FEM analysis of the distortion of thin-walled sealing part affected by the machining-induced residual stress

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Abstract. Thin-walled sealing parts are typical difficult machining parts due to their lower stiffness and higher machining accuracy requirements. Among all the influential factors on the distortion of thin-walled parts, machining-induced residual stress (MIRS) plays a key role. In this paper, the effects of the MIRS changed with the number of cuts and the allocation of cutting depth on the distortion of the sealing part are investigated. Firstly, the MIRS is obtained by a finite element cutting simulation model of the AISI304L stainless steel material. Then, the obtained MIRS is applied to the workpiece, and the distortion of the workpiece is simulated after releasing the clamping constraints. The simulation results show that the multi-cutting processes and the reasonable allocation of cutting depth have a remarkable influence on the control of the workpiece distortion.

1. Introduction

With the higher performance requirements and the technical development, the thin-walled sealing parts are extensively used in aerospace, automotive and precision machinery fields. However, the thin-walled sealing parts generally have complicated structure and higher machining accuracy. As a result, they have become typical hard-to-machine parts. The MIRS caused by cutting has an important influence on the machining quality of the workpiece, and different MIRS will cause different degrees of part distortion [1]. Keith A. Young et al. [2] investigated the correction between MIRS and distortion of thin-walled machined parts. The findings reveal that the stress caused by machining can account for most of the deformation with the thickness of parts less than 3.3mm and of course cannot be ignored in deformation prediction models. Therefore, by studying and mastering the distribution, influencing factors and evolution process of the MIRS, the distortion of thin-walled parts will be controlled effectively.

The distribution of MIRS and the deformation of the workpiece induced by MIRS have been investigated extensively. Soroush Masoudi et al. [3] studied the distortion of workpiece, which
affected by the machining force, machining temperature, stress distribution, and workpiece thickness. The findings reveal that reducing the machining force, temperature and increasing the thickness of workpiece lead to a decrease in potential distortion. B. Denkena et al. [4] studied the MIRS of the workpiece, which affected by cutting parameters and cutting edge geometry. Studies show that reducing the cutting width, increasing the feed per tooth and using larger radii at the secondary cutting edge result in more obviously compressive residual stress. Coto et al. [5] found that, by decreasing feed speed and increasing cutting speed, the optimal stress state is obtained on the surface of workpiece. Jiang et al. [6] investigated the effect of tool diameter on MIRS and workpiece deformation. Studies show that a larger diameter of tool can reduce the distribution of tensile-residual stress and decrease workpiece deformation.

The above studies concentrate on residual stress distribution with single-process. Furthermore, in recent years, the redistribution of residual stress with sequential cuts has been widely investigated. Guo et al. [7] established a two-dimensional orthogonal FEM model, and studied the effects of cutting force, cutting temperature, clamping and the number of passes on the MIRS of workpiece. Simulation result shows that the cutting force is the most important factor affecting MIRS, and when the thickness of the second cut is small, the MIRS may be changed from tensile stress to compressive stress. Li et al. [8] studied the redistribution mechanisms of residual stress and the distortion of the workpiece at different cutting depths. The findings reveal that from roughing to finishing, as the depth of cut decreases, the stress gradually decreases; the stress of the previous surface layer has a great influence on the final surface stress of workpiece, and the depth of cut needs to be planned at different processing stages. Guo et al. [9] studied internal residual stress and deformation of the workpiece changing from roughing to finishing. The findings reveal that, by using heat treatment between two processes, the residual stress will be significantly reduced on the surface of the workpiece, and the stress will quickly enter a stable state on the sub-surface of the workpiece; what’s more, the deformation of workpiece decreases as the change of cutting depth from roughing to finishing.

Limited by the computer's computing power, few scholars have simulated the 3-D cutting under multi-process. In this paper, in order to analyze the distortion of workpiece affected by the number of cuts and the allocation of cutting depths, the 3-D cutting process under multi-process has been simulated. Firstly, the finite element cutting simulation model of the AISI304L stainless steel material is used to predict the MIRS. Then the extracted residual stress is applied to the workpiece for distortion simulation.

