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A Generating Method of One-stroke Random Toolpath and Its Influence on Surface Quality of Fluid Jet Polishing

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Abstract—**A regular toolpath, the spiral or raster, inevitably leaves repetitive signature in the surface and such signatures can cause unwanted diffraction effects in critical applications. The aim of this paper is to generate one type of random toolpath to obtain high quality surfaces. Based on the conditions that need to be met for random toolpaths in automatic polishing process, such as no cross, continuous, cover the surface, this paper proposes a method, named as "Guide path", to generate a new random toolpath. Then the effect of path spacing and turning point on the removal uniform was simulated with "Gauss" and "W" shape removal functions respectively. How the new random toolpath may affect the removal of material under different path spacing in fluid jet polishing (FJP) was investigated and compared with the raster toolpath. The results show that, when the path spacing is more than 0.4mm, the surface polished by using the raster toolpath has obvious trajectory information, while it was no by using the random toolpath. In addition, the power spectral density (PSD) of the surface polished by the random toolpath is obviously smaller than the surface polished by the raster toolpath. However, the PV value of the polished surface using random toolpaths is higher than the raster toolpath, due to the fluctuations of the path spacing and with a greater number of turning points in the random toolpath.**

Keywords- *Polishing; Random toolpath; Fluid jet polishing (FJP); Surface quality*

I. INTRODUCTION

Optical components with ultra-smooth and free surface profile are widely used in the metrological and observatory devices used in astronomy [1], aerospace [2] and nuclear energy [3] applications. This kind of ultra-smooth surface is usually achieved by polishing process. In the past, the components form accuracy relies heavily on the level of the operator's skill. Computer control optical surfacing (CCOS) technique was proposed in 1970s [4-6], in which surface error correction capability and efficiency are all improved. The proposing of this technology achieves the automation of the polishing process and the predictable, controllable of the machining accuracy. Tool paths are important for the automation of surface polishing. When a periodically changing path is used for polishing, such as a spiral path or a raster path, periodic surface shape errors will remain on the surface of the workpiece. These features, usually at the few-nanometer level, can be revealed by white-light interferometry and give main peaks in the surface power spectral density (PSD) plot. Such signatures can cause unwanted diffraction effects, such as scattering, in critical applications [7].

Computer controlled polisher was proposed to accomplish accurately shape correction polishing with a small tool. The small tool travels over the workpiece surface along a predetermined path. This path and the velocity along the path are controlled by computer. The material removed by the tool is defined as the tool removal function[8]. The tool travels over the workpiece with a varying velocity as described by a dwell time function[9]. The material removal distribution along the toolpath is solved by convolution of the dwell time and the tool removal function. According to the principle of the CCOS processing technology and the polish processing characteristics, the random toolpath should have the following characteristics:

1) No cross. Crossings of paths will enhance path interference and repetitive processing at intersections. It would increase the difficulty of deterministic polishing control.

2) Continue and traverse the workpiece surface. Discontinuous machining toolpaths mean that the polishing head would frequent start-stop or in-out during machining. For most polishing technology, this process is unstable, which can introduce unexpected errors and increase the control difficulty.

Path planning technology has a wide range of applications in many areas[10]. The research of polishing toolpath has always been with the development of CNC machine tools, the complexity of the processing surface shape and the pursuit of processing quality, processing efficiency and other goals. In the end of last century, Tam has made efforts to improve path evenness through pitch adjustments based on changes in surface slope and through line spacing selection based on tool size and surface profile considerations. By using bi-directional scanning path with pitch adaptation, mirror-like surface finishes were obtained [11]. However, the paper does not study the signature in the surface leaved by this path. Christina, Zeeko Company, present a pseudo-random tool path for use with CNC sub-aperture polishing techniques. The results show that, the random unicursal tool path avoided introducing periodic structure, and the PSD curve of the machined surface is suppressed compared to the raster path, in which the main peaks representing periodic

