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# Stress-Induced Deformation of Thin Copper Substrate in Double-Sided Lapping

Jiang Guo<sup>1</sup>, Zengxu He<sup>1</sup>, Bo Pan<sup>1</sup>, Bin Wang<sup>1</sup>, Qian Bai<sup>1</sup>, Jinxing Kong<sup>2</sup> and Renke Kang<sup>1\*</sup>

## Abstract

Double-sided lapping is an precision machining method capable of obtaining high-precision surface. However, during the lapping process of thin pure copper substrate, the workpiece will be warped due to the influence of residual stress, including the machining stress and initial residual stress, which will deteriorate the flatness of the workpiece and ultimately affect the performance of components. In this study, finite element method (FEM) was adopted to study the effect of residual stress-related on the deformation of pure copper substrate during double-sided lapping. Considering the initial residual stress of the workpiece, the stress caused by the lapping and their distribution characteristics, a prediction model was proposed for simulating workpiece machining deformation in lapping process by measuring the material removal rate of the upper and lower surfaces of the workpiece under the corresponding parameters. The results showed that the primary cause of the warping deformation of the workpiece in the double-sided lapping is the redistribution of initial residual stress caused by uneven material removal on the both surfaces. The finite element simulation results were in good agreement with the experimental results.

**Keywords** Machining deformation, Double-sided lapping, Residual stress, Finite element simulation

## 1 Introduction

High-precision pure copper substrates and wafers are indispensable materials for precision physical experiments and ultra-large-scale integration (ULSI) because of their excellent electrical conductivity and other physical properties [1, 2]. As a difficult-to-cut material, there are many problems in using traditional processing methods [3]. Therefore, double-sided lapping has gradually been proposed to become one of the key processing methods in precision machining due to its high removal rate, excellent flatness, high parallelism and symmetrical stress introduction [4, 5]. However, since the pure copper thin substrates are sensitive to stress, the performance

stability of precision parts will be affected [6] and warping deformation may occur during the processing, resulting in deterioration of workpiece flatness.

Some research showed that the factors causing workpiece deformation are related to the existence of initial residual stress and the introduction of machining stress [7, 8]. For the processing deformation caused by stress, the most researches at present are mainly focused on turning and milling processes. Huang et al. studied the influence of initial residual stress and machining stress on the deformation of the monolithic component. And the finite element model was established to predict the machining deformation. It was concluded that the deformation caused by the machining stress accounted for about 10% of the total deformation of the part, and the deformation caused by the initial residual stress of the blank accounts for about 90% [9]. Gao et al. established a numerical analysis model which only considered the deformation caused by the initial residual stress of the workpiece. The model was validated by finite element simulation and experiment [10]. By verifying the

\*Correspondence:

Renke Kang  
kangrk@dlut.edu.cn

<sup>1</sup> State Key Laboratory of High-Performance Precision Manufacturing, Department of Mechanical Engineering, Dalian University of Technology, Dalian 116024, China

<sup>2</sup> Institute of Mechanical Manufacturing Technology, China Academy of Engineering Physics, Mianyang 621999, China

influence of different processing strategies on the deformation, it was concluded that symmetrical or semi-symmetrical processing was beneficial to reduce the deformation [11]. Masoudi et al. studied the effects of machining force, temperature, stress distribution, and work piece thickness on deformation in turning thin-walled workpiece made of Al7075-T6 alloy [12]. Young et al. obtained the relationship between tool parameters and machining residual stress when milling 7050-T7451 aluminum alloy and the influence of relevant influencing factors on machining deformation [13]. Gao et al. established a semi-analytical model to study the influence of initial stress on thin-walled part and clarified the deformation principal [14]. Nervi et al. conducted experimental research on aluminum alloys. It was concluded that when the thickness of the workpiece was smaller, the degree of processing deformation was positively related to the processing residual stress [15]. Cerutti et al. considered the influence of fixture, processing sequence and other factors in the processing of aeronautical parts and established the finite element prediction model of processing deformation, which provided the basis for optimizing the process [16, 17]. For the study of the acquisition method of machining stress, Zhang et al. proposed a new method for predicting deformation caused by surface processing stress in finite element models. Compared with the mapping method, the new method based on equivalent force method took less computer resources and greatly improved computational efficiency [18]. However, few studies have been reported on the prediction of machining deformation in lapping.

