

Investigation on Magnetorheological Finishing of thin Copper Substrate

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Title page

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ORIGINAL ARTICLE

Investigation on magnetorheological finishing of thin copper substrate

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Abstract: Thin copper substrates in precision physical experiments are commonly machined by double-sided lapping to obtain high flatness. However, the flatness is limited by the accuracy of lapping plate, process vibration and so on in double-sided lapping process. Hence, magnetorheological finishing (MRF) with its good performance on profile modification is employed to improve the flatness. Nevertheless, thin copper substrates, which are sensitive to the stress, deformed easily with uneven material removal on the surface. In this paper, MRF is conducted on machining thin copper substrate for the first time considering deformation induced by stress. A finite element model is established to evaluate the deformation by residual stress, and the results show that the deformation tends to be more

serious with the increase of the material removal. According to the simulation results, the material removal is optimized considering both deformation and efficiency, and a series of experiments are conducted on a $\Phi 100 \times 2.8$ mm workpiece to verify the simulation results. The experimental results show that the flatness is further improved from peak to valley (PV) $6.6 \mu\text{m}$ to PV $2.3 \mu\text{m}$ with optimized processing parameters. Hence, the feasibility of magnetorheological finishing on thin copper substrate is demonstrated.

Keywords: Magnetorheological finishing • Thin copper substrate • Flatness • Deformation

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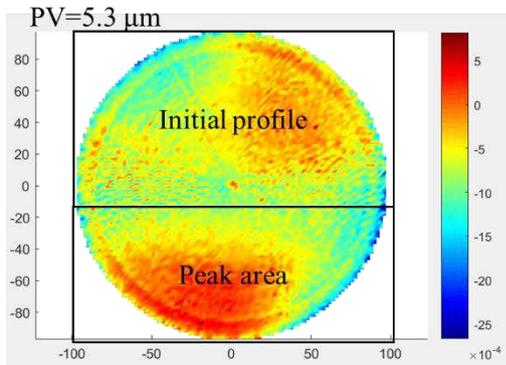
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1 Introduction

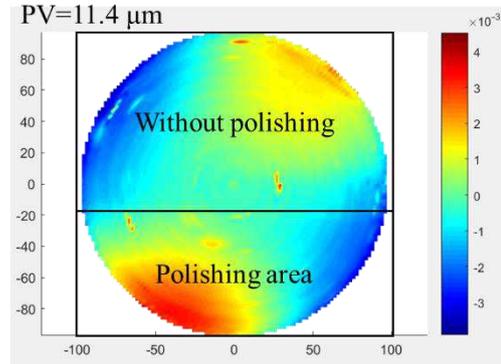
Thin copper substrates with the flatness superior to $2 \mu\text{m}$ are highly required in the precision physical experiments [1, 2]. Normally, it is fabricated by double-sided lapping process to achieve the extremely high flatness [3]. However, the flatness is limited by the accuracy of lapping plate, process vibration and so on in double-sided lapping process. To further improve the flatness of thin copper

substrates, we put forward a new process route of adding magnetorheological finishing (MRF) process after double-sided lapping.

MRF is an ultra-precision machining process, and has been widely used in fabrication of optical components as a profile modification process [4-8], which removes the material by particles in the slurry [9-13]. In the MRF process, the trajectory and dwell time are calculated based on the measured profiles, in which more material is removed in the peak regions than that in the valley regions. Continuous efforts have been made on the MRF process, but most investigations focused on the optics materials [14-17]. The flatness has been improved largely with the optimization of the MRF process on the workpiece with strong stiffness, such as potassium dihydrogen phosphate (KDP) crystal, quartz glass and so on [18-20]. Furthermore, some models have been established to predict the material removal rate on the optical component surface [21, 22]. Additionally, the error control and compensation method were proposed on fused silica mirror MRF process to obtain the high flatness based on the prediction models [23]. However, the MRF process on machining metal materials, especially the weak stiffness structures have not been investigated. The weak stiffness structure has a great difference with the optics component due to the sensitivity to the stress, and deformation will occur as the residual stress is relaxed unevenly. Hence, residual stress is an obstacle to achieve high flatness. An experiment was carried out to observe the deformation induced by residual stress with the initial flatness about 5 μm . To obtain the deformation caused by the stress relaxation, only the peak area was processed, and the deformation shown in Figure 1 is obvious on the whole surface rather than the peak area. Thus, the deformation influences the flatness after MRF process, and it should be analyzed to decrease the deformation.



(a)



(b)

Figure 1 Profiles (a) before and (b) after MRF

In this paper, an MRF process was applied to machining thin copper substrate. A finite element method (FEM) model was established to predict the deformation caused by residual stress. The deformation was evaluated by simulation with different material removal, and the MRF process can be optimized according to the simulation results. In the process, the polishing pressure is decreased to cut down the processing stress, which will suppress the deformation of the substrate. The optimized process parameters, including immersion depth, rotational speed of the polishing wheel, and material removal gap were obtained by a series of experiments. By this process, a thin copper substrate was machined, and the flatness was improved from 6.6 μm to 2.3 μm with the MRF process. Additionally, the residual stress was low in the surface.

2 Simulation model

Due to the weak stiffness of the substrate, deformation cannot be avoided in MRF process. Hence, a simulation was conducted to predict the deformation by stress relaxation. ABAQUS is employed as a solver in this paper since it could support user definition programs as input to define variables like residual stress. The simulation was performed on pure copper with Young's modulus (E) 119 MPa, and Poisson's ratio (ν) 0.3, which was machined by double-sided lapping, to evaluate the deformation caused by the stress relaxation, and the flow chart of simulation

was illustrated in Figure 2. An exemplary analogy part was designed based on a thin copper substrate sized $\Phi 100 \times 2.8$ mm as shown in Figure 3. According to stress distribution characteristics, the residual stress can be divided into two parts in the finite element model. The former is the residual stress in the surface induced by the double-sided lapping process which is -149 MPa and -135 MPa on x and y directions respectively, and the latter is the internal residual stress from annealing in Figure 4 obtained in our previous research. Because the residual stress was measured in an actual workpiece, no deformation happened on the workpiece after the stress introduction. To obtain the deformation caused by the stress relaxation during the process, the model was divided into 64 pieces to set the residual stress respectively. As boundary conditions, the middle element which is the central element of the 32nd piece was fixed, and the element will not deform by the stress after the material removal. In the model, the surface is assumed as an ideal flat, and the residual stress is distributed uniformly in each layer. Furthermore, the model meshed in two ways, which is refined mesh area on the surface, and the coarse mesh area in the body.