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features disappear [7]. But they do not introduce the random path generation method. To avoid marks or specific patterns on the part, Pessoles choose to generate trochoidal tool path on fractal curves to cover the surface in a multidirectional manner. Hilbert's curves were used in machining as they have the advantage of covering the entire surface [12]. This paper only discusses the changes of the surface roughness, but also does not study the regularity information caused by the toolpath. Cheng investigated the affection of the tool path on the removal of material in polishing. They proposed that, for more uniform removal of material the spacing between paths on the workpiece surface should be as consistent as possible, and the distribution of path direction changes should be as uniform as possible [13]. Michael treats the toolpath planning as a contact mechanics problem. Simulation has been conducted to show the effectiveness of this new tool-path method [14]. To obtain high quality surfaces, Université propose Spade and Triangular optimized patterns to optimizes both surface covering and tool wear and the experiment results show that the Triangular pattern provides a uniform probability density function [15]. Cao built a theoretical model to predict and simulate the surface generation in FJP [16].

From the above description, the polishing path has a very significant influence on the polishing process. However, due to the high difficulty of the generation of random paths, the research about the random toolpath polishing is very few. In this paper, we put forward one method named as "Guide path" to reduce the programming difficulty and solving time of the new random toolpath. Comparison experiments of FJP with raster toolpath and the new random toolpath were conducted. The white-light interferometer (ZYGO New View 7100) was used to observe the micro topography of the polished surface. The laser interferometer (ZYGO GPI XP/D) was used to observe the power spectral density (PSD) and the peak-to-valley height (PV) of the polished surface.

II. RANDOM TOOLPATH GENERATION

This paper presents the method of "Guide path" to generating random toolpaths through computer programs by three steps. Firstly, mesh the surface and the matrix mapped with each node on the meshed surface is settled, so that the path planning problem is transformed into the element ordering problem. Secondly, introduce the random toolpaths generation method of "Guide path", and get trajectory vectors. Finally, get the required random toolpath based on the trajectory vector.

A. Surface meshing

First, mesh the surface by using the rectangle grid (Fig. 1a). The path pitch decided the mesh size. Secondly, to establish a mapping matrix *E*, the number of rows and columns of the matrix is determined by the distribution of nodes on the meshed surface, as shown in Fig. 1b. Finally, the nodes on the surface and the elements in the mapping matrix correspond to each other according to their relative positions. The elements in the matrix to which the surface nodes are mapped are set to 0, and the unmapped elements can be NaN. This occurs when the machined surface is not rectangular, as shown in Fig. 1b. When machining surfaces, the toolpath can be got by list the non-NaN elements of the mapping matrix according to certain rules. When a raster toolpath is used to machine the surface shown in Fig. 1a, the elements in the mapping matrix can be set as shown in Fig. 2.

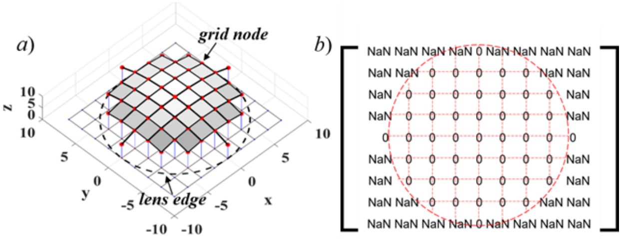

Figure 1. (a) Schematic of the surface meshing and (b)its mapping matrix *E*

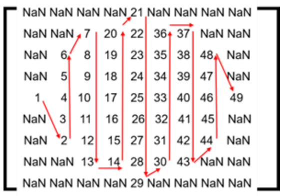

Figure 2. Mapping matrix of a raster toolpath

B. Guide path method

According to the above description of the requirements of random toolpaths, we can know that it is very difficult to directly generate the random toolpath through programming and the generating efficiency will becomes very low with the mapping matrix increases. To solve this problem, this paper proposes a method named as "Guide path" to reduce the difficulty of generating random toolpaths. This method based on the theory is that "always forward in the right or left side of the road which without interruption and don't have enclosed space and turn back in the end then you will come back to the starting point and never stand on one same point except the start and the end point". This principle can be explained as shown in Fig. 3. An ant crawls on a two-dimensional tree. If it is always on the right side of the tree trunk, it will surely return to the starting point. If the tree fork is randomly distributed, the moving path of the ant is also random. The two-dimensional tree can be regarded as the "Guide path" mentioned above, and the moving path of the ant is the needed random toolpath.

