ABSTRACT

Large deformation and cutting vibration is an important problem in the process of manufacturing ultrathin blade of integral impeller, thus the deformation of the ultrathin blade under concentrated load is analyzed in this paper. The non-uniform allowance process is applied to optimize the manufacturing process of impeller, by which the manufacturing experiment is done on impeller. The results show that the maximum error optimization rate is 62.06% and the average error optimization rate is 55.47%, thus the strategy can effectively reduce the milling deformation of ultrathin blade, especially the manufacturing error of the front blade and the trailing edge with poor rigidity. The research is of significance to the actual production of integral impeller with complex curve surface, and also suitable for the unusual-shaped blade.

INTRODUCTION

The integral impeller is the key part of turbomachinery, which has an important role on mechanical properties of turbomachinery. Based on the advanced manufacturing technology such as structure technology, material technology and computer integrated manufacturing technology, the design of integral impeller took an appearance of new style and characteristics, such as big distortion camber of blade, wide blade chord, thin blade and bigger sweep forward and so on[1]. The thinnest thickness of some ultra-thin blade applied in the field of aerospace is 0.5mm or less ($\delta_{\text{min}} \leq 0.5\text{mm}$). Such parts with complex surface modeling has weak rigidity and the material removal rate in the whole manufacturing process of which is up to 85%~95%, thus such manufacturing defect as overcut and undercut usually appear in the manufacturing process due to the comprehensive influence of
force, clamping force, cutting vibration, metal fiber deformation and residual stress, which may even cause blade fracture and scrap page.

At present, the researches on the milling rigidity of the parts with weak rigidity mainly focus on theoretical analysis and numerical simulation analysis. Chenwei Shan[2] invented a process to strengthen the rigidity of thin blade based on non-uniform stock. FEA analysis on the deformation of aircraft engine blade in the processing was carried on by Li Hao[3] and Jia Liwei[4], the deformation was compensated in the program to realize offline compensation of engine blade’s processing error. Chengming Le[5] proposed a cold and hot manufacturing process for aluminum alloy thin-wall parts. Zengqiang Wang[6] and his partners have also studied error compensation technology of the deformation of complex thin-wall parts. The geometric error of the part and the deformation of the cutting tool were predicted by Habibi[7] using mechanical model, and the code of tool/geometric error was corrected by applying cube compensation method. The system rigidity of the impeller of professional manufacturer in the process of manufacturing was mainly improved by cutting tool selection and fixture selection. The professional manufacturer of the impeller always improves the system rigidity by choosing cutting tools and the clamp[8]. However there is still lack of the research on the process optimization to improve the manufacturing precision by the use of the variable rigidity of integral impeller itself in the process of manufacturing.

The integral impeller with complex surfaces ultra-thin blade was chosen in this paper as the object. The deformation rule of ultra-thin blade was studied by loading force on it, and the design of non-uniform stock reservation on the blade height direction and transverse direction was proposed. Thus the bending strength of the weak rigidity structure of ultra-thin blade could be strengthened, process parameters could be optimized, milling vibration could be effectively reduced and the manufacturing precision of the integral impeller could be finally improved, which can meet the requirements of the design documents and technical documents.

**FEA ANALYSIS OF THE DEFORMATION OF THE BLADE**

**Empirical Equation of Milling Force**

The empirical equation of the milling force of the ball end mill is applied in this paper. According to the the principle of metal cutting, there are complex index relationship between cutting force and cutting parameters with certain material and geometry parameters of cutting tools. The general equation is as follows:

\[
\begin{align*}
F_x &= C_{Fx} n^x a_p^y f_z^m R^n \\
F_y &= C_{Fy} n^y a_p^x f_z^m R^n \\
F_z &= C_{Fz} n^z a_p^y f_z^m R^n
\end{align*}
\]