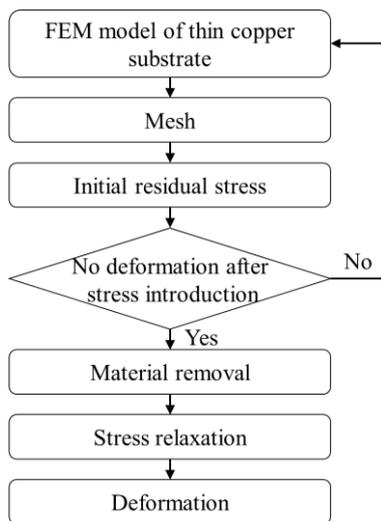


Figure 2 Flow chart of simulation

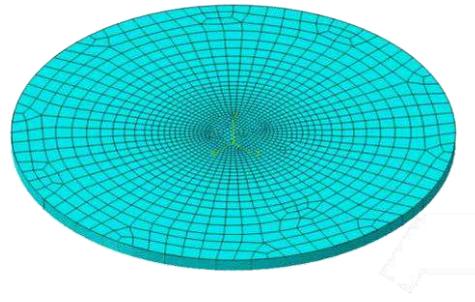


Figure 3 Thin copper substrate model

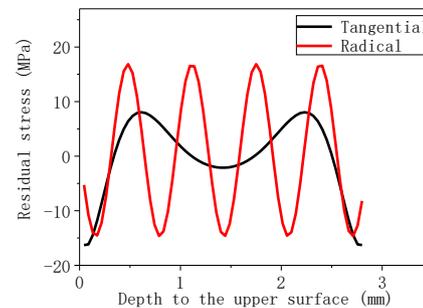


Figure 4 Initial residual stress distribution

Based on the FEM model, the technology of “element birth and death” was used to simulate the material remove process, and various material removal tendency is selected on different profiles. Due to the concave profiles after double-sided lapping, the material removal decreasing from the edge to the central area to modify the profile. Considering that the material is removed by abrasives in the slurry, the machining stress of the MRF process is ignored in the simulation. The material removal gap between the peak area and the low area is set from 1 μm to 5 μm respectively. The effect of initial residual stress and material removal on the deformation can be calculated. In the simulation, 5 loops are set on the surface, and the material removal is different on each loop.

3 Experimental

Pure copper was used as the workpiece material. Polishing force was measured by a force sensor Kisler 9109AA with response threshold less than 0.002 N for the drag and normal force sensors respectively on a $\Phi 100$ mm \times 10 mm

substrate as shown in Figure 5. With different parameters, the forces were measured during the spot experiments, which means polishing a fixed area on the workpiece under the condition of the wheel rotating around its axis and no feed motion. The pressure and the tangential force were measured simultaneously, because both forces influenced the machining stress after polishing. In the process, the immersion depth (d), which is the depth of the part immersed in the MR fluid ribbon, the ribbon height (h) and the rotational speed of the polishing wheel (rot) were optimized from the parameters listed in Table 1. The MR fluid consists of 30 wt. % carbonyl iron (CI) as the magnetic component, 13 wt. % of cerium oxide (CeO_2) as the abrasive, with the balance made up of deionized (DI) water and fluid stabilizers.

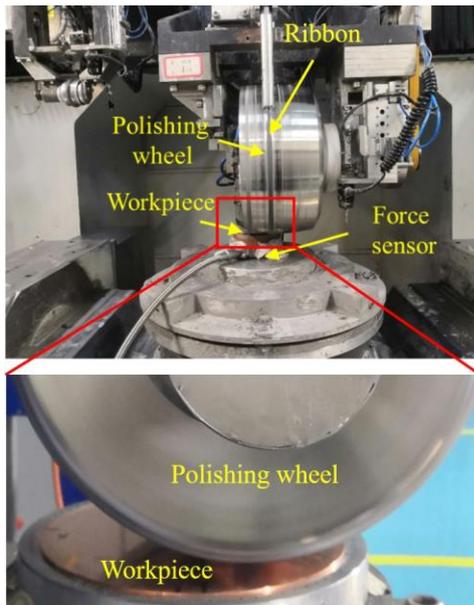


Figure 5 Setups of pressure measurement

Table 1 Experiment parameters

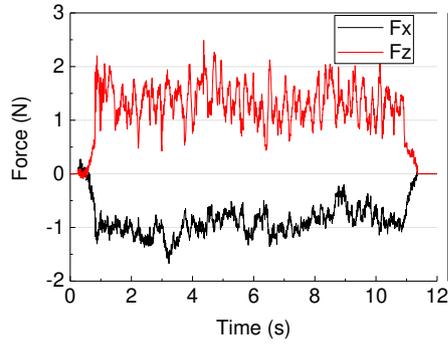
No.	d (mm)	rot (rpm)	h (mm)
1	0.2	160	1.3
2	0.3	160	1.3
3	0.4	160	1.3
4	0.2	100	1.3
5	0.3	100	1.3
6	0.4	100	1.3

The processing experiment with optimized parameters selected by the force measurement, was conducted to verify the simulation results on a $\Phi 100 \times 2.8$ mm workpiece. Before the MRF, the residual stress in the surface was distributed uniformly, and showed compressive stress with the value over 100 MPa. After the experiment, the residual stress was measured by Electronic Speckle Pattern Interferometry (ESPI) hole drilling method [24], and the flatness was measured by flatness measuring instrument (FlatMaster 200 by Corning Incorporated, New York, USA).

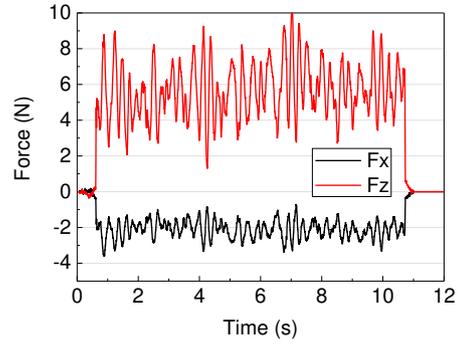
4 Results and discussion

4.1 Polishing pressure

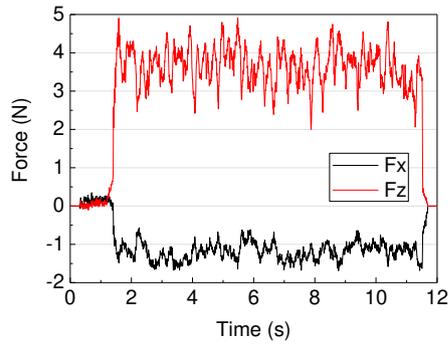
In the MRF process, the pressure and tangential force are two main factors influencing the material removal rate [25, 26], and the pressure may cause deformation of the thin copper substrate. Thus, to lower the pressure and tangential force, the experiments were conducted with different immersion depths and rotational speeds of the polishing wheel. Figure 6 shows the force time histories obtained during spot experiments using different immersion depth ranging from 0.2 to 0.4 mm, and different rotational speed of the polishing wheel. With the increase of the immersion depth, the normal polishing force increased from 1.5 N to 6 N, and the tangential force increased from 1 N to 2 N. With the decrease of the rotation speed, the normal polishing force and the tangential force increased respectively. With the larger immersion depth, the cutting depth was larger, thus, the pressure was increased obviously. On the other hand, for the rotational speed of the polishing wheel, it is inversely proportional to the pressure because of the changing of slurry shear rate. The slurry shear rate is inversely proportional to the pressure, and the slurry shear rate will increase with the rotational speed raising.



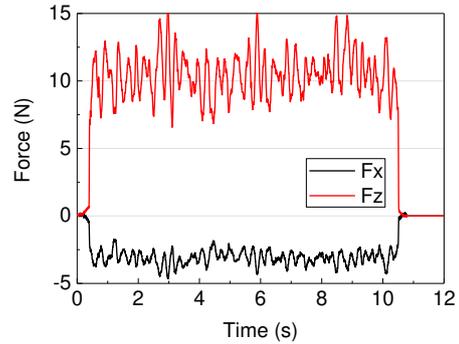
(a)



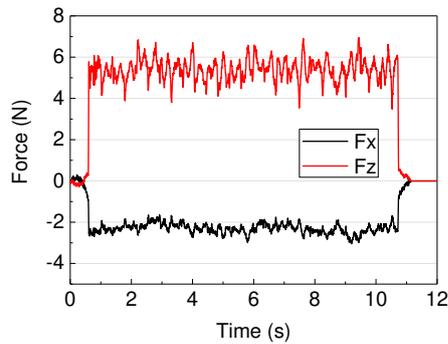
(d)