Compared with the generation of random toolpaths, it is very easy to generate the guide path by programming because there are fewer restrictions. Moreover, when the required path spacing are the same, the surface is meshed by twice the path space, or the number of rows and columns of the mapping matrix *E* is reduced by half to obtain the guide matrix E_0 for generating the guide path. Then, the generation of the guide path becomes the element ordering problem in the guide matrix E_0. Fig.4 shows the flow chart of the sorting method of the elements in the guide matrix.

Figure 3. Schematic of the “Guide path” method

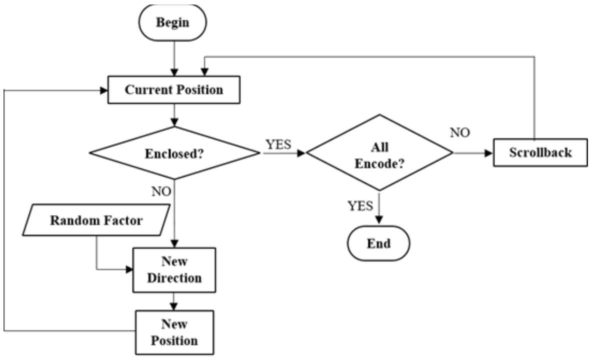

Figure 4. The flow chart of the element sorting in the guide matrix

In the flow chat, the current position is to store the element corresponding to the current position to the path vector T_0. The enclosed judgment is to search the path vector T_0 for whether all the neighboring element of the current element has passed and thus avoid the path closing. Fig.5 shows the method of judging the path direction under different surrounding conditions. Fig.5a shows the situation of current position has multiple directions to choose. The next position can be determined by the computer to generate a random number and added into the path vector T_0. When the judgment result is that there is no direction to choose, it means that all the neighboring elements have already been passed (as shown in Fig. 5b), and not all the elements in the guide matrix have been passed, follow back to find the location from the path vector T_0 until there is a direction to choice, as shown in Fig.5c.

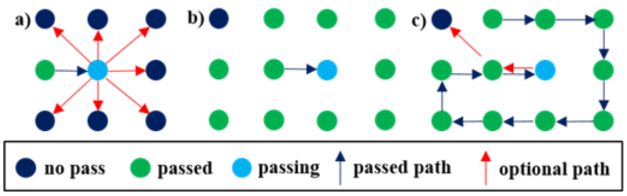

Figure 5. Judging method of the direction under different surrounding conditions in the path searching

C. Toolpath generation

Fig. 6a shows a graphical representation of the guide path using the element ordering method shown in Fig. 4 to sort the non-empty elements in Fig.1b. Where the blue line is the path from the beginning of the search until it has to turn back, and the red line is the bifurcation. As can be seen from the figure, the search for the entire surface was complete after four times turn back. According to the guide path and its direction shown in Fig. 6a, we can get a random path by giving a certain offset, as shown in Fig. 6b.

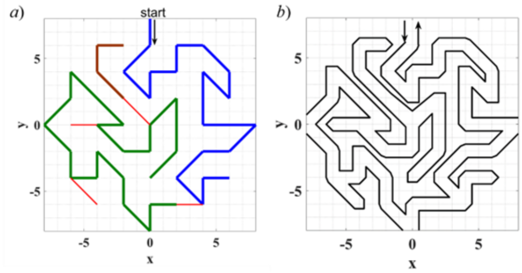

Figure 6. (a)Guide path and (b) random toolpath

From the random toolpath shown in Fig. 6b, the starting point and the end point are next to each other, which is helpful for controlling the path of retraction and prevent touching. Due to the existence of turning point inside the machining area and the inconsistency of the turn angle, the path spacing cannot be consistent. This situation causes a reduction in the uniformity of the material removal, which will lead to an increase of the PV value on the polishing surface, but further reduces the periodicity of the residual error caused by the toolpath.

