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Open Loop Fuzzy Optimizer for Computer Controlled Polishing

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***Abstract*—**Computer Control Polishing (CCP) was developed during the last four decades to administrate the operation of almost all polishing methods. To this end, , enhancing the simulation of CCP process not only improves the quality of final products but also trims operation time and, consequently, leads to accelerate the manufacturing of optical lenses. In this study, a new method has been developed and applied for simulation of polishing process based on discretizing continuous toolpath to small distance—100 µm in length—which accordingly heightens the accuracy of simulation process. Smoothing feed rate fluctuation over toolpath is also a side benefit of the represented method that precludes damage to machine and workpiece. To proceed with CCP, we conducted an open-loop fuzzy controller approach to optimize the tool feed rate distribution over the toolpath. The method has the ability to optimize feed rate to reduce surface error for a variety of toolpaths and lens geometries. The simulation and experimental results of series of tests on a BK7 plano-plano lens show about 85% of surface roughness improvement. High percentage of improvement and the resemblance between simulation and experimental results respectively confirmed the accuracy of simulation method and the capability of optimization algorithm.

***Keywords*—**Optical lens manufacturing, Computer Control Polishing, dwell-time optimization, fuzzy controller, simulation.

I. INTRODUCTION

EXTENSIVE growth of opto-electronic technologies has created a remarkable demand for high quality lenses which has driven the optics industry toward more efficient processes for the manufacturing of moderate volumes of different lenses. Grinding, lapping and polishing are the main steps toward the mass production of glass lenses. In brief, grinding roughly forms the surface curvature; lapping removes tool marks remaining from previous step; and, finally, polishing leads to desired surface quality and geometry. Being directly responsible for the quality of final products, polishing process is the most determinant step and, accordingly, several methods are established to streamline its operation. Since traditional methods were impractical for polishing modern free-form lenses [1], Computer Control Polishing (CCP) was established as an alternative approach to operate the manufacturing process of optical lenses [2]. Resulting in very high surface qualities, CCP has been widely applied for polishing optical lenses even for flat or spherical surfaces. In this method, locally controlling the amount of removed material improves surface quality. Following that, removed material can be controlled by modifying in tool feed rate, tool pressure, tool path, [3] or a combination of them of which feed rate controlling is the subject of this study.

As a response to the cumulative demand for high quality lens polishing, many polishing mechanisms have been developed which can be generally divided in two categories. The first group design large intellectualized tools (about 10% of workpiece area) which continuously alter to fit itself into different curve radius [4]. This category, which in fact is a closed loop active controller, can only be applied to the strain free condition such as passive blank mirror with high rigidity [5]. Martin and Burge are the pioneers who left a significant influence in this field. In 1990, Martin et al. developed a stress lap machine for figuring large optics elements [6] and succeeded to fabricate a 1.8-m f/1 ellipsoid mirror with 25 nm of overall surface error. In 1994, the same team [17], working in Steward Observatory mirror lab in Arizona, reported the successful fabrication of a mirror with 3.5 m in diameter and with a better surface finish (16 nm rms). Their work was unique because of the size of the mirror, the quality of surface, and also operation time since the fabrication process took only 5 months. In 2000, Sug-Whan Kim et al. developed a stress lap polishing machine in the UK [8]. In these machines, while the tool fits to workpiece surface curvature and moves randomly, polishing parameters—such as speed and pressure—constantly change based on the surface local errors to improve the surface[9]. In these methods, TIF variation in different situations including over the edges is a main problem which happens as a result of change in pressure and cause undesired results. In 2009, Dae Wook Kim et al. developed a method to consider TIF variation in different workpiece positions in order to increase the efficiency of stress-lap polishing methods [10].