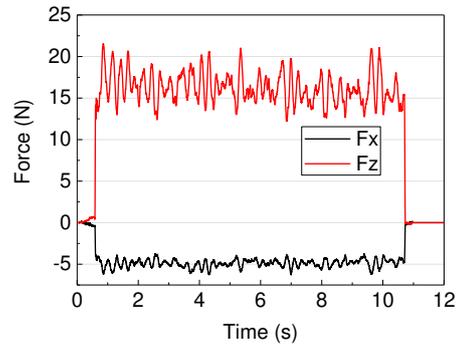
(b)



(e)



(c)



(f)

Figure 6 Pressure measurement with different immersion depths and rotation speed of the polishing wheel (a) $d=0.2$ mm, $rot=160$ rpm, (b) $d=0.3$ mm, $rot=160$ rpm, (c) $d=0.4$ mm, $rot=160$ rpm, (d) $d=0.2$ mm, $rot=100$ rpm, (e) $d=0.3$ mm, $rot=100$ rpm, (f) $d=0.4$ mm, $rot=100$ rpm

4.2 The MRF spot

The spot obtained on an ultra-flat surface is a key point in magnetorheological polishing for calculating the trajectory. Thus, a spot experiment was conducted on a copper workpiece with a dimension of $\Phi 30 \times 5$ mm by common MRF technology, and the flatness of the surface is about 1 μm . The workpiece was fixed on the machine, and spot polishing was conducted on the surface with the spotting time 4 s. Then, the removal function spot is obtained by subtraction of the initial and the machined surface profiles measured by a laser interferometer. The size of removal function spot always reflects the removal rate of the process, which is always proportional to pressure and tangential force. In the experiment, the rotational speed of polishing wheel is 160 rpm, and the immersion depth of 0.2 mm and 0.4 mm is employed. The results illustrated in Figure 7 reveal that the spot is larger with deeper immersion depth, and the material removal rate increases simultaneously.

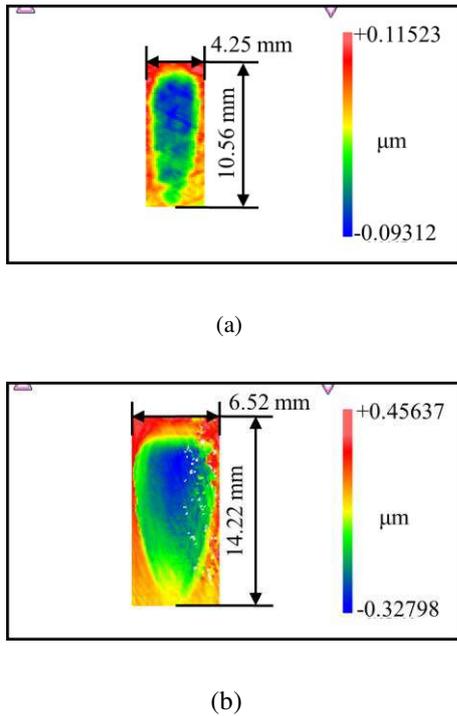


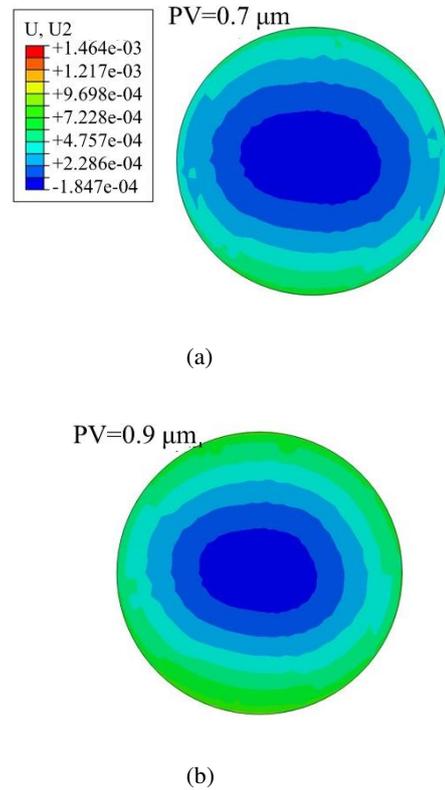
Figure 7 Removal function with different immersion depth (a) 0.2 mm, (b) 0.4 mm

4.3 Simulation results

Due to the concave and convex profiles after the

double-sided lapping process, the material was removed unevenly without machining stress in the simulation. According to the concave profiles, more material was removed in the center than the edge area. The deformation after the material removal with the gap 1 μm , 2 μm , 3 μm , 4 μm and 5 μm between the central and the edge was simulated. The simulation results of deformation were shown in Figure 8, considering the effect of residual stress. As can be seen from Figure 8, thin copper substrate appears concave deformation, with a law of generally symmetric distribution.

The deformation shown in the simulation results indicates that the deformation increases with the gap deepening. Thus, to achieve the requirement of flatness under 2 μm PV in precision physical experiment, a limitation is needed to control the deformation, and the limitation of deformation can be set as 1 μm , as the flatness under 1 μm can be easily obtained after MRF process. In the simulation, with gap depth 3 μm , the deformation is about 1 μm , while the deformation is about 1.3 μm with gap depth of 4 μm . Because the final flatness after the process is expected to about 2 μm , the gap with the depth 4 μm is not suitable in machining thin copper substrate.



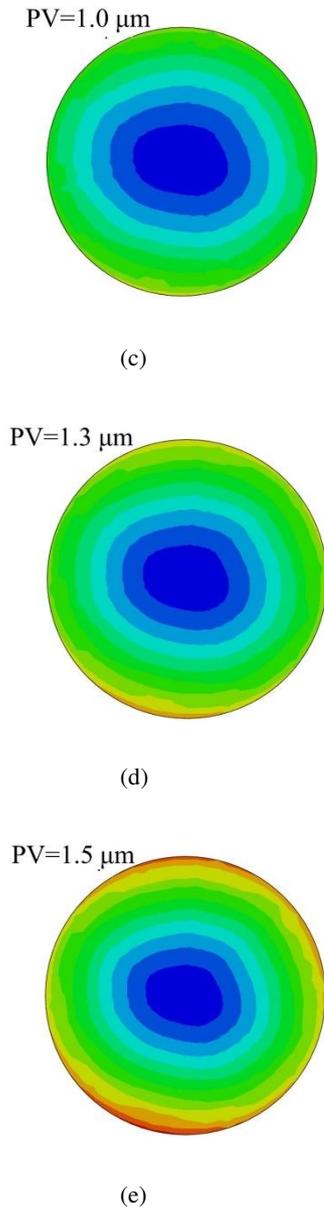


Figure 8 Deformation with different gaps. (a) 1 μm , (b) 2 μm , (c) 3 μm , (d) 4 μm and (e) 5 μm

4.4 Experimental results

The flatness was influenced by the material removal and the deformation of the workpiece. The material removal can be planned by the initial profile and the dwell time of the polishing wheel. The calculation profile based on the dwell time was illustrated in Figure 10 based on the initial profile shown in Figure 9, and the reduction of the PV is about 3.4 μm .

