Technology Development For Stainless Steel Grinding And Polishing Using A Robot Manipulator

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Abstract

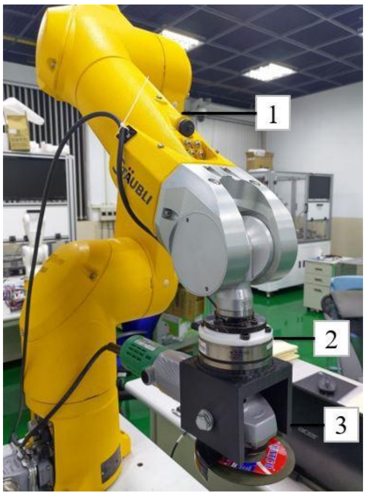
The time required for grinding and polishing is roughly four times longer than the time required for welding in the processing of metals. The processing *Traditional industries still mostly employ hand grinding and polishing techniques. Unfortunately, these processes have the following drawbacks: prolonged processing times, high labour costs, and unreliable product quality. This work uses a robotic arm's high flexibility to create a tool-holding grinding and polishing system with force control mechanisms in order to overcome the aforementioned restrictions. In particular, the size, weight, and processing expense of the stainless steel pieces are taken into account while choosing the off-the-shelf handheld grinder and attaching it to the robotic arm. The robotic arm also has a force/torque sensor to make sure the system is active compliant when contact machining. The developed technique can reduce the surface roughness of 304 stainless steel to 0.47 m for flat surfaces and 0.76 m for circular surfaces, according to the experimental results. Also, the processing trajectory is designed in the simulation environment of the CAD/CAM software, which can produce effective collision detection and arm position determination results.*

Keywords: *Active compliant, hybrid position/force con- trol, robot manipulator, surface machining, surface roughness*

1. Introduction

The effects of an ageing population and dropping birthrates in some nations are just two of the numerous issues the globe is currently dealing with. The labour force is gradually getting older, and the world's fertility rate is still declining, according to statistics provided by the UN. The level of national competition will be greatly impacted by this. After the labour pool has shrunk, it is crucial for the government and businesses to figure out how to replace workers. Robotic arms have been used by several businesses to replace human labour. Robotic arms are currently used in industry for automated activities. Robots have been employed in applications ranging from the production of electronics to agriculture, the medical industry, and even service sectors since Joseph Engelberger created the first robotic arm in 1959. Robotic arms can therefore be used in any surgery. The construction of intelligent robotic arms has been explored as a new area of study to satisfy human requirements and environmental constraints. For common contact processing activities like grinding and polishing, there are various processes that call for experienced operators. that is labor- and time-intensive Using the high-efficiency robot arm can replace the procedure. As a result, it has become a well-liked research subject. The two types of handled workpieces and hand-holding tools used in modern robotic polishing systems. The latter is appropriate for smaller things, while the former is utilised for lar ge workpieces [1]. In studies on modern robotic arm polishing, the majority of robotic arms clamp workpieces that need to be ground and polished. For instance, Zhu et al. [2] offered a combination of a force model and an abrasive belt grinding force to evaluate the surface roughness of a workpiece, whereas Ma et al. [3] carried out polishing with a constant force in a self-designed abrasive belt grinding system. The main drawback of this technology is that the workpiece cannot be clamped once its weight or size exceeds the capabilities of the robotic arm. Hence, the hand-holding polishing tool is ideal for polishing large workpieces. Also, the design and combination of the robotic arm's end effector and the grinding tool are the foundation of this robotic polishing system's research [4-6]. For robotic grinding and polishing applications, an active contact flange (ACF) based on active compliance technology and powered pneumatically has been on the market [7]. The price is still high.

In this study, a force sensor and a cost-effective robotic polishing system comprising a grinding



and polishing module are suggested. Moreover, experiments are performed on 304 stainless steel, a material that is frequently utilised in the sector. Two categories of grinding experiments were used in this investigation. The initial set of studies is positioning the robotic arm along the path that RoboDK has planned (a robot simulation software). The alternative experiment type uses a hybrid position/force control that combines force control with planning path.

2. System Description

In this section, the experimental architecture includ- ing hardware and computer software are described.

