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DEVELOPMENT OF BILATERAL CONTROL SYSTEM FOR PROCESS MACHINING SUBJECT TO CHANGING CUTTING CONDITIONS

Finishing processes such as deburring are performed on a wide variety of products in various quantities by machinists on a piece-by-piece basis in order to improve surface finish. Deburring is a major contributor to time and cost of the improvement of the surface finish. During deburring, the intended quality of the surface finish is very much dependent on the operator's skills. This work is concerned with understanding and interpreting how a bilateral robot can assist the deburring process. We propose a control method based on a machining model that is made up of several components, including the cutting tool, spindle speed, feedrate of the tool and other important constituent elements of the machining system. Machining operations are carried out for selected cutting conditions. A haptic robot is directly connected to the machine-tool and the operator. The motion of the haptic robot is controlled automatically under machining conditions in which it is possible to achieve highly accurate surface finish. The force feedback from the haptic robot influences the continuous adjustments made by the machining operator. Mathematical equations for the haptic interaction between the robot and process machining, involving time delays, are established. For specific range of cutting conditions, the regimes wherein the bilateral control system enhances the surface finish of the work piece in a sustained way are located. The regimes and effectiveness of the control system are quantified experimentally.

1. INTRODUCTION

At present, a great number of working processes are carried out automatically by using industrial robots. Such a production method has been widely adopted in the mass production of many applications. However, if production is limited to a number of diversified products, deburring the products is difficult because of time and accuracy constraints. For example, a long time is required to prepare CAD/CAM data for the geometric configuration and machining setup of specific products. Coping with the differences in the set position or warping of the products is not an easy task either. These tasks are typically carried out manually by machinists. The machinist is required to carefully control the force and

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kinematic motion of the tool so as to prevent the occurrence of disturbances. If the ability of the machinist is insufficient, these tasks will in turn cause machining errors or a deviation from the intended production tolerances.

To solve the problems associated with deburring and surface finish improvement effort has been made to establish continuous interactions between haptics and process machining. In the study by Sakito et al [1], an adaptive system that estimated the friction between the tool and work piece, was used to control any adverse effect from the tool's rotation. The adaptive system does not require information about the quality and shape of the work piece to transmit the most suitable cutting force for process machining stabilization. Bilateral control is another type of master-slave control method that has been used as well [2-4]. This control system can transmit forces that provide the machine-tool operator a feeling of independence even if the robot is controlled remotely. Yamada et al [2] investigated the machining process using the bilateral control system constructed by combining a PHANoM1.5/6DOF (SenAble Technologies) and a force display device driven by hydraulics. We examine the interaction between process machining and bilateral control system to improve surface finish.

When a haptic device or bilateral control is applied to the machining support system, the contact force or feed speed does not easily reach a stabilization point compared with automated machining. As a result, the accuracy of the product depends on the skill of the operator. In previous studies, a hybrid control method with position and force control systems has been used [3, 4]. However, this control method cannot produce a constant value for the peak height of the machined surface due to the irregular change of cutting velocity, spindle speeds or irregular state of burrs. As a result, there are over cuttings and shortfalls in the cutting force. A method for controlling the cutting parameters is thus required. Such a method must be more robust than previous control methods and also adaptable to changes in feeds and spindle speeds.

In this study, a bilateral control system that is constructed to support process machining stabilization is proposed. For this control method, the gain is continuously altered by the machining conditions. The value of this gain is set at the force signal between the master and slave robot. The gain is also used to control the slave robot to move automatically to some acceptable normal direction during machining. Furthermore, a control method based on the machining conditions that is constructed in terms of the cutting force, cutting velocity, feedrate, spindle speed, machining quantity and efficiency, is proposed. This method updates the cutting parameters mutually, and thereby ensures the attainment of steady state machining. This proposed method for controlling the cutting force, tool speed, feedrate and spindle speed can be implemented by the operator or robot. By using this method, the problems that will occur when a haptic device or bilateral control is applied to the machining support system are accounted for.

