Precise machining based on Ritz non-uniform allowances for titanium blade fabricated by selective laser melting

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Abstract
Selective laser melting (SLM) is an increasingly concerned trend in Ti-6Al-4V blade manufacturing, while the SLMed Ti-6Al-4V blade cannot be used directly because of poor surface integrity and high residual stresses. Precise machining after SLM is a feasible solution but also a challenge. The low rigidity of the blade will lead to deformation when machining. The deformation can lead to surface error and may make defect parts. Two-step machining processes to address the problems were proposed in this paper. First, a non-uniform allowances distribution was allocated and optimized in semi-finishing based on Ritz solution to elastic deformation. The blade was simplified as a cantilever thin plate with various thicknesses, and the thicknesses of finishing allowances were designed and optimized on the premise of ensuring the thin-wall stiffness of the blade, so as to realize the design of Ritz non-uniform allowances. Then, finishing machining was conducted to achieve precise parts. A blade deformation model was established to evaluate part distortions with cutting force moving and changing. Finite element analysis (FEA) and experimental validation in ball-end milling of a blade were conducted. FEA results and experimental results showed dimensional errors have been reduced up to 50%. Further surface tests demonstrated that the mean surface roughness reduced from 7.88 to 0.815 μm. And the residual surface stresses of the SLM samples changed after semi-finishing machining due to the residual stresses relaxation and redistribution. The results demonstrated that the proposed method enhanced the surface quality of the blade fabricated by SLM.

Keywords Precise machining · Selective laser melting · Blade · Ritz non-uniform allowances · Ti-6Al-4V alloy

1 Introduction
Additive manufacturing (AM) is a rather new type of metal parts manufacturing technology developed in recent years. Selective laser melting (SLM) is a typical common AM technology. It is a powder layer fusion technology that can produce complex structures with relatively good surface quality [1]. Ti-6Al-4V titanium alloy is a common SLM forming material. It has high strength to weigh ratio, high corrosion resistance, and good performance at elevated temperatures, and has been widely used in the aerospace field [2]. However, the surface quality and the manufacturing tolerances of Ti-6Al-4V parts built with SLM still require finishing processing to produce the final products. Furthermore, SLM is known to generate tensile residual stresses during the building process, while machining is an optional operation to change from tensile stress to compressive stress. At the same time, most workpieces fabricated by SLM are thin-walled parts. The cutting forces in the process of machining tend to produce unnecessary deformation, resulting in part distortions of machined parts (see Fig. 1). The post machining accuracy must be considered for SLM forming components. The part distortion prediction is necessary before machining. Some methods can be adopted to keep the errors within a certain tolerance range. For different methods to improve the machining accuracy, modelling and simulations to predict the part distortions are useful in verification before expensive experimental tests [3]. Some strategies are listed for improving the final surface topography [4]:

1 Changing machining strategy. Limiting cutting forces and adding sacrificial stiffeners can increase minimum
stiffness, but they often lead to inefficient productivity [5].

(2) On-line error compensation. The surface after machining is measured on-line in real time, and the subsequent processing is modified. Because the machine tool cannot respond to the adjustment in real time, this method has the problem of time delay, which also affects the machining efficiency [6].

(3) Off-line error compensation. Numerical methods are commonly used to predict and simulate the deformation of parts and tools in the process of machining. Compensations for deformation are conducted to improve the machining accuracy.

Although there is a certain deviation between the simulation results and the experimental results, which is due to the incompleteness of the factors considered, off-line error compensation is still a rather better choice based on productivity and usability. Many researchers pay attention to the off-time deformation modelling, error control, and compensation of thin-walled parts.

Song et al. [7] and Shi et al. [8] established a mathematical model for predicting the machining deformation of complex thin-walled structural such as blades by introducing the Rayleigh–Ritz solution. Wu et al. [9] predicted the deformation in thin-walled frame parts based on the finite element model and proposed two methods, large depth of cut and tool path optimization in thin-walled parts. Chen et al. [10] proposed a layered complete compensation and multiple iterative optimization compensation methods for aeronautical annular thin-walled parts to compensate for machining errors caused by machining deformation. They [11] also used multi-layer cutting to improve the machining accuracy of thin-walled parts. Tian et al. [12] performed eigenvalue sensitivity analysis on each position of the thin-walled flat piece to obtain the machining vibration-sensitive area of the workpiece. The characteristic sensitivity analysis and the non-uniform residual distribution were performed to obtain the semi-finished blank workpiece. The test showed that the method has a better control effect on machining vibration and machining deformation and can obtain better surface quality. Shan et al. [13] adopted linear variation sinusoidal trigonometric function based on the geometric shape of the workpiece, the non-uniform margin design of the cantilever direction, and the cross-section direction of the blade. Rahman et al. [14] used a three-dimensional volumetric error model to describe two methods for modifying NC programs for machine tool modelling and measurement. Ratchev et al. [15] and Guo et al. [16] set the establishment of the cutting force model and used elastic mechanics and finite element calculation analysis method to calculate the elastic deformation of thin-walled parts during machining.