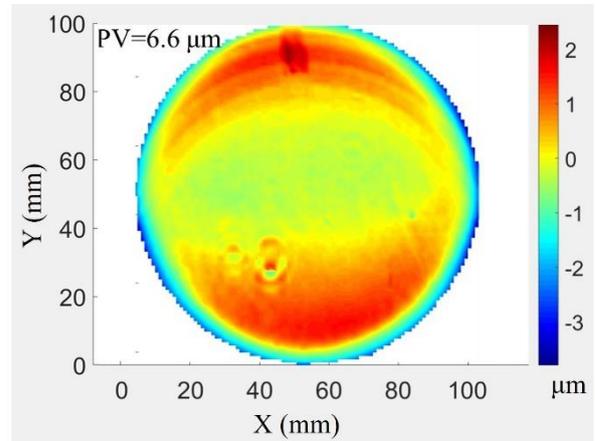


Figure 9 The initial profile of $\Phi 100$ mm substrate

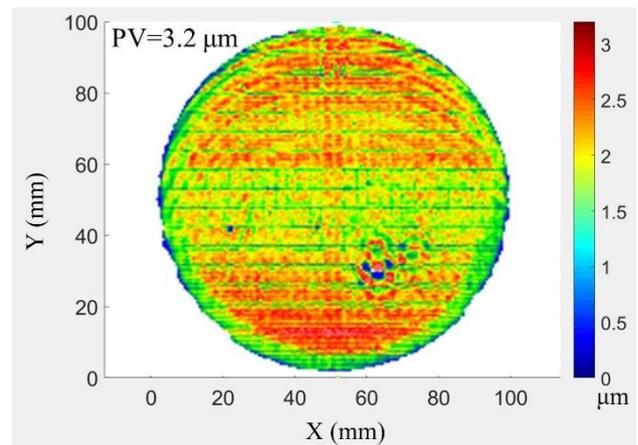


Figure 10 The calculation profile after MRF

The deformation of the workpiece is always caused by pressure and stress. In the process, the immersion depth of 0.2 mm was selected to verify the deformation obtained in the simulation. To avoid workpiece deformation, the annealing process was carried out before the MRF process to relax the internal stress, and the low pressure was selected in the polishing experiment. The results shown in Figure 11 revealed that the flatness was improved from 6.6 μm to 2.3 μm after MRF. During the process, the gap between the peak and valley area has been reduced by about 4 μm on the $\Phi 100 \times 2.8$ mm workpiece.

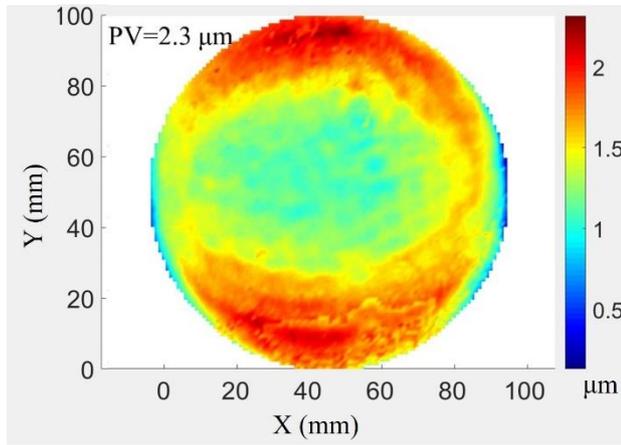


Figure 11 The profiles of $\Phi 100$ mm substrate after MRF

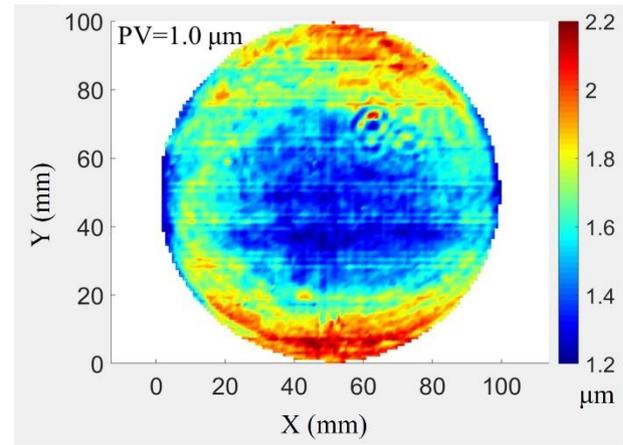
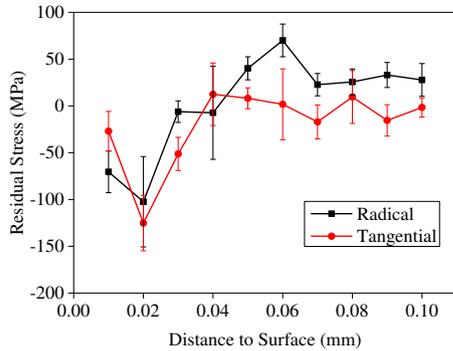


Figure 12 The deformation during MRF process

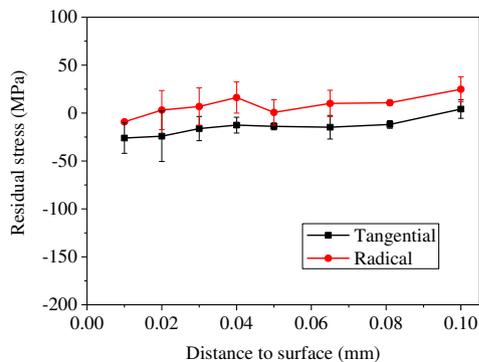
To verify the simulation results, the deformation after MRF process shown in Figure 12 is calculated by subtraction of the calculation (Figure 10) and the experimental results (Figure 11). The deformation is about $1.0 \mu\text{m}$ in the experiments with the material removal of about $3 \mu\text{m}$, and it agrees well with the simulation results which is about $1.0 \mu\text{m}$. Nevertheless, the profiles have small differences between the simulation and the experiment, which can be explained as follows. Firstly, the material removal on the workpiece is not the same in each loop, which will cause the deformation different after the process. Secondly, the residual stress in the initial surface is not the same in one layer, which could make the amount of the deformation different. Next, the ideal flat was assumed in the simulation, which would make a little error between the experiment and the simulation. Finally, the material removal in the simulation was considered as stress free process, while it is impossible in the experiment. Although the deformation profile is not same in the simulation and experiment, the convergence of the flatness is obvious, which shows the process available on finishing the thin copper substrate.

4.5 Residual stress after MRF

Residual stress in the surface is mainly caused by machining stress, which should be evaluated after the optimization of the polishing force. In the process, the residual stress layer was removed, and the residual stress combined with residual machining stress and the internal stress relaxation is left in the surface. The residual stress was measured in five random locations on the surface. In the Figure 13 (b), the radial direction is the polishing direction, and the tangential direction is perpendicular to the polishing direction. The results measured by ESPI hole drilling method with the accuracy ± 20 MPa in Figure 13 showed that the residual stress after MRF was similar to the chemical mechanical polishing surface, which can be considered as a stress free surface. Comparing with the initial residual stress, the internal stress was relaxed, and the introduction of the machining stress is low after MRF because the material is removed by the abrasives in the slurry, which is not a rigid tool. Furthermore, the residual stress in the surface can reflect the combination of machining stress and internal stress. Thus, the uneven material removal has little effect on the internal stress relaxation and machining stress introduction after the parameter optimization.



(a)



(b)

Figure 13 Residual stress in the surface (a) before MRF, (b) after MRF

5 Conclusions

The feasibility of MRF process on thin copper substrate finishing was demonstrated in this paper. To suppress the deformation of the substrate, the polishing pressure was adjusted to lower the machining stress, and the simulation was conducted to calculate the deformation. The simulation results were verified by the experiments. The major conclusions are summarized as follows:

- (1) The MRF process with low stress is feasibly on machining the thin copper substrate.
- (2) The deformation after MRF can be well predicted by simulation.
- (3) The flatness was improved from 6.6 μm to 2.3 μm on

$\Phi 100 \times 2.8$ mm substrate.

The MRF process is able to improve the flatness, and the residual stress in the surface is low. Future work will be focused on the deformation prediction after MRF process on larger substrates.