The second group utilizes tools with small area (about 1% of workpiece area) which, as a result, the tool miss fitness problems would be overcome and different geometries can be polished. In this category, Computer Controlled Polishing (CCP) method is used to locally control the amount of removed material by an open loop passive controller is applied. Ronald Aspdone [1] was one of the pioneers to develop CCP method. Converting both the matrix of tool influence function (TIF) and the matrix of surface profile to hexagonal matrix, he modeled

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the influence of tool travelling over a lens surface in a way that he could simulate the whole polishing process. In his method, based on the initial surface profile, a toolpath would be generated to mostly cover peak area of surface which improves the surface quality. Robert Jones, who is one of the most influential people in this field, conducted lots of research to develop CCP method in the period of 1977 to 1995[11-15]. Modeling tool movement by convolution integration, he achieved a high accuracy in simulating polishing process [11]. Also, he proposed a method based on de-convolution to calculate required dwell time map for decreasing surface roughness. In contrast with the previous method, removed material was controlled by modifying tool feed rates over workpiece. Not only polishing process was operated by this method, but also Robert Jones applied computer control to operate the grinding process [13]. In 1982, he applied CCP method to polish large mirror 60° segments with 91 cm in diameter [14]. He succeeded to decline surface roughness by 65% and reduce it to 7.5 nm for rms. In 1992, CCP method was modified by Tianning Cao and Jianping Zhang [16] to make an aspheric lens out of a spherical one. Although the idea of change a spherical mirror to an aspherical during grinding process was already represented and applied with Martin and Burge's group, Tianning Cao and Jianping used the methodologies developed by Robert Jones. In 2007, using time variant tool influence function, Schinhaerl et al [3] controlled the amount of removed material by changing the tool pressure during the polishing process. To decrease polishing time, tool moves with its constant maximum available speed but the pressure between tool and workpiece varies over the time in order to control the amount of removed material over the workpiece. He also developed a method based on using the combination of dwell time and pressure.

II. SIMULATION OF POLISHING PROCESS

The method applied in this study to stimulate the polishing process includes three main steps; i) discretizing tool path, ii) optimizing dwell time, iii) calculating the amount of removed material over the workpiece surface to estimate final surface profile. The simulation of polishing process is illustrated in flowchart shown in **Figure 1**. In the first step, the selected toolpath would be discretized into small distances with 100 µm in length. As a result, any toolpath including spiral, raster or even random can be simulated for polishing purposes. In this work, a spiral tool path was selected converted to discretized distances as illustrated in **Figure 2**. Increasing the number of distances per unit length, despite multiplying computer processing time, would leads to diminish fluctuation of feed rates, to minimize polishing time, and to advance surface quality. Furthermore, smooth tool feed rates impedes damages not only to workpiece but also to polishing machine. As a result of discretizing toolpath, the influence of tool travelling over it can be modeled by modeling tool traveling over each small distance. For this purpose, tool travelling over each small distance is modeled by placing the tool in the center point of each distance—tool positions—which are shown in **Figure 3**. Therefore, the tool stays at each tool position as long as it takes for the tool to travel over the distance.

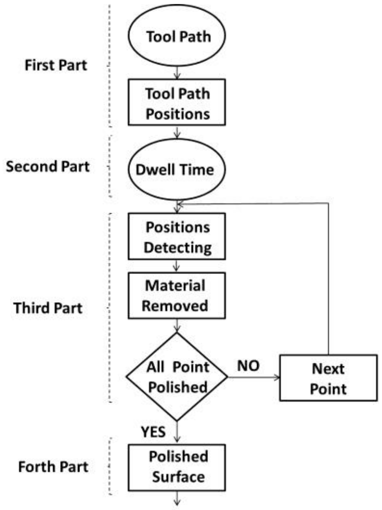


Figure 1 Diagram of polishing simulation process

To echo, the tool travelling over toolpath which makes material removal has been modeled by relocating the tool several times per second. In this method, the location of tool center would be updated for 20 to 120 times per second.

In the second step, the main purpose is to allocate a specific dwell time to each tool position. The dwell time could be determined through an optimization process which, in this study, is explained in next section. This step would determine a proper dwell time for all tool positions.