In this paper, a Ti-6Al-4V titanium alloy blade was taken as the research object to solve poor surface quality after SLM processing. The error caused by the deformation of the thin-walled parts during the machining process was obtained. Because of residual stresses in SLM parts, there was potential distortion in machining with the release of residual stresses. Two-step machining strategies were proposed to get a precise workpiece. The two-step machining processes were proposed by performing the roughing-semi-finishing-finishing processes. A semi-finish
was conducted to get the non-uniform semi-finished product based on the proposed Ritz solution in the first step. In the second step, finishing machining was conducted to get the final surface.

2 Non-uniform allowances based on machining error prediction model

The blade, one of the most important thin-walled parts, is widely used in aerospace and aeronautic industries, and it is a common component in SLM. The purpose of this section is to establish a mathematical model to predict the part distortions of the blade with complex shape during the milling process after SLM, then non-uniform allowances were allocated based on the Ritz solution.

The following assumptions are made to simplify the calculation of the defined thin-walled blade workpiece [17]:

(1) Milling cutter and the fixture can be considered rigid, and the material of the workpiece is isotropic;
(2) The deformation of the blade is considered as pure elastic deformation;
(3) The milling force loaded on the blade is converted to the concentrated force moving along the feed direction;
(4) There is no initial stress in the workpiece.

The finished surface is generated by the cutter swept envelope. For a given cutting point, the dimensional surface errors are equal to the elastic displacements caused by the cutting force.

The part distortions of the whole blade are determined by the normal distance between the surface swept by the cutter and the rebounded surface after machining. Since the part distortions are measured as the normal deviations between the actual machined surface and the designed surface, the predicted errors are equal to the elastic deformation in every machined area [18].

2.1 Deformation prediction mathematic model

For a complex blade, it can be simplified as a thin cantilever plate. Figure 2 shows the geometry of the blade and its simplified thin cantilever plate used in this paper, respectively. As seen in Fig. 2, the blade has a twisted surface with various thicknesses along the length and height. The blade becomes a cantilever plate with varying thicknesses after it is flattened. The thin cantilever plate is clamped at one edge and other edges are free (Clamped-Free-Free-Free plate).

For the blade, the stiffness in the lateral direction is much higher than in the perpendicular direction. The part distortions after milling are mainly determined by the perpendicular deformation. The governing equation of thin-wall distortions is a fourth-order partial differential equation. The differential equation based on Kirchhoff’s assumptions can be expressed as formula 1 by a transversal deflection [19]:

\[
D\left(\frac{\partial^4w}{\partial x^4} + 2\frac{\partial^4w}{\partial x^2\partial y^2} + \frac{\partial^4w}{\partial y^4}\right) - q = 0
\]

where \( w(x, y, t) \) is displacement of plate at any \((x, y)\) at any particular time, \( q \) is the external load, \( D = Eh^3/(12(1 - \mu^2)) \). Where \( E \) is Young’s modulus of plate, \( h \) is thickness of plate, and \( \nu \) is Poisson’s ratio for plate material.

A typical solution for formula 1 is shown as formula 2, based on our previous research.

\[
w = (C_1 + C_2\sin\frac{\pi y}{2b\sqrt{2 - \mu}} + C_3\cos\frac{\pi y}{2b\sqrt{2 - \mu}})(1 - \cos\frac{\pi x}{2a})
\]

Fig. 2 Blade model and its simplification
where $a$ and $b$ are the length V-direction and U-direction along the plate, respectively, and $D$ is the flexural stiffness of the plate depending on the plate thickness and material properties. The undetermined coefficients $C1$, $C2$, and $C3$ are determined by external load and boundary conditions.