6 Declaration

Funding

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Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

The author' contributions are as follows: Jinag Guo, Renke Kang and Wen Huang were in charge of the whole trial; Bo Pan wrote the manuscript; Yunfei Zhang, Kailong Li, Dongxing Du, Bin Wang, Chao Wang and Xianglong Zhu assisted with sampling and laboratory analyses.

Competing interests

The authors declare no competing financial interests.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

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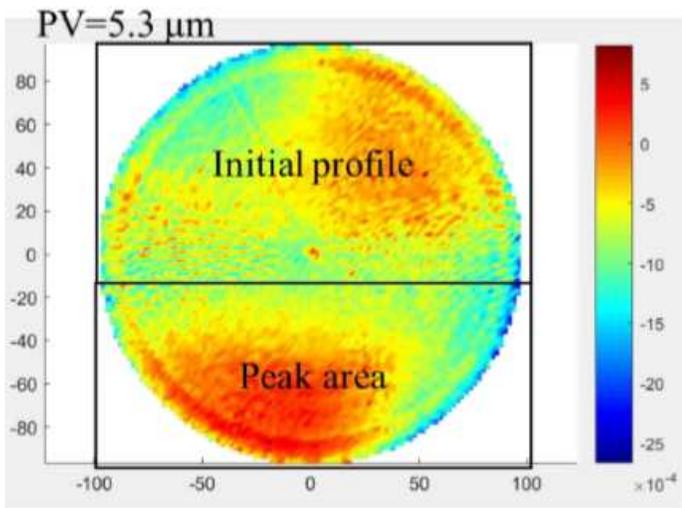
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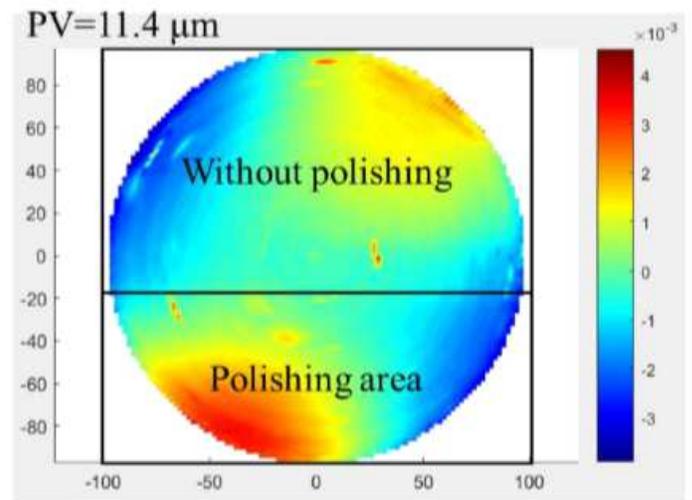
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Figures



(a)



(b)