Hardware Architecture

Hardware in this robotic polishing system mainly in- cludes a robotic arm, a force sensor, and a grinding

module. The industrial robotic arm (Stäubli TX60L) has six degrees of freedom which exhibits a high de- gree of flexibility, solid structure, and special reduc- tion gear system. The main task of the robotic arm in- volves accepting the instructions provided by the host computer and conducting grinding and polishing on the workpiece. Second, the force sensor (ATI Axia80 EtherCAT F/T sensor) plays the role of calculating the grinding force in this robotic polishing system. The maximum force that this sensor can measure is 500 N and the torque is 20 Nm. The application level of the force sensor is extremely wide, including robotic arm loading work, contact force feedback, and constant force work. Finally, to reduce cost, a self-designed tool holder by 3D printing and the off-the-shelf handheld grinder are combined into a grinding module. The grinding module performs functions including cut- ting, grinding, and polishing solely by changing the granularity of the grinding wheel. Figure 1 shows the hardware architecture used in this study.

Software Architecture

All software algorithms in this robotic polishing sys- tem are executed in a host computer. The program- ming language in host computer is C#. Tasks of the host computer involve sending commands via Eth- ernet to the robot controller for moving the robotic arm, reading data of the force sensor via EtherCAT, monitoring the postures of the robot arm during op- eration, and generating polishing path using RoboDK package. Note that combination of TwinCAT (the Win- dows Control and Automation Technology, a C# proj- ect) and EtherCAT is used as an easy-to-configure au-tomated system. Figure 2 depicts the communication protocol used in this study.

Fig. 1. Robotic polishing system: 1 robot arm, 2 force sensor, 3 grinding module

Fig. 2. System communication protocol

3. Control Method

This section describes the force control strategy of the system for grinding and polishing tasks. Most robotic arms, either industrial or collaborative, are typically used for repetitive and time-consuming ac- tions, such as pick-and-place, locking, and assembly. The common point of these actions is that they use a pure position-control architecture to perform tasks. However, under pure position control, irrespective of the force applied in the working environment, the ro- botic arm will move to the position based on the co- ordinate point provided by the operator. This control method may generate contact forces, such as those for mechanical processing, which often lead to the exces- sive force, and thereby causing damage to the robotic arm or processed workpieces. Therefore, the ability of the robotic arm to comply with external forces is an extremely important issue. To solve the aforemen- tioned problems, the force control strategy can enable the robot to interact with the force it experiences dur- ing operation, such as imparting the same force to an object, or adjusting when encountering geometrical differences in assembly tasks. Force control exhibits evident certain advantages in terms of safety consid- erations or adapting to the environment. Generally, control strategies are divided into two categories: in- direct force control strategies and direct force controlstrategies.

Direct Force Control

When compared with indirect force control, the direct force control strategy employs a force/torque sensor that senses external force, and the measured force is fed back to the robot for path trajectory correction to ensure compliance of the end effector of the robotic arm [8]. In this control strategy, trajectories of force and motion are considered for robot control and can be further matched with indirect force control. For robots it is often required to maintain external forces within a certain range. Hybrid position/force control is a common direct force control strategy. This control strategy involves simultaneous control of the force and movement of the end effector of the robotic arm. To perform hybrid position/force control on the ro- bot, a surface is created first. Then, position control is performed in the tangential direction of the surface and force control is performed along the normal di- rection of the surface. The force and position are con- trolled in two directions to form a hybrid position/ force control strategy. When the robot starts per- forming work, it searches for the contact force on the unconstrained axis, and it only moves along this axis until it generates contact force with the surface of the object. Throughout the process, the force/torque sen- sor sends the force data back to the controller. Once contact is realized, a constant force is applied to the constrained axis for control, and the force is always maintained when the programmed trajectory is exe- cuted. Hence, this ensures that the position of the end effector of the robotic arm and force are controlled ina closed loop.

In this study, a proportional-derivative (PD) con- troller is used for force control. Thus, the force of grinding and polishing can be maintained via a PD controller. In this experiment, the force control is applied to the position path of the robotic arm, and Cartesian coordinates of the robotic arm are adjusted according to the contact force. This ensures that the position changes and continuously caters to the force value to obtain a constant force effect. The PD formula designed in this study is shown as follows

Z_{n+1} denotes the new coordinate position of the robotic arm in the surface normal direction, Z_n denotes the current coordinate position, $F_{e(n)}$ denotes the error between the desired force value F_d (gravity compensation is included) and the current force val- ue, and $F_{e(n-1)}$ represents the last error value. Figure 3 shows a force comparison with and without force control. The figure shows that in the contact force ex- periment, position control directly through the path does not have the ability to adjust the position. Hence, this leads to a larger force deviation. However, the force that is obtained by adjusting the position via thePD controller is controlled within the desired value.