### 2.2 Ritz solution for solving blade part distortions

Ritz energy solution is used to solve the simplified equations. The Ritz solution [20] is based on the principle of minimum potential energy. The true displacement of the system is obtained by solving the displacement that minimizes the system’s potential energy. For the thin-walled part cutting system, the total potential energy of the system can be divided into the strain energy $U$ of the deformed blade and the virtual energy $V$ generated by the cutting force, as shown in formula 3 to formula 5:

$$
\Pi = U + V
$$

$$
U = \frac{D}{2} \int \left\{ \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} \right)^2 - 2(1 - \mu) \left[ \frac{\partial^2 w}{\partial x^2} \frac{\partial^2 w}{\partial y^2} - \left( \frac{\partial^2 w}{\partial x \partial y} \right)^2 \right] \right\} dxdy
$$

$$
V = -\iint qwdx dy
$$

Based on the minimum potential energy theorem, a discrete solution using the Ritz energy solution is proposed. For a specific machining point $(x_c, y_c)$, seen in Fig. 3, the strain energy $U$ can be calculated by formula 6.

$$
U(x_c, y_c) = \frac{E}{24(1 - \mu^2)} \left\{ \int_{f_1}^{f_2} \int_{s_{x_c}}^{a} h^3 \delta dxdy + \int_{s_{x_c}}^{y_c} \int_{x_{s_{x_c}}}^{a} h^3 \delta dxdy + \int_{f_1}^{f_2} \int_{s_{y_c}}^{a} h^3 \delta dxdy + \int_{f_1}^{f_2} \int_{a}^{y_c} h^3 \delta dxdy \right\}
$$

where $f_1$ and $f_2$ are the boundaries of the blade along the $u$ direction and $a_c$ is the length of discrete area which is to be machined in processing. $h$ is the thickness of the blade and $h'$ is the machined thickness of the blade.

According to the measure data, formula 7 is fitted for two edges. According to Table 1, the fitting model of the blade thickness at each position, seen in Fig. 4, is shown in formula 8. The fitting accuracy $R^2$ is 0.97, which proves an acceptable fitting degree.

$$
\begin{align*}
&f_1 : y = 0.10998x \\
&f_2 : y = -0.10998x + 36.66
\end{align*}
$$

### Table 1 Thickness of each position in SLM blade (mm)

| Ratio along V-direction (x-axial) | Ratio along U-direction (y-axial) |
|----------------------------------|----------------------------------|
| 0  | 3/30 | 6/30 | 10/30 | 15/30 | 20/30 | 24/30 | 27/30 | 29/30 | 1 |
| 0  | 0.598 | 1.102 | 1.495 | 1.782 | 1.953 | 2.009 | 1.953 | 1.782 | 1.495 | 1.102 | 0.598 |
| 14/50 | 0.548 | 1.010 | 1.370 | 1.632 | 1.788 | 1.841 | 1.788 | 1.632 | 1.370 | 1.010 | 0.548 |
| 28/50 | 0.498 | 0.917 | 1.244 | 1.482 | 1.624 | 1.672 | 1.624 | 1.482 | 1.244 | 0.917 | 0.498 |
| 38/50 | 0.462 | 0.851 | 1.154 | 1.376 | 1.507 | 1.551 | 1.507 | 1.376 | 1.154 | 0.851 | 0.462 |
| 44/50 | 0.440 | 0.811 | 1.100 | 1.311 | 1.437 | 1.479 | 1.437 | 1.311 | 1.100 | 0.811 | 0.440 |
| 48/50 | 0.426 | 0.785 | 1.065 | 1.269 | 1.390 | 1.431 | 1.390 | 1.269 | 1.065 | 0.785 | 0.426 |
| 1  | 0.419 | 0.772 | 1.047 | 1.247 | 1.367 | 1.407 | 1.367 | 1.247 | 1.047 | 0.772 | 0.419 |
The thicknesses of machined surface are calculated as 
\[ h(x, y) = (1 - 0.006x) \left[ -0.0042 \left( \frac{y - 18.33}{1 - 0.006x} \right)^2 + 0.0011 \left( \frac{y - 18.33}{1 - 0.006x} + 2 \right) \right] \]

The thicknesses of machined surface are calculated as \( h'(x, y) = h(x, y) - a_p \), and \( a_p \) is the set depth of removal material, where the deformation caused difference assumed to be negligible.

