Surface Topography of the Metal surface in Robot Polishing under Control Force

Wenliang Zhao\textsuperscript{1,2}, Imran Mohsin\textsuperscript{1,3}, Longlong Huang\textsuperscript{1,4} and Kai He\textsuperscript{1,5}

\textsuperscript{1}Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen, China
\textsuperscript{2}Shenzhen Key Laboratory of Minimally Invasive Surgical Robotics and System, Shenzhen, China
\textsuperscript{3}University of Chinese Academy of Sciences, Beijing, China
\textsuperscript{4}Yanshan University, Qinhuangdao, Hebei, China
\textsuperscript{5}The Chinese University of Hong Kong, Hong Kong, China

wl.zhao@siat.ac.cn; imran@siat.ac.cn; ll.huang@siat.ac.cn; kai.he@siat.ac.cn

Abstract. Polishing is an important finishing process in the field of manufacturing, which enhances product quality and increases its life span. Compared with manual polishing, robotics polishing has advantages in terms of cost and productivity. This paper presents a new study on the surface topography of metal workpiece in the robotic polishing test. Various workpieces with different surface roughness were polished with the industrial robot under similar polishing parameters, and the variation of surface topography with polishing was studied utilizing microscopic scanning.

1. Introduction

The polishing process produces a smooth and high-precision surface. It is an important final step in many part manufacturing processes [1]. It is mainly used in bathroom hardware, automotive industry, machine part manufacturing industries and so on. Depending on the workpiece surface condition, the polishing is basically divided into three major steps, namely rough polish, medium polish and fine polishing [2]. This multistep polishing process uses the different tool at various stages. The average roughness after rough grinding can be between 1.25 µm to 10 µm, and the roughness after fine polishing stage ranges from 0.2 µm to 0.4 µm. At present, the polishing process still relies heavily on the skills of professional workers. This makes it time-consuming, expensive and faulty. In addition, workers are often in an environment with heavy dust and high noise. Automated polishing is a solution and should be adopted urgently.

The parameters that affect the polishing effect in the case of the rotary sanding tool are contact force, material removal rate, abrasive grit size and grinding path planning [3-4]. The contact force between the end of the grinding tool and the surface of the workpiece is an important influence parameter. The contact mode between the grinding tool and the workpiece is divided into active compliance control and passive compliance control. For higher product precision and high adaptability, it is often used. The combination...
of active compliance and passive compliance control [5-6]. Due to the difference in the material of the object to be polished and the uneven polished surface, the grinding force may change during the conventional grinding process, which results in a decrease in the quality of the grinding and accelerated wear of the grinding tool. To achieve a good surface grinding quality, it is necessary to output a constant grinding pressure according to different grinding materials and working conditions.

In order to achieve fineness, even specular gloss in most industrial applications, different abrasives are used in various stages of sanding (e.g., grit #120, 180, 240, 320...). This makes it possible to reduce the roughness without deforming the object to be polished [7]. Therefore, when grinding, it is necessary to select different sizes of sandpaper according to the requirements of surface roughness [8]. Similarly, polishing tool path planning and off-line programming are also important factors affecting the quality of grinding and polishing efficiency, especially for parts with complex three-dimensional surfaces. The robot's grinding path and offline programming program can be obtained from the 3D model of the part. The evaluation methods for measuring the quality of polishing can be divided into macroscopic methods and microscopic methods. Macroscopically, the surface finish of parts is mainly viewed [9-11]. Microscopically, it is mainly observed by surface roughness and microscopic scanning. The micromorphology of the surface of the part is observed with the grinding time [12-13].

In this paper, three workpieces with different surface roughness are polished under the same polishing parameters. The effect of tool used is analyzed on micro level with the surface topography for different number of polishing cycles. The final average surface roughness of the three parts almost same.

2. The system overview

2.1. Robot polishing system

The automated polishing system used in this study consists of an industrial robot with six degrees of freedom, a force control system and a flexible polishing tool as shown in figure 1. The Motoman UP50 arm robot with DX100 controller is used for robotic polishing. Motoman system is based on computer-aided design/computer-aided manufacturing (CAD/CAM) software systems and PC-aided production. It has 50 kg payload which is enough to support polishing tool, force sensor weight and interacting force during polishing. The polishing tool attached with the variable speed motor (Range from 0 rpm to 3000 rpm) is used to control tool speed for better surface quality. The simulation software Robotmaster is used for offline programming and trajectory optimization for the polishing.

![Figure 1. Setup for robotic polishing.](image)
2.2. The force control system

The controlled interaction between the polishing tool and the surface is crucial for the better surface finish, therefore, an active contact flange ACF is used. Figure 2 shows the ACF-110-04 by Ferrobotics which is a numeric feedback control system. It has 1.8 Kg dead weight and required 7 bar air pressure. It can maintain a force between 1 N to 100 N. It operated with the software that allows setting force values and continually shows the status of force and position. It also has gravitational compensation which works well with changing orientation.