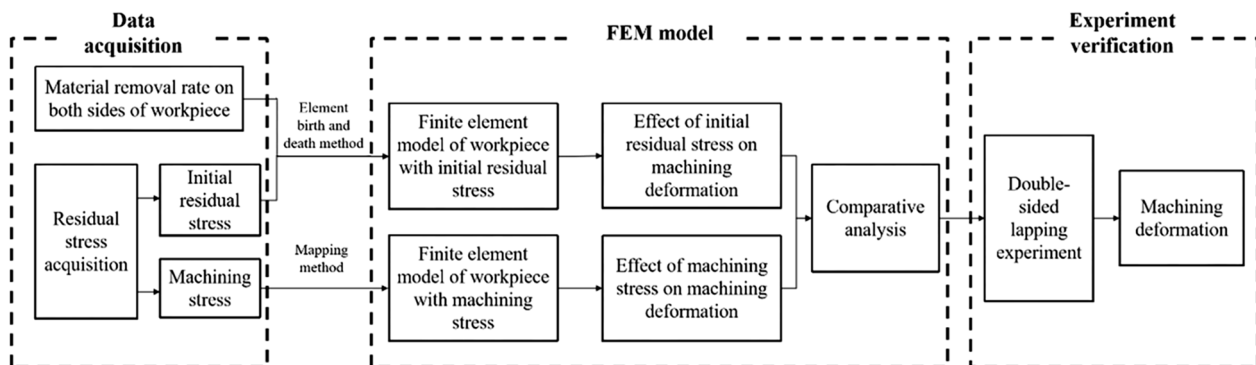
This paper introduces a novel deformation prediction approach in double-sided lapping using finite element model. The effects of initial residual stress, machining stress and their distribution characteristics on the deformation of thin copper substrate during lapping are considered respectively. The initial data used in the finite

element model of deformation prediction were obtained through experiments. The double-sided lapping process was simulated by the element birth and death method and the mapping method to predict the deformation of workpiece. The simulation results showed that the primary cause of the warping deformation of the workpiece in the double-sided lapping is the redistribution of initial residual stress caused by uneven material removal on the both surfaces. The prediction approach is verified by a double-sided lapping experiment.

## 2 Methodology

For thin copper substrate, the deformation is sensitive to stress during the double-sided lapping process. In order to predict the deformation of the workpiece, the finite element method is used to study the effects of initial residual stress and machining stress [19]. The initial residual stress is measured by hole-drilling method. And, the machining stress is calibrated by X-ray diffraction (XRD), which is a usual nondestructive method [20] and can't gauge internal stress of the workpiece directly. Both stress has no striking differences on measuring results under such depth in our experiments [21]. The procedure of deformation analysis in double-sided lapping is as shown in Figure 1. Firstly, the initial data used in the simulation including initial residual stress, machining stress and material removal rate need to be acquired by experiments.

After that, a finite element model was established to study the effects of residual stress on deformation of the workpiece. For initial residual stress, the redistribution of residual stress after double-sided lapping will lead to deformation of the workpiece. To study the effect of initial residual stress, the state of initial residual stress of workpiece needs to be introduced into the finite element model. In the finite element model, the workpiece is divided into several layers along the thickness direction.



**Figure 1** Schematic illustration of procedure of deformation analysis in double-sided lapping

The average values of the measured initial residual stresses along different thicknesses are introduced into the corresponding layers. The material removal process was simulated using element birth and death method based on the material removal rate in the double-sided lapping. Considering the simulation time and accuracy, the mesh in the processing area is refined, while the mesh in the non-processing area is sparse. The influence of material removal on the workpiece deformation is illustrated by non-equal surface material removal. After the material is removed, the deformation of the workpiece caused by redistribution of initial residual stress can be obtained by finite element analysis. For machining stress, it usually exists on the surface of workpiece after double-sided lapping, which is difficult to obtain directly. Therefore, this paper uses the mapping method to obtain the processing stress required in the finite element model indirectly. In the method, the thicker workpiece is machined by the same process, and the deformation after the process is ignored due to the strong rigidity of the workpiece. Then, the residual stress is evaluated in the surface, and it can be considered as the machining stress of the process. In order to study the effect of machining stress on workpiece deformation, only the machining stress on the surface of workpiece obtained through the above methods is introduced into the finite element model. The effects of uniformity of processing stress on the same surface is considered by introducing processing stress through sub-regions. The deformation of the workpiece caused by machining stress can be obtained through finite element analysis.

Finally, after introducing residual stress into model and performing material removal with element birth and death method, the deformation of the workpiece could be predicted and the accuracy of the proposed prediction approach for workpiece deformation was also verified by the double-sided lapping experiment.

### 3 Data Acquisition

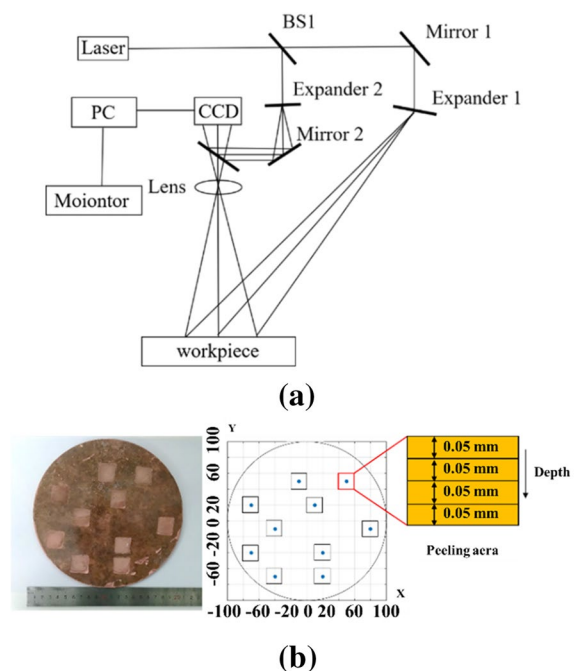
#### 3.1 Initial Residual Stress

To predict the effect of initial residual stress on workpiece deformation, the initial residual stress state of the workpiece needs to be obtained and introduced into the finite element software as an initial condition. The acquisition process of thin copper sample for double-sided lapping including rolling, annealing, turning, annealing, in which the two annealing treatments are to reduce the residual stress. In order to obtain the initial residual stress of the workpiece, the stripping method combined with the electronic speckle pattern interferometry hole-drilling method (PRISM by Stresstech Oy, Vaajakoski, Finland) was used to measure the original residual stress [21, 22]. To get the average stress on the whole surface,