III. Toolpath Parameter

Path spacing directly affects the density of the toolpath. When choosing a smaller path space, the control program can be very large and there is a high demand on the dynamic response of the machine tools. On the contrary, it is easy to leave obvious path signature on the polished surface. When the surface residual error caused by the path spacing is within the acceptable range, the choice of a larger path spacing will be more conducive to the implementation of the processing. When choosing a random toolpath, there are many turning points inside the machining surface, and the influence of the turning point on the uniformity of material removal also needs to be studied.

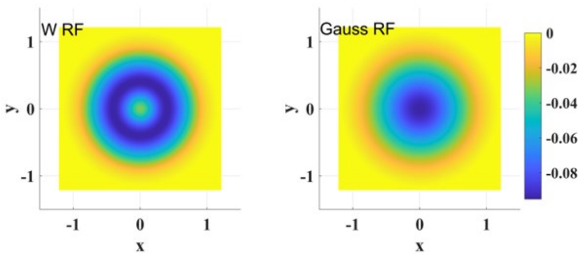

Figure 7. W-like removal function and Gauss-like removal function

In this paper, the numerical simulation of the difference of residual error of the polished surface under the different path spacing and different turn angle is carried out. Fig. 7 shows two types of removal function (RF) with the same width and depth. The W RF can be obtained in the vertical FJP processing. The RF of the other polishing methods, like bonnet polishing[17] and ion beam polishing[18], are generally Gauss like.

A. Path spacing

When the raster toolpath with different path spacing is used for polishing to the same depth, the surface profile along the perpendicular direction of the toolpath is shown in Fig.8.

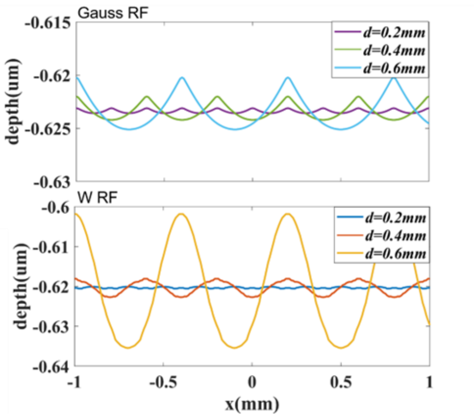

Figure 8. The polished surface profile with different path spacing

It can be seen from Fig. 8 that the variation period of the polished surface using the W and Gauss removal functions is consistent with the selected path spacing. The peak-to-valley height of the surface polished with W removal function increases rapidly with the increase of the path spacing and significantly larger than the Gauss removal function. This is due to the edge gradient of the W RF larger than the Gauss RF when the width is the same.

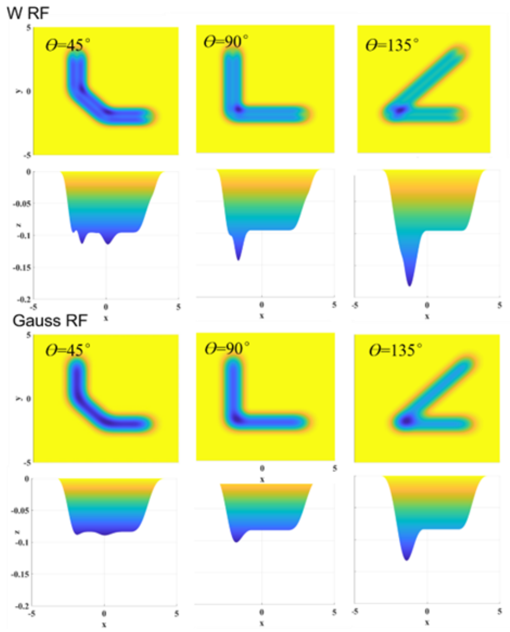

Figure 9. Influence of path turning point on uniformity of material removal

B. Turn point

Fig. 9 shows that the larger the turn angle, the removal at the turn point is deeper. The removal depth at the turn point by the W RF is greater than the Gauss RF. From the perspective of removal uniformity, the fewer the number of turn points inside the machined surface the better.

