3. Block diagram of proposed method

Hand Stiffness Estimation

We used a stochastic gradient algorithm with an adaptive digital filter to estimate hand stiffness [6]. A schematic is shown in Fig. 4. From the start of processing, pressing force $F(t)$ is input of the plant model for hand stiffness, and also is target input signal $d(t)$ of the adaptive filter. The robotic hand position $x(t)$ is input of the adaptive filter, and it then estimates continuously transfer function $K(t)$ of the adaptive filter so that the filter's output becomes equal to target input signal $d(t)$. Because the transfer function of the adaptive filter is the inverse model of the hand stiffness model, by successive estimation of the transfer function of the adaptive filter, the transfer function of hand stiffness is estimated continuously as equation 1.

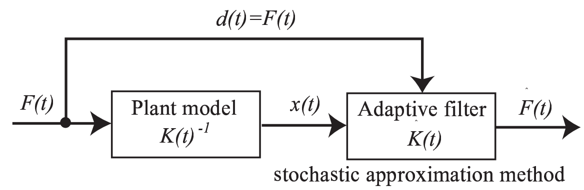

FIGURE 4. Block diagram of estimation of hand stiffness

$$\hat{w}(t) = \hat{w}(t-1) + k(t)z(t)\left\{d(t) - z^t(t)\hat{w}(t-1)\right\}, t = 0, 1, \cdots \tag{1}$$

where $\hat{w}$ is the coefficient vector of the transfer function, k is the coefficient of the transfer function, and z is the vector that ranks input $x(t)$ and output $y(t)$.

Stochastic approximation is used to estimate the coefficient of the transfer function. This algorithm updates the coefficient of the adaptive digital filter in real time. If observed value $y(x)$ is represented as a relational expression has unique solution $h(\theta) = \xi$ like equation 2, and $h(\theta)$ is known, then stochastic approximation is a method to obtain the square root of $h(\theta) = \xi$ by successive calculating using equation 3 on the condition that $k > 0$.

$$y(x) = h(x) + v \tag{2}$$

$$x(t+1) = x(t) - k[h(x(t)) - \xi], \ (t = 0, 1, \cdots) \tag{3}$$

However, $h(\theta)$ is unknown, so we give $k(t)$ and $x(0)$ as initial values, and solve the square root of $h(\theta) = \xi$ by successive calculating using equation 4. This is called the Robbins-Monro algorithm.

$$x(t+1) = x(t) - k(t)[y(x(t)) - \xi], \ (t = 0, 1, \cdots) \tag{4}$$

We estimate hand stiffness from pressing force and manual position when force control is found using actual equipment. The pressing force and manual position are shown in Fig. 5, and the hand stiffness estimate is also shown in Fig. 6. These experimental results show that if variation of the robotic manual position is great, the hand stiffness estimate becomes small, and conversely, if the variation is small, the hand stiffness estimate becomes great. Moreover, it can be seen that the worker's hand stiffness fluctuates due to force control.

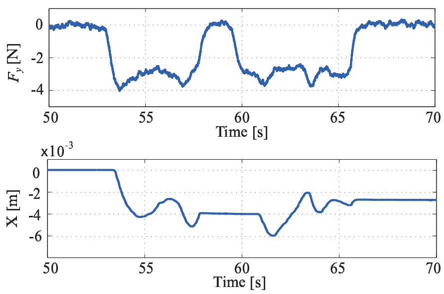

FIGURE 5. Force and end effector position of hand stiffness estimation experiment

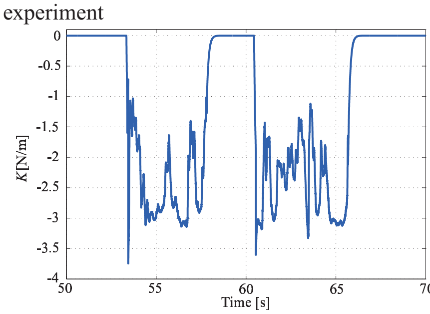

FIGURE 6. Value of hand stiffness estimation of hand stiffness estimation experiment

Grinding Force Control based on Hand Stiffness Estimation

As a general theory of grinding, if the tool rotation is large, the grinding force is small. Based on empirical knowledge, the relation between pressing force F_n in the normal direction of surface contact and grinding force F_t in the directional force is $F_t/F_n = 1/2 \sim 1/3$. This relation shows that the ratio of grinding force to pressing force becomes linearly lower depending on an increase in tool rotation, namely, grinding force varies by variation of tool rotation. Thus we can control grinding force by controlling tool rotation.

In this study, equation (5), which is a theoretical formula using tool rotation in the grinding process, is used as grinding force control [7],

$$SGE = \frac{F_t v_t}{\dot{V}} \tag{5}$$

where SGE is the specific grinding energy, F_t is the grinding force in the directional force, v_t is the tool rotation and V is the work rate. In this study, we define equation (5) as following equation (6), in which grinding force is controlled by varying tool rotation so that grinding force becomes target one.

$$v_t = \frac{\dot{V} \cdot SGE}{F_t} \tag{6}$$

We can ultimately control the grinding force depending on equation (7) by expressing the relation between the worker's hand stiffness and grinding force as equation (7) using machining coefficient α,

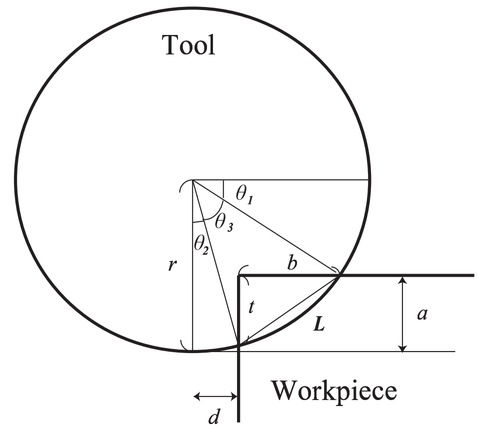

FIGURE 7. Machining model of slit collar

$$v_t = \frac{H_d \dot{V}_z L \cdot SGE}{\alpha \hat{K}(b_c/b_d)} \tag{7}$$

$$\dot{V} = H_d \frac{b_c}{b_d} \dot{V}_z L \tag{8}$$

where L is the length interested grinding, b_c is the width of surface contact, b_d is the width of surface contact in the target force and $\dot{V}_z$ is the feed rate of the tool. The length interested grinding L is obtained from the machining model of the slit part of the slit collar in this study shown in Fig. 7. Assuming that there is a triangle having the same area as the grinding surface which machines at target force, H_d is the height of the triangle which has a base dimension equal to L. Because this height is complex, it is approximated by a ratio of b_c to b_d for H_d. From this model, L is finally defined by equation (14) using equation (9) to (13). Because the cut depth t varies depending on the size, the type of material and the hardness of the grinding stone, we measured cut depth when we actually pressed into the workpiece of use with a constant pressing force, and refer to its value. The relation between the pressing force and the cut depth is approximated linearly from conventional study, and this relation is defined as equation (15) by an identification experiment using this workpiece and grinding stone.

$$\theta_2 = \arcsin(d/r) \tag{9}$$

$$a = t + r(1 - \cos\theta_2) \tag{10}$$

$$\theta_1 = \arcsin\{(r-a)/r\} \tag{11}$$

$$\theta_3 = \pi/2 - (\theta_1 + \theta_2) \tag{12}$$

$$b = \sqrt{r^2 - (r-a)^2} - d \tag{13}$$

$$L = \frac{2\pi r \cdot \theta_3}{2\pi} \tag{14}$$

$$t = 0.0416 \times f_n \tag{15}$$

We carried out a grinding experiment to verify the above grinding force control system based on hand stiffness estimation. The experimental result of estimation of hand stiffness is shown in Fig. 8. This result shows that grinding force is controlled by variation of tool rotation depending on the hand stiffness estimate.

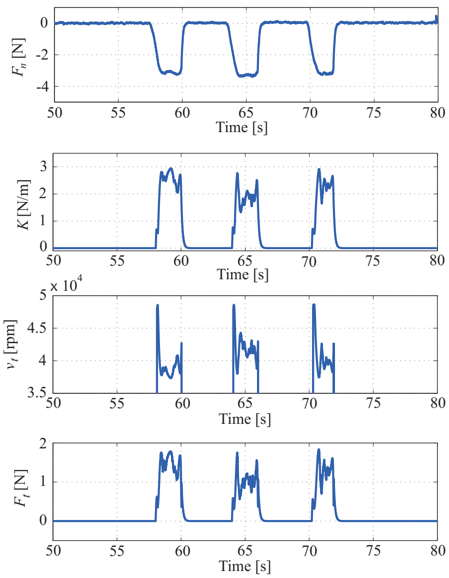

FIGURE 8. Experimental result of estimation hand stiffness of grinding force control

MACHINING EXPERIMENT

We carried out a machining experiment to verify the effectiveness of the proposed method described in the previous section. The machining experiment was that a worker feeds tool in direction of feed direction pressing grinding tool to part of machining with worker's direct grasping rotating tool. We use a slit collar of stainless SUS304, which is an alloy of chrome and nickel, as the workpiece, and machine part of the slit collar. The following three cases were set up for this experiment: machining without control. (Case 1); implementing only constant force control (Case 2); and implementing the grinding force control system of the proposed method (Case 3). In this regard tool rotation speed is 35000[rpm] in Case 1 and Case 2.

First, machining without control was implemented. Measured values of pressing force and grinding force during machining experiment are shown in Fig. 10. In the case of implementing machining without control, the worker can't keep the pressing force constant, because the worker has to adjust the force depending on the machining description. Therefore, because the cut depth and grinding force vary significantly, the effects on the hand increase and machining accuracy decreases accordingly.

Next, constant force control was implemented. Measured values of the pressing force, hand stiffness estimate and grinding

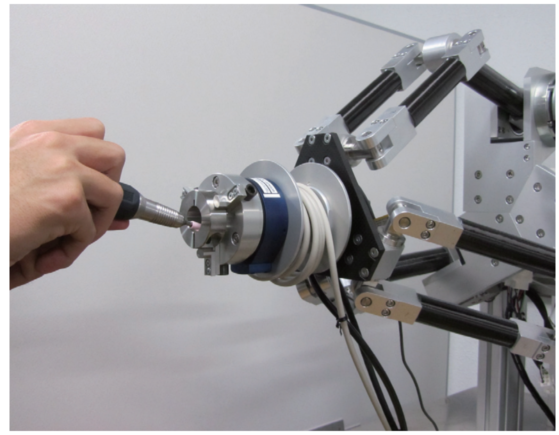

FIGURE 9. Experimental appearance

force are shown in Fig. 11. Stable control of the pressing force is performed at close to reference force because of force control. However, despite variation of the hand stiffness from up-and-down movement of the hand, the grinding force is proportionate to the pressing force. Clearly the worker is likely to be affected by the grinding force.

Finally, the grinding force control system of the proposed method was implemented. Measured values of the pressing force, hand stiffness estimate, tool rotation and grinding force are shown in Fig. 12. Stable control of the pressing force is performed at close to reference force because of force control, and the tool rotation is controlled depending on hand stiffness during force control. As a result, the worker is not likely to be affected by the grinding force because the grinding force is controlled depending on the hand stiffness estimate.

Next, we evaluated the results obtained for the three cases in the machining experiment. The machined surfaces were observed by optical microscopy at a magnification of 175 times. Each machining experiment was performed three times. Fig. 13 shows the machined surface of each machining when grinding force control was implemented. The difference between the maximum value and the minimum value of the thickness of the machining surface is shown in Table 2. These measuring results show that use of the proposed method reduced the thickness error. The rates of reduction with the use of the proposed method for each machining were 56.03% for non-control and 56.46% for only force control.

CONCLUSION

In this study, for machining in which the tool rotation direction is perpendicular to the feed direction, we developed a system that supports a worker's hand work with a fixture-type machining support robot. With force control implemented conventionally, we proposed a method that estimates a worker's manual situation by estimating hand stiffness during machining. The experimen-

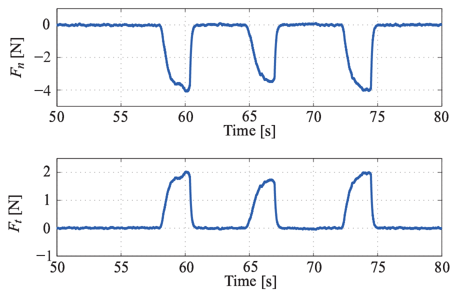

FIGURE 10. Experiment result with non-control

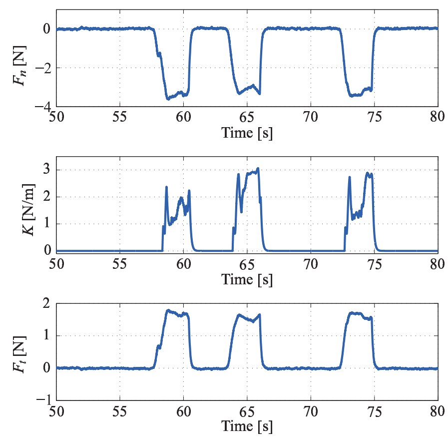

FIGURE 11. Experiment result with force control

TABLE 2. Experimental result of grinding error

	1st [μm]	2nd [μm]	3rd [μm]
Case 1	87.74	69.88	108.26
Case 2	64.33	86.53	116.47
Case 3	28.77	35.66	52.05

tal results showed that the grinding force can be controlled by varying the tool rotation depending on this hand stiffness. Even in cases when a worker is likely to be affected by grinding force due to a low level of hand stiffness, we enable controlling of machining accuracy by minimizing the grinding force and controlling manual instability.

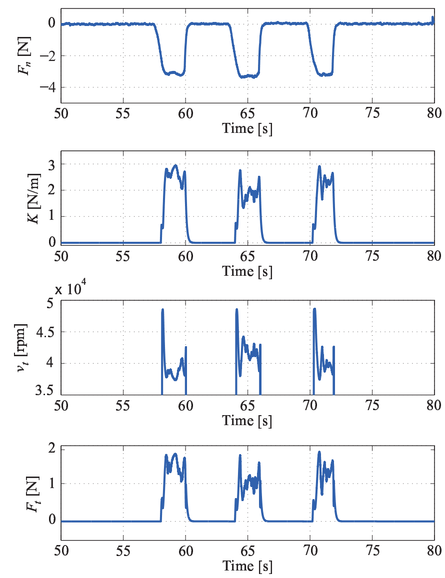

FIGURE 12. Experiment result with grinding force control

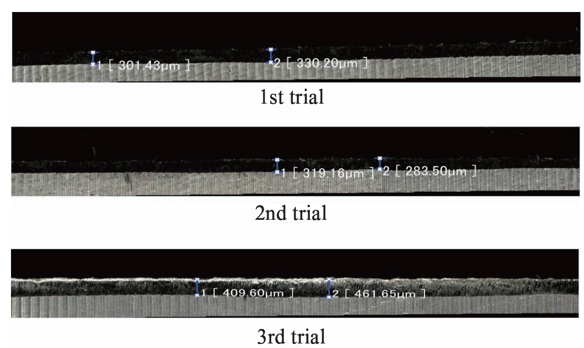

FIGURE 13. Machining surface with grinding force control machining

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