Development of Grinding and Polishing Technology for Stainless Steel With a Robot Manipulator

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Abstract

In traditional industries, manual grinding and polishing technologies are still used predominantly. However, these procedures have the following limitations: excessive processing time, labor consumption, and product quality not guaranteed. To address the aforementioned limitations, this study utilizes the good adaptability of a robotic arm to develop a tool-holding grinding and polishing system with force control mechanisms. Specifically, off-the-shelf handheld grinder is selected and attached to the robotic arm by considering the size, weight, and processing cost of the stainless steel parts. In addition, for contact machining, the robotic arm is equipped with a force/torque sensor to ensure that the system is active compliant. According to the experimental results, the developed system can reduce the surface roughness of 304 stainless steel to 0.47 µm for flat surface and 0.76 µm for circular surface. Moreover, the processing trajectory is programmed in the CAD/CAM software simulation environment, which can lead to good results in collision detection and arm posture establishment.

Keywords: *Active compliant, hybrid position/force control, robot manipulator, surface machining, surface roughness*

1. Introduction

The world is facing many problems, including the effects of an aging society and declining birthrate in some countries. According to the statistics by the United Nations, the global fertility rate continues to fall, and the labor force is gradually aging. This will significantly affect national competitiveness. It is of utmost important for the government and enterprises to find ways to replace labor after the supply of labor has declined. Many companies started introducing robotic arms to replace manpower. Currently, the industry uses robotic arms for automated operations. Since the first robotic arm was invented by Joseph Engelberger in 1959, robots have been used in applications ranging from manufacturing of electronics to agriculture, medical industry, and even service sectors. Therefore, it is possible to use robotic arms in any operation. To satisfy human needs and environmental restrictions, the design of intelligent robotic arms has been considered as a new topic of research.

For typical contact processing tasks, such as grinding and polishing, several steps require experienced operators. During the welding and polishing for metal processing, the time for grinding and polishing is nearly four times the welding time. However, this time-consuming and labor-intensive processing procedure can be replaced by utilizing the high-efficiency robot arm. Hence, it has become a popular research topic. Modern robotic polishing systems are divided into hand-holding tools and handheld workpieces. The former is used for large workpieces, and the latter is suitable for smaller objects [1]. In the studies on modern robotic arm polishing, most of the robotic arms are used for clamping workpieces that should be ground and polished. For example, Zhu et al. [2] proposed a combination of a force model and abrasive belt grinding force to evaluate the surface roughness of a workpiece, and Ma et al. [3] performed polishing with a constant force in a self-designed abrasive belt grinding system. The major limitation of this system is that once the weight or size of the workpiece exceeds the range of the robotic arm, the workpiece cannot be clamped. Therefore, in the polishing process of large workpieces, the hand-holding polishing tool is optimal. Furthermore, the research of this robotic polishing system is based on the combination and design of the end effector of the robotic arm and grinding tool [4-6]. In addition, it is worth mentioning that an active contact flange (ACF) based on active compliant technology and powered pneumatically has been available in the market for robotic grinding and polishing application [7]. The cost is yet expensive.

In this study, a cost-effective robotic polishing system equipped with a grinding and polishing module and a force sensor is proposed. Furthermore, experiments are conducted on 304 stainless steel, which is commonly used in the industry. The grinding experiments in this study are classified into two types. The first type of experiments involve the position control of the robotic arm according to the path planned by RoboDK (a robot simulation software). The other type of experiments involve a hybrid position/force control that combines the planning path and force control.

2. System Description

In this section, the experimental architecture including hardware and computer software are described.

2.1 Hardware Architecture

Hardware in this robotic polishing system mainly includes 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 degree of flexibility, solid structure, and special reduction gear system. The main task of the robotic arm involves 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 cutting, grinding, and polishing solely by changing the granularity of the grinding wheel. Figure 1 shows the hardware architecture used in this study.

2.2 Software Architecture

All software algorithms in this robotic polishing system are executed in a host computer. The programming language in host computer is C#. Tasks of the host computer involve sending commands via Ethernet 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 operation, and generating polishing path using RoboDK package. Note that combination of TwinCAT (the Windows Control and Automation Technology, a C# project) and EtherCAT is used as an easy-to-configure automated system. Figure 2 depicts the communication protocol used in this study.