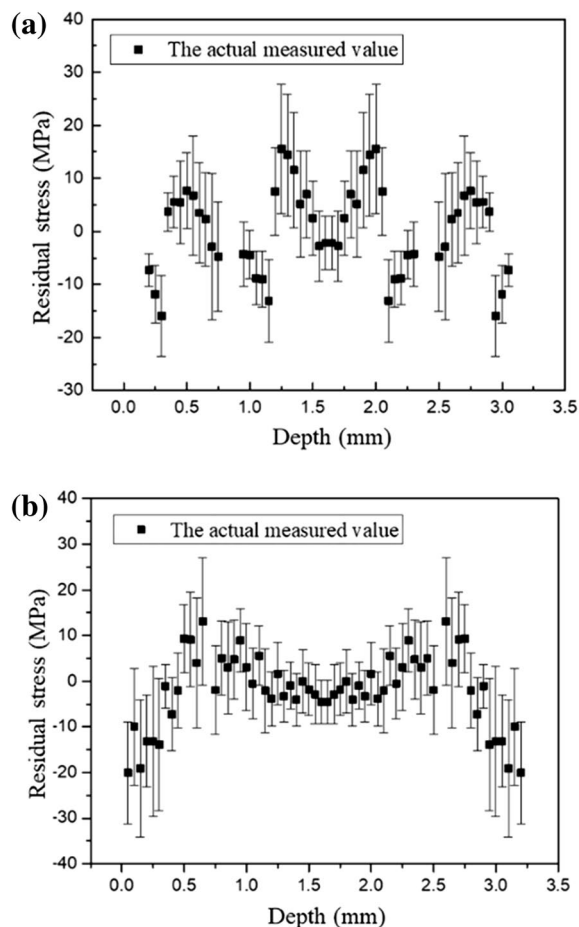
10 positions were selected randomly on the workpiece for peeling. Because the workpiece is manufactured by rolling and turning methods symmetrically, the residual stress distributes symmetrically along the  $Z$  direction. The measuring principle and method are as shown in Figure 2 [23]. Initial residual stress distribution along the  $X$  and  $Y$  direction of the workpiece is presented in Figure 3.

#### 3.2 Machining Stress

Similar to the initial residual stress, the acquisition of machining stress is a prerequisite for finite element simulation. During the machining process, external factors such as force and temperature will lead to additional machining stress [24, 25]. Generally, there are two ways to obtain processing stress. 1) Through the finite element simulation of the machining process, the machining stress state is obtained. For milling and turning, the finite element simulation of the machining process is easy. However, due to the random position distribution and the varied shape and size of the abrasive particles during grinding process [26], the double-sided lapping process is complicated, which is difficult to establish a finite element simulation. 2) Obtain the machining stress state through experiments. However, it is difficult to measure the machining stress directly due to the machining stress release in low-rigidity workpiece after double-sided lapping process. Therefore, the mapping method has been proposed and gradually applied



**Figure 2** (a) Measuring principle of PRISM [22] and (b) method

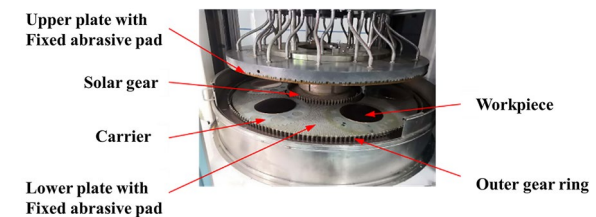


**Figure 3** Initial residual stress thickness direction distribution in pure copper thin substrate: (a) Y direction, (b) X direction

to the study of machining deformation. Residual stress results of simple and thicker workpiece can be obtained by experiment or simulation, which can be mapped to more complex actual workpiece to derive the effect of machining stress on the actual workpiece [27, 28]. Therefore, this paper chose pure copper component with  $\Phi 200 \text{ mm} \times 7 \text{ mm}$  which had been subjected to multiple heat treatments to reduce the initial residual stress, mapped the residual stress results of the workpiece to the workpiece with 3.2 mm thickness, to obtain the influence of the machining stress on the deformation under the relevant processing parameters.

Double-sided lapping was carried out on the double-sided lapping machine (YJ-6B5LA & YJ-6B5LC by Yujing Machinery Co., Ltd., Hunan, China) shown in Figure 4. The experimental parameters are shown in Table 1.

