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Initial residual stress experiment and simulation of thin-walled parts for layer removal method①

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Abstract

Thin-walled parts have low stiffness characteristic. Initial residual stress of thin-walled blanks is an important influence factor on machining stability. The present work is to verify the feasibility of an initial residual stress measurement of layer removal method. According to initial residual stress experiment for casting ZL205A aluminum alloy tapered thin-walled blank by a common method, namely hole-drilling method, three finite element models with initial residual stress are established to simulate the layer removal method in ABAQUS and ANSYS software. By analyzing the results of simulation and experiments, the cutting residual stress inlayer removal process has a significant effect on measurement results. Reducing cutting residual stress is helpful to improve accuracy of layer removal method.

Key words: initial residual stress, thin-walled parts, layer removal method, finite element

0 Introduction

The problem of residual stress has always been much concerned. In the process of casting, forging, welding and cutting, unequal plastic deformation caused by force and temperature variation is the main reason for residual stress[1-4] which has a direct influence on mechanical properties, resistance to stress corrosion, fatigue strength, dimensional stability and service life of workpiece. Most countries have conducted long-term research[5]. Measuring methods of residual stress can be currently divided into two categories: physical method consists mainly of X-ray diffraction, ultrasonic, magnetic strain, etc.; mechanical method consists mainly of layer cutting, trepanning or drilling, etc[6]. However, most residual stress measurement technologies are only suitable for measuring residual stress of surface or shallow surface. It is difficult to ensure the accuracy of inside workpiece[7] of residual stress measurement. Europe, the United States and other countries have studied neutron method and hard X-ray method which could directly measure triaxial residual stress distribution inside thick plate, but currently these technologies are only used in laboratory study[8,9].

The layer removal is a method for measuring internal residual stress of workpiece which mills the material from workpiece surface and measures the residual stress value of each exposed surface. Elastic mechanics method is used to calculate stress revision value after layer removal, and further obtaining the value before layer removal inside the workpiece. According to the existing revision theories, the layer removal method applies to cylindrical, circular tube of great axial-diameter ratio and plate with great width-thickness ratio[10]. In practical application, the method is mostly used in combination with X-ray method. However, new cutting residual stress in milling process would be produced. And the coupling effect with the initial residual stress of blank often falsifies the measurement result. That needs further study.

The aim of the present work is to study the reliability and accuracy of layer removal method. According to experimental results of initial residual stress for casting ZL205A aluminum alloy tapered thin-walled blank, the finite element model with initial residual stress is established to simulate the experimental process by

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using a birth and death element method and milling simulation method. Then error and the rationality of layer removal method have been analyzed by comparing the simulation with the experiment.

1 Initial residual stress experiment

In the existing methods, the hole-drilling method is more mature. This method is more commonly used in engineering, because of its easiness of operation, cheapness of equipments, small damage area of workpiece, and high precision[11,12].

Andersen[13] improved the hole-drilling method, in which drilling depth was increased gradually to determine strain values of strain gauge film gate at different depths. Furthermore the principal stress values at each depth were calculated based on these strain values. Eq. (1) is as follows:

$$\varepsilon_{ij}^{k} = \frac{1+v}{2E}\sum_{j=1}^{i} a_{ij}(\sigma_{1j}+\sigma_{2j}) + \frac{1}{2E}\sum_{j=1}^{i} b_{ij}(\sigma_{1j}-\sigma_{2j})\cos 2\beta_j \quad (1)$$

where, i refers to the number of increments drilled, j is the increment in which the stress is acting, ε_{ij}^{k} is strain value of strain gauge at each depth, σ_{1j} and σ_{2j} are principal stresses within increment j, a_{ij} and b_{ij} are unit stress release coefficients, β_j is the angle measured counter-clockwise from the direction of principal stresses and strain gauge.

1.1 Experiment process

In the experiment, ZL205A casting aluminum alloy tapered thin-walled blank of 50mm in small end diameter, 300mm in big end diameter, 850mm in length and 32mm in thickness is used. Hole-drilling equipment is HTZ-12 omnipotence precision drilling device shown in Fig. 1. Detection device is HT21B portable digital residual stress detector shown in Fig. 2. A 1.5mm diameter hole in a typical measurement point of workpiece is drilled and a compensation plate is pasted on the position away from the measuring point to compensate for strain changes caused by temperature. The measurement and compensation position is shown in Fig. 3.