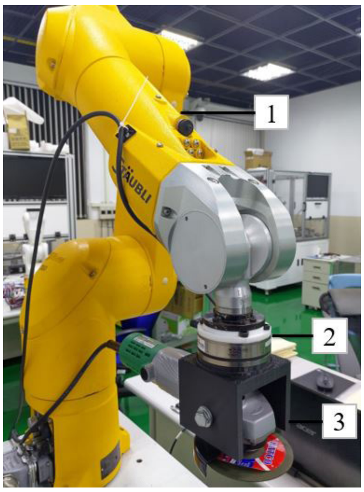

Fig. 1. Robotic polishing system: 1 robot arm, 2 force sensor, 3 grinding module

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 actions, 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 robotic arm will move to the position based on the coordinate point provided by the operator. This control method may generate contact forces, such as those for mechanical processing, which often lead to the excessive 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 aforementioned problems, the force control strategy can enable the robot to interact with the force it experiences during 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 considerations or adapting to the environment. Generally, control strategies are divided into two categories: indirect force control strategies and direct force control strategies.

3.1 Indirect Force Control

Force control of robotic systems usually uses force/torque sensors to process the external forces measured in the environment. However, indirect force control does not require force/torque sensors. Under this control strategy, when the robot's current position coordinates deviate too far from the target position, a force is exerted to control it. Therefore, there is no clear closed-loop feedback control, which implies that the control mechanism cannot handle the large external force due to the trajectory deviation, and the flexibility is relatively poor when compared to that of the direct force control. Indirect force control involves two control strategies: impedance control and admittance control. Among the strategies, the spring damping system is the most accurate representation of impedance control. The contact force and arm motion are used as input and output, respectively. This implies that the impedance mechanism controls the robot, and the external force generated by the environment ensures compliance of the movement process.

3.2 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 robot, 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 direction of the surface. The force and position are controlled in two directions to form a hybrid position/force control strategy. When the robot starts performing 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 sensor 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 executed. Hence, this ensures that the position of the end effector of the robotic arm and force are controlled in a closed loop.

In this study, a proportional-derivative (PD) controller 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

$$Z_{n+1} = Z_n + K_P \frac{F_{e(n)}}{F_d} + K_D \frac{F_{e(n)} - F_{e(n-1)}}{F_d} \tag{1}$$

where 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 value, 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 experiment, 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 the PD controller is controlled within the desired value.

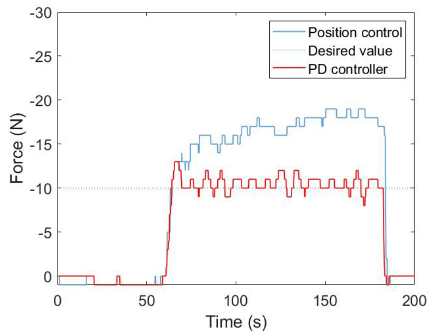

Fig. 3. Comparison of grinding force

4. Machining Procedures and Path Planning

This section describes the machining process of robotic arm grinding and polishing and the machining path for different shapes of workpieces.

4.1 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 corrosions. Additionally, weld beads and scratches also affect 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. However, 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 machining 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 following rules of thumb are advised for robotic arm grinding 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.

4.2 Path Planning

The grinding path of a flat workpiece is relatively simple. 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 grinding 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 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 diameter 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 continuously 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 workpiece. A schematic diagram of path planning using RoboDK package is shown in Figure 4.

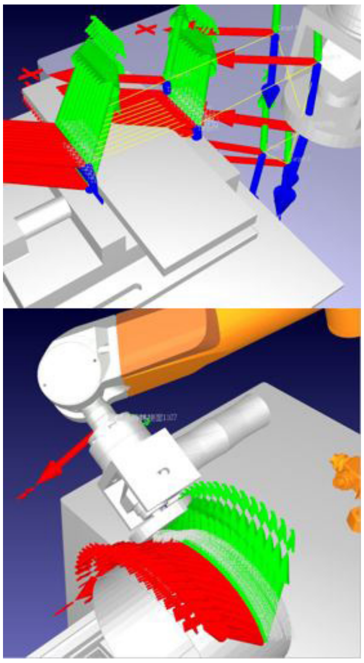

Fig. 4. Grinding and polishing path simulation of flat (top) and curved (bottom) workpieces

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 employed for adjusting the grinding path in Z direction through the PD controller in (1). During the grinding 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 constant. 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. Moreover, the surface roughness is related to the grinding force, and excessive force can easily lead to poor surface 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 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.