Because the stress was uniformly distributed in the surface and the depth of the stress layer is small (about 20  $\mu\text{m}$ ) [4], the residual stress of the machined surface is



**Figure 4** Experiment setups

measured by XRD ( $\mu\text{-X360s}$  by Pulstec, Japan). The position of measurement and results are shown in Figure 5.

### 3.3 Double-Sided Removal Rate

In order to simulate the actual machining process, it is necessary to obtain the material removal rate of the upper and lower surfaces of the workpiece. In the process of double-sided lapping, the removal rate of workpiece is related to the processing parameters, and the removal rate of upper and lower surfaces of workpiece is also different, so it is necessary to measure the removal rate of double-sided lapping under the corresponding parameters [29, 30]. As the removal amount is small, the confocal microscope is used for measurement. The difference before and after lapping is the material removal values of corresponding parameters, as shown in Figure 6. The measurement positions and results are shown in Figure 7. As can be seen from Figure 7(b), the material removal rate on the upper and lower surfaces is close to 2:1 under the experimental conditions in Table 1.

## 4 Simulation Results

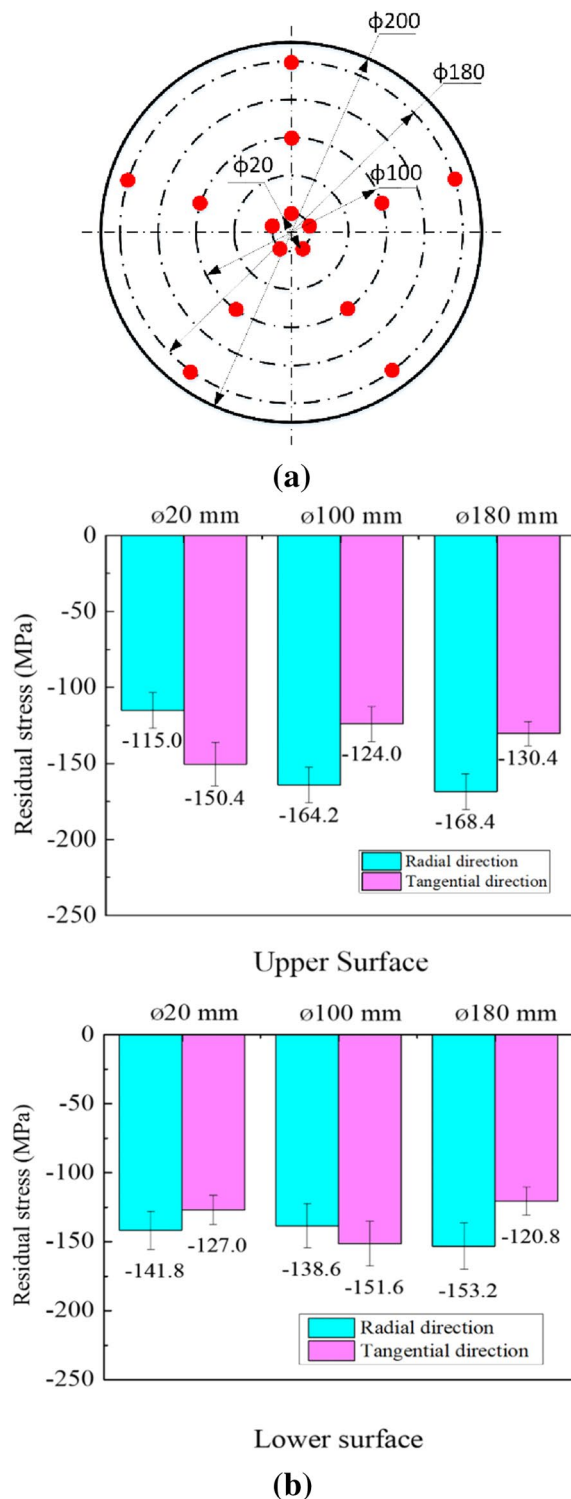
### 4.1 Double-Sided Removal Rate

In order to investigate the effect of initial residual stress on machining deformation, a finite element simulation was performed using commercial software ABAQUS. In the simulation, the workpiece model is a thin copper sheet of  $\Phi 200 \text{ mm} \times 3.2 \text{ mm}$ , and its mechanical properties are shown in Table 2. The initial residual stresses in Figure 3 are introduced into the workpiece model using a predefined field. Considering the processing time, based on material removal rate of 2: 1 between the upper and

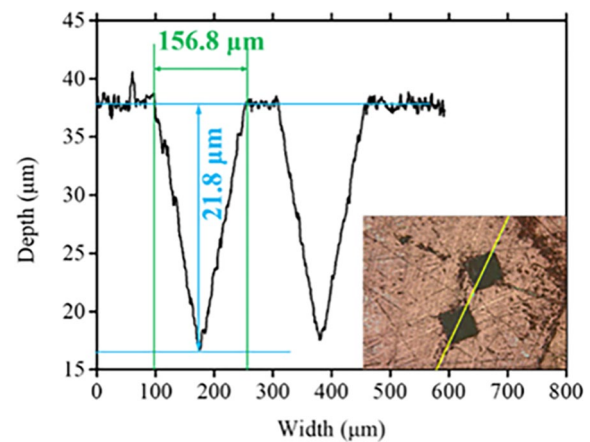
**Table 1** Experiment conditions

Machine	Pressure (psi)	Upper plate rotation speed (r/min)	Lower plate rotation speed (r/min)	Slurry	Processing time (min)
Double-sided lapping	1.5	40	40	Water	30