Figure 1

Profiles (a) before and (b) after MRF

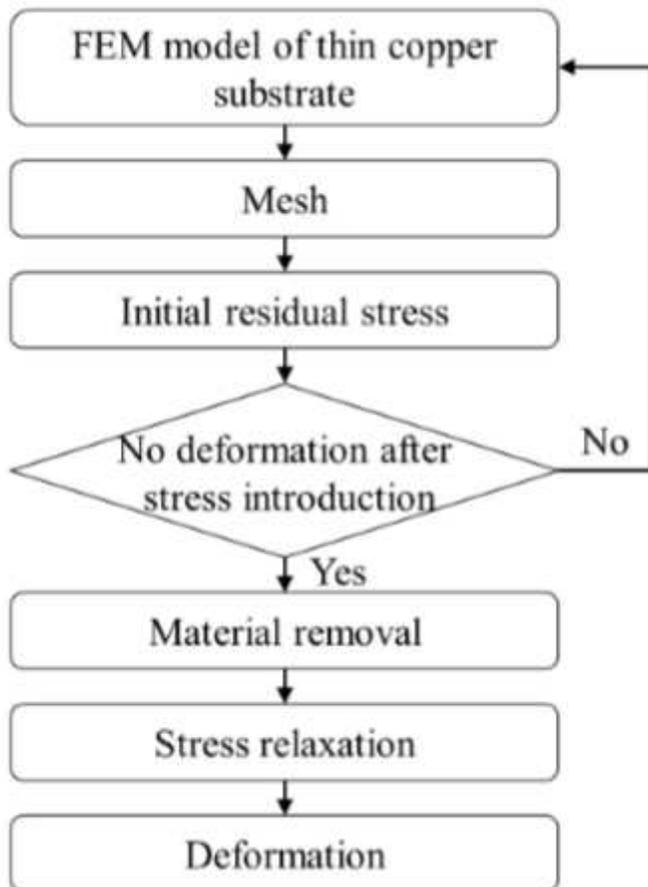


Figure 2

Flow chart of simulation

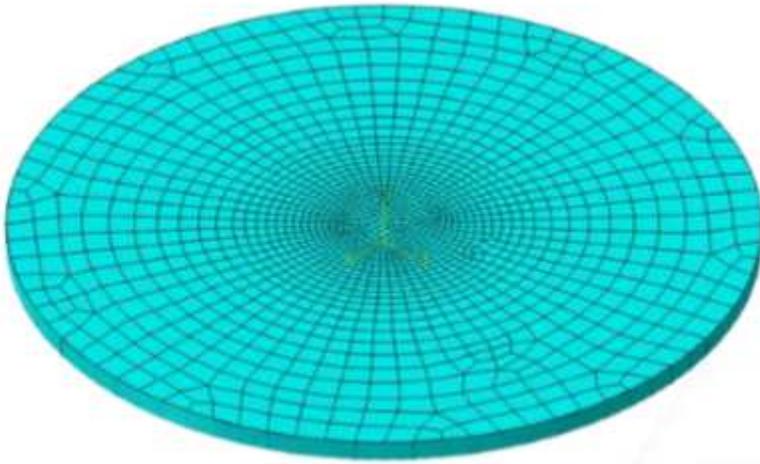


Figure 3

Thin copper substrate model

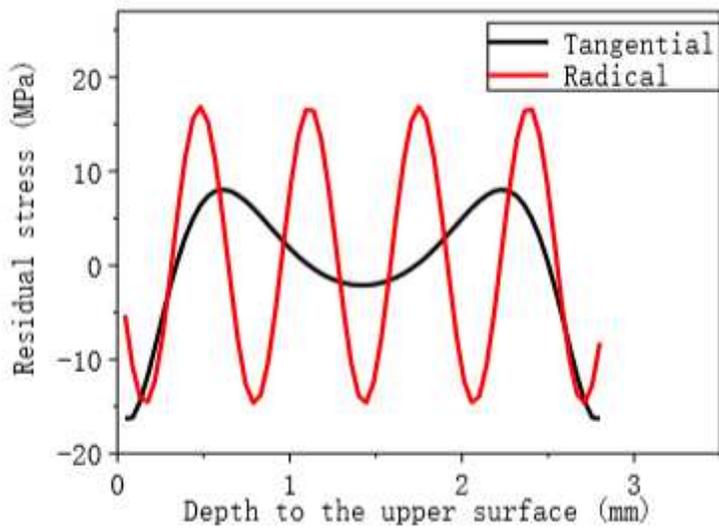


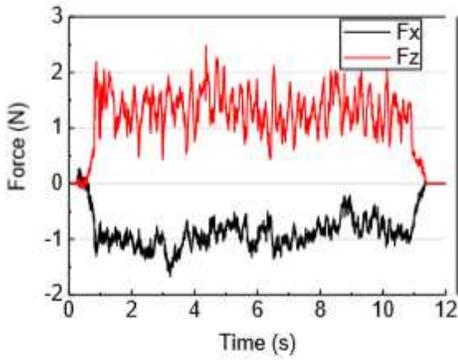
Figure 4

Initial residual stress distribution

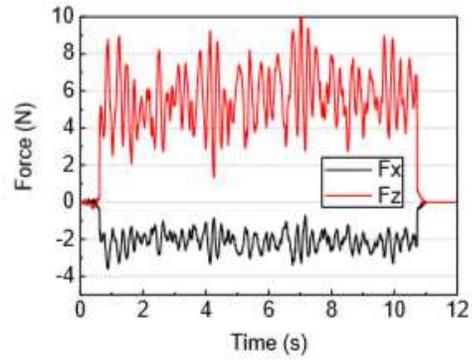


Figure 5

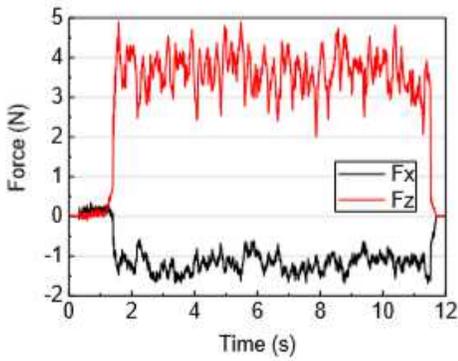
Setups of pressure measurement



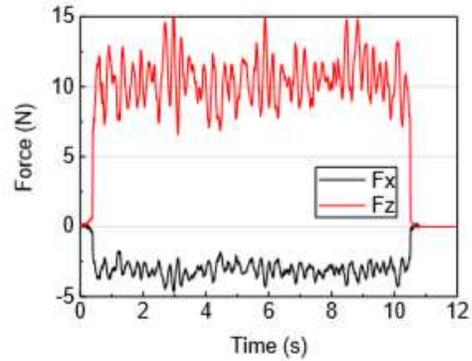
(a)



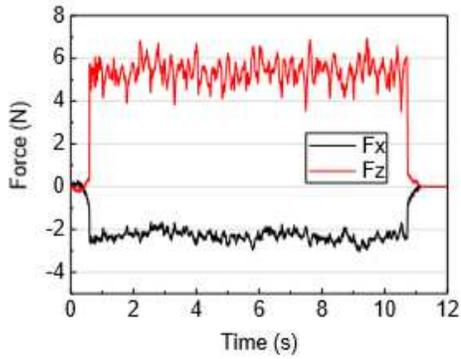
(d)



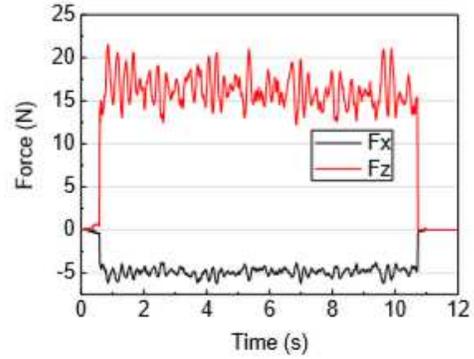
(b)



(e)



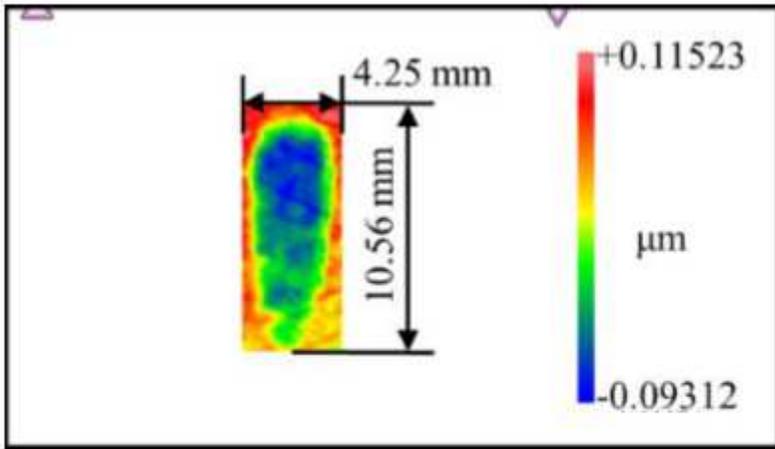
(c)



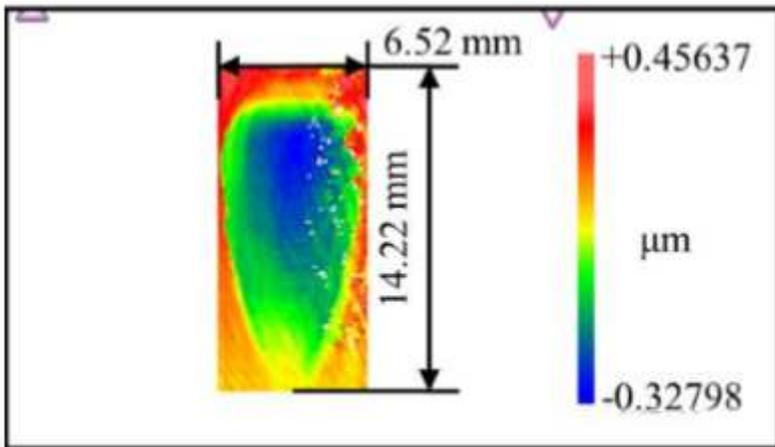
(f)

Figure 6

Pressure measurement with different immersion depths and rotation speed of the polishing wheel (a) $d=0.2$ mm, $rot=160$ rpm, (b) $d=0.3$ mm, $rot=160$ rpm, (c) $d=0.4$ mm, $rot=160$ rpm, (d) $d=0.2$ mm, $rot=100$ rpm, (e) $d=0.3$ mm, $rot=100$ rpm, (f) $d=0.4$ mm, $rot=100$ rpm



(a)



(b)