Where \( F_x, F_y, F_z \) is the three direction of the milling force, \( C_{Fx}, C_{Fy}, C_{Fz} \) is the coefficient, they reflect the material and milling conditions, \( a_p \) is cut depth, \( n \) is the Spindle speed, \( f \) is the cut feed, \( R^n \) is the nominal radius of the ball-end cutter, \( x, y, z, m \) is undetermined coefficients. The base material of the
integral impeller is 6061 aviation duralumin in this paper, the performance parameter is shown in Tab.1.

| Density (g/cm³) | Poisson ratio | Tensile strength (MPa) | Yield strength (MPa) |
|-----------------|---------------|------------------------|----------------------|
| 2.7             | 0.33          | 310                    | 276                  |

The mechanical model of ball end mill is as equation (2)[9].

\[
\begin{align*}
F_x &= 2.68n^{0.011}a_p^{0.566}f_z^{0.371}R^{0.365} \\
F_y &= 0.302n^{0.227}a_p^{0.336}f_z^{0.5369}R^{0.5825} \\
F_z &= 2.6656n^{0.01}a_p^{0.5664}f_z^{0.3722}R^{0.3679}
\end{align*}
\] (2)

FEA Simulation of the Deformation of Blade

The only constrain should be defined at the connection of the blade root and the hub due to the special structure of the impeller. And the cantilever theory can be applied here, thus the blade root can be completely constrained. The blade has complex structure which is belong to undeveloped ruled surface. The surface equation of the blade is \( S(u,v) \), the cross section direction is defined as \( u \), the height direction is defined as \( v \).

1) A sheet with the sizes 60 mm x 45 mm, the top thickness of which is 0.8mm and the bottom thickness of which is 1.8mm is defined to be the object for the proximate analysis of static deformation trend, it is named Blade_1. Another sheet is defined as Blade_2. The line at the 20% and 50% height of the thin plate is defined as the dividing line. Where the two sides of the plate with the height between 0 ~20% were thickened 0 mm, the two sides of the plate with the height between 0 ~20% were thickened 0.2 mm, the two sides of the plate with the height under 50% were thickened 0.5 mm. Force of 5N was loaded on the crown, and the load is gradually increased to 30N, results is shown in Table 2.

| \( F \) (N) | Displacement of Blade_1 (mm) | Stress of Blade_1 (N/mm²) | Displacement of Blade_2 (mm) | Stress of Blade_2 (N/mm²) |
|-------------|------------------------------|---------------------------|------------------------------|---------------------------|
| 5           | 0.132                        | 6.959                     | 0.0351                       | 2.984                     |
| 10          | 0.263                        | 13.92                     | 0.0703                       | 5.968                     |
| 15          | 0.394                        | 20.72                     | 0.1054                       | 8.953                     |
| 20          | 0.526                        | 27.63                     | 0.141                        | 11.937                    |
| 25          | 0.657                        | 34.54                     | 0.176                        | 14.920                    |
| 30          | 0.789                        | 41.45                     | 0.211                        | 17.905                    |

It obviously that under the same concentrated load the maximum displacement of the gradually thickened thin-walled part is reduced about 73.4% and the maximum stress is reduced about 57.1% of that of the original structure. Thus the gradually thickened structure has significant bending resistance.

2) The continuous tooling path on direction \( u \) is discretized into 11 cutting position, and the continuous tooling path on direction \( v \) is discretized into 10
cutting position. The milling force on direction $x, y, z$ is calculated according to ball end mill model. The milling force at contact point of each tool is loaded on node which is nearest to the point. Thus the deformation law is solved.

It can be seen from Fig.1 that the largest deformation is at front blade $u = 1$ and at the blade tail $u = 11$. The minimum deformation is at $u = 6$ and $u = 7$. Through the averaging of the deformation at all the nodes with the same code name that the largest deformation is still at the blade edge and the minimum deformation is at the middle of the blade.