Figure 2. Active contact flange (ACF 110-04): (a) controller, and (b) force sensor.

2.3. Polishing tool

The polishing or sanding tool is mainly composed of sanding wheel, safety cover, servo motor and a force control sensor. Sanding wheel used in this work is a flap wheel with 6 inches diameters as shown in figure 3. Its body is made of non-metallic material. The sand brush consists of two parts, one part is the bristles and the other part is sandpaper. The roots of the two parts are glued and pressed together with a T-shaped metal foil and the bristles mainly play a supporting role. It has 28 segments of brush and abrasive segments with grit #400. After the sandpaper, brush is inserted into the T-groove of the wheel body and the end of the wheel is positioned with a rubber ring. The weight of the device is extremely reduced because the brush wheel and the sand brush are all non-metal materials. The sand brush is evenly arranged along the circumferential direction of the brush wheel at a certain interval, which is favorable for promptly discharging the crumbs when grinding to avoid scratching the surface of the workpiece.

Figure 3. Polishing tool without safety cover.

Figure 4 shows the tool with safety cover on the workpiece for polishing. The servo motor can change the rotation speed and transmit the rotary motion to the grinding wheel shaft through the timing belt. The force sensor is installed between the robot and the sanding wheel to ensure that the force between the sanding tool and the workpiece is constant.
Figure 4. Polishing tool: (a) tool cover and sensor, (b) flap wheel side view, and (c) flap wheel front view.

2.4. Workpiece and tool path for polishing

In this experiment, three sets of the workpiece are used which are same in sizes but having different surface roughness. It is a steel (Q235) strip with a dimension of 460 mm x 38 mm x 3mm. The roughnesses of the three different workpieces are 0.462 µm, 0.801 µm and 2.837 µm. Figure 5 shows the polishing area as well as the tool path for polishing the workpiece. Tool feed is in one direction and it is maintained for each workpiece and every polishing cycle.

Figure 5. Workpiece with tool path.

3. Results and discussion

Figure 6 shows the experimental setup of the robot polishing system. The robotic arm with a controlled force sensor connected with polishing tool (flap wheel) is in process on the metal surface. This flexible robot can repeat the action with acceptable precision and offers large working envelope. It has sufficient payload which is enough to support tool weight, sensor weight and interacting force generated during polishing.

Figure 6. Robot polishing system.
Figure 7 shows the super depth of field three-dimensional microscope. It has the large depth of field observations with high resolution and super deep depth of field.

![Optical microscope](image)

**Figure 7.** Optical microscope (Model: Keyence VHX-2000C).

In this experiment, set of three workpieces with the same dimensions and different surface roughness is used for the robot polishing or sanding experiments. The surface roughnesses (Ra) for three workpieces are 0.462 µm, 0.801 µm and 2.837 µm, respectively as shown in figure 8.

![Three workpieces](image)

**Figure 8.** Three workpieces with different roughness: (a) first workpiece Ra = 0.462 µm, (b) second workpiece Ra = 2.837 µm, and (c) third workpiece Ra = 2.837 µm.

Before the start of the experiment, all three workpieces were scanned by confocal microscopy using a super-depth three-dimensional microscope (model: KEYENCE VHX-2000) with a magnification of 100x. The initial surface topography of the three sets of parts before sanding was observed.

For the first workpiece which is comparatively smooth (Ra = 0.462), the selected center area under microscope is shown in figure 9. It can be seen that the surface is relatively flat and the surface distribution has some scratches. These scratches have width in between 10 µm to 20 µm.
Figure 9. Microscopic results of first workpiece before sanding: (a) selected point on workpiece, (b) magnified photo (100 x zoom), and (c) magnified photo in 3D.

Figure 10 shows the selected area on the second workpiece (Ra = 0.801). It has some visible spots on the surface. The spot average height is from 20 µm to 50 µm.

Figure 10. Microscopic results of second workpiece before sanding: (a) selected point on workpiece, (b) magnified photo (100 x zoom), and (c) magnified photo in 3D.

Microscopic scanning of the rusted area of the third workpiece (Ra = 2.837µm), is shown in figure 11. The surface is very rough and not flat and there are many small ridges on the surface. Under the microscope, very high protrusion can be seen. These are up to 34.45 µm high and the maximum length is 324 µm which is irregularly distributed.

Figure 11. Microscopic results of third workpiece before sanding: (a) selected point on workpiece, (b) magnified photo (100 x zoom), and (c) magnified photo in 3D.

We analyze the change of the three workpieces’ polishing area under the microscopic field, as shown in figure 12. The first workpiece is very smooth before polishing, after three times polishing, it shows little change under the view of the microscope. The second workpiece’s initial roughness is 0.801µm, and after the polishing, the ridges height ranges from 34.45um to 11.71µm. The third workpiece’s initial roughness is 2.837um, after grinding steps, the ridges of the surface become more lower, finally reach to 30.52um.
Figure 12. Magnified surface of three workpieces (P1, P2 and P3) under microscope for different polishing cycles

Figure 13 shows the photo of the all three polish workpieces. These are polished under same polishing parameters.