IV. EXPERIMENTAL PROCEDURE

A. FJP system

In this paper, fluid jet polishing (FJP) technology was used to study the characteristics of the new random toolpath application. In the FJP process, the polishing liquid is formed by mixing CeO2 and water. A diaphragm pump is used to pressurize the polishing liquid, and a filter damper is used to suppress the fluctuation of the jet pressure. The size of the nozzle is usually 0.5-1mm [19].

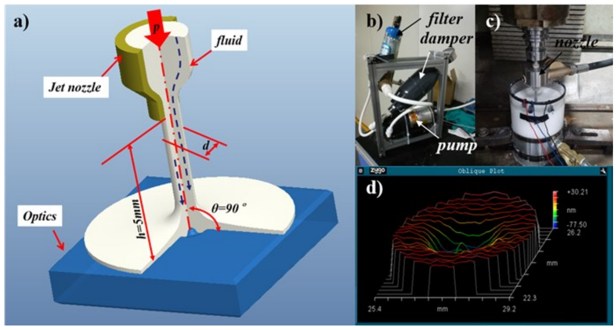

Figure 10. (a) Schematic diagram of the vertical jet setup and definition of parameters (b) Hydraulic system of FJP (c) FJP tool head and workpiece hold (d) Removal function's 3D profile

Fig.10a shows the experimental setup and definition of parameters. In the present work, the jet tilt angle θ, the jet pressure P and the jet distance h were kept constant. Tab.1 shows the experimental parameters. Fig.10c shows the jet nozzle and the workpiece holder. Which mounted on the spindle and worktable of a CNC machine tool separately. To avoid splashes, the workpiece and the nozzle were submerged by the fluid. Fig.10d shows the removal function profiles, measured by the laser interferometer. It shows that the removal shapes distribute circularly, and the cross section of the removal function has a W-shape.

TABLE 1. EXPERIMENTAL PARAMETERS FOR TESTING THE TOOLPATH

Fluid concentration	10g/L	**Pressure**	7±0.01 bar
Jet distance	5mm	**Material**	BK7
Nozzle diameter	1mm	**Grain**	CeO2(≈1.5um)
Impingement angle	90°		

B. Different toolpath

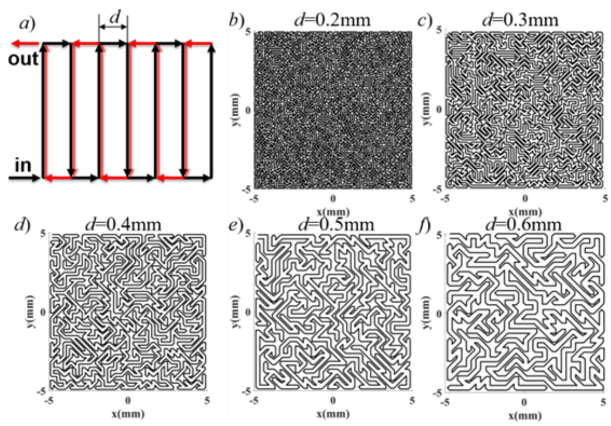

Figure 11. Schematic of raster toolpath a) and the random toolpath of different path spacing b)-f)

In this paper, two types of toolpaths (the raster toolpath, the new random toolpath) under five different paths spacing (0.2mm, 0.3mm, 0.4mm, 0.5mm, 0.6mm) were used to polish the surface in the range of 10×10mm, as show in fig.11. The experiments were performed on flat surfaces of BK7 glasses, PV=1/10λ (λ@632.8nm).