**Figure 5** (a) The position of measurement and (b) results



**Figure 6** Indentation shape measurements

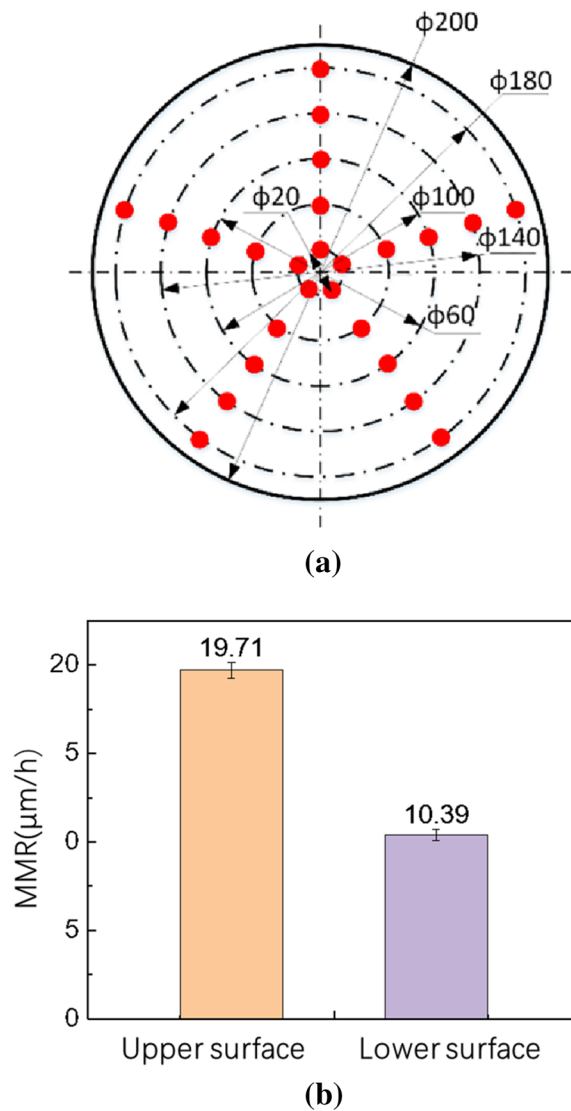
lower surfaces, the removal simulation was performed on the workpiece using element birth and death method to process the workpiece to 3.05 mm. To make the model easier, the model is based on several assumptions: (1) The initial residual stresses are uniformly distributed in each layer of the surface; (2) The workpiece surface is an ideal flat; (3) The material removal on the same surface is uniform; (4) The machining stress introduction is ignored during the material removal.

The element type of the mesh set in the FEM is C3D8R, with a total of 112896 elements and 119136 nodes. In order to ensure that the workpiece can be deformed freely without rigid movement, the five nodes at the center of the workpiece, which are more evenly distributed, are selected as fixed constraints. The meshing situation and the position of five fixed constrained points are as shown in Figure 8.

After the material is removed, the initial residual stress is redistributed, and the deformation simulation results are shown in Figure 9.

In order to study the influence of material removal on the deformation of workpiece, the above finite element model was simulated by equal removal of upper and lower surface materials. The workpiece was processed to 3.15 mm by the method of element birth and death according to the material removal rate of 1:1 on upper and lower surface. The deformation simulation results are shown in Figure 10.

Figure 9 is a deformation diagram of the machining process after considering only the influence of the initial residual stress with uneven material removal

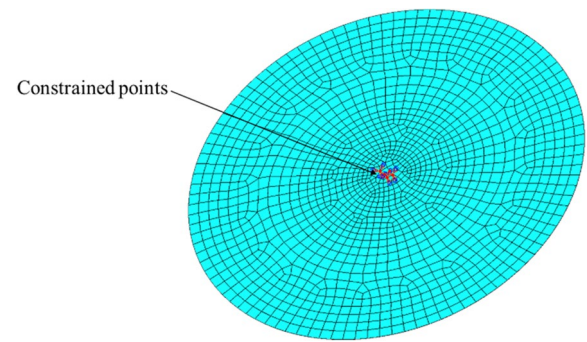


**Figure 7** (a) Measuring positions and (b) results

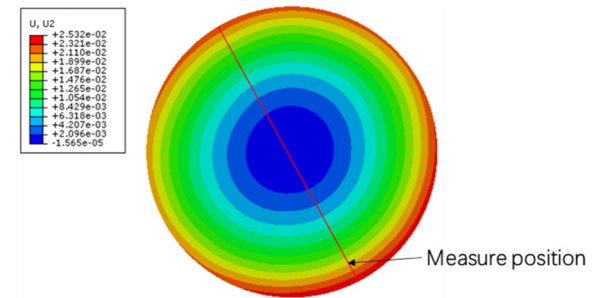
**Table 2** The main mechanical properties of the thin copper sheet