![Figure 13. Three sets of workpieces after grinding.](image)

Table 1 shows some important polishing parameters that was used during polishing the all three workpieces. It includes robot payload, its repeatability, contact force, tool speed, tool grit number and feed rate.

| Parameters                      | Values       |
|---------------------------------|--------------|
| Payload                         | 50 Kg        |
| Repeatability of UP50           | ±0.07 mm     |
| Constant sensor force           | 20N          |
| Grinding head rotation speed    | 200 r/min    |
| Abrasive paper grit #           | 400          |
| Feed rate                       | 28 mm/s      |

4. Conclusion
After the same conditions of grinding, the surface of the three sets of workpieces became smooth and metallic luster. The scratches of the smooth workpiece part1 were significantly reduced, and the scratch depth became
shallow. The spot on the surface of the ordinary workpiece part 2 disappeared. The rough part part 3 rust area after the polishing completely disappears, the surface becomes flat, and the local bulge becomes less, and the height of the bulge becomes lower.

The shape of the side profile after grinding the three sets of workpieces is as shown in the figure above. It can be seen from the figure that there is no large fluctuation in the shape of the side profile of the three sets of workpieces, indicating that the surface of the three sets of workpieces is smooth, without large protrusions or deep gullies. The roughness of smooth workpiece 1 after grinding is $Ra=0.171$, the roughness of ordinary workpiece 2 after grinding is $Ra=0.192$, and the roughness of rough workpiece 3 after grinding is $Ra=0.226$. The roughness of three groups of workpieces after grinding is similar, indicating that the robotic grinding system has an ideal grinding effect, which can grind workpieces with different roughness to a similar smoothness.

The robot can get better grinding effect under the action of constant force, and this robot system can be applied to the future grinding work, such as the surface grinding of automobile, aircraft and other parts.

5. References

[1] Mohsin I, He K, Cai J, et al, “Robotic polishing with force controlled end effector and multi-step path planning,” Information and Automation (ICIA), 2017 IEEE International Conference on. IEEE, 2017: 344-348.

[2] Pei Z J, Strasbaugh A, “Fine grinding of silicon wafers: designed experiments,” International Journal of Machine Tools and Manufacture, 2002, 42(3): 395-404.

[3] Tam H Y, Cheng H B, Wang Y W, “Removal rate and surface roughness in the lapping and polishing of RB-SiC optical components,” Journal of Materials Processing Technology, 2007, 192: 276-280.

[4] Takeuchi, Yoshi, Naoki Asakawa, and Dongfang Ge, “Automation of polishing work by an industrial robot: system of polishing robot,” JSME international journal. Ser. C, Dynamics, control, robotics, design and manufacturing 36.4 (1993): 556-561.

[5] Basanez, Luis, and Jan Rosell, “Robotic polishing systems,” IEEE robotics & automation magazine 12.3 (2005): 35-43.

[6] Tam, H. Y., L. Zhang, and M. Hua, “Material removal by fixed abrasives following curved paths,” Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 218.7 (2004): 713-720.

[7] Tsai, Ming-June, and J. F. Huang, “Efficient automatic polishing process with a new compliant abrasive tool,” The International Journal of Advanced Manufacturing Technology 30.9-10 (2006): 817-827.

[8] Xie, Yongsong, and Bharat Bhushan, “Effects of particle size, polishing pad and contact pressure in free abrasive polishing,” Wear 200.1-2 (1996): 281-295.

[9] Feng-yun, Lin, and Lü Tian-sheng, “Development of a robot system for complex surfaces polishing based on CL data,” The International Journal of Advanced Manufacturing Technology 26.9-10 (2005): 1132-1137.

[10] Reclik, D., and G. Kost, “The comparison of elastic band and B-Spline polynomials methods in smoothing process of collision-free robot trajectory,” Journal of Achievements in Materials and Manufacturing Engineering 29.2 (2008): 187-190.

[11] Freund, Eckhard, and Bernd Luedemann-Ravit, “A system to automate the generation of program variants for industrial robot applications,” IEEE/RSJ International Conference on Intelligent Robots and Systems. Vol. 2. IEEE, 2002.

[12] Rosa, Benoit, Jean-Yves Hascoët, and Pascal Mogno, “Topography modeling of laser polishing on AISI 316L milled surfaces,” Mechanics & industry 15.1 (2014): 51-61.

[13] Eriksen, Rasmus Solmer, et al, “Manufacture of functional surfaces through combined application of tool manufacturing processes and Robot Assisted Polishing,” CIRP annals 61.1 (2012): 563-566.

Acknowledgment

This work is supported by Shenzhen Science and Technology Project (JSGG20170818101946757) and Shenzhen Key Laboratory Project (ZDSYS201707271637577). The work is also supported by CAS-HK joint laboratory of Precision Engineering.