2. MACHINING SUPPORT SYSTEM

In this study, we use a three-dimensional haptic device (Falcon, Novint) as the master robot and use a machining support robot that has six degrees of freedom (6DOF), force

sensors and a rotating tool on the hand as the slave robot. The Falcon has a parallel link mechanism and produces output signals for the position of three axes and an ON/OFF signal from a button. The base side of the slave robot consists of a prismatic joint with 3DOF. Two axes in the middle constitute the fixed rotation joint. The tip side of the robot consists of a rotating joint with 3DOF. The base and tip side of the robot are driven by a motor. The base side of the robot uses a prismatic joint made by IAI Co., Ltd. The lead is 0.010 m, resolution is $2.5 \cdot 10^{-6}$ m, rated maximum velocity is 0.05 m/s, maximum velocity is 1.0 m/s, and maximum torque is 1.9 Nm. The motor of the tip side of the robot uses a servomotor (Harmonic Drive Systems, Inc.), for which the maximum torque is 11.0 Nm, maximum revolution is 60.0 rpm, and resolution is $8.0 \cdot 10^5$ p/rev. A schematic representation of the master- slave robot and a model of the slave robot are shown in Figures 1 and 2. We used these two robots to form a bilateral control system that adjusts the machining support system. The force sensor uses a 6DOF force sensor (Nitta Co.). The tool is a V11HS drill (Minitor Co., Ltd.) that is a fixed carbide cutter of 0.003 m in diameter. The spindle speed of the drill is 5000-50000 rpm, and the maximum torque is 0.023 Nm. For the test, we used die-cast aluminum alloy ADC12 as material for the work piece. The x-axis and y-axis of the force sensors are set in the normal direction and tangential direction of the machining side during machining, respectively. The size of the burr is about 0.02-0.3 mm.



Fig. 1. Appearance of master and slave robot

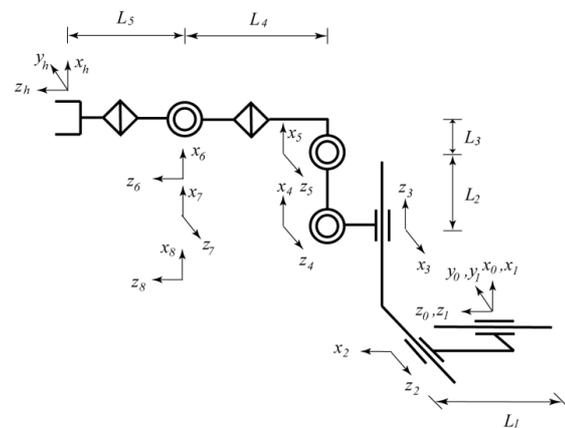


Fig. 2. Modelling of slave robot

3. DESIGN OF CONTROLLER

3.1. CONCEPT OF PROPOSED BILATARAL CONTROLLER

To develop the machining support system via bilateral control, it is important that the machining process is known, and that it can be used in the development of automatic controlled robots. In the proposed control system for the machining process, the value of the

gain that is generated by the machining condition is set to the force signal between the master and slave robot. The system model of this controller is shown in Fig. 3. By this gain, the dominant rate of the master and slave robot to the system can be controlled. This means that the controller can select several patterns of control algorithms. For example, the slave robot is controlled by the master robot during normal control and controlled to trace the reference path calculated by machining theory during cutting. The motion equation of the interaction between the master and slave is given in equations (1) and (2), respectively:

$$M_m \ddot{x}(t) = -c_m \dot{x}(t) - c_{mp} \dot{x}(t - \tau_{m1}) + \mu_{m1} [c_d \{y(t - \tau_{s1}) - x(t - \tau_{m1})\} + k_d \{\dot{y}(t - \tau_{s1}) - \dot{x}(t - \tau_{m1})\}] + f_{op}(t) + \mu_{m2} f_{env}(t - \tau_{s2}), \quad (1)$$

$$M_s \ddot{y}(t) = -c_s \dot{y}(t) - c_{sp} \dot{y}(t - \tau_{s1}) + \mu_{s1} [c_d \{x(t - \tau_{m1}) - y(t - \tau_{s1})\} + k_d \{\dot{x}(t - \tau_{m1}) - \dot{y}(t - \tau_{s1})\}] + f_{env}(t) + \mu_{s2} f_{op}(t - \tau_{m2}), \quad (2)$$