During the third step, a specific procedure would be repeated for all surface points to calculate the depth of removed material. To calculate the height reduction of element (i,j) of the surface located in $p = (x, y)$, all tool positions which influence this point should firstly be distinguished (**Figure 4**). We call them ITPs (Influential Tool Positions) for point p.

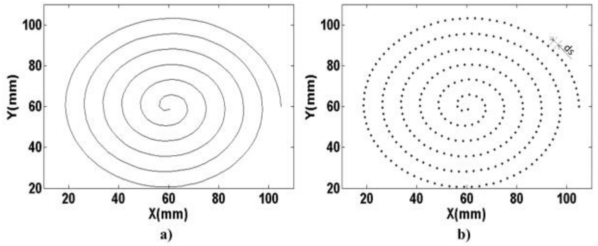


Figure 2 a) Spiral tool path, b) tool path discretized to small distances

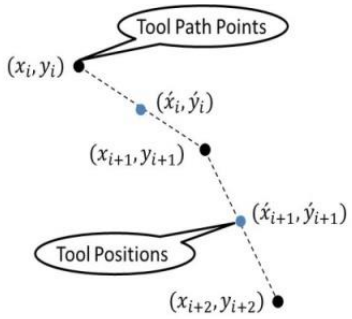


Figure 3 Tool path point and tool positions over a tool path

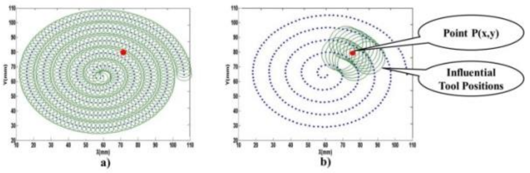


Figure 4 a) All tool positions over the tool path, b) distinguished influential tool positions

Based on TIF profile, each of ITPs makes different material removal rates on the point p which can be calculated by spotting the location of point p in TIF profile. After calculating the material removal rate of ITPs, the total height reduction can be calculated based on Equation (1).

$$MR(i,j) = \sum_{q=1}^{n} MRR(i,j,k_q) * dt_{k_q} \qquad (1)$$

where dt_k is the dwell time specified for k^{th} tool position. Repeating the previous step for all elements of the matrix of the surface profile ends to calculate the profile of polishing over the whole surface. Finally, in last step, the final surface can be predicted by subtracting the profile of polishing from the initial surface.

III. DWELL TIME OPTIMIZATION BASED ON FUZZY LOGIC METHOD

In this research, a fuzzy logic open loop controller was used to optimize the dwell time distribution over the tool path. To this end, the high error areas are located and their ITPs would be prioritized based on their ability to reduce the error. Then, enough dwell time would be distributed among them with two considerations: diminishing the error value for a specific ratio and not disfiguring the other areas. Any spot of the surface profile would be influenced with many tool positions—between 1000 to 3000—, which they also cover a large area of the surface. Hence, it is a complicated job to distribute dwell time among them while considering their influence over other areas. In this project, writing simple rules, a fuzzy logic algorithm is designed to do this job. It is worth noting that, the ability of different tool positions to reduce the surface error is an important parameter which should be evaluated regardless from surface error profile. As it is shown in **Figure 5**, although the value of error profile under tool position 1 is great, but tool position 1 is unable to reduce it. On the other hand, tool position 2 has covered a smaller amount of error, but it poses a better situation to reduce the error. Neglecting tool ability to reduce surface error would make it hard to improve the surface roughness and also would increase the time of polishing process.

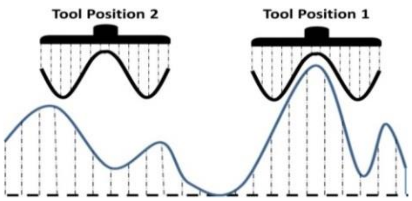


Figure 5 Comparing tool positions ability in reducing surface error

Following that, first, surface error profile and TIF profile should be normalized with respect to their maximum value. Then, the set of value (α,β,γ) could be calculated for each surface point under each ITPs, as it is shown in **Figure 6**.