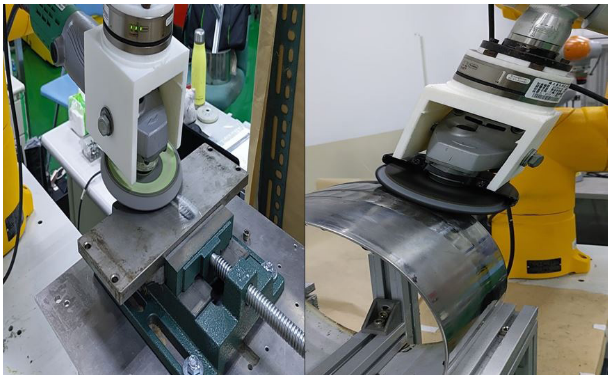

Fig. 5. Photos of grinding and polishing of flat (left) and curved (right) workpieces

5.1 Results of the Flat Workpiece

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

$$MAE(\%) = \frac{\sum_{n=1}^{N} \left| F_{e(n)} \right| / N}{F_d} \times 100 \quad (2)$$

and 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 experiment 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 during 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 (granularity: 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% improvement in surface roughness was achieved by hybrid position/force control over pure position control.

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

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

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 already 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 polishing 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 corresponding process was shown in Table 4, where in the final polishing task approximate 32.14% improvement (from 1.12 µm to 0.76 µm) was obtained by the hybrid position/force control over pure position control. The finished workpiece surfaces were illustrated in Figure 7. Indeed, the curved workpiece surface was smoother and brighter by the hybrid position/force control.

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

Experiment Process	Position control (%)	Hybrid position/ force control (%)
#320	75	23.7
#400	51.45	29.8
Polishing	19.7	20

Tab. 4. Surface roughness of stainless steel of each process

Experiment Process	Position control (µm)	Hybrid position/ force control (µm)
#320	1.76	1.01
#400	1.25	0.96
Polishing	1.12	0.76

6. Conclusion

In this study, a robotic arm and two experimental methods were used to realize the automatic grinding and polishing of stainless steel. Furthermore, a 6-steps machining process for polishing stainless steel along with some practical rules of thumb was proposed. Grinding and polishing with pure position control is simple to implement, however it could have untouched areas on the workpiece in the planned path due to deformation and/or wear of the grinding wheel, especially for the curved workpiece. For example, the last step of polishing curved workpiece in Table 3 has 19.7% MAE in the polishing force for position control which is comparable to 20% MAE for hybrid position/force control. But position control gives worse surface roughness 1.12 µm as compared to 0.76 µm by the hybrid position/force control as shown in Table 4, this is because almost half of the polishing path is untouched by the cloth wheel using pure control method (during this period the zero polishing force is excluded in the calculation of MAE).

By using a force/torque sensor in the robot arm, the developed hybrid position/force control method was excellent in terms of the consistency of machining force and the surface quality of the finished workpiece. Therefore, problems such as uneven applied force by either human operator or pure position control, manufacturing and/or positioning errors in the workpiece, and deformation and/or wear of the grinding wheel can be alleviated to certain extent by adding force control in the machining process. The flat and curved stainless steel in the experiments were surface finished to reach respective 0.47 µm and 0.76 µm in surface roughness by the proposed machining procedures with hybrid position/force control. According to DIN standard for surface quality of stainless steel [15], the results in this study reached 1J-2J grade in the category of Mechanically Polished & Brushed Stainless Steel Finishes, with which grade the stainless steel is usually used in furniture, elevator door, and upholstery accessories. For comparison with a skilled worker, the surface roughness obtained by a skilled worker basically can reach about 0.4 µm, which is not far from what this paper can achieve. However, a skilled worker is hard to find and expensive to hire, and requires years of training but has a limited working hours per day. The technique developed in this paper can help save training costs and excessive labor expenses.