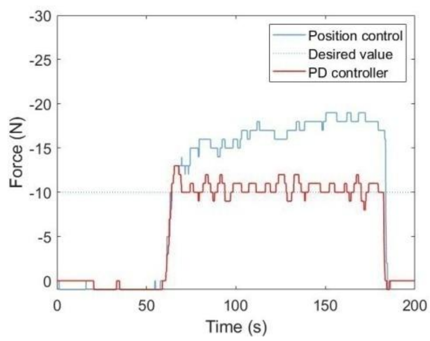


Fig. 3. Comparison of grinding force

4. Machining Procedures and Path Planning This section describes the machining process of ro-botic arm grinding and polishing and the machining path for different shapes of workpieces.

Process Design

The workpiece used in this study is 304 stainless steel. This kind of stainless steel has wide applications and is used mainly for food-grade utensils, containers, and furniture. The surface of stainless steel is usually stained due to chemical and electrochemical corro- sions. Additionally, weld beads and scratches also af- fect the surface of the workpiece. Therefore, grinding and polishing using grinding wheels with a variety of particle sizes and cloth wheels is proposed to regain excellent stainless steel surfaces. To date, this type of mechanical processing method still exists in major factories and is done mostly by skilled workers. How- ever, stainless steel exhibits high toughness and thus is not easy to grind. In this study, by consulting skilled workers in this field, the hands-on experience by the authors, and also by referring to modern grinding and polishing technology principles [9, 10], a 6-steps ma- chining process is proposed. First, grinding wheels made by polyvinyl alcohol (PVA) with grit size of 60 and 120 are used for rough grinding. Then grinding wheels with grit size of 240 and 320 are followed for fine grinding. Furthermore, a grinding wheel with grit size of 400 is employed for final grinding. Lastly, cloth wheel with polishing wax is applied in the final step for the polishing process. Based on this processing sequence, the surface of stainless steel can reach the #300 grade as per the Japanese standard, namely a smooth and mirror-grade surface.

After the process design is completed, the follow- ing rules of thumb are advised for robotic arm grind- ing and polishing stainless steel:

1. During grinding and polishing processes, the total material removal should not exceed 0.3 mm in thick to the maximum possible extent. Essentially, within this range, the workpiece will not be affected.
2. When performing rough grinding, the feed rate must be greater than that of fine grinding.
3. The number of repetitions of each process needs to be reduced. Grinding and polishing are techniques for removing material. Repeating too many times will excessively increase the amount of material removed.
4. The angle of the grinder with respect to surface tangent during grinding varies across individuals. Typically, it is in the range of 30°–45°. However, approximately 5° and up is sufficient for robotic arm grinding and polishing.
5. The grinding wheel with high grit size wears faster than the one with low grit size, so care must be taken for the latter grinding processes.
6. As far as the grinding and polishing process is concerned, the correct method involves holding the grinder to move forward for a certain distance after the grinding wheel touches the workpiece and then pulling it up. It is important not to move grinder back and forth because it can easily result in uneven surfaces.

In the study, stainless steel workpieces are divided into flat workpieces and curved workpieces. Both of which require path planning using RoboDK package as described in the next subsection.

Path Planning

The grinding path of a flat workpiece is relatively sim- ple. We use a robotic arm equipped with a grinder and choose the grinding surface of the grinding wheel as the TCP (tool center point) position. A grinding area with a width of 42.55 mm and length of 100 mm is considered based on the TCP coordinates. The grind- ing path is a straight line divided into 20 points, and the tool orientation remains unchanged along the path. In grinding and polishing operations, the robotic arm

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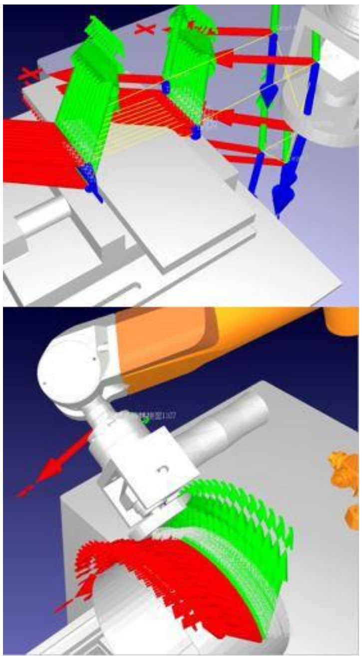
moves forward in a straight line throughout the entire process and is pulled up at the end in a manner similar to a skilled worker. The rough grinding and fine grinding process are performed 1–2 times, and the polishing process is performed 5–6 times.