Fig. 1 HTZ-12 omnipotence precision drilling device

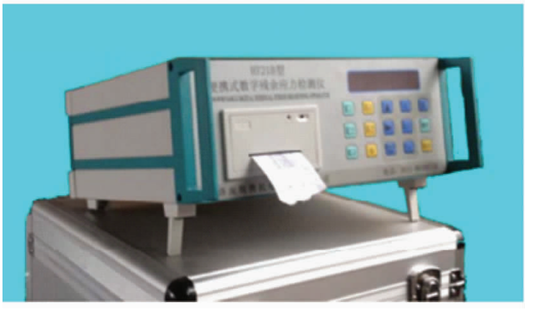

Fig. 2 HT21B portable digital residual stress detector

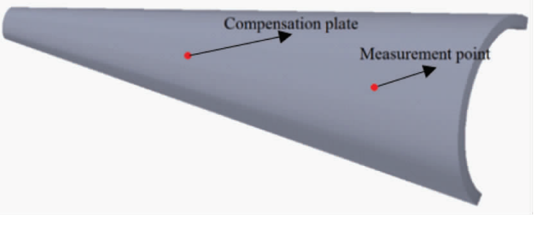

Fig. 3 Hole-drilling position

1.2 Experimental results

Because of the same surface technology in casting, residual stress of the blank is central symmetrical distribution in the thickness direction. It only needs to measure experiment values of 2 – 16mm in the thickness. Drilling eight times in the measurement point, the thickness is respective 2, 4, 6, 8, 10, 12, 14, 16 mm. At the end of each drilling, strain values of the point are obtained and then the residual stress in each thickness is calculated by Eq. (1) as shown in Table 1 and Fig. 4.

Table 1 Experimental results of initial residual stress

Thickness (mm)	The stress in x-direction (MPa)	The stress in y-direction (MPa)
2	–114.7669	–105.7367
4	–8.7840	0.1401
6	31.9871	34.5158
8	6.1613	6.1554
10	3.3202	1.6167
12	–1.6383	–2.0686
14	–4.5229	–4.0868
16	–2.4770	–2.4770

As shown in Fig. 4, initial residual stress of the blank is mainly distributed in the range of 6mm below the surface. When the thickness is greater than 6mm, residual stress values of x and y directions become smaller. The stress is compressive stress in the thickness ranging from 2mm to 4mm and tensile stress in the thickness ranging from 4mm to 6mm, which makes the blank in a state of stress balance.

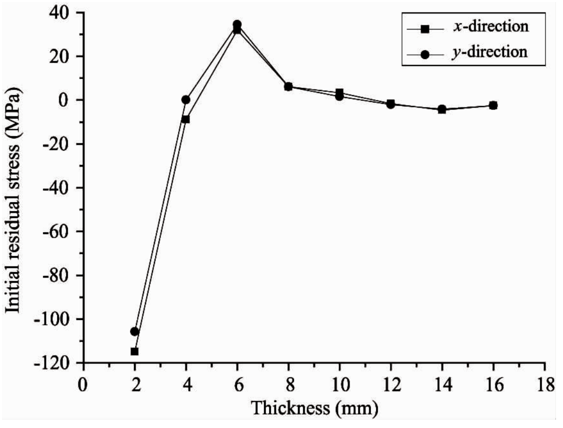

Fig. 4 Residual stress curve in the thickness

2 Numerical modeling procedure by birth and death element method

In order to study the reliability and accuracy of the layer removal method, a three-dimensional finite element model with initial residual stress is established according to experimental results. In this model, birth and death element method of finite element analysis software ANSYS is used for simulation analysis. The birth and death element technique is the method of reactivated or killed element in the analysis. When cutter feed is to remove the material, the corresponding finite elementsare will be killed. The elements of the birth or death do not mean to add or remove element, but are multiplied by a very small reduction factor (default value is 1.0E-6) to make the element of mass, load, damping, strain and stress to 0. These removed elements would still show in the window. In order to prevent singular matrix, the stiffness is not set to 0.