![Figure 1. u Direction Deformation Trend of Blade.](image1)

![Figure 2. The Surface Chart of the Attenuation Velocity of Deformation.](image2)

The decreasing curve of the deformation is shown in figure2. The decreasing rate of $u = 1$ and $u = 11$ is 0.1691 and 0.173, which of other points are all below 0.09. The maximum decreasing rate of the root curve happened at the two edges is $k_{\text{max1}} = 0.8333$ and $k_{\text{max2}} = 0.7$, which of other points are all below 0.5. The decreasing rate of the average deformation curve at the two edges is $k_1 = 0.152$ and $k_2 = 0.1594$, which of other points are all below 0.1.

According to deformation of direction $u, v$, the deformation law of the whole blade can be obtained.

1) The front edge and tail edge of the blade have the largest deformation in direction $v$.

2) The crown of the blade has the largest deformation and the root has the minimum deformation in direction $u$.

3) The deformation is easy to happen at the front and tail with thin structure. Farer the distance with the root, larger the deformation.

**OPTIMIZATION STRATEGY OF THE NON-UNIFORM ALLOWANCE**

The deformation law of ultrathin blade can be obtained by above analysis. The vibration and deformation of milling can be effectively reduced through cutting by area in direction $u$ and gradually increasing the blade thickness in direction $v$. The Process is as follows:

1) The blade is layered in direction $v$. Supposing that the blade height is $H$, the blade is divided into 10 equal parts from crown to root, $C_x$ is the ratio of the
height of layer $x$ to the whole height, $L_x$ is the length of layer $x$. The first layer is the first two parts from crown to root, that $L_1=C_1$, $H=20\% H$, and so on. The allowance in direction $u$ is set. $\Delta_x$ is the thickness increase of layer $x$ at direction $u$, thus

$$\begin{align} 
\Delta_x &= \frac{C_x \varepsilon}{H} + \Delta_{x-1} \\
\varepsilon &= \frac{H}{\delta} \\
x &= 1, 2, 3
\end{align}$$

(3)

Where $\varepsilon$ is the ratio of average thickness of the blade height and the thickest thickness of impeller shroud and blade root, $\bar{\delta}$ is the average thickness of the maximum thickness of impeller shroud and blade root, $H$ is overall height of the blade, $\Delta_0 = 0$.

If $\Delta_x \leq 0.4 \text{mm}$, path number is 1, if $\Delta_x > 0.4 \text{mm}$, path number can be increased according to different tools to insure the roughness of the ultrathin blade.

2) The blade of the integral impeller with axial flow type is spindle shaped, the middle of the front blade and tail blade are even thinner. From the above analysis, there are large deformation in the area which is 5\%~25\% near front or tail, the rigidity of the middle area of the blade about 25\%~75\% is well. Therefore, the non-uniform allowance strategy is designed as figure 4 that the blade is cut by area. The front blade and tail blade with weak rigidity are cut firstly because the rigidity is still well, thus the size of two parts can meet the requirement. Then the middle part of the blade with good rigidity is cut. The process of ultrathin blade is shown in Fig4.

![Figure 3. Non-uniform Allowance Process.](image1)

![Figure 4. Machining Process of Impeller.](image2)
EXPERIMENTAL VERIFICATION

The axial flow type integral impeller with complex surface curve is taken as the object in this experiment with the maximum diameter of \( D = \phi 247.7 \text{mm} \) and the height of \( H = 50 \text{mm} \). The material is 6061 aluminum alloy. The diameter of the hub is \( D_h = \phi 159.5 \text{mm} \), the maximum width at the crown is \( W_{\text{tip}} = 37.77 \text{mm} \), and the minimum width at the root is \( W_{\text{root}} = 17.21 \text{mm} \). The maximum thickness of the blade is \( \delta_{\text{max}} = 3.077 \text{mm} \), at which point the ratio of the height to the average thickness of the maximum thickness of the crown and root is \( \lambda = 20.72 \). While the minimum thickness of blade is only