When grinding a curved workpiece with a diam- eter of 212.30 mm, the grinding wheel moves along the surface for an arc length of 237.92 mm. Along the curved path, the number of points is 96 and the X-axis and Z-axis of the tool coordinate change continuous- ly so that Z-axis always keeps normal to the surface. The grinding and polishing operations for the curved



workpiece is similar to that for the flat workpiece as described in the previous paragraph. Furthermore, it is necessary to focus on collision detection and path generation due to the large curvature of the work- piece. A schematic diagram of path planning using RoboDK package is shown in Figure 4.

Fig. 4. Grinding and polishing path simulation of flat (top) and curved (bottom) workpieces

5. Experimental Results

The study is divided into two experimental methods, namely position control [11] and hybrid position/ force control [12, 13], and two types of workpiece, flat and curved workpieces. First, in the position control experiment, the robotic arm directly uses the path planned by the RoboDK package and the converted coordinate position for the experiment. Simultaneously, the force sensor is turned on and is responsible for monitoring the force value during pure position control. Second, in the experiment of hybrid position/force control, force sensor is em- ployed for adjusting the grinding path in Z direction through the PD controller in (1). During the grind- ing and polishing process, the coordinate position of the end effector of the robot arm is updated, and the robot attempts to maintain the grinding force as con- stant. In terms of parameter settings, the rotation speed of the grinder is fixed at 12000 rpm and the feed rate of the robotic arm is set to 25 mm/s. More- over, the surface roughness is related to the grinding force, and excessive force can easily lead to poor sur- face quality. After a few tries in the study, the results indicated that when the applied force exceeded 30 N, the cloth wheel responsible for the polishing task was easily burnt and the stainless-steel surface was overheated and oxidized. Thus, the desired

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applied force for grinding and polishing is set to 10 N in the experiment. The robot arm grinding and polishing processes are shown in Figure 5.

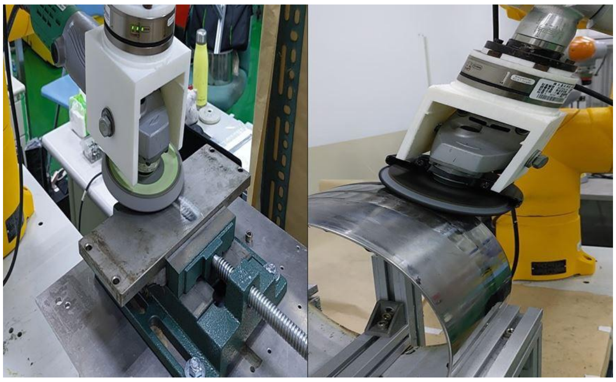

Fig. 5. Photos of grinding and polishing of flat (left) and curved (right) workpieces

5.1 Results of the Flat Workpiece

The experimental results of the study were summa- rized into two parts, namely the mean absolute error (MAE in %) of the grinding and polishing force of each process

Tab. 1. MAE error between the actual grinding force and desired force

Experiment Process	Position control (%)	Hybrid position/ force control (%)
#60	29.3	11
#120	37.73	12.11
#240	97.99	20.44
#320	153.8	22.45
#400	197.9	14.07
Polishing	42.63	15.09

Tab. 2. Surface roughness of stainless steel of each process

Experiment Process	Position control (µm)	Hybrid position/ force control (µm)
#60	2.27	2.10
#120	1.66	1.60
#240	1.26	1.19
#320	0.95	0.80
#400	0.80	0.66
Polishing	0.68	0.47

$$MAE(\%) = \frac{\sum_{n=1}^{N} |Fe(n)| / N}{Fd} \times 100 \quad (2)$$

d the value of the surface roughness (arithmetic mean deviation S_a) [14] of stainless steel after each process is completed. To measure surface roughness, a 3D surface profiler (Keyence VR 3000) with a high- magnification lens (40x) was used to evaluate the machining quality for each process. In the results of the flat workpiece, given that the position control ex- periment was not aided by force control, a large gap existed between the grinding and polishing force and the desired value. In the hybrid position/force control experiment, force control was added to the original path such that the force response was improved dur- ing flat grinding, and the force error was significantly reduced. In other words, the robotic arm attempted to process the workpiece surface with the desired grinding force. The MAE of machining force for each process using PVA sponge wheel for grinding (granu- larity: 60–400) and cloth wheel for polishing of the two experiments was listed in Table 1. Large force deviation using only position control was apparently reduced by applying hybrid position/force control in each process. Improved surface roughness for each corresponding process was listed in Table 2, and the finished workpiece surfaces were shown in Figure 6 with clearly seen mirror effect on both surfaces. For flat workpiece, surface roughness has been reduced from 3.04 µm before grinding to final 0.68 µm and