2.1 Finite element model in ANSYS

In the finite element simulation, in order to improve the computational efficiency and easily apply for birth and death element method, the structure of the model is simplified to a rectangle of 200mm × 200mm × 32mm as shown in Fig. 5. The material property of ZL205A aluminium alloy is assigned to the model. Density is 2.8g/cm^3. Young's modulus is 68GPa. Poisson ratio is 0.33. Yield stress is 455Mpa. The eight-node hexahedron SOLID185 is used to discretize the model. In order to correspond with the experiment, the model is discretized into 16 layers and 2mm in each layer in the thickness direction.

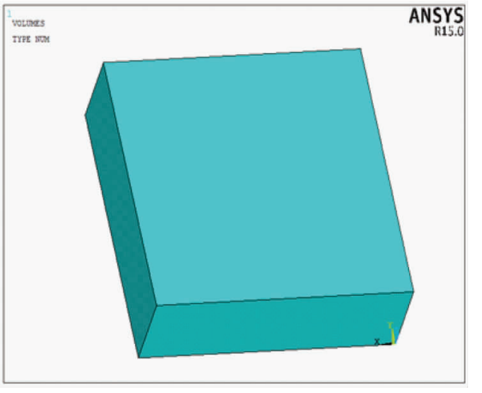

Fig. 5 Geometric model

2.2 Initial residual stress in ANASYS

Since the initial residual stress is not applied to a few faces, lines or points, but to the whole model, ANSYS parametric design language (APDL) is used to simplify the process of operation. According to residual stress test results, an IST file with initial residual stress data is generated by APDL, and then applied to corresponding element symmetrically. The flow chart of applying initial residual stress by APDL is shown in Fig. 6. The model with initial residual stress in x-direction is shown as Fig. 7, and in y-direction is shown as Fig. 8.