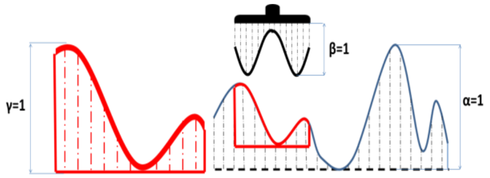


Figure 6 Defining the set of values (α,β,γ) for a surface point under each of its ITPs

Considering a point under each of its ITPs, α is the global error, γ is the point local error (local area is the area effected by the related tool position) and β is the tool influence over the point of this position. Accordingly, while the parameter α of a point is constant for all the time, its parameters γ and β change for each ITPs. Therefore, parameter α helps to consider surface error, two parameters β and γ help to evaluate the tool position ability to diminish that error regardless of its value. To conducting fuzzy logic optimizer, sets of values of (α,β,γ) are required as inputs and, subsequently, parameter δ would be outputted for each point under each of its ITPs (**Figure 7**). The membership function shown in **Figure 8** is selected for input parameters (α,β,γ) and the membership function shown in **Figure 9** is selected for output parameter δ.

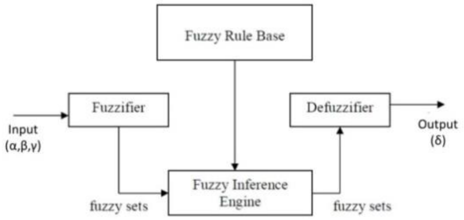


Figure 7 Fuzzy logic decision maker algorithm

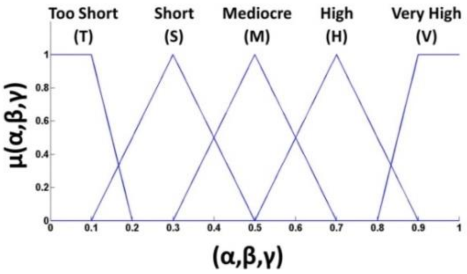


Figure 8 Membership function for the set of input values (α,β,γ)

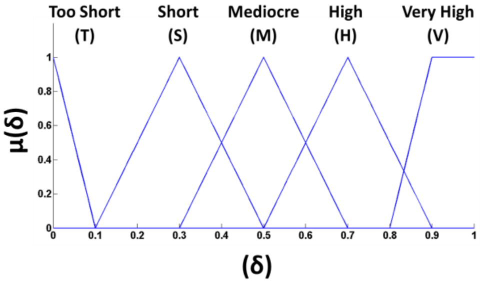


Figure 9 Membership function for the out value δ

TABLE I SOME EXAMPLE OF FUZZY LOGIC RULES

If α is	and β is	and γ is	then δ is
V	V	V	V
M	M	M	M
M	M	V	S
M	V	T	T
T	any	any	T

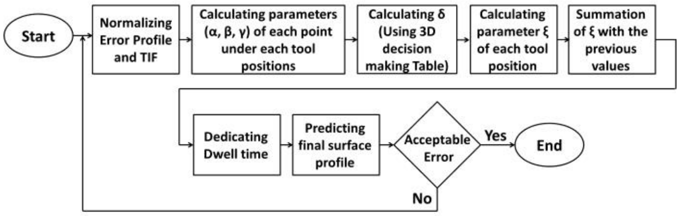
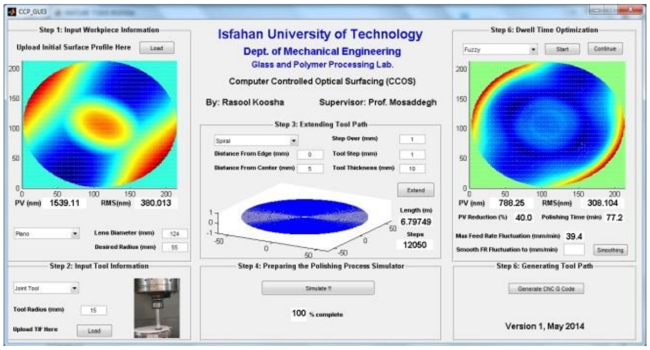