Then, virtual work \( V \) is calculated by the work done by the cutting force, as seen in formula 9.

\[ V(x_c, y_c) = \int_{y_c-a_e}^{y_c} \int_{x_c-a_e}^{x_c} F_n w(x, y) dx dy \] (9)

The following equations are based on the Ritz solution, where the variables \( C1, C2, \) and \( C3 \) were calculated.

\[ \frac{\partial \Pi(x_c, y_c)}{\partial C_1} = 0, \quad \frac{\partial \Pi(x_c, y_c)}{\partial C_2} = 0, \quad \frac{\partial \Pi(x_c, y_c)}{\partial C_3} = 0 \] (10)

Substitute back \( C1, C2, \) and \( C3 \) in the assumed solution and each cutting time-domain deformation response of the plate is obtained.

### 2.3 Milling force–deformation coupling prediction model

The effects of deflections for actual cutting forces are not neglected, so an iterative correction algorithm is developed to ensure computation reliability and accuracy. Research results showed that cutting forces were the dominant factors that cause elastic deformation during the machining process. In this study, the forces were only related to the selection of machining parameters. The real-time changing of cutting forces caused by cutting edge cutting was not considered.

The coupling relation between cutting forces and machining distortion was taken into account. Hence, an iteration cutting force algorithm was conducted. The cutting forces were modelled as a moving load along the feed direction to simulate the tool moving along the length of the developed model. The milling forces along the normal to the feed direction became perpendicular load acting on a thin cantilever plate workpiece. A Kistler piezoelectric dynamometer (5698A) was used for machining force measurement to simulate the milling force in the developed model. For blade machining, incline angular was constant so that the calculated cutting force was effective. The incline angular in this paper was set to \( 20^\circ \) [21], as seen in Fig. 5. The parameter of experiments is shown in Table 2. An exponent cutting forces model was used for forces calculation. The fitting models were showed as formula 11. Due to the influence of deformation, the actual cutting depth is less than the designed cutting depth. Therefore, the interpolation method was used to solve the depth of the actual machining iteratively, and when the thickness error of the two steps was less than 1 \( \mu m \), the iteration ended.

\[
\begin{align*}
F_x &= 6.2840n^{0.2011}f^{0.1391}a_p^{0.5657}p^{0.1208} \\
F_y &= 49.879n^{0.1318}f^{0.3518}a_p^{0.7156}p^{0.1804} \\
F_z &= 92.278n^{0.1147}f^{0.3719}a_p^{0.2572}p^{0.5242}
\end{align*}
\] (11)
The discrete allowances elements were faired linearly. The blank model with a non-uniform allowances can be obtained as shown in Fig. 6. Non-uniform allowances allocation based on the above method for the finishing of the SLM titanium blade was allocated. The distribution of the allowances is shown in Table 3. As seen in Fig. 6, the maximum allowance is 0.5 mm while the minimum is 0.1 mm.

### Table 2 Cutting force experiments

| Cutting speed $n$ (r/min) | Feed $f_z$ (mm/z) | Cutting axial depth $a_p$ (mm) | Pitch $p$ (mm) | $F_x$ (N) | $F_y$ (N) | $F_z$ (N) |
|-------------------------|------------------|-----------------------------|--------|---------|---------|---------|
| 4000                    | 0.01             | 0.1                         | 0.1    | 3.9342  | 4.0330  | 14.2870 |
| 6000                    | 0.03             | 0.1                         | 0.3    | 5.2964  | 7.3130  | 32.9494 |
| 7000                    | 0.04             | 0.1                         | 0.5    | 6.4656  | 8.4650  | 54.0447 |
| 5000                    | 0.02             | 0.1                         | 0.7    | 5.0791  | 6.0899  | 51.2042 |
| 6000                    | 0.04             | 0.25                        | 0.1    | 8.1752  | 14.4401 | 26.2529 |
| 7000                    | 0.02             | 0.25                        | 0.3    | 7.4082  | 11.8803 | 31.2424 |
| 5000                    | 0.01             | 0.25                        | 0.5    | 6.6266  | 9.0826  | 38.7016 |
| 7000                    | 0.03             | 0.25                        | 0.7    | 8.7867  | 14.5916 | 55.7250 |
| 7000                    | 0.02             | 0.4                         | 0.1    | 9.6675  | 16.1882 | 26.8982 |
| 5000                    | 0.04             | 0.4                         | 0.3    | 10.8125 | 22.9683 | 39.1205 |
| 4000                    | 0.03             | 0.4                         | 0.5    | 11.2966 | 21.5253 | 51.5833 |
| 6000                    | 0.01             | 0.4                         | 0.7    | 10.7737 | 14.6345 | 41.3644 |
| 5000                    | 0.03             | 0.55                        | 0.1    | 10.2253 | 11.5557 | 17.5511 |
| 7000                    | 0.01             | 0.55                        | 0.3    | 13.5249 | 18.0868 | 33.4873 |
| 6000                    | 0.02             | 0.55                        | 0.5    | 15.2008 | 24.1575 | 46.5286 |
| 4000                    | 0.04             | 0.55                        | 0.7    | 16.4294 | 32.5781 | 66.9200 |