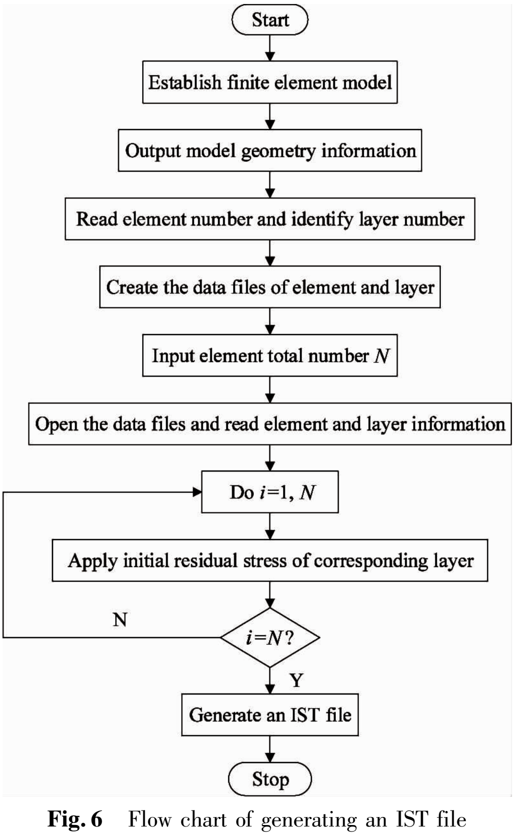

Fig. 6 Flow chart of generating an IST file

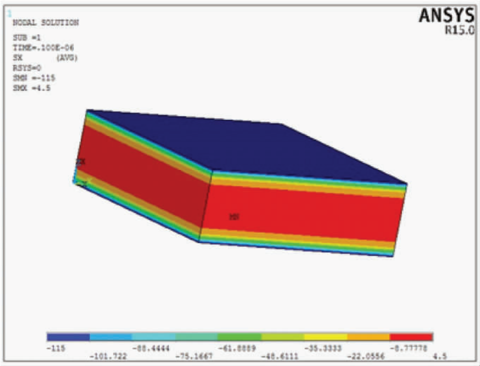

Fig. 7 Initial residual stress of in x-direction

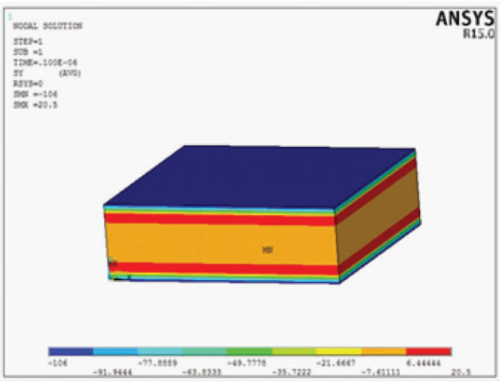

Fig. 8 Initial residual stress in y-direction

2.3 Simulation parameters

The mathematical model between milling parameters and residual stress is shown in Eq. (2)[14]. In order to reduce the influence of milling residual stress on simulation results, reasonable cutting parameters are selected, in which milling speed is 3000r/min, milling depth is 2mm and feed rate is 300mm/min.

$$\begin{cases} \sigma_x = 4.175 \times 10^{-10} \cdot a_p^{2.47} \cdot v^{0.66} \cdot f^{2.156} \cdot a_w^{1.7} \\ \sigma_y = 1.1 \times 10^{-15} \cdot a_p^{0.3757} \cdot v^{1.3689} \cdot f^{4.1} \cdot a_w^{0.27} \end{cases} \quad (2)$$

where a_p is axial cutting depth (mm), v is milling speed (m/min), f is feed rate (mm/min), a_w is radial cutting depth (mm) and d is cutter diameter (mm).

According to the actual layer removal process, circular milling path is selected. As shown in Fig. 9, the elements of three circular paths are gradually killed by using birth and death element method. A circular boss of 10 mm diameter is retained and the stress value is recorded in the boss. After recording, similarly, the elements of boss are killed. This process is repeated 16 times. The 2mm thickness elements are killed at one time. In Fig. 10, when recording stress value, the x-direction average value of No. 1, 2, 3 node is set as x-direction measured value, and the y-direction average value of No. 3, 4, 5 node is set as y-direction measured value.

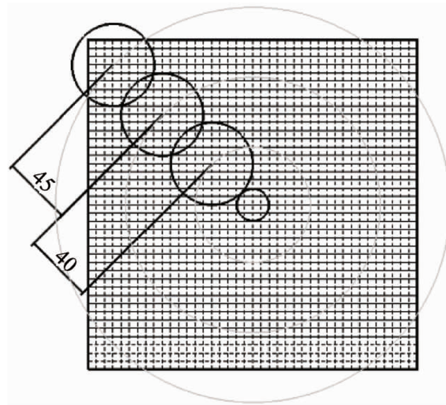

Fig. 9 Sketch of simulation path

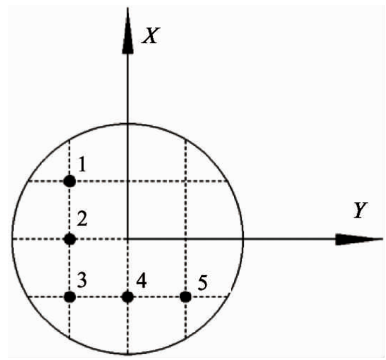

Fig. 10 Sketch of data point

2.4 Simulation results using birth and death element method

The thickness of the finite element model is 32mm. At one time, the 2mm of each layer is killed. After one layer is killed, the stress value of boss is recorded. In simulation, residual stress distribution of the model is shown in Figs 11 and 12. According to the measurement method of Fig. 10, the simulation results are shown in Table 2.