V. RESULTS AND DISCUSSION

The white-light interferometer (ZYGO NewView 7100) and the laser interferometer (ZYGO GPI XP/D) were used to observe the microstructure and the surface profile. The spatial resolution is 0.003mm and 0.04mm separately. The measurement range of the white-light interferometer select 1.88×1.41mm.

Fig.12 shows the measurement results of the polished surface by using the white-light interferometer. The mean low-pass filter was used to filter the measurement results (sample length = 0.02 mm). It shows that the surface polished by the raster toolpath has obvious path residual error when the path spacing more than 0.4mm and as the path spacing increases, the residual error of the toolpath becomes more obvious. However, the surface polished by the new random toolpath has not found any path signature with the path spacing increases.

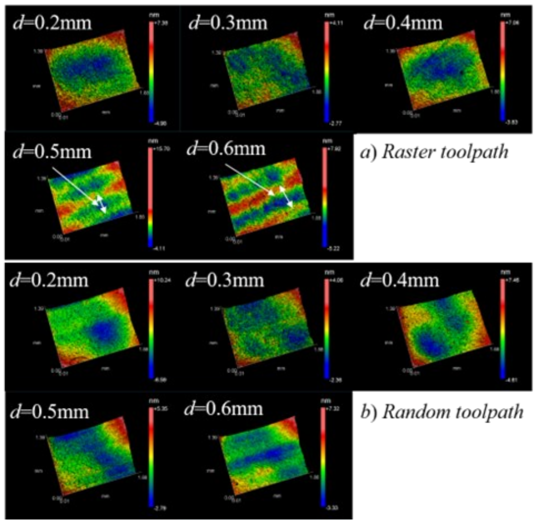

Figure 12. The distribution of residual error on the FJP processed surface under different path spacing