3 Methodology

3.1 SLM progress

The SLM blade samples were built using an MLab Cusing machine M2 from CONCEPT LASER. Ti6Al4V powders were prepared as the bed powder fusion to form the samples. The chemical composition of the powder is listed in Table 4. The processing parameters were adjusted to be optimized according to the previous studies, as seen in Table 5. No further changes to the process parameters were made during the build process. Figure 7 shows the samples fabricated. The designed blade has a height of 50 mm, and the thickness varies from 1.99 to 2.88 mm. Note that in this case, the base of the built titanium blade has one plat step to make it easier to perform accurate machining and measurements. Once the SLM forming was finished, the parts were cleaned and stresses relieved according to the specification.

3.2 Machining experiments

The semi-finishing and finish machining were conducted with a 5-axis CNC milling machine (Willemin 408S2). The two-fluted carbide ball end with a diameter of 6 mm and a helix angle of 30° was used to cut SLM samples, the same kind of tools used in Sect. 2.3. The tool paths for the five-axis milling of the blade were generated with HyperMill software using a 5X-ISO module (see Fig. 8). Machining tests were carried out with oil coolants. In addition, a ruby probe was used to calibrate the benchmark plane of the finishing machining. Other than allowances, the machining conditions for the two samples were the same.

Two-step machining processing was carried out to obtain a better machining quality. An optimum non-uniform blank with calculated allowances was achieved in the first step. The blade geometries after semi-finishing with two different allowances were used for comparison. Uniform blade geometry had identical allowances of 0.5 mm. The
Ritz allowances were generated with the continuous envelope surface by connecting the discretely non-uniform allowances, according to Sect. 2.3. A spline curve connects each point. A traditional machining strategy was applied to fulfill the final machining in the second step.

### 3.3 Finite elements method verification

The finite element analysis (FEA) approach can be used for part distortion prediction. In this paper, part distortions were caused by elastic deformation, so FEA is also a method for part distortions verification. To verify the proposed Ritz method, FEA was used to compare the part distortions produced by different allowances allocation. The geometry model of the blade was imported into the Ansys software, and the coordinate system in the Ansys software was consistent with the coordinate design system of the blade. Material attributes of SLM Ti-6Al-4V alloy used in the FEA were Young’s modulus of 110 GPa, the density of 4430 kg/m³, and Poisson’s ratio of 0.3. Efficient hexahedral units were used to divide the grids [18]. The FE model of the initial workpiece was built with a fixed constraint to the blade bottom surface. Cutting force was loaded using the APDL*Model Change keyword. The elemental cutting forces were then equally distributed into the grid nodes involved in the swarf region. Meanwhile, these forces were all described in the OX0Y0Z0 coordinate system. Thus, after the deformation of the workpiece was computed, the spatial displacements of the grid nodes should be converted into the OXYZ coordinate system for iterative computation, shown in Fig. 9. The whole analysis process is shown in Fig. 10. During the simulation of machining, the removal of material was realized through the concept of element death in FEA software. In addition to uniform allowances and Ritz non-uniform allowances, sinusoidal allowances as one more non-uniform allowances were analyzed for comparison.

### 3.4 Result measurement

#### 3.4.1 Part distortion measurement

The surface displacement profiles of the two allowances allocation samples were measured with a HEXAGON coordinate measuring machine by using a 1.5-mm-diameter touch probe. The measurement accuracy of this instrument was 2 μm. The measurements were carried out in a temperature-controlled room with a temperature of 20 °C. The part distortions were calculated considering the distance between the measurement points and locations of the 3D designed model. The measuring direction was normal to surface of the part along the V-direction. The predicted part distortions at 5 × 7 sampled points on the designed surface were compared with the experimental measurement. The five ratio values along the U-direction were 0.15, 0.35, 0.55, 0.75 and 0.90, and seven ratio values along the V-direction were 0.08, 0.22, 0.36, 0.50, 0.64, 0.78 and 0.92. The measure points located on or close to the boundaries were not considered to avoid unwanted measure uncertainties. Because the surface had a little curvature, there would be errors during measurement, as shown in Fig. 11. In Fig. 11(c), the measurement error can be calculated by the following equation:

\[
\text{Error} = r \cdot \left( \frac{1}{\cos \alpha} - 1 \right)
\]

where \(r\) is the radius of the sphere and \(\alpha\) is the angle of surface curvature.