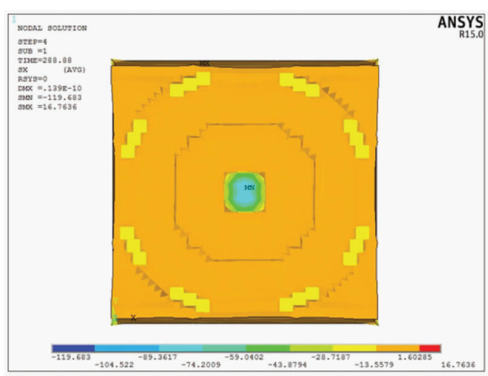

Fig. 11 Residual stress of x-direction in simulation

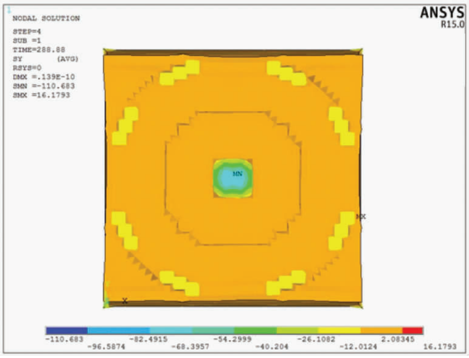

Fig. 12 Residual stress of y-direction in simulation

Table 2 Simulation results using birth and death element method

Thickness (mm)	The stress in x-direction (MPa)	The stress in y-direction (MPa)
2	−114.77	−105.74
4	−8.78	0.14
6	31.99	34.52
8	6.16	6.16
10	3.32	1.62
12	−1.64	−2.07
14	−4.52	−4.09
16	−2.48	−2.48
18	−2.54	−2.76
20	−4.58	−4.03
22	−1.60	2.31
24	3.30	−1.42
26	6.16	6.00
28	29.55	34.04
30	−7.76	0.08
32	−105.17	−100.73

3 Numerical modeling procedure by milling simulation method

3.1 Finite element model in ABAQUS

ABAQUS software has its own CAD module, but it is still immature in comparison with professional CAD software. So some complicated models generally need to use software such as UG, Solidworks. for modeling, and are imported into the ABAQUS interface. In this paper, a tool is established in the Solidworks software, and then repaired by the geometric repair tool in the ABAQUS part module. As shown in Fig. 13, tool is cemented carbide end-milling cutter of four edges, in which the diameter is 50mm, rake angle is 16°, clearance angle is 27°, and helix angle is 39°. The workpiece is a rectangle of 200mm × 200mm × 32mm. Because the structure is relatively simple, it can be directly established in the ABAQUS. In accordance with the actual clamping, the degrees of freedom of workpiece at its bottom are completely fixed to avoid the workpiece movement and rotation.

In the simulation, the workpiece should achieve mesh refinement and the tool should reduce mesh, which not only ensures accuracy of results but also saves solution time and memory consumption. The mesh of workpiece is divided into 50,280 elements. Element type is an 8-node hexahedral three-dimensional reduced integral unit (C3D8RT). The mesh of tool is divided into 1134 elements. Element type is tetrahedral element (R3D4). The assembly drawing of tool and workpiece is shown in Fig. 14. To be consistent with the finite element model of birth and death element method, milling speed is set to 3000r/min, milling depth is 2mm, and feed rate is 300mm/min.

Fig. 13 Geometric figure of tool

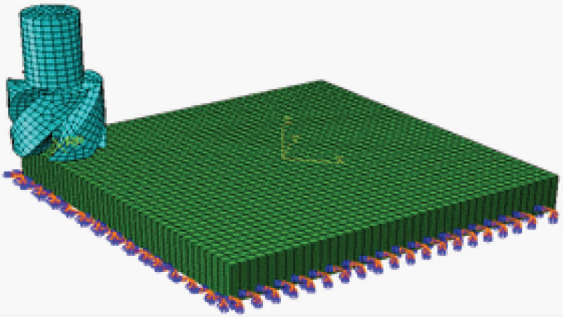

Fig. 14 Assembly drawing

3.2 Initial residual stress in ABAQUS

In order to apply initial residual stress, the model is discretized into 2mm in thickness each layer. According to the experimental results of residual stress, in load module of ABAQUS, initial residual stress is applied to the model symmetrically. The model with initial residual stress is shown as Fig. 15.

3.3 Simulation results using milling simulation method

In simulation, residual stress distribution of the model is shown in Figs 16 and 17. According to the measurement method of Fig. 10, the simulation results are shown in Table 3.