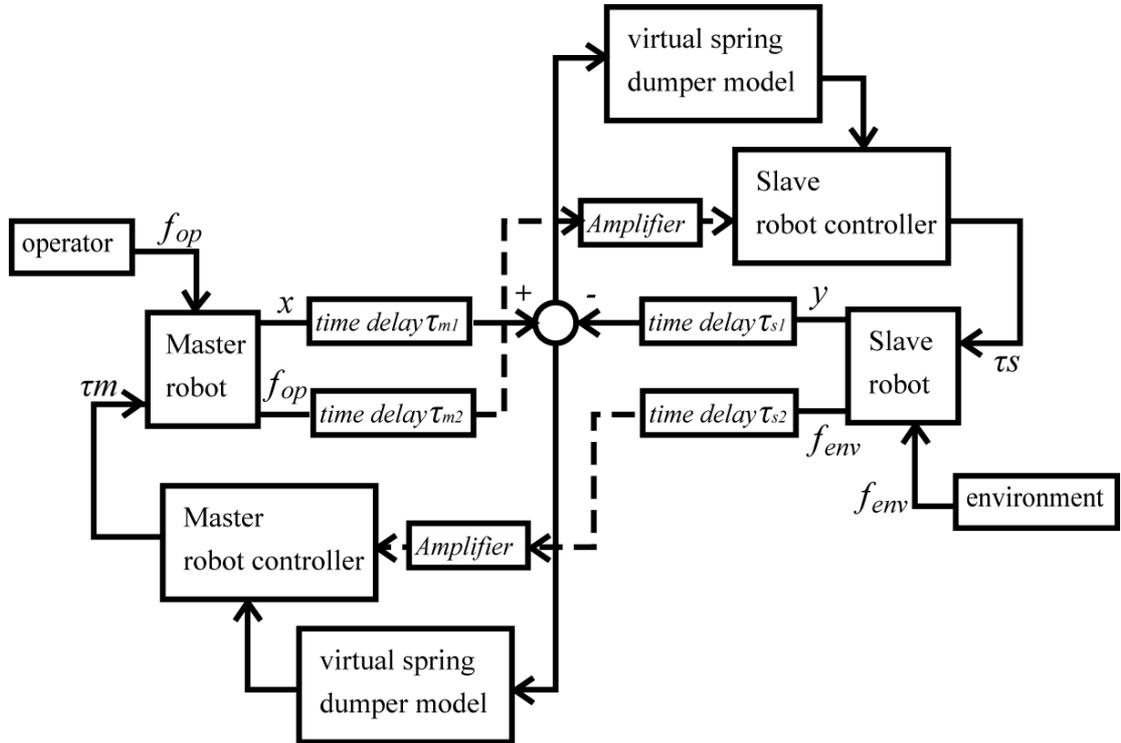


Fig. 3. Proposed bilateral control system for machining support

where x and y represent the position of the master and slave robot. M_m and M_s are the mass coefficients, c_m and c_s denote the viscosity coefficients. The parameters k_d and c_d represent

the spring and viscosity coefficients between master and slave robot. f_{op} is the force that is added by the operator while f_{env} is the force added by environment. The values of c_{mp} and c_{sp} are chosen in such way that they are able to stabilize the master and slave robot by some defined cutting conditions. τ_{m1} and τ_{s1} are the respective time delays induced by the filter. The modulation of the measured value of the encoders is carried out by the filter. The time delays τ_{m2} and τ_{s2} are the values generated by the filter which modulates the measured value of the force sensor. In this study, a master robot and slave robot are controlled by one computer. In this way, there is no time delay caused by transfer of signal.