### Table 3
Non-uniform allowance of each position in SLM blade (mm)

| Ratio along V-direction (x-axial) | Ratio along U-direction (y-axial) |
|----------------------------------|----------------------------------|
| 0 | 1/30 | 3/30 | 6/30 | 10/30 | 15/30 | 20/30 | 24/30 | 27/30 | 29/30 | 1 |
| 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| 0.218 | 0.245 | 0.275 | 0.307 | 0.350 | 0.373 | 0.350 | 0.307 | 0.275 | 0.245 | 0.218 |
| 0.138 | 0.147 | 0.159 | 0.172 | 0.187 | 0.195 | 0.187 | 0.172 | 0.159 | 0.147 | 0.138 |
| 0.117 | 0.123 | 0.130 | 0.137 | 0.145 | 0.150 | 0.145 | 0.137 | 0.130 | 0.123 | 0.117 |
| 0.108 | 0.112 | 0.119 | 0.127 | 0.132 | 0.137 | 0.132 | 0.127 | 0.119 | 0.112 | 0.108 |
| 0.105 | 0.110 | 0.116 | 0.123 | 0.130 | 0.123 | 0.116 | 0.110 | 0.105 | 0.1 | 0.1 |

### Table 4
Chemical composition of Ti-6Al-4V (mass fraction, %)

| Al | V | O | Fe | C | N | H | Ti | Others |
|----|---|---|----|---|---|---|----|--------|
| 5.5–6.75 | 3.5–4.5 | 0.13 | 0.14 | 0.007 | 0.007 | 0.002 | Bal | <0.05 |
3.4.2 Residual stress measurement

Residual stresses in the machined parts were measured using the X-ray diffraction technique, consisting of determining the variations in peak positions due to distortions of the crystalline lattice. The measurements were performed using an X-350A residual stress measurement system with a portable MG40P standard $\Psi$-$2\theta$ goniometer. The parameters used in the X-ray analysis are shown in Table 6. The errors of residual stress of titanium alloy measured by XRD are 10%. All the stress analysis directions were along the SLM building direction ($\sigma_{xx}$). The positions of surface residual stress were located at the centerline of the blade. The five measure points were along the V-direction, and their ratio values were 0.78, 0.15, 0.35, 0.55, 0.75, and 0.90. The point of $v=0.75$ was selected to analyze the stress profile in depth. The depth profiles of residual stresses were determined through the electro-polishing material removal in steps of 0.01 mm.

3.4.3 Surface roughness measurement

The average surface roughness ($R_a$) was taken in account for the present research. The roughness of machined surface mainly depends on the row spacing direction relative to the machining. The surface roughness was measured by using an ISR-S400 5-μm stylus type instrument from INSIZE. The measurement accuracy of this instrument was 0.002 μm. The measurements were conducted five times, and a mean value was taken for final results. The five measuring points were located in the upper left, lower left, upper right, lower right, and middle of the blade. The residual height in machining row spacing was the maximum roughness direction, so the measure direction was along the U-direction.

4 Result and discussion

The machined blades are shown in Fig. 12. The surface topography was obviously different between before and after machining processes. The machined surface roughness of blades with uniform allowances and Ritz allowances was $0.854 \pm 0.282 \mu m$ and $0.815 \pm 0.241 \mu m$, respectively, while the roughness of the as-built surface was $7.88 \pm 1.292 \mu m$.

4.1 FEA results

The simulated deformations of the blade with three different allowances after milling are shown in Fig. 13. The part distortions of uniform allowances were larger than that of the other two non-uniform allowances. The largest error area of the blade was mainly located on the tip of the blade. The relative stiffness of the two tips of the blade was small and the deformation was large. The deformation decreases until the base of the blade along the V-direction.