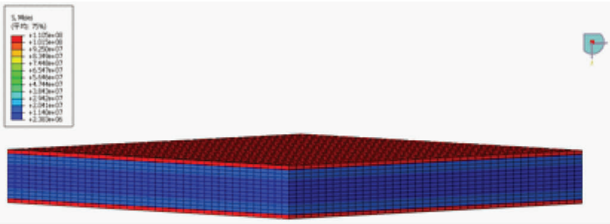

Fig. 15 Initial residual stress in ABAQUS

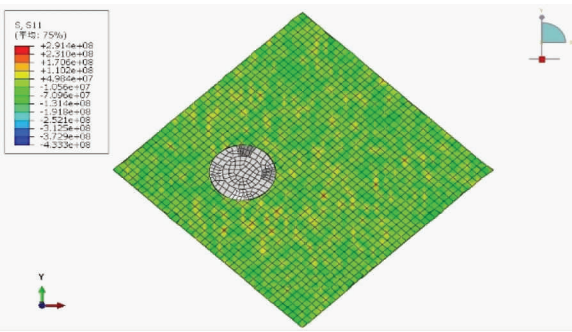

Fig. 16 Residual stress of x-direction in simulation

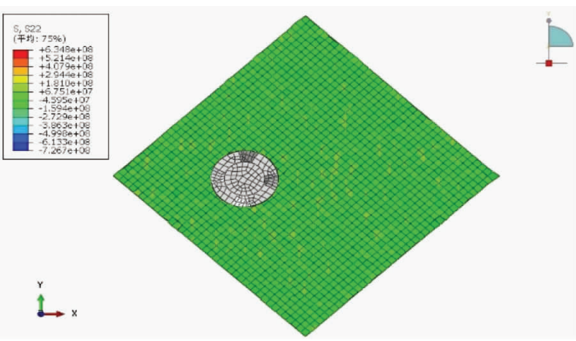

Fig. 17 Residual stress of y-directionin simulation

Table 3 Simulation results by using milling simulation method

Thickness (mm)	The stress in x-direction (MPa)	The stress in y-direction (MPa)
2	−205.45	−170.81
4	−90.62	−0.47
6	92.85	48.46
8	99.70	178.30
10	119.74	89.70
12	−71.95	−48.59
14	−67.57	−132.70
16	−45.34	−55.09
18	−63.34	−75.42
20	−40.02	−46.00
22	3.86	−67.24
24	−118.75	102.04
26	135.48	107.24
28	22.33	52.16
30	−44.20	−0.56
32	−148.20	−105.80

4 Results and discussion

Figs 18 and 19 are the comparison between simulation results in ANSYS and experiment. Because of the birth and death method of ANSYS, cutting tool and cutting force are not considered. The residual stress values of simulation and experiment have little difference.