Figure 10 Dwell time optimization flowchart



PV (nm) 1539.11 RMS(nm) 380.013

Plano

Lens Diameter (mm) 124

Desired Radius (mm) 55

Spiral

Distance From Edge (mm) 0

Distance From Center (mm) 5

Step Over (mm) 1

Tool Step (mm) 1

Tool Thickness (mm) 10

Length (m) 6.79749

Steps 12050

Fuzzy

PV (nm) 788.25 RMS(nm) 308.104

PV Reduction (%) 40.0

Polishing Time (min) 77.2

Max Feed Rate Fluctuation (mm/min) 39.4

Smooth FR Fluctuation to (mm/min)

Joint Tool

Tool Radius (mm) 15

Upload TIF Here

100 % complete

Figure 11 Tool box programmed for operating the software level of CCP method

Since there are 3 parameters as inputs and the input parameter membership has 5 different bounds, 125 different fuzzy rules are written for fuzzy interface engine. Some example of this rules are listed in **TABLE I**. The rules are written in a way that in each iterations the area with the highest level would be targeted.

In this research, singleton function is selected as a fuzzifier and center of gravity method is selected for defuzzifier. Parameter δ can be calculated for a wide range of input parameters (α,β,γ) and be restored in 3D table—decision making table—for future access to accelerate the process. The flowchart illustrated in **Figure 10**, has been followed to keep distributing dwell time to find the desired surface finish.

In this fellow chart, parameter "ξ" is defined specifically for each tool positions which is the product of multiplication of all values of δ related to that tool position. This value would be updated in each iteration based on the new surface profile. dwell time would be dedicated to tool positions as a proportion of their ξ values with respect to maximum and minimum possible feed rates which are caused by machine and workpiece limitations. For the CNC mashine we used, the tool speed distribution is to vary between 50 mm/min and 700 mm/min over the tool path. The toolbox illustrated in **Figure 11** has been programmed for conducting CCP in software level which inputs the initial profile and geometry of a surface accompanied with tool path preferences and generates the CNC G code based on the optimized dwell time.

IV. OPERATING COMPUTER CONTROLLED POLISHING FOR PLANO-PLANO LENSES.

To evaluate simulation process and the fuzzy logic optimizer ability to improve surface quality, a series of tests has been conducted. To bring to light, a BK7 plano-plano lens with 124 mm in diameter, which is shown in **Figure 12**, was selected for polishing tests.

An interferometer used to measure surface profile in terms of wavelength of helium-neon light (λ) which is 632.8 nm. The results of initial surface profile are shown in **Figure 13**, indicating the surface roughness of 2.377 µm for PV and 647 nm for rms.