3.2. DESIGN OF THE BILATERAL CONTROL SYSTEM FOR MACHINING

In this study, we use two sets of values for gains μ . During normal control, μ_{m1} and μ_{s1} are set as $\mu_{m1}=1, \mu_{s1}=1$. The master robot is not equipped with the force sensor, and thus μ_{m2} is set as $\mu_{m2}=0$. The slave robot controller has a compliance controller in order not to yield to the over load from the slave robot when it contacts with some object. During machining, μ_{m1} and μ_{s1} are set as $\mu_{m1}=1, \mu_{s1}=0$ in the normal direction. By using this condition, the slave robot has a completely dominating rate to the system.

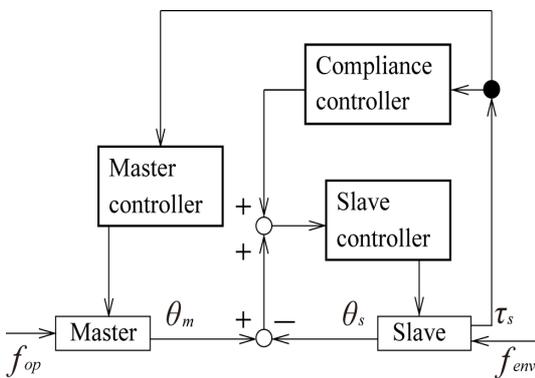


Fig. 4. Controller during normal operation

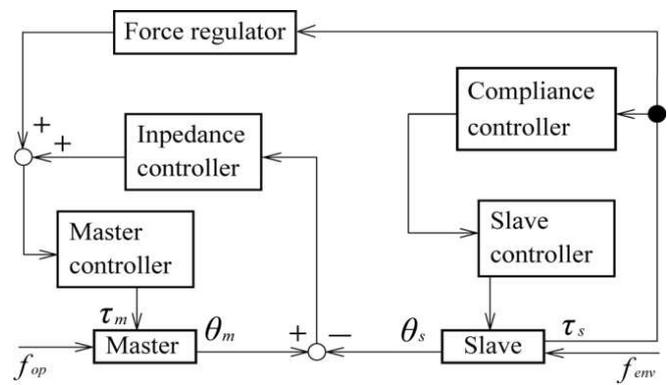


Fig. 5. Controller during machining

In addition, the slave robot has a controller which controls the slave robot independently based on the machining theory. As a result, the slave robot will move independently with a motion calculated by the machining theory. These control activities are depicted in the block diagrams in Figs 4 and 5. The control blocks show how the master and slave components are related. In both figures the input and output parameters appearing equations (1) and (2) are shown. The specific organization of the control algorithms is obtained from these blocks.

4. EQUALIZATION OF THE MACHINING VALUE BY USING A MUTUALLY UPDATING METHOD

In this section, we propose a correcting method for the destabilized cutting value caused by changes in the cutting velocity, spindle speed and cutting force. The process machining is constituted by the cutting force, tool speed, feed speed and the material removal rates. Mathematically, we represent the cutting force as follows:

$$F_c = K_s S = K_s \frac{adv}{n} \quad (3)$$

$$a = a_s \frac{\theta_s \pi}{360} = e \frac{F_c n}{vd} \quad (4)$$

$$d = \frac{DW}{Z} \quad (5)$$

In these equations (3)-(5), F_c is the cutting force, K_s is the specific cutting resistance, S is the cutting area, a is the cutting depth, v is the cutting velocity, n , is the spindle speed, a_s is a transfer coefficient between a and θ_s , θ_s is the circumference of the contact area, W is the cutting width, D is the diameter of the end mill and Z is the number of cutting teeth. In this study, $K_s=20$, $D=0.003$ m, $Z=10$. Here, the direction of the machining tool is fixed. So, we assume that the cutting width W and the cutting depth a are set by setting the machining area aW . At this time, the machining area is controlled to be set within a certain definite range by controlling each input parameter. Ranges of each input value are set for the machining conditions. These ranges are set to hold the static property of the machining. At this time, we consider the virtual mass point m in virtual three-dimensional space. This mass point is given by the force from the virtual wall that is created by acceptable ranges of each machining parameter. An overview of this system is shown in Fig. 6. The virtual walls created by acceptable range of machining force, spindle speed or cutting velocity without cutting area are perfectly parallel with each axes. Because each condition has a maximum acceptable value and a minimum acceptable value, these walls construct the octahedron at a maximum. At this time, these walls are assumed to yield the repulsive force in response to the deviation between each input value and mean value of the maximum acceptable value and minimum acceptable value. They are in which A_i and B_i are determined by the user, and

$$G_i = \sigma \times A_i (e^{B_i(i_{max}-i_{min})} - 1)$$

$$\sigma = \begin{cases} 1, & i \leq (i_{max} + i_{min})/2 \\ -1, & i > (i_{max} + i_{min})/2 \end{cases} \quad (6)$$

these parameters control the movement of the virtual mass point. If the input value is out of the acceptable range, one can set $G_i=10$. A_i are determined with trial and error to converge

into an acceptable range with stability. Because G_i becomes $G_i=10$ when each input value is at its maximum or minimum value, B_i is calculated as follows:

$$B_i = \frac{2}{(i_{max} - i_{min})} \log \left(\frac{G_i}{A_i} + 1 \right) \quad (7)$$

The effect of the correction is low around the mean value and high around the acceptable value when such an energy distribution is used. Because the virtual walls constructed by the maximum machining value and the minimum machining value is a curved surface, the unit vectors to these walls from the position of the virtual mass point are calculated by v , F_c and n . These vectors are determined by Lagrange's method of undetermined multipliers. That is,

$$e \times \frac{F_c n}{vd} - a_{max} = 0 \quad (8)$$

or

$$e \times \frac{F_c n}{vd} - a_{min} = 0 \quad (9)$$

and thus we have

$$f(v, F_c, n) = (v_n - v)^2 + (F_{cn} - F_c)^2 + (n_n - n)^2 \quad (10)$$

In the above equations, v_n , F_{cn} and n_n show the position where the deviation from the position of the virtual mass point has an extreme value on the virtual wall calculated by acceptable machining values. The extreme value of (10) that satisfies (8) and (9) has to be calculated. This problem can be rewritten as follows:

$$F_{cn} = \frac{4F_c - 2\lambda en}{4 - \lambda^2 e^2} \quad (11)$$

$$n_n = \frac{4n - 2\lambda e F_c}{4 - \lambda^2 e^2} \quad (12)$$

$$v_n = \frac{e F_{cn} n_n}{a_{max} d} \quad (13)$$

$$\begin{aligned} & a_{max}^2 d^2 e^4 \lambda^5 + 2v a_{max} d e^4 \lambda^4 \\ & - a_{max}^2 d^2 e^2 \lambda^3 \\ & + (-8F_c n e^3 - 16v a_{max} d e^2) \lambda^2 \\ & + (16a_{max}^2 + 16F_c^2 e^2 + 16n^2 e^2) \lambda \\ & - 32F_c n e + 32v a_{max} d = 0 \end{aligned} \quad (14)$$

In these equations, λ has five real solutions at maximum. Therefore, we define the effect from the wall to be inversely proportional to the magnitude of the vector. The

viscosity coefficient is introduced into this equation to stabilize the motion of the virtual mass point. We use the parameter values, namely: $M=0.001$ and $C=75$, K is set as $K_f = (f_{max} - f_{min})/2$, $K_r = (r_{max} - r_{min})/2$, $K_v = (v_{max} - v_{min})/2$.