Parameter	Value
Young's modulus (MPa)	119000
Poisson's ratio	0.34
Density ( $\text{kg/m}^3$ )	8960

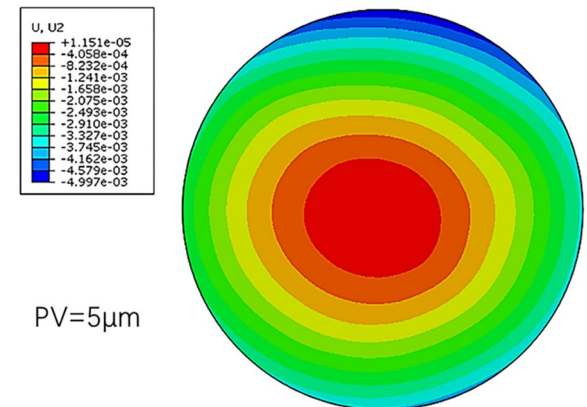
of upper and lower surfaces. It can be seen that the workpiece undergoes symmetrical warping deformation, and the maximum deformation of the workpiece occurs at the edge of the workpiece, and the maximum deformation is 25.32  $\mu\text{m}$ . It can be seen from Figure 10



**Figure 8** The meshing situation and the position of five fixed constrained points in the middle layer



**Figure 9** Deformation finite element simulation result with uneven material removal of upper and lower surfaces



**Figure 10** Deformation finite element simulation result with even material removal of upper and lower surfaces

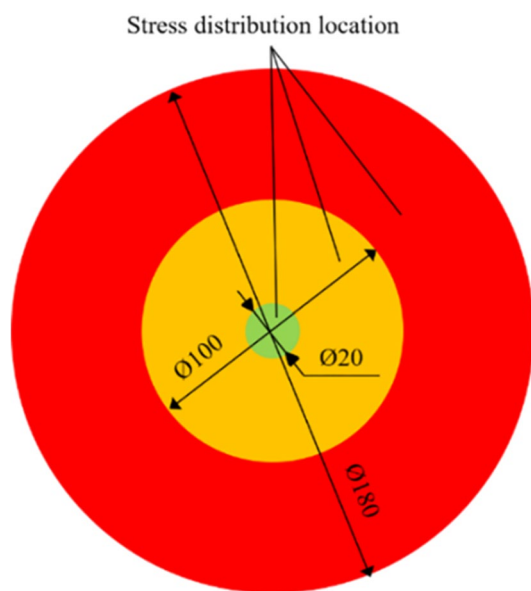
that the maximum deformation of the workpiece is only 5.00  $\mu\text{m}$  with the uniformly material remove of the upper and lower surface. Because the material is removed uniformly, the residual stress can be released

uniformly which has little effect on the deformation of the workpiece. However, due to the uneven removal of the upper and lower surface materials during double-sided lapping, the redistribution of initial residual stress results in warpage of the workpiece.

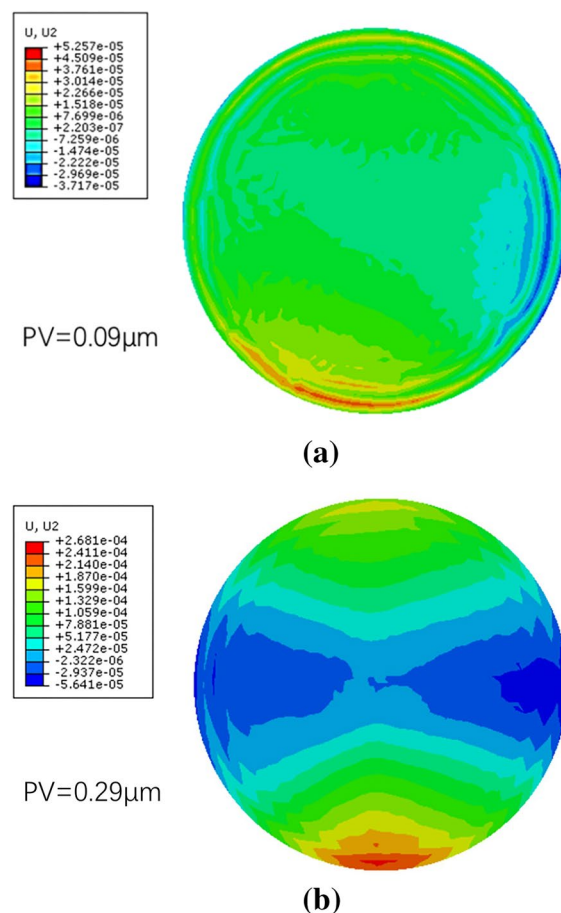
#### 4.2 Effect of Machining Stress

In view of the influence of processing stress on deformation, there are two mapping strategies. After measuring all the points in Figure 5, strategy I is to calculate the average of the residual stresses values on the upper and lower surfaces and add them into the finite element model directly. In the counterpart, considering the uneven distribution of the workpiece pressure and the abrasive trajectory during the lapping process, the distribution of residual stress on the surface will present like concentric annulus along radius direction [31]. Strategy II is to consider the uneven distribution of the residual stress on the workpiece surface caused by the two factors. According to the above analysis and measurement results in Figure 5, the finite element simulation was carried out by adding stress in three zones on the upper and lower surfaces of the finite element model with thickness of 3.15 mm as shown in Figure 11. The simulation result is shown in Figure 12.