![Diagram of 5-axis milling generated with HyperMill](image-url)
Fig. 9 Diagram of coordinate transformation

The relative stiffness of the blade was high at the base of the blade. As seen in Fig. 13, the dimensional part distortions of the blade first increased and then decreased non-linearly along the U-direction. The maximum deformation of the uniformed blade was 0.1940 mm, while the ones of sinusous allowances and Ritz allowances were 0.1165 mm and 0.0748 mm, respectively. It showed that the magnitude of the machining errors with a non-uniform allowances can be significantly reduced by at least 62% compared to errors with uniform allowances. Also, it shows that the precision of the thin-walled blade with non-uniform allowances strategies was greatly improved. The finite element simulation results showed that, compared with the traditional uniform allowances distribution method, the non-uniform allowances distribution method proposed in this paper could effectively ensure the stiffness of parts and reduce the part distortions of parts. At the same time, the maximum error produced by proposed method was smaller than that produced by sinusoidal allowances in reference [12].

4.2 Experiment results

The tool path started in the suction side on the blade top. So the maximum part distortion was located in point 1 on line #1, as shown in Fig. 14(a). The maximum machined part distortion resulting from the uniform allowances reached 0.30 mm. However, the machined part distortion result from the proposed Ritz non-uniform allowances was about 0.15 mm. The machined part distortions were generally reduced by 50%. Three specific part distortions on both blades were compared along the tool path. The trend of the experimental part distortions of the blade sampling points along the u and v directions was in good agreement with the simulation results, but the relative magnitude of the errors was determined by a certain error. The maximum prediction error is 50%, and the average prediction error was 30%. Figure 14 shows the comparison of the part distortions of the two kinds of allowances at the selected position on the blade, in which the part distortions of line # 1 are along the V-direction, and line # 2 and line # 3 are along the U-direction.

As illustrated in Fig. 14(b), the part distortions decreased gradually along the v direction, consistent with the blade with uniform allowances. The two allowances showed the maximum part distortion at the tip of the blade. By evaluating the stiffness of the transition state of each machining feature, the Ritz non-uniform allowances were distributed to ensure the stiffness requirements in the finishing process. The distribution tendency was consistent with the FEA results.

Figure 14(c)–(d) compares and analyzes the part distortion of uniform allowance and Ritz allowances at the positions of \( v = 47 \) mm (# line 2) and \( v = 30 \) mm (# line 3) along
the feed direction. On \( v = 47 \text{ mm} \) (# line 2), the part distortion values of experiment and simulation showed a uniform non-linear first decreasing and then increasing trend with the increase of the machining path along the feed direction. Nevertheless, on \( v = 30 \text{ mm} \) (# line 3), the variation along the feed direction was not as large as that near the blade tip, and the difference of relative maximum part distortion was smaller.

### 4.3 Residual stress results

As shown in Fig. 15, the residual stress at each point of the blade showed a certain difference. Figure 15(b) shows the values of residual stresses along the \( V \)-direction at five specific points of the machine blades and unmachined samples with Ritz non-uniform allowances. The values of residual stresses along the \( V \)-direction increased with the distance from the base. Before machining, the residual stresses of the SLM sample were tensile, while the machined surfaces of both blades presented compressive residual stresses. As for the as-built SLM blade, with the increasing number of layers, heat accumulated in the formed layers, which reduced the temperature gradient in part. Hence, the tensile stresses showed a trend that decreases from top to bottom. Consistent with the previous study, residual stresses on the top surfaces were compressive because the ploughing effect of cutting tools was obvious on the machined surface. The experimental results
revealed the influence of the machining process on residual stresses (Fig. 15). The machined effects to residual stresses could reach about 0.1 mm, as seen in Fig. 15(c).

### 4.4 Discussion

The surface roughnesses of SLMed parts were large due to contour remelting and powder sticking during SLM manufacturing. After being machined, the surface roughnesses of SLMed parts were greatly reduced. The residual height of ball-end milling had a certain influence on the finish surface, resulting in the roughness of adjacent row spacing, and the roughness was about 1 μm.