A simulation is performed with this control method. The cutting velocity is given randomly. The change of the target contact force, the target tool speed and the target machining value are shown in Fig. 7. From these results, the convergence of each parameter into the acceptable range is shown. In addition, the over run of the machining value caused by a decrease in the cutting velocity is corrected by changing other parameters.

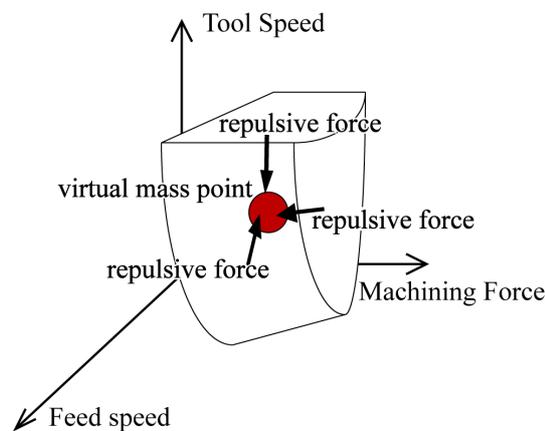


Fig. 6. Concept of proposed control method

5. MACHINING EXPERIMENT

We performed the machining experiment with the bilateral control system constructed in the previous chapter. The machining force is controlled to be constant by moving the position of the slave robot toward the normal direction and the feed speed depends on the control by the operator. Experimental results are shown in Fig. 8. In the experiment, the tool is operated at overload values caused by over cutting. As a result, the machining was not performed successfully. The machining surface height was not kept constant, owing to the irregular changes in the cutting velocity. Next, we performed a machining experiment with the proposed method. The machining force, feed speed, tool speed and calculated cutting depth are measured in this experiment. The experimental results are shown in Fig. 9. The measured values are shown by a solid line and the maximum acceptable value and minimum acceptable value are shown by dashed lines. To control the feed speed, the viscosity coefficient of the master robot is increased or decreased. As such, the limitation of the feed speed is carried out only to the maximum speed and the operator can control the robot with arbitrary operations. Machining is performed about 0.8 seconds after measurements are started as shown by the dashed line.