Only considering the deformation of the workpiece with the corresponding thickness caused by the machining stress, the finite element simulation results are shown in Figure 12. It can be seen that the warpage degree of the simulation results using strategy II is greater than that of strategy I. However, due to the approximation of the



**Figure 11** Stress added strategy



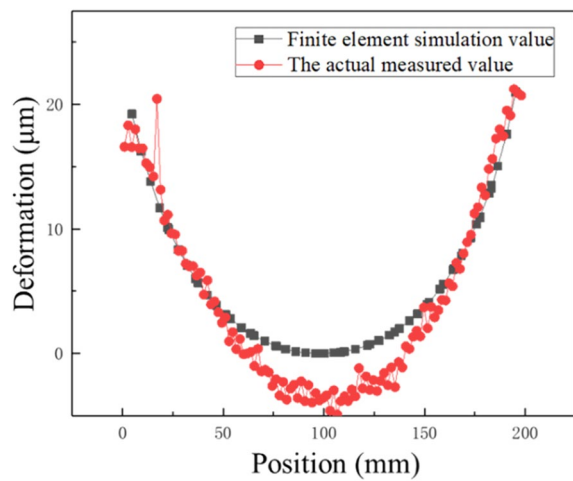
**Figure 12** Simulation results of workpiece deformation caused by processing stress: (a) Strategy I; (b) Strategy II

stress induced by double-sided lapping on both sides of the workpiece under this parameter, the deformation is very small, which is only 0.29  $\mu\text{m}$  and can be neglected.

From the results listed above, it is obvious that the deformation caused by initial residual stress is much larger than the machining stress. Thus, the deformation after double-sided lapping is mainly caused by the initial residual stress.

#### 5 Experiment Verification

In order to verify the accuracy of the proposed finite element model for predicting deformation,  $\Phi 200 \text{ mm} \times 3.2 \text{ mm}$  workpieces were selected, and a double-sided lapping machine was used for the double-sided lapping process deformation test. Using the experimental parameters in Table 1, the workpieces thickness was machined to 3.15 mm, and the deformation of the workpiece was measured by a coordinate measuring instrument. Since the three-coordinate measuring machine cannot measure the position at the extreme edge, the



**Figure 13** Measurement results of workpiece deformation with uneven material removal of upper and lower surfaces

**Table 3** Comparisons between experimental and simulated values of machining deformation

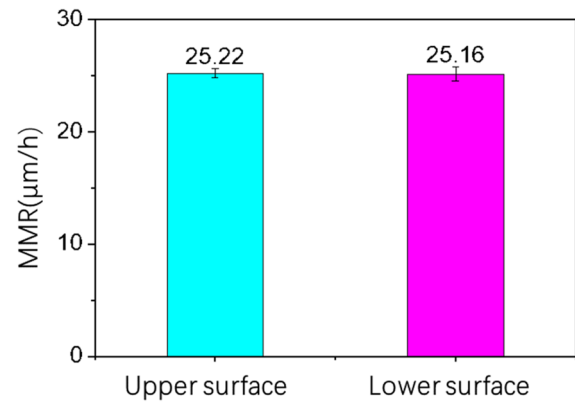
Effect factors	Initial residual stress	Machining stress	
Finite element simulation deformation value (μm)	20.96	Strategy I 0.09	Strategy II 0.29
The actual measured deformation value (μm)	27.12		

**Table 4** Experiment conditions

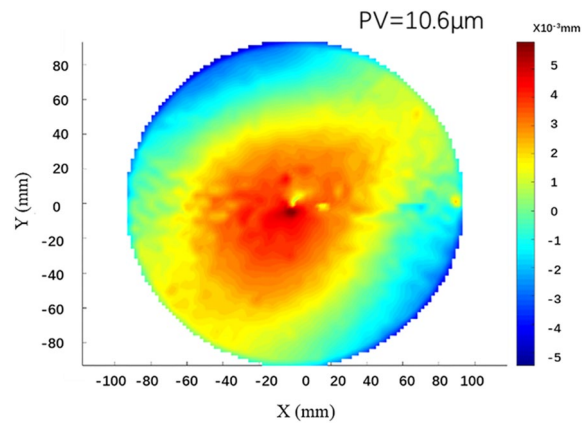
Machine	Pressure (psi)	Upper plate rotation speed (r/min)	Lower plate rotation speed (r/min)	Slurry	Processing time (min)
Double-sided lapping	1.5	10	40	Water	30

measuring position is the diameter of the largest deformation, and the measuring length is 190 mm. The actual measurement results and simulation results are shown in Figure 13. The maximum simulated deformation value and the measured value are compared in Table 3.

