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A novel method for deformation prediction caused by initial residual stress

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Abstract
Thin-walled copper parts with high precision are widely used in physical experiments. However, during double-sided lapping, the initial residual stress of the workpiece tends to cause deformation, which affects the machining accuracy. Therefore, it is necessary to establish a model to predict the workpiece deformation caused by the residual stress in actual manufacturing. However, the value of the residual stress is low after annealing, in some cases the measurement error will be unacceptable. To improve the accuracy of the prediction model, a deformation prediction method based on support vector regression (SVR) - genetic algorithm (GA) is proposed in this paper. First, a finite element method (FEM) model for double-sided lapping was established. Then, the relationship between residual stress and deformation is constructed using the SVR model. The optimization process was derived using GA to search for the optimal residual stress adjustment data. Finally, experiments are carried out to prove the effectiveness of the proposed method.
Keywords: Initial residual stress; Double-sided lapping; Support vector regression; Genetic algorithm; Deformation

1. Introduction

During the double-sided lapping, the workpiece is easy to deform due to the release of initial residual stress after the material is removed. Therefore, it is of great significance to establish a model to reflect the influence of residual stress on the deformation of parts.

In recent years, deformation caused by residual stress has attracted wide attention. Richter – Trummer et al. established a FEM to predict the deformation during high-speed milling [1]. Huang et al. has considered the initial residual stress and the machining residual stress. Simulation and experimental results show that the deformation caused by initial residual stress accounts for 90% [2]. To establish the FEM prediction model, the residual stress needs to be measured. Righetti et al. used X-ray diffraction (XRD) to analyse the initial residual stress of 7050 aluminium alloy [3]. Du et al. measured the residual stress of aluminium alloy along the depth direction by XRD method combined with stripping method [4]. To measure the initial residual stress quickly, the electronic speckle pattern interferometry (ESPI) combined with the stripping method was adopted in this paper.

To improve prediction accuracy, this paper proposed a method by amending initial residual stress slightly based on SVR-GA. Firstly, a FEM model was established to predict deformation. Then, the relationship between the initial residual stress and the deformation was established by using SVR model. Then, the GA was used to amend the initial residual stress. At last, relevant experiments have also been carried out to prove its validity.

2. Data acquisition

2.1. Initial residual stress

The size of thin-walled pure copper samples are Ø 100 x 3.2 mm. The combination of ESPI (Prims by Stresstech Oy, Vaajakoski, Finland) and the stripping method is used to measure the initial residual stress along the depth of the workpiece. The initial residual stress distribution along the thickness direction of the workpiece can be obtained.

2.2. Deformation

The experiments were carried out on a double-sided lapping machine (YJ-6B5LA, Hunan Yujing Machinery Co., Ltd.). Experimental parameters are shown in Table 1. After double-sided lapping, flatness was measured using a flatness measuring instrument (Flatmaster, Corning Tropel, New York, USA) at 0 h, 0.5 h, 1 h and 1.5 h after machining. The measured results of workpiece deformation are PV =10.83µm, PV =12.14µm, PV =13.42µm, PV =14.61µm, respectively.

Table 1 Experimental parameters

Machine	Pressure (psi)	Upper plate rotation speed (rpm)	Lower plate rotation speed (rpm)	Slurry
Double-sided lapping	1.5	8	40	Water

2.3. Double-sided removal rate

A high-speed CNC machine (NHM800, Beijing Ninghua Technology Co., Ltd., Beijing, China) is used to scrape V-shaped grooves on the upper and lower surfaces of workpiece. The surface topography measuring device (PF60, Sansei Corporation, Tokyo, Japan) is used to measure the depth of V-shaped grooves before and after processing. The measured material removal rates of the upper and lower surfaces were 14.84 µm/h and 19.52 µm/h, respectively.

3. Deformation Prediction model by FEM

The geometrical model was established according to the size of the thin-walled pure copper sample, and the material is defined as pure copper. The mesh consists of C3D8R elements. Next, the initial residual stress is loaded into the model. The center of the workpiece is fixed constraint. Then, "element life and death" method is used to simulate actual material removal. Finally, the deformation results of the workpiece can be obtained after the residual stress is redistributed.

4. Amending initial residual stress based on SVR-GA

4.1. Establish SVR model

The SVR model can be expressed as follow:

$$f(x) = wx + b \tag{1}$$

In Eq. 1, w is the weight and b is the deviation.

Gaussian kernel function is selected, and its form is as follows:

$$K(x_i, x_j) = \exp(-\gamma \|x_i - x_j\|^2) \quad (2)$$

The results of training and prediction are shown in Figure 1. The average error of the training set and testing set were 16.7% and 11.8%, respectively.