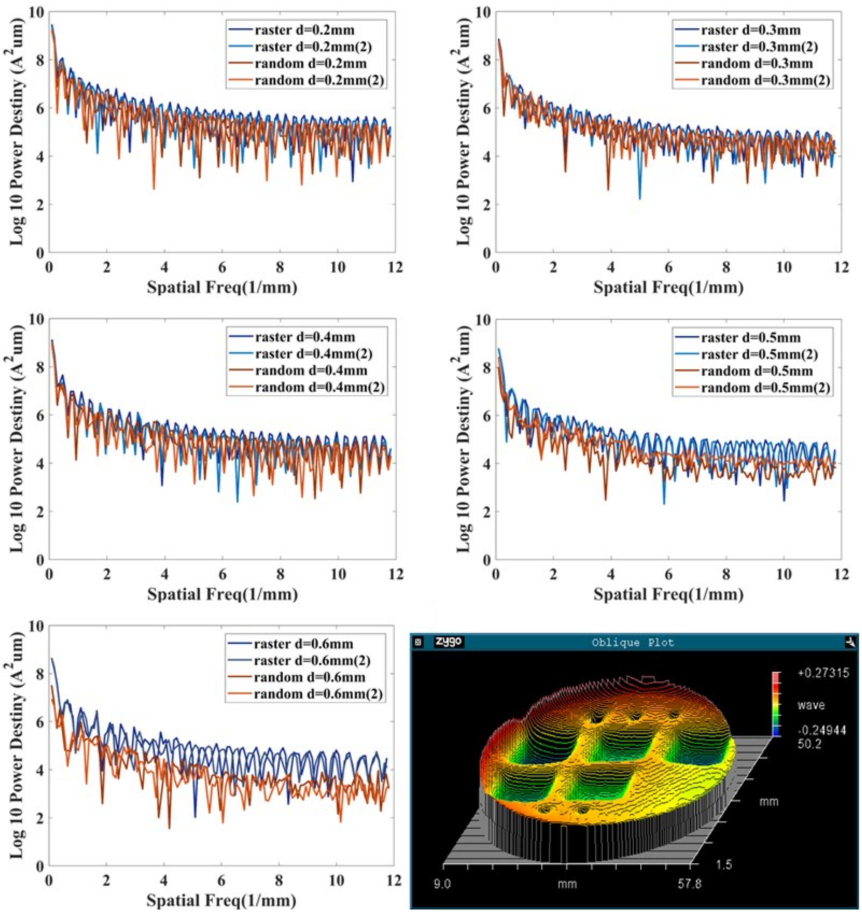

Figure 13. PSD comparison of polishing surfaces for different toolpaths

The PSD of the surface polished by the raster toolpath is measured in the perpendicular direction of the toolpath. Fig.13 shows that when the path spacing is less than 0.5mm, the PSD of the polished surface using the raster toolpath and the random toolpath has no obvious difference. When the path spacing is greater than 0.4mm, The PSD of the surface polished by the random toolpath is significantly smaller than the surface polished by the raster toolpath.

Fig.14 shows the measurement results of the surface area PV value within 5×5 mm. As the path spacing increases, the surface PV value increases gradually, but the increasing gradient is not as large as the simulation results shown in Fig.8. This may be due to the slurry flows at a higher speed on the workpiece surface during the FJP processing, causing the surface peak to be removed with higher efficiency. The PV value of the surface polished by the new random toolpath is significantly larger than the surface polished by the raster toolpath. This is due to the fluctuation of the path spacing and the large number of turning point in the random toolpath.

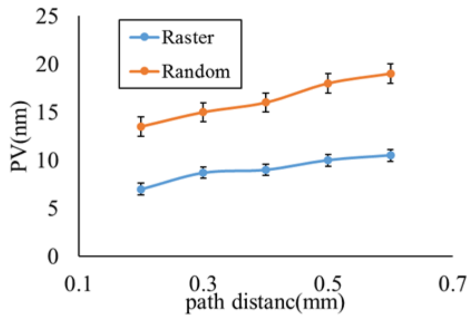

Figure 14. The PV value of the surface polished under different path type and path space

VI. CONCLUSION

In this article, we proposed a generation method of random toolpath. The generated toolpaths completely meet the polishing requirements of no cross, continue, and traverse the workpiece surface. The new random toolpath also has the characteristics of inconsistent path spacing and has many turning points. Through experiments found that the surface polished by the raster toolpath appears obvious path signature with the increase of the path spacing, while the surface polished by random toolpath does not appear and has smaller surface power spectral density (PSD). Due to the fluctuations of the path space and with many turning points in the random toolpath, the PV value of the polished surface using random toolpaths is larger than the raster toolpath. Due to the slurry flows at a higher speed on the workpiece surface during the FJP processing, causing the surface peak to be removed with higher efficiency. Therefore, the increasing gradient of the PV value is not as large as the simulation results.

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REFERENCES

[1] M. Clampin, "The James Webb Space Telescope (JWST)," Advances in Space Research, vol. 41, no. 12, pp. 1983-1991, 2008, doi: 10.1016/j.asr.2008.01.010.

[2] A. Beaucamp and Y. Namba, "Super-smooth finishing of diamond turned hard X-ray molding dies by combined fluid jet and bonnet polishing," CIRP Annals - Manufacturing Technology, vol. 62, no. 1, pp. 315-318, 2013, doi: 10.1016/j.cirp.2013.03.010.

[3] C. J. Stolz, "The National Ignition Facility: the world's largest optical system," SPIE, vol. 6834, pp. 683402-683402-9, 2007, doi: 10.1117/12.773365.

[4] R. Aspden, R. McDonough, and F. R. Nitchie, Jr., "Computer assisted optical surfacing," Appl Opt, vol. 11, no. 12, pp. 2739-47, Dec 01 1972, doi: 10.1364/AO.11.002739.

[5] R. A. Jones, "Optimization of computer-controlled polishing," Applied optics, vol. 16(1), pp. 218-224., 1977.