Using the experimental parameters in Table 4 for a double-sided lapping experiment, the material removal rates on the upper and lower surfaces of the workpiece are almost the same, as shown in Figure 14. The measurement results are shown in Figure 15 that the maximum deformation of the workpiece is 10.6 μm.



**Figure 14** Materials removal rate of upper and lower surface



**Figure 15** Measurement results of workpiece deformation with even material removal of upper and lower surfaces

It can be seen from the above that in the process of double-sided lapping, because of the existence of the initial residual stress of the workpiece, the stress redistribution of the workpiece in the process of uneven material removal will eventually lead to warping deformation of the workpiece. However, because of the machining stress under this processing parameter, the two-sided introduction of the workpiece is almost the same. Although warping deformation will also occur, the value is small and can be neglected. The experimental results are in good agreement with the simulation results, and the error is nearly 29.39%, which is within acceptable range. There are three possible reasons explaining the error. 1) Limited by measuring instruments, the measurement of residual stress existence error. In addition, there is a gap between the residual stress distribution obtained by the fitting method and the actual workpiece. 2) The workpiece model in the finite element adopts an ideal plane, but the initial



sample after heat treatment will be deformed. 3) Due to the influence of pressure and relative velocity of the workpiece and the abrasives, the material removal at the center and edges of the workpiece surface is uneven, which affected the actual machining deformation.

## 6 Conclusions

In this paper, a finite element simulation model for predicting the deformation of double-sided lapping is created. The initial residual stress, machining stress and their distribution characteristics are considered. The effects of these two factors on the machining deformation were studied. The results reveal that the root cause of the warping deformation of the workpiece in the double-side lapping is the redistribution of initial residual stress, which is caused by uneven material removal of the both surfaces. The main conclusions are as follows.

- (1) The mechanism of machining deformation of parts was studied. Because of the existence of the initial residual stress of the workpiece and the introduction of the machining stress, the stress redistribution of the workpiece in the process of uneven material removal will eventually lead to warping deformation of the workpiece.
- (2) A finite element simulation model was established. The influence of material removal on deformation of the workpiece was performed based on initial residual stress. The uneven removal of the upper and lower surface materials during double-sided lapping results in more serious deformation of the workpiece compared with uniform material removal.
- (3) The effects of machining stress on workpiece deformation were studied. Different loading strategies were applied in the finite element model, the results indicated that, under the experimental parameters, the initial residual stress plays a major role in the deformation of the workpiece, and the machining stress has little effect on the deformation of the workpiece due to the similarity introduced by the double-sided.
- (4) Under the experimental parameters, the maximum warpage of the workpiece is 27.12  $\mu\text{m}$ , which is compared with the simulation results, which proves the accuracy of the simulation mode.

Future work will focus on coupling effects of uneven material removal in-plane, initial residual stress and machining residual stress to optimize the prediction model on the deformation of workpiece.

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## Author Contributions

JG and RK was in charge of the whole trial; ZH wrote the manuscript; BP, BW, QB and JK assisted with sampling and laboratory analyses. All authors read and approved the final manuscript.

## Authors' Information

Jiang Guo, is currently a professor and a Ph.D. candidate supervisor at *State Key Laboratory of High-Performance Precision Manufacturing, Department of Mechanical Engineering, Dalian University of Technology, China*. His main research interests include mechatronics engineering, fluid power transmission and control, ocean engineering.

Zengxu He, is currently a master candidate at *State Key Laboratory of High-Performance Precision Manufacturing, Department of Mechanical Engineering, Dalian University of Technology, China*. His research interests focus on residual stress control in precision Ultra-precision machining and intelligent manufacturing.

Bo Pan, is currently a Ph.D. candidate at *State Key Laboratory of High-Performance Precision Manufacturing, Department of Mechanical Engineering, Dalian University of Technology, China*. His research interest is ultra-precision machining on weak stiffness structures, including double-sided lapping, chemical mechanical polishing and magnetorheological finishing.

Bin Wang, is currently a master candidate at *State Key Laboratory of High-Performance Precision Manufacturing, Department of Mechanical Engineering, Dalian University of Technology, China*. His research interests focus on aerospace thin-walled parts machining and residual stress simulation technology.

Qian Bai, is currently an associate professor at *State Key Laboratory of High-Performance Precision Manufacturing, Department of Mechanical Engineering, Dalian University of Technology, China*. Her main research interests focus on ultra-precision machining theory and technology, machining process modeling and simulation, molecular dynamics simulation.

Jinxing Kong, is a senior engineer from *Institute of Machinery Manufacturing Technology, China Academy of Engineering Physics (CAEP)*. His main research interests focus on multi-energy field assisted ultra-precision machining difficult-to-cut materials and their surface integrity.

Renke Kang, is currently a professor and a Ph.D. candidate supervisor at *State Key Laboratory of High-Performance Precision Manufacturing, Department of Mechanical Engineering, Dalian University of Technology, China*. His main research interests focus on ultra-precision and non-traditional machining technology, semiconductor machining technology and equipment, difficult-to-cut material high-precision machining technology, digital manufacturing equipment.

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## Competing Interests

The authors declare no competing financial interests.

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