It is noted that the developed polishing technique can also be applied to a workpiece with both flat and curved surfaces, since the employed RoboDK software can deal with straight and curved path. In addition, the desired applied force was set to 10 N for both flat and curved surfaces in the experiment, hence the control algorithm can be used throughout the entire object without difficulty.

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REFERENCES

[1] J. Li, T. Zhang, X. Liu, Y. Guan and D. Wang, "A Survey of Robotic Polishing". In: *2018 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 2018, 2125–2132, 10.1109/ROBIO.2018.8664890.

[2] D. Zhu, X. Xu, Z. Yang, K. Zhuang, S. Yan and H. Ding, "Analysis and assessment of robotic belt grinding mechanisms by force modeling and force control experiments", *Tribology International*, vol. 120, 2018, 93–98, 10.1016/j.triboint.2017.12.043.

[3] K. Ma, X. Wang and D. Shen, "Design and Experiment of Robotic Belt Grinding System with Constant Grinding Force". In: *2018 25th International Conference on Mechatronics and Machine Vision in Practice (M2VIP)*, 2018, 1–6, 10.1109/M2VIP.2018.8600899.

[4] M. Jinno, F. Ozaki, T. Yoshimi, K. Tatsuno, M. Takahashi, M. Kanda, Y. Tamada and S. Nagataki, "Development of a force controlled robot for grinding, chamfering and polishing". In: *Proceedings of 1995 IEEE International Conference on Robotics and Automation*, vol. 2, 1995, 1455–1460, 10.1109/ROBOT.1995.525481.

[5] M. A. Elbestawi, K. M. Yuen, A. K. Srivastava and H. Dai, "Adaptive Force Control for Robotic Disk Grinding", *CIRP Annals*, vol. 40, no. 1, 1991, 391–394, 10.1016/S0007-8506(07)62014-9.

[6] J. A. Dieste, A. Fernández, D. Roba, B. Gonzalvo and P. Lucas, "Automatic Grinding and Polishing Using Spherical Robot", *Procedia Engineering*, vol. 63, 2013, 938–946, 10.1016/j.proeng.2013.08.221.

[7] "Active contact flange", FerRobotics Compliant Robot Technology GmbH. https://www.ferrobotics.com/en/services/products/active-contact--flange/. Accessed on: 2022-08-30.

[8] B. Siciliano and L. Villani, *Robot Force Control*, Springer US, 1999.

[9] W. B. Rowe, *Principles of modern grinding technology*, William Andrew, 2014.

[10] N. Kurihara, S. Yamazaki, T. Yoshimi, T. Eguchi and H. Murakami, "The proposal of automatic task parameter setting system for polishing robot". In: *2015 12th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*, 2015, 479–481, 10.1109/URAI.2015.7358808.

[11] J. Kim, W. Lee, H. Yang and Y. Lee, "Real-time monitoring and control system of an industrial robot with 6 degrees of freedom for grinding and polishing of aspherical mirror". In: *2018 International Conference on Electronics, Information, and Communication (ICEIC)*, 2018, 1–4, 10.23919/ELINFOCOM.2018.8330691.

[12] P. G. M. Cáceres. *Grinding Force Control of the Cutting Edge of a Blade by a Robot Manipulator*, Master's Thesis, National Taipei University of Technology, Taipei, Taiwan, 2019, https://hdl.handle.net/11296/wnu34a.

[13] M. Fazeli and M. J. Sadigh, "Adaptive hybrid position/force control for grinding applications". In: *2012 IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CYBER)*, 2012, 297–302, 10.1109/CYBER.2012.6392569.

[14] E. Jansons, J. Lungevics and K. A. Gross, "Surface roughness measure that best correlates to ease of sliding". In: *15th International Scientific Conference, Engineering for Rural Development*, 2016.

[15] "Stainless Steel Finishes Explained – EN & ASTM," (2019), Andreas Velling, https://fractory.com/stainless-steel-finishes-en-astm/. Accessed on: 2022-08-30.