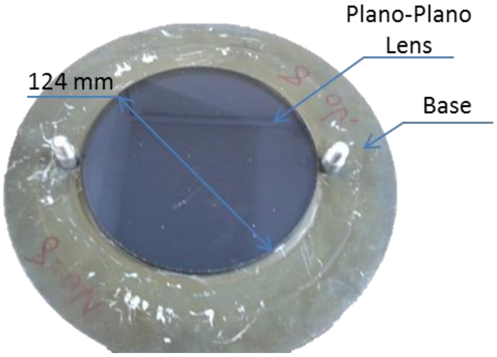


Figure 12 BK7 plano-plano lens with 124 mm in diameter

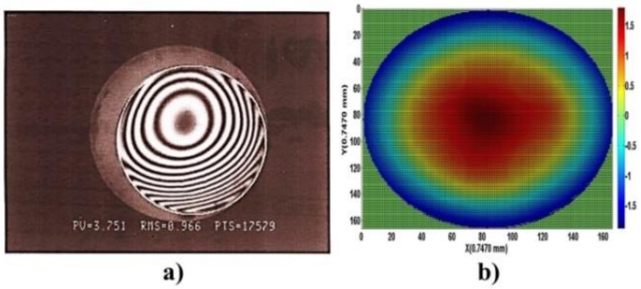


Figure 13 The initial surface profile of plano-plano lenses

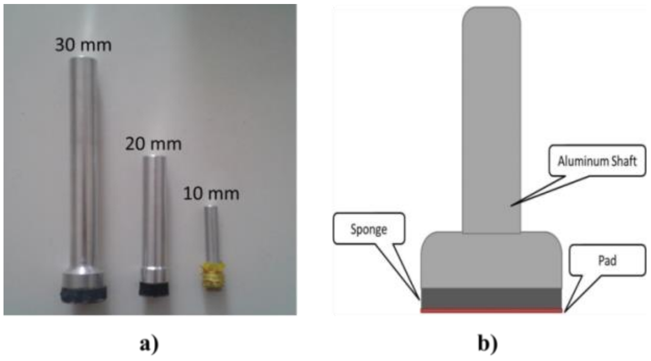


Figure 14 a) Polishing tools, a) Schematic of polishing tools

The polishing tools, which are used in this study, are aluminum shafts with different diameters which are shown in **Figure 14(a)**. As it is schematically shown in **Figure 14(b)**, there is a sponge between aluminum shaft and polishing pad to avoid tool miss fitness.

The TIF was experimentally measured through several tests under the condition of 250 rpm of spindle speed and 10 N of contact force. The TIF of the 30 mm tool is measured and shown in **Figure 15**.

The toolbox programmed in previous section was used to extend the tool path over the surface, optimize the dwell time distribution, and, finally, generating the CNC G code to administrate the physical level. Based on the simulation results (**Figure 16**), the final surface roughness has been reduced to 433 nm for PV and 64nm for rms, it means that the whole surface error has been reduced 82% for PV and 91% for rms in 429 minutes of polishing.

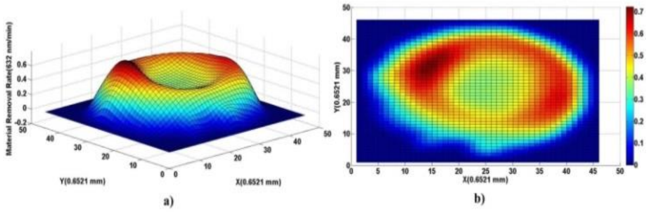
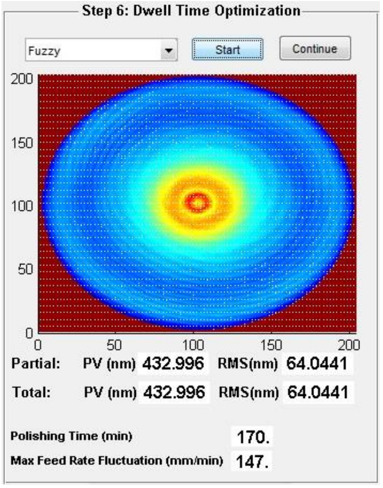


Figure 15 Experimental TIF profile of a 30 mm tool a) 3D view, b) top view



Partial: PV (nm) 432.996 RMS(nm) 64.0441

Total: PV (nm) 432.996 RMS(nm) 64.0441

Polishing Time (min) 170.

Max Feed Rate Fluctuation (mm/min) 147.