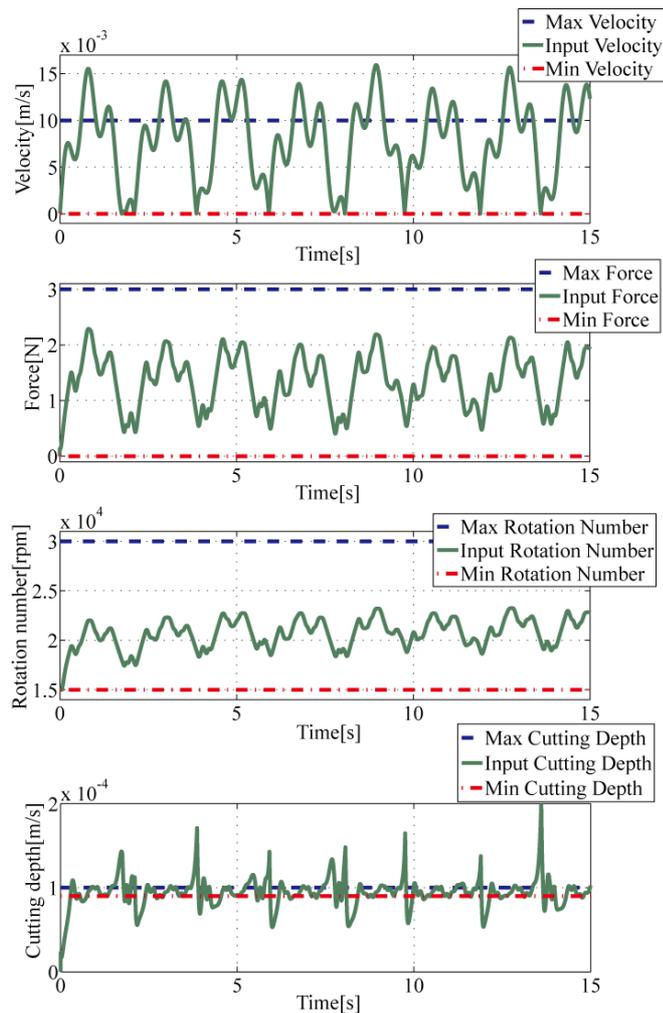


Fig. 7. Simulation result with proposed method

Each machining surface of experiment result experiment is shown in Fig. 10 and the height of the machining surface with proposed method is shown in Fig. 11. The feedrate was manipulated irregularly as in the previous experiment. Compared with the previous experiment, the disarray of the machined surface caused by over cutting or the absence of the machining value was prevented and the machining experiment is performed successfully. The changes in the machining force and the tool speed are found to move the cutting depth into an acceptable tolerance. A vibratory change of the calculated cutting depth caused by cutting the burrs is observed. However, this change did not stress the tool speed. This effect is caused by using the virtual mass model and eliminating such an impalpable change. This effect makes it possible to stabilize the machining and to achieve a well finished machined surface. The machining force was not controlled successfully for around 2 s after measurements began and the tool speed took high values to make the cutting depth constant. From these experimental results, it is verified the proposed method is effective in making the machining value constant. The accuracy of the machined surface is about $40 \mu\text{m}$ in the normal direction. However, the cutting width in the tangential direction