[6] R. A. Jones, "Grinding and polishing with small tools under computer control," Los Angeles Technical Symposium. International Society for Optics and Photonics, 1979.

[7] C. R. Dunn and D. D. Walker, "Pseudo-random tool paths for CNC sub-aperture polishing and other applications," Opt. Express, vol. 16, no. 23, pp. 18942-18949, 2008/11/10 2008, doi: 10.1364/OE.16.018942.

[8] Z. Guo, T. Jin, L. Ping, A. Lu, and M. Qu, "Analysis on a deformed removal profile in FJP under high removal rates to achieve deterministic form figuring," Precision Engineering, vol. 51, pp. 160-168, 2018, doi: 10.1016/j.precisioneng.2017.08.006.

[9] Z. Guo, T. Jin, Q. Liu, A. Lu, and M. Qu, "Extraction of workpiece rotary symmetrical error and its deterministic removal by fluid jet polishing," Optical Engineering, vol. 57, no. 1, p. 015103, 2018. [Online]. Available: https://doi.org/10.1117/1.OE.57.1.015103.

[10] Z. Cui, Z. Miao, Y. He, and X. Cong, "Overview of NC Machining Tool Path Optimization Based on Digital Twin Technology," in 2021 IEEE International Conference on Electrical Engineering and Mechatronics Technology (ICEEMT), 2-4 July 2021 2021, pp. 800-804, doi: 10.1109/ICEEMT52412.2021.9602603.

[11] H.-y. Tam, O. Chi-hang Lui, and A. C.K. Mok, "Robotic polishing of free-form surfaces using scanning paths," Journal of Materials Processing Technology, vol. 95, no. 1, pp. 191-200, 1999/10/15/ 1999, doi: https://doi.org/10.1016/S0924-0136(99)00338-6.

[12] X. Pessoles and C. Tournier, "Automatic polishing process of plastic injection molds on a 5-axis milling center," Journal of Materials Processing Technology, vol. 209, no. 7, pp. 3665-3673, 2009, doi: 10.1016/j.jmatprotec.2008.08.034.

[13] H.-y. Tam and H. Cheng, "An investigation of the effects of the tool path on the removal of material in polishing," Journal of Materials Processing Technology, vol. 210, no. 5, pp. 807-818, 2010/03/19/ 2010, doi: http://dx.doi.org/10.1016/j.jmatprotec.2010.01.012.

[14] M. Rososhansky and F. Xi, "Coverage based tool-path planning for automated polishing using contact mechanics theory," Journal of Manufacturing Systems, vol. 30, no. 3, pp. 144-153, 2011, doi: 10.1016/j.jmsy.2011.05.003.

[15] J. Chaves-Jacob, J.-M. Linares, and J.-M. Sprauel, "Improving tool wear and surface covering in polishing via toolpath optimization," Journal of Materials Processing Technology, vol. 213, no. 10, pp. 1661-1668, 2013, doi: 10.1016/j.jmatprotec.2013.04.005.

[16] Z. C. Cao, C. F. Cheung, and M. J. Ren, "Modelling and characterization of surface generation in Fluid Jet Polishing," (in English), Precis Eng, vol. 43, pp. 406-417, Jan 2016, doi: 10.1016/j.precisioneng.2015.09.005.

[17] D. D. Walker et al., "The 'Precessions' tooling for polishing and figuring flat, spherical and aspheric surfaces," OPTICS EXPRESS, vol. Vol. 11, No. 8, 21 April 2003 2003

[18] T. Wang et al., "Study on an effective one-dimensional ion-beam figuring method," Opt Express, vol. 27, no. 11, pp. 15368-15381, May 27 2019, doi: 10.1364/OE.27.015368.

[19] D. A. Axinte et al., "High Energy Fluid Jet Machining (HEFJet-Mach): From scientific and technological advances to niche industrial applications," (in English), Cirp Ann-Manuf Techn, vol. 63, no. 2, pp. 751-771, 2014, doi: 10.1016/j.cirp.2014.05.001.