Figure 7

Removal function with different immersion depth (a) 0.2 mm, (b) 0.4 mm

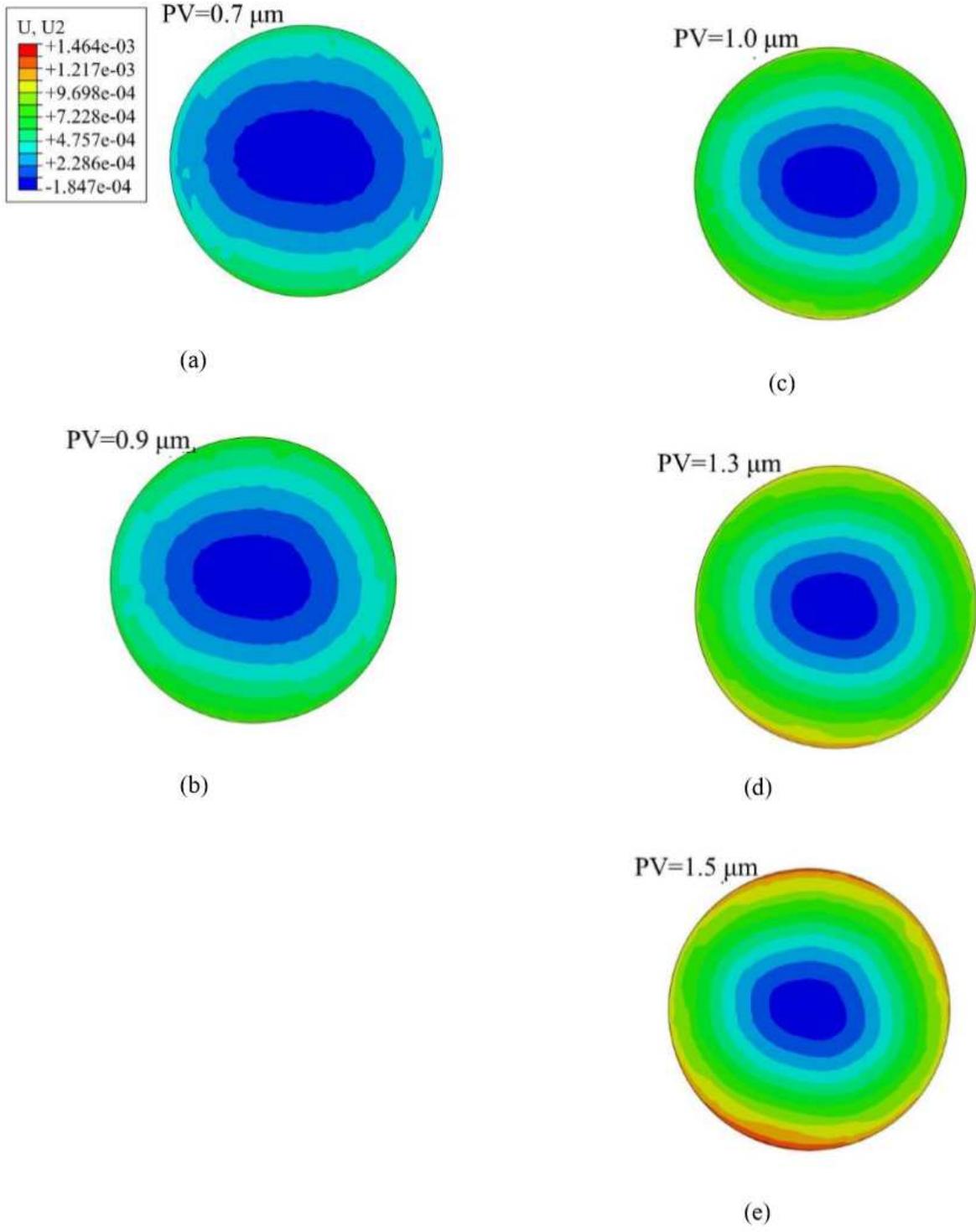


Figure 8

Deformation with different gaps. (a) 1 μm , (b) 2 μm , (c) 3 μm , (d) 4 μm and (e) 5 μm