0.47 µm respectively by position control and hybrid position/force control. Approximate 30.88% im- provement in surface roughness was achieved by hy- brid position/force control over pure position control.

Fig. 6. Finished flat workpieces: position control (top)and hybrid position/force control (bottom)

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Fig. 7. Finished curved workpieces: position control(top) and hybrid position/force control (bottom)

5.2 Results of the Curved Workpiece

For curved workpiece, because the surface was al- ready smooth in the beginning thus only the last 3 steps of fine grinding (using grinder with grit size 320 and 400) and polishing (by cloth wheel) were conducted. MAE errors of the grinding and polish- ing force of each process for the two control methods were compared in Table 3, where in general hybrid position/force control outperformed the position control. Improved surface roughness for each cor- responding process was shown in Table 4, where in the final polishing task approximate 32.14% improve- ment (from 1.12 µm to 0.76 µm) was obtained by the hybrid position/force control over pure position con- trol. The finished workpiece surfaces were illustrated in Figure 7. Indeed, the curved workpiece surface wassmoother and brighter by the hybrid position/force control.

Tab. 3. MAE error between the actual grinding forceand desired force

Experim ent Process	Position control (%)	Hybrid position/ force control (%)
#320	75	23.7
#400	51.45	29.8
Polishin g	19.7	20

Tab. 4. Surface roughness of stainless steel of eachprocess

Experim ent	Position control	Hybrid position/

Process	(µm)	force control (µm)
#320	1.76	1.01
#400	1.25	0.96
Polishin g	1.12	0.76

6. Conclusion

In this study, automatic grinding and polishing of stainless steel was achieved using a robotic arm and two experimental techniques. Also, a 6-step machining procedure for polishing stainless steel was suggested along with some useful guidelines. Pure position control for grinding and polishing is easy to implement, but it may leave undisturbed regions of the workpiece along the planned path due to wheel deformation and/or wear, especially for curved workpieces. As an illustration, Table 3's final polishing step for a curved workpiece has a 19.7% MAE in the polishing force for position control, which is comparable to a 20% MAE for hybrid position/force control. However, position control produces a surface roughness of 1.12 m as opposed to 0.76 m by the hybrid position/force control, as shown in Table 4. This is because utilising the pure control approach, the cloth wheel leaves almost half of the polishing route untouched (during this period the zero pol- ishing force is excluded in the calculation of MAE).

The devised hybrid position/force control system was good in terms of the consistency of machining force and the surface quality of the final workpiece thanks to the use of a force/torque sensor in the robot arm. Consequently, by including force control in the machining process, issues like uneven applied force by either a human operator or pure position control, manufacturing and/or positioning mistakes in the workpiece, and deformation and/or wear of the grinding wheel can be somewhat mitigated. By using the suggested machining techniques with hybrid position/force control, the flat and curved stainless steel in the trials were surface polished to reach, respectively, 0.47 m and 0.76 m in surface roughness. The findings in this study met the 1J-2J grade in the category of Mechanically Polished & Brushed Stainless Steel Finishes of the DIN standard for stainless steel surface quality [15], which is the grade at which stainless steel is typically used in furniture, elevator doors, and upholstery accessories. By comparison, an experienced worker can generally create a surface roughness of roughly 0.4 m, which is not far from what this paper can accomplish. A skilled worker, on the other hand, is difficult to find, expensive to hire, and has a set number of daily working hours all while requiring years of training. The method developed in this research can reduce the need for extensive training and personnel costs.Because the used RoboDK software can handle both straight and curved paths, it should be emphasized that the created polishing approach may be applied to a work piece with both flat and curved surfaces. Also, in the experiment, the desired applied force was adjusted to 10 N for both flat and curved surfaces. As a result, the control method may be easily implemented throughout the entire object.

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