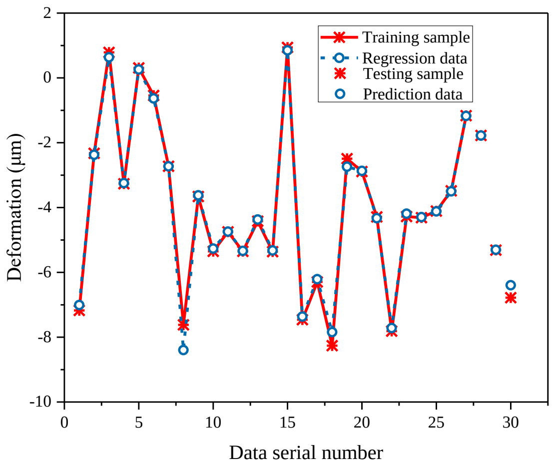

Figure 1. SVR model training and testing results

4.2. Genetic algorithm optimization of initial residual stress

To obtain an accurate prediction model, the amended initial residual stress should be able to match the simulation results with the actual machining results. Therefore, the designed fitness function is as follow:

$$F(x) = \sum_{i=1}^{n} (Y_i - X_i - k) \quad (3)$$

In Eq. 3, n is the number of actual machining results. X_i and Y_i are the difference between the PV value after and before the i-th machining and simulation, respectively. k is the difference between edge and center material removal caused by machining trajectory.

The adjustment value of the initial residual stress optimized by the GA is σ_1=-5.63, σ_2=-6.78, σ_3=-9.82.

5. Verification experiment and simulation

5.1. Verification experiment

Using the experimental parameters in Table 1, the workpiece was processed to 2 h in double-sided lapping machine. The deformation measurement results are shown in Figure 2.

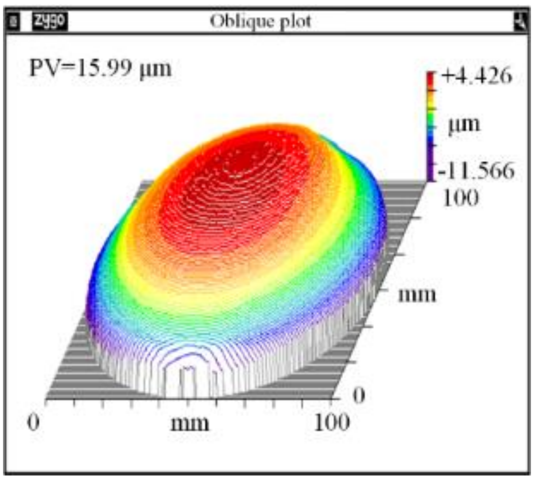

Figure 2. Deformation measurement results of the workpiece after 2 h of machining

5.2. Simulation

Using the amended residual stress and the "element birth and death" method to simulate the material removal, the results are as shown in the Figure 3.

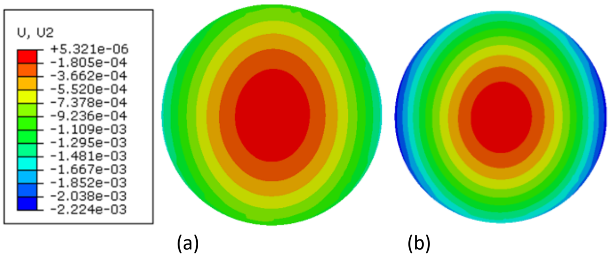

Figure 3. Simulation deformation of the workpiece before amending: (a) PV=1.15 µm after 1.5 h, (b) PV=1.57 µm after 2 h

5.3. Analysis of experimental and simulation results

The deformation caused by initial residual stress relative to the initial workpiece after machining is shown in Figure 4. It can be concluded that the deformation prediction results after amending the initial residual stress are in good agreement with the experimental results in terms of value and trend. Therefore, the application of SVR-GA to amend the initial residual stress of the FEM model is effective, and the prediction accuracy is improved from 31.1% to 15.4%.

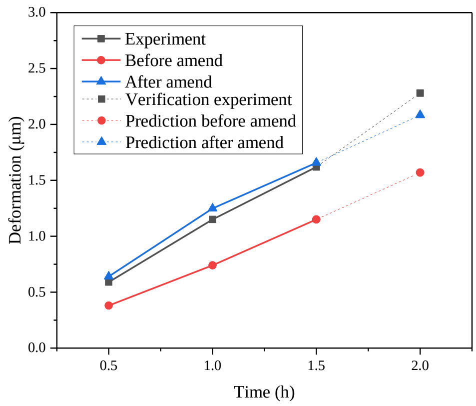

Figure 4. Deformation caused by initial residual stress relative to the initial workpiece after machining

6. Conclusion

To improve prediction accuracy of FEM model, this paper proposed a method to amend initial residual stress slightly based on SVR-GA. Primary conclusions drawn from the paper include:

1. The main reason for workpiece warpage deformation is the redistribution of the initial residual stress after material remove.
2. SVR method was applied to establish the relation between residual stress and deformation. The prediction error of the testing set was 11.8%. And the initial residual stress was amended by GA.
3. The revised initial residual stress improves the prediction accuracy of the FEM from 31.1% to 15. 4%.

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