The part distortion results of the machined blade with non-uniform allowances based on the Ritz method were presented and compared to that with uniform allowances in this paper. The distortions' variation caused by the second-time machining decreased with the smaller cutting volumes. Moreover, the initial and machining-induced residual stresses could be released. Therefore, the experiments and FEA simulations validated the

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### Table 6 Parameters used in the X-ray analysis of Ti-6Al-4V

| Parameters          | Value                  | Parameters          | Value                  |
|---------------------|------------------------|---------------------|------------------------|
| Test material phase | α-Ti                   | ψ angular          | 0°, 24.2°, 35.3°, 45° |
| Wavelength radiation| Cu – Kα               | Filter              | Ni                     |
| Bragg angle 2θ      | 137°–147°, (hkl) = (213)| Voltage             | 22 kV                  |
| Stress constants    | –277 MPa               | Current             | 6 mA                   |
| Scanning step       | 0.1°                   | Collimating tube diameter | 3 mm                  |
| Elastic constants   | 11.8878 Pa⁻¹          |                     |                        |

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Fig. 11 Diagram of part distortion measurement. (a) Measuring points, (b) measuring direction, and (c) measuring error diagram

Fig. 12 Blade samples after SLM. (a) Blade before machining, (b) machined blade with Ritz allowances, and (c) machined blade with uniform allowances
accuracy and effectiveness of the proposed model. Such results indicated that the proposed non-uniform allowances based on Ritz method for SLM parts could be used for high precision machining. Nevertheless, the experimental results were not fully consistent with the results of FEA. The FEA results obtained with different allowances were smaller than the experimental ones measured by coordinate measuring machine. The cutting force, cutting heat, and the fixture load in the cutting experiments, which were not considered in the FEA model, were the main reasons for the errors. Meanwhile, the errors introduced in three coordinate measurements could not be completely avoided, and most experimental methods and empirical models only showed a trend of the comparative results.

Rapid heating and cooling cycle in SLM will lead to a large thermal gradient in forming structure. It will result in large residual stress, especially in build direction. When there is residual tensile stress on the surface, the initiation and propagation of surface cracks will accelerate. When compressive stresses are generated, they help to improve fatigue performance and corrosion resistance [22]. The equivalent stresses on the flank of the tool will produce compressive residual stresses on the surface of the finishing blade. The depth of the compressive layer approximates the radius of the cutting edge. Residual stresses in axial direction were a little more compressive than the residual stresses in feed direction [23]. Structural and dynamic performance of the blade changed as the cutting process was continually carried out. All the changes and changing cutting temperature generated different residual stresses in each region of the surface of the workpiece after machining [24]. However, the machining-induced stresses were compressive, and the compressive residual stresses were beneficial to the application of parts.

Fig. 13 Residual errors on pressure side and suction side of machined blade with three kinds of allowances
Fig. 14 Comparison of part distortions for milling of blades with uniform allowances and Ritz allowances. (a) Schematic diagram of measure points, (b) Results of line #1, (c) Results of line #2, and (d) Results of line #3.
Conclusions

Blade parts fabricated by SLM have poor surface integrity and high residual stresses. In this paper, a novel machining strategy for Ti-6Al-4V blade parts fabricated by SLM was proposed. The part distortions caused by the elastic deflection were considered. A two-step machining strategy was proposed and proved to improve the machining accuracy and surface quality. FEM simulation and experiment validation were conducted to validate the efficiency of the proposed method. The main findings are summarized as follows:

1. SLM-fabricated parts have poor surface and high tensile residual stresses. The average surface roughness is 7.88 μm. Tensile residual stresses range from 20 to 222 Mpa. Poor initial surface morphology and roughness of as-built Ti-6Al-4V sample result from melt traces and bonded powders; high tensile residual stresses are related to fast cooling rate during SLM processing.

2. Ritz energy solution for thin wall deformation is suitable for predicting part distortions. Compared to experiments validation, the prediction model has good consistency with the experiment results. The non-uniform allow-

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Fig. 15 Residual stresses of the blade with Ritz allowances after machined. (a) Schematic diagram of measure points, (b) Residual stress results of pitched points, and (c) Residual stress results of pitched points along depth.
ances based on the Ritz solution could decrease the part distortions, the maximum part distortion decreased by 50%, and the finite element analysis and the experiment results showed the method could decrease the errors due to deformation.
3. Two-step machining could improve the surface precision and better residual stresses. Residual stress after machining was compressive stress, which was beneficial when the fatigue strength of the blade was considered and hence was sought after. Meanwhile, better surface roughness of 0.815 μm was achieved.
4. The experimental validation showed that simulated modeling of machining deflections for the blade leads to an acceptable prediction of the dimensional part distortions. The present research provided the support for the potential application to achieve better surface quality for SLM blades. The non-uniform allowances method has been successfully implemented in the SLM blade milling, and its principle can be transferred to other thin-walled SLMed parts. Although the results are encouraging, the proposed method cannot eliminate surface errors. Moreover, the method may be unable to handle special parts, such as lattice parts. Further researches need to be explored.

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Declarations

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