2. Theoretical analysis of distortion induced by MIRS

The theoretical analysis is divided into two parts in this section. Firstly, distortion mechanism is analyzed, which caused by MIRS. Secondly, the formula of stress field coordinate transformation is discussed.

2.1. Analysis of distortion mechanism induced by MIRS

MIRS is induced by the combination of plastic deformation, thermal stress and phase-transformation during processing. Since the cutting temperature of the workpiece is lower than the phase-transformation temperature [10], the plastic deformation of the surface material and the elastic action of the inner layer material have been considered in this paper. Fig. 1 shows distortion mechanism of the workpiece caused by the MIRS.
After the surface of workpiece is subjected to cutting action, the thickness of the workpiece
metamorphic layer (t) is generated. At the same time, the MIRS and the depth of stress are σ₀ and h, respectively. When removing clamping constraints, part of the stress (σ₂) will be balanced by elastic
distortion, and the other part of the stress (σ₁) will reach equilibrium again.

Figure 1. Workpiece distortion induced by MIRS.

2.2. Coordinate transformation of stress field

After the MIRS has been obtained, the value of the residual stress will be assigned to the model of
the workpiece. However, the curves of MIRS are generally obtained in local coordinates system, LCS
(xyz), and the transformation of the stress field obtained by local coordinates system (xyz) to the
global coordinate system, GCS (x'y'z') needs to be considered. The schematic of stress field
transformation is shown in Fig. 2, and the transformation formula is shown in Eq. (1).

Figure 2. Schematic of stress field transformation.

\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\end{bmatrix} = \begin{bmatrix}
\epsilon_x & \epsilon_y & \epsilon_z \\
\tau_{xy} & \tau_{yz} & \tau_{zx} \\
\tau_{yx} & \tau_{yz} & \tau_{zx} \\
\end{bmatrix} \begin{bmatrix}
l_1 \\
l_2 \\
l_3 \\
\end{bmatrix}
\]

Where \([\sigma] \) is the MIRS in LCS, \([\sigma'] \) is the MIRS in GCS, and \([\beta] \) is transformation matrix of coordinate.
3. Simulation process

In this paper, the simulation process consists of two parts: the MIRS simulation and the workpiece distortion simulation. Fig. 3 shows the schematic of the workpiece distortion simulation. In general, the commercial software of ABAQUS can be used to predict MIRS. Furthermore, distortion is predicted for the workpiece by inputing MIRS to the software of ABAQUS. And then, when clamping system is unloaded, the distortion induced by the MIRS is calculated.

The cutting simulation process can be divided into three processes: steady state cutting, unloading cutting forces, cooling the workpiece to room temperature. Considering computer's computing power, it is necessary to assume that the MIRS caused by machining is evenly distributed in the same radius layer of the workpiece.

![Figure 3. Schematic diagram of the workpiece distortion simulation.](a) cutting process (b) residual stress extraction (c) the distortion of parts]

3.1. Modeling of cutting process

In the analysis of cutting process simulation, the size of the model is \(2\text{mm} \times 1\text{mm} \times 1\text{mm}\), and it is determined by the following two points: (1) After the chip removed, the size of the base material satisfies the residual stress extraction. (2) The size of the model in the direction of cutting speed should be assured that the tool can enter a steady state cutting. The material of the workpiece is AISI304L stainless steel, and the material of the cutting tool is cemented carbide. Tables 1 and 2 show the physical properties of the cutting tool and the Johnson-Cook model parameters of the workpiece material, respectively. Other material parameters are referenced [9].