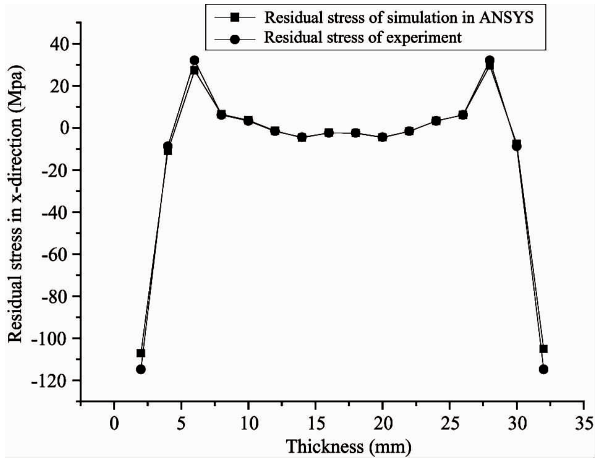

Fig. 18 Comparison curves of residual stress in x-direction

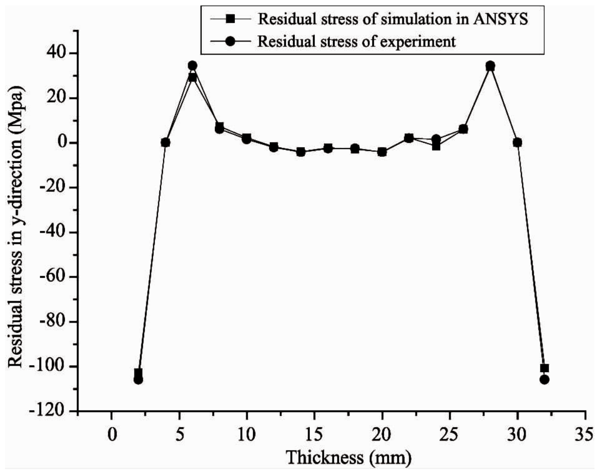

Fig. 19 Comparison curves of residual stress in y-direction

Figs 20 and 21 are the comparison between simulation results in ABAQUS and experiment. Because of

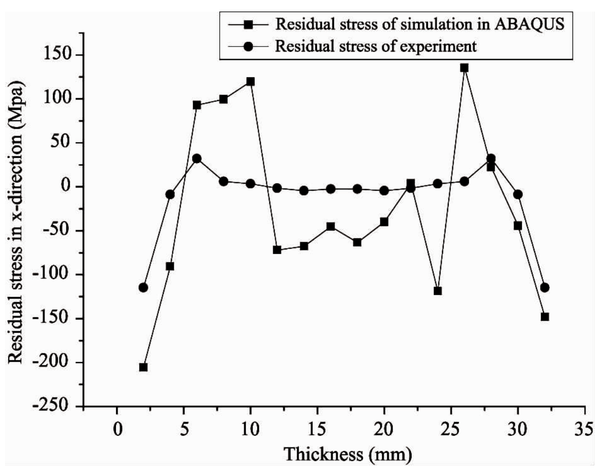

Fig. 20 Comparison curves of residual stress in x-direction

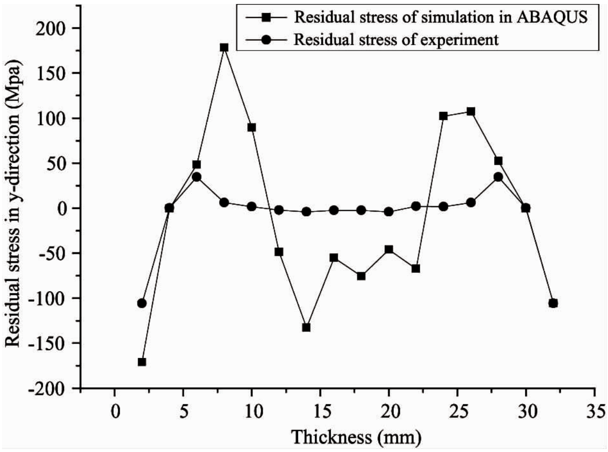

Fig. 21 Comparison curves of residual stress in y-direction

milling simulation method of ABAQUS, cutting tool and cutting force are considered. The residual stress values of simulation and experiment have much difference. When milling to the middle layer, the difference of the stress values of simulation and experiment is greater. Therefore, the cutting residual stress produced in the milling process has a great influence on the measurement results. Especially when milling to the middle layer, the factor of cutting residual stress in the measurement must be taken into consideration.

5 Conclusions

In the present work, according to initial residual stress experiment for casting ZL205A aluminum alloy tapered thin-walled blank by using hole-drilling method, three finite element models with initial residual stress are established to simulate layer removal process in ANSYS and ABAUQS software, making the following conclusions:

(1) The residual stress values have little difference between simulation results in ANSYS and experimental results. This is because the birth and death method of ANSYS does not consider cutting tool.

(2) The residual stress values have much difference between simulation results in ABAQUS and experimental results. The reason is that in milling simulation method of ABAQUS, new cutting residual stress is produced by the tool and cutting force.

(3) In ABAQUS, when milling to the middle layer, the stress values of simulation and experiment have great difference and the deviation is obvious.

(4) According to the comparison of simulation and experiment results, for the actual initial residual stress measurement of layer removal method, especially internal measurement, cutting residual stress generated during the milling process is an important influence on measurement results. Reducing cutting residual stress is helpful to improve accuracy of the method.

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