Figure 16 The first step of polishing (using 20 mm diameter tool)

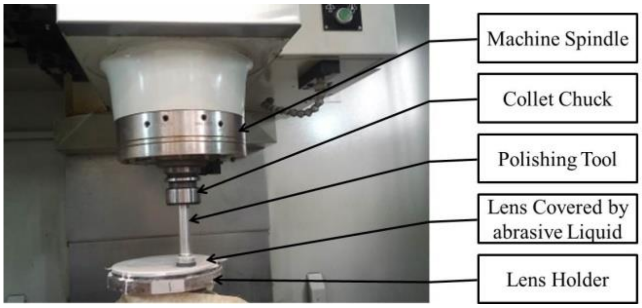


Figure 17 Palno-plano lens under polishing process using a 3-axis CNC machine

In physical level, a 3-axis CNC machine was employed to operate the polishing process which has 1µm accuracy for its linear movement. The whole set-up is shown in **Figure 17** and the polishing parameters are listed in **TABLE II**.

The final surface profile of polishing process is shown in **Figure 18**. As it is shown in the figure, the surface roughness has reduced to 0.538λ (340 nm) for PV and 0.118λ (74 nm). It means that the error of surface has reduced 85.6% for PV and 87.8% for rms (the percentage of eliminated error over initial error). Comparing simulation results and experimental results indicates a remarkable difference in surface profile over the edges which happens as a result of variation the pressure distribution in contact area and changes the TIF. Considering PV and rms as the surface roughness indicators, the results of simulation and experimental results differ roughly 5 percent in both of them.

TABLE II TEST CONDITIONS FOR POLISHING PROCESS OF PLANO-PLANO LENSES

Value	Parameter
124 mm	Lens diameter
30 mm	Tool diameter
53/100 gr/ml	Abrasive density
250 rpm	Spindle speed
0.6 mm, 6.5kPa	Pressure
Spiral	Tool path
1 mm	Step over
134 min	Polishing Time

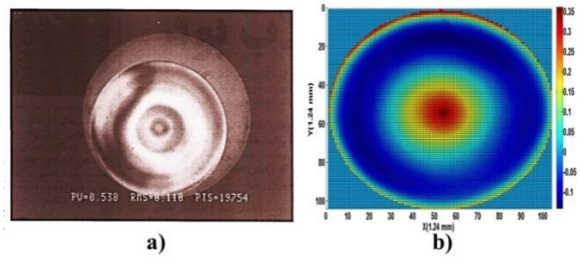


Figure 18 a) Initial surface fringe measured by interferometer, b) initial surface profile

V. CONCLUSION

In this study, a new method was represented for simulating polishing process based on tool path discretization. As a result, a variety of polishing toolpaths could be easily and precisely modeled with 100 micron accuracy. Applying polishing process with small tool steps leads to moderate in feed rate fluctuation which significantly reduces damage to workpiece and machine. Finally, the comparison between experimental results and simulation results shows that the method has succeeded to simulate polishing process over the surface excluding over the edges. The simulation process was directly related to TIF profile and, since the pressure distribution changes over the edges, the TIF would change and lead to inaccurate results in simulation. To optimize dwell time, an open loop fuzzy optimizer was programed to distribute dwell time over the toolpath. The goal of optimizer was to lessen the surface error in the minimum time. Following that, a method was represented to evaluate the ability of tool positions to diminish the error. As a result, the controller not only inputs the error profile but also the priority of tool positions in smoothing the surface which, by the way, makes the fuzzy interface engine decide more accurately. Moreover, fuzzy logic guarantees the privilege of applying different optimization strategies easily just by updating fuzzy rules. Represented methods were applied to polish a plano-plano lens with 124 mm in diameter, in which surface error reduced from 3.751λ (2.377µm) to 0.538λ (340 nm) for PV and from 0.966λ (647 nm) to 0.118λ (74 nm) for rms. Based on the obtained results, surface error declined by 85.6% in PV and 87.8% in rms. Comparing the results of simulation tests with results of experimental tests shows only 5% difference which indicates the accuracy of simulation method.

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