Due to the fluctuation of cutting force, the cutting simulation precision can be visually reflected. The fluctuation curves of the main cutting force under different grid sizes are shown in Fig. 4. In theory, when the mesh is sufficiently fine, the main cutting force is basically no fluctuation. When the mesh size of the machining area is \(0.02\text{mm} \times 0.0125\text{mm} \times 0.0125\text{mm}\), the simulation efficiency and simulation precision can be balanced. The simulation model of 3-D cutting is shown in Fig. 5.

| Density (kg/m³) | Young’s modulus (GPa) | Poisson’s ratio | Conductivity (W/m·°C) | Coefficient of thermal expansion (10⁻⁶/°C) |
|----------------|-----------------------|----------------|-----------------------|------------------------------------------|
| 14800          | 635                   | 0.3            | 79.6                  | 5                                        |

Table 1. Physical properties of cemented carbide materials.

| A (MPa) | B (MPa) | C     | m     | n     | Tm(°C) | Tt(°C) |
|---------|---------|-------|-------|-------|--------|--------|
| 452     | 694     | 0.0067| 0.996 | 0.311 | 1400   | 20     |

Table 2. Johnson-Cook model parameters of AISI304L stainless steel.
Figure 4. Cutting force curves under different grid sizes.

Grid type 1 (0.0125mm × 0.0125mm × 0.0125mm),
Grid type 2 (0.02mm × 0.0125mm × 0.0125mm),
Grid type 2 (0.02mm × 0.025mm × 0.0125mm)

3.2. Modeling of distortion simulation

In the analysis of distortion simulation process, the size of the model is 120mm × 252mm, and the thinnest thickness of workpiece is defined with 1.5mm. By simplifying the small structural features of the thin-walled sealing parts, such as chamfering, the simplified geometric model is obtained (Fig. 6).

With the software of ABAQUS, distortion of workpiece is predicted. The setting for the FEM is shown in Fig. 7. The unit type adopts the eight-node hexahedral element type, C3D8R. The MIRS needs to be applied according to the layer in the thickness direction of the workpiece, and the mesh size of the stress application area is divided into 0.45mm × 0.45mm.

Considering the severe distortion of the workpiece under the three-jaw chuck clamping, the expanding mandrel is used for clamping. In the finite element simulation, the clamping boundary condition is set by constraining all the degrees of freedom of all the nodes in the inner hole. By selecting three noncollinear points in the inner hole, whose translation freedom degrees of the directions XYZ, YZ, and Z were constrained respectively, the rigid displacement of the workpiece was constrained. This way ensures that when releasing the clamping boundary condition, the workpiece can distortion freely due to the redistribution of MIRS.

Figure 6. Geometric model of workpiece.

Figure 7. Finite element model of workpiece.
4. Simulation results and discussions

4.1. Cutting conditions and machining schemes

The machining allowance for simulation is 0.4mm. To analyze the influence of the number of cuts and the allocation of cutting depth on the distortion of the workpiece, four machining schemes are proposed. The machining schemes and cutting conditions are shown in Table 3. Scheme 1 is compared with other schemes to analyze the effect of the number of cuts on the distortion of the workpiece. The influence of allocation of cutting depth on the distortion of the workpiece is compared in Scheme 2, Scheme 3 and Scheme 4.

**Table 3.** The machining schemes and simulation conditions of workpiece.

| Machining schemes | Number of cuts | Cutting depths of first cut (mm) | Cutting depths of second cut (mm) | Cutting speed (m/s) | Feed rate (mm/r) | Tool parameters |
|-------------------|----------------|---------------------------------|----------------------------------|---------------------|-----------------|-----------------|
| Scheme 1          | 1              | 0.4                             | 0                                |                     |                 |                 |
| Scheme 2          | 2              | 0.3                             | 0.1                              | 2.3                 | 0.15            | γ₀ = 15°        |
| Scheme 3          | 2              | 0.2                             | 0.2                              |                     |                 | α₀ = γ°         |
| Scheme 4          | 2              | 0.1                             | 0.3                              |                     |                 |                 |

4.2. Analysis of MIRS

![Figure 8](image1.png)  
(a) Initial cutting of the tool  
(b) Steady-state cutting

**Figure 8.** the cloud diagram of machining-induced stress.

![Figure 9](image2.png)  
(a) Residual Stress σ₁₁  
(b) Residual Stress σ₂₂

**Figure 9.** Effect of the first cut on the MIRS.

Scheme 1 (1st cut, 0.4mm), Scheme 2 (1st cut, 0.3mm)  
Scheme 3 (1st cut, 0.2mm), Scheme 4 (1st cut, 0.1mm)
Fig. 8 shows the cloud diagram of machining-induced stress in cutting. It can be seen from the figure that the stress is mainly generated in the first deformation zone during the steady state cutting process. After the tool passes through the machining surface, a thin layer of residual stress caused by machining is formed in the third deformation zone.