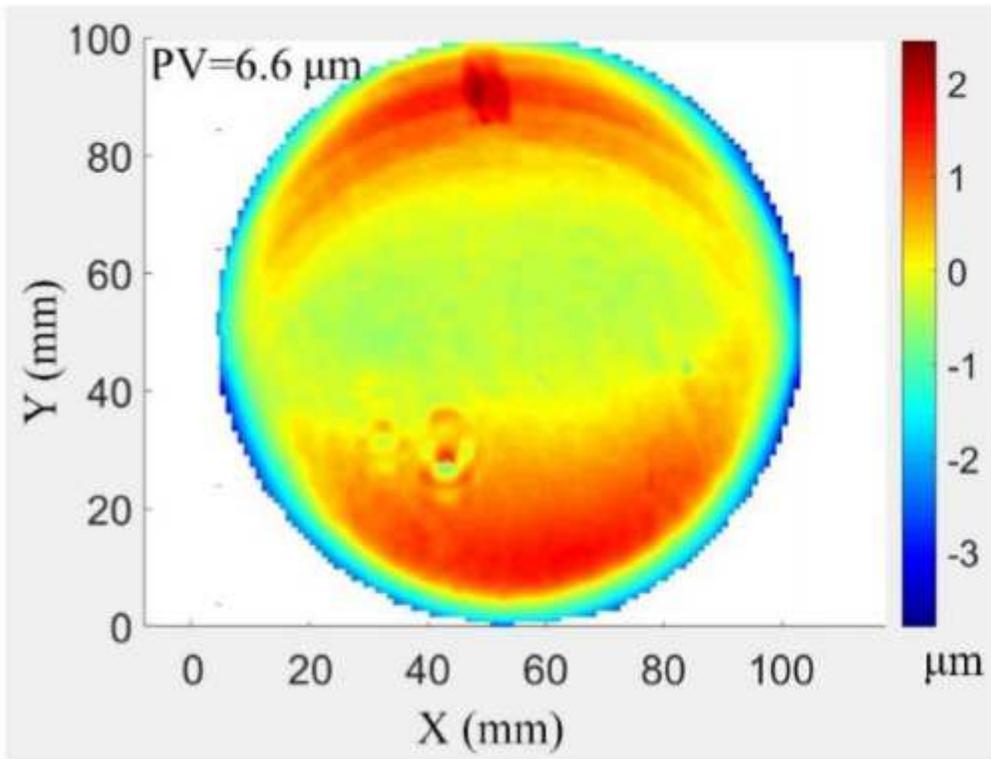


Figure 9

The initial profile of $\Phi 100$ mm substrate

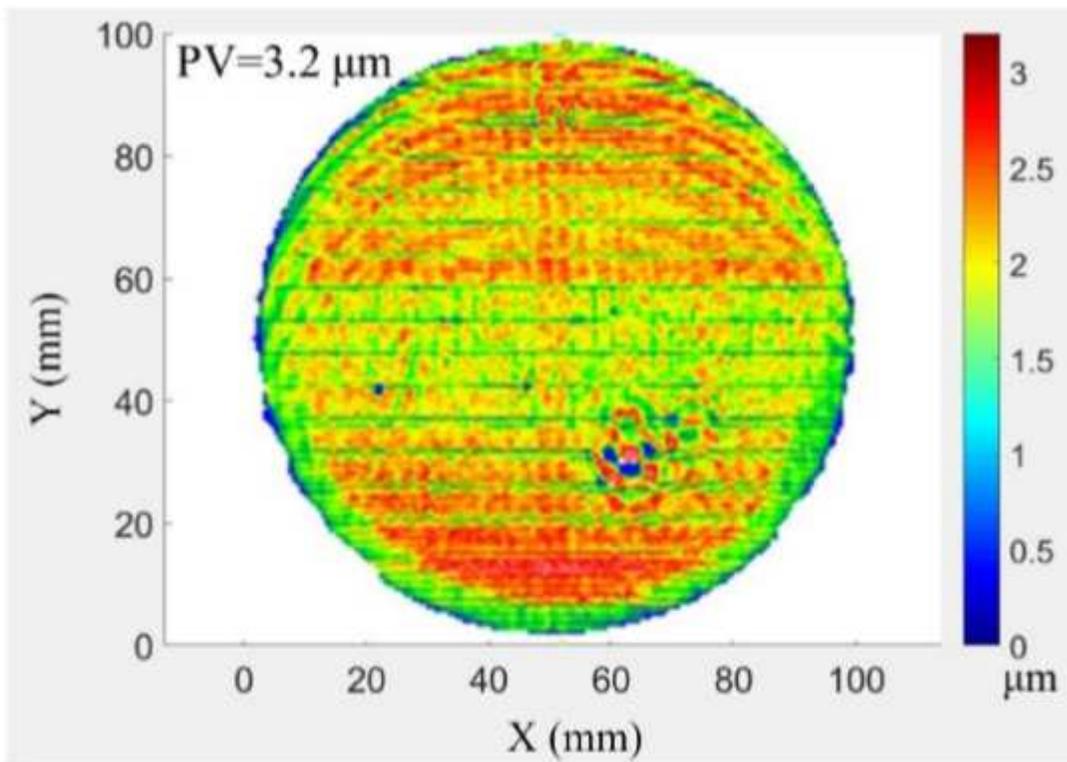


Figure 10

The calculation profile after MRF

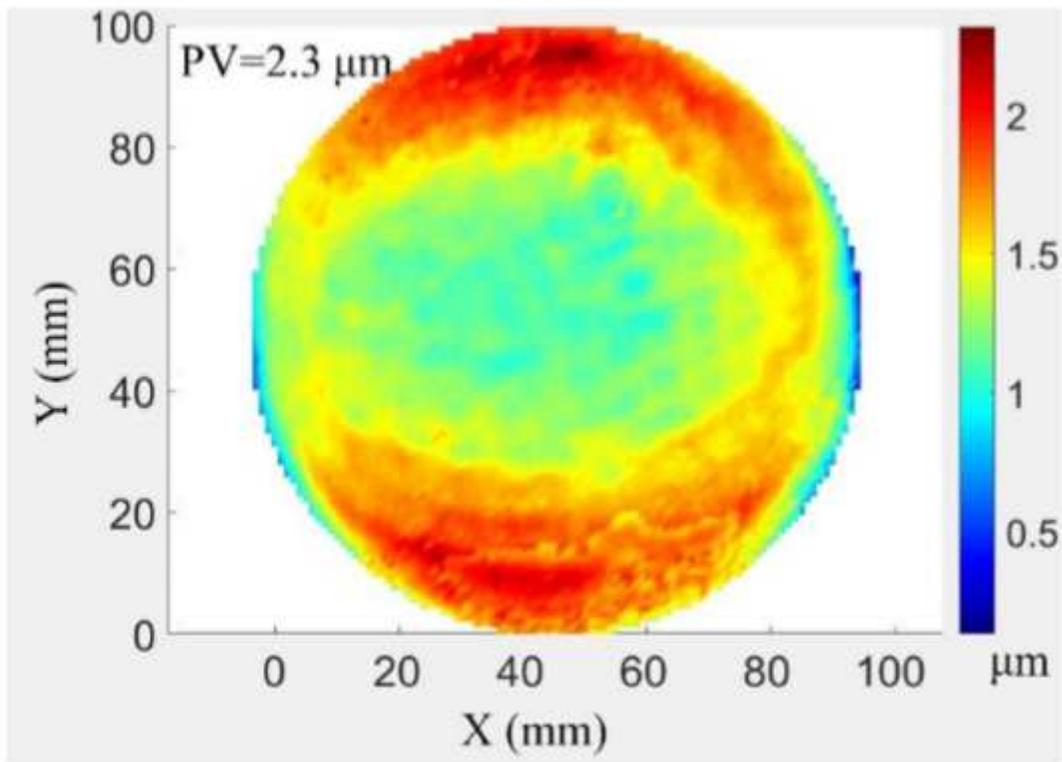


Figure 11

The profiles of $\Phi 100$ mm substrate after MRF

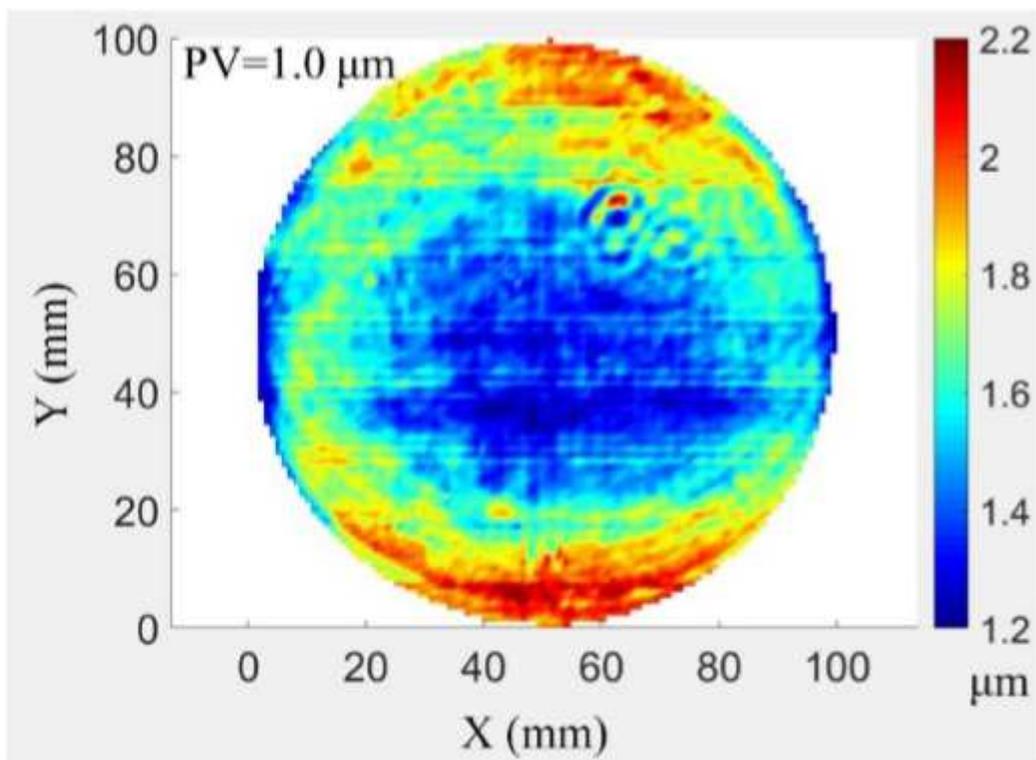
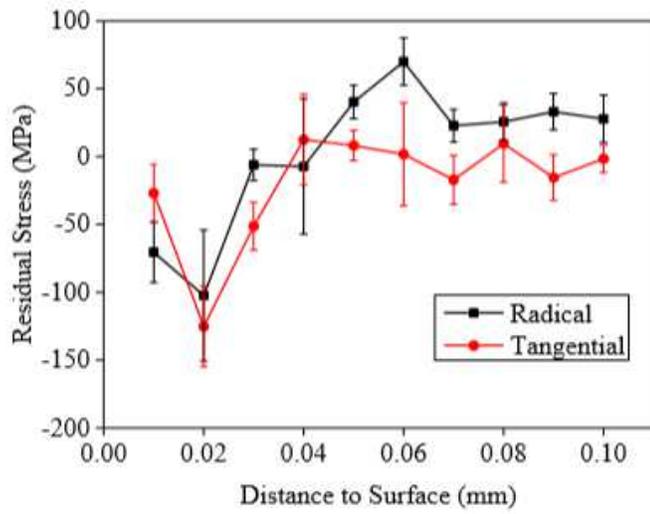
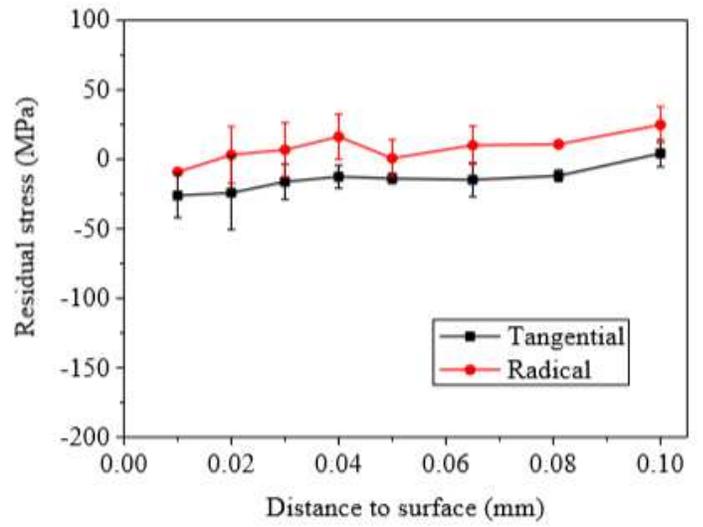


Figure 12

The deformation during MRF process



(a)



(b)

Figure 13

Residual stress in the surface (a) before MRF, (b) after MRF