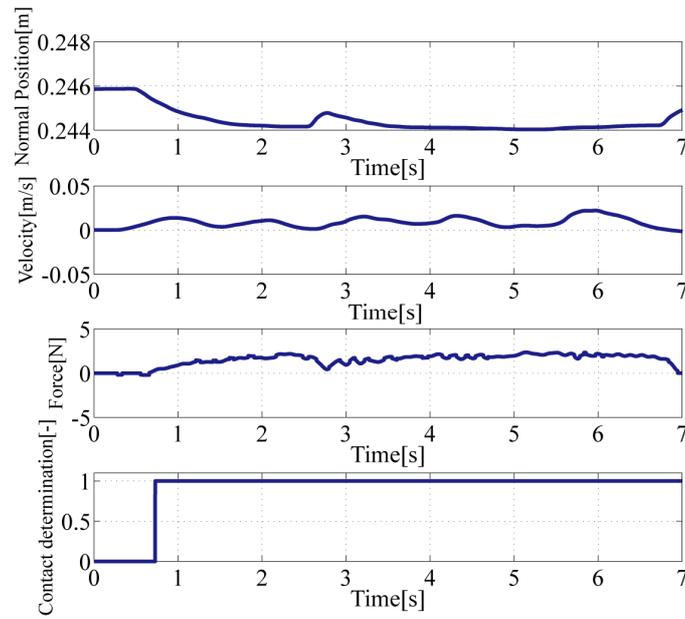


Fig. 8. Experiment result without any assignment

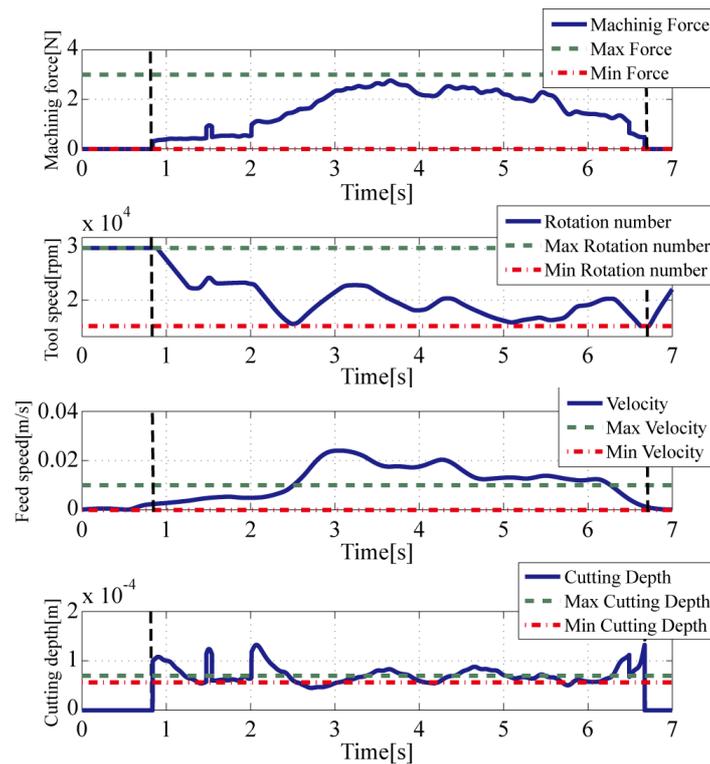


Fig. 9. Experiment result with proposed method

was $390 \sim 510 \mu\text{m}$ with a target width of $500 \mu\text{m}$. In this study, the change rate of the tool speed is set to change gradually in order to stabilize the machining value. However, the change in the machining force was found to be discontinuous while deburring with this system. Improving the reactive property with the stability of the system is required.

6. CONCLUSION

In this study, a bilateral control system for a finish machining process is designed. This system controls the slave robot with automatic compliance control in the normal direction during machining. In addition, a control method is proposed that ensures process machining stabilization. The control method updates the input values based on the machining conditions and model equations constructed in terms of the machining force, cutting velocity, spindle speeds and others. It is demonstrated that the use of the proposed control method prevents the destabilization of the machining process. The bilateral control improves the deburring process and the cutting velocity is changed by irregular control of the slave robot. By using this method, a finish machining support system with a bilateral control system that is not affected by the skill of the worker is established.

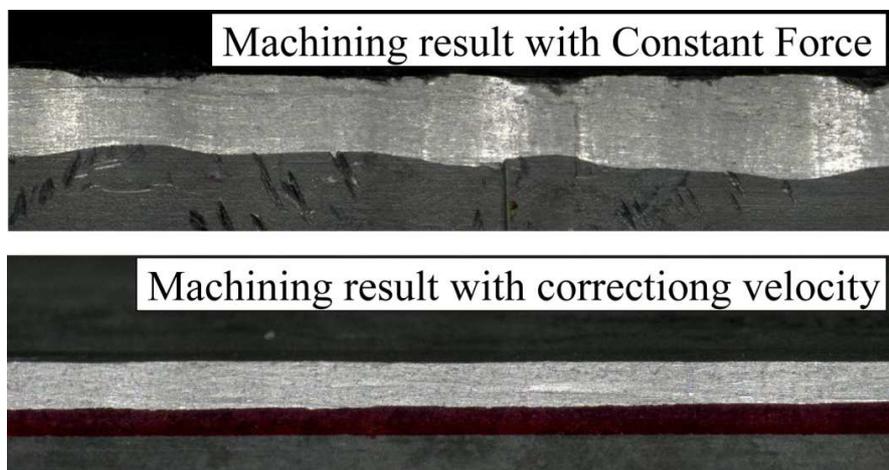


Fig. 10. Comparison of machining surfaces

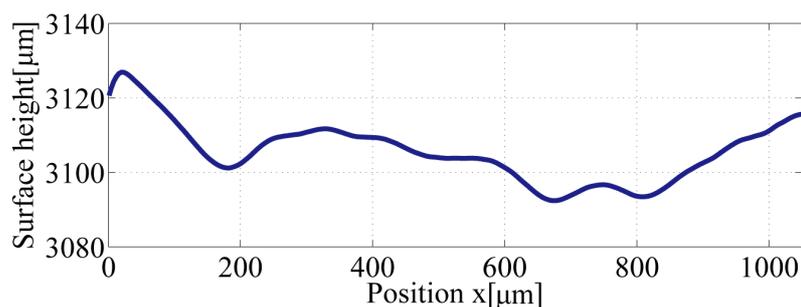


Fig. 11. Graph of machining surfaces of experiment result with proposed method

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