The MIRS affected by different schemes under the first cut is shown in Fig. 9. \( \sigma_{11} \) is the residual stress in the direction of cutting speed, and \( \sigma_{22} \) is the residual stress in the direction of cutting depth. It can be observed that the depth of residual stress is about 0.25mm. Moreover, the residual stress is tensile stress on the surface of the workpiece, and compressive stress on the sub-surface. By comparing the residual stress curves of different schemes, it can be seen that as cutting depth increases (cutting depth ranges from 0.1mm to 0.4mm), the residual stress of the machined surface and the depth of the stress layer increase.

The MIRS affected by different schemes under the second cut is shown in Fig 10. By comparing the residual stress under different number of cuts (scheme 1 has once, and other schemes have twice), the depth and amplitude of residual stress are the highest in scheme 1. It can be considered that scheme 1 only has one cutting, and the material removal amount is the largest. By comparing residual stress under different allocation of cutting depth (scheme 2, scheme 3 and scheme 4), the residual stress distribution of three scenarios is similar. However, compared with the first cut, the residual stress amplitude of scheme 2 and scheme 3 increases obviously. It can be considered that the material removal amount of the second cut in the schemes 2 and 3 is smaller than the thickness of the residual stress layer induced by the first cut, and there is obvious stress superposition in the stress layer. In scheme 4, the amount of material removal for the second cut is similar with the thickness of the residual stress layer induced by the first cut, and the amount of stress superposition is small.

4.3. Analysis of workpiece distortion

The MIRS (Fig. 10) is applied to the workpiece along thickness direction of the thin-walled parts, and workpiece is distorted when releasing the clamping boundary condition. During this process, a remarkable distortion of the workpiece has been induced by the residual stress, as shown in Fig. 11.
The distortion values of the workpiece under all machining schemes are shown in Table 2. It can be observed that distortion values of the workpiece vary from 0.0144mm (scheme 2) to 0.023mm (scheme 1). Notably, compared with scheme 1, the distortion of scheme 2 is dropped by 37%. Scheme 3 has obvious stress superposition in the stress layer, and the final distortion is slightly different from that of the scheme 4. The distortion trend of the workpiece under four different schemes is consistent with the residual stress analysis in Fig. 10.

| Machining schemes | Distortion values (mm) | Distortion value reduction |
|-------------------|------------------------|---------------------------|
| Scheme 1          | 0.023                  |                           |
| Scheme 2          | 0.0144                 |                           |
| Scheme 3          | 0.0175                 |                           |
| Scheme 4          | 0.0184                 | \(\frac{(0.023 - 0.0144)}{0.023} \times 100\% = 37\% \) |

5. Conclusions

There are many factors affecting the residual stress and distortion of the thin-walled sealing parts during cutting process, which makes the dimensional, form and position accuracies of the workpiece hard to control. In this work, the effects of the number of cuts and the allocation of cutting depth on the distortion of the workpiece are investigated.

(1) The MIRS is tensile stress on the surface of the workpiece, and compressive stress on the sub-surface. As the cutting depth increases, the magnitude and depth of the residual stress on the machined surface increase accordingly.

(2) After the first cut, when the depth of the second cut is greater than the depth of residual stress, the thickness of the residual stress layer produced by first cut will be eliminated basically; when the depth of the second cut is less than the thickness of the residual stress layer, the residual stress are superimposed on each other.

(3) The MIRS has an important influence on the distortion of the thin-walled sealing parts. When the cutting depth of the last cut is small and the MIRS is not notably superimposed with the previous
cutting, the distortion of the workpiece is small. Therefore, the number of cuts and the allocation of cutting depth are important factors for reducing the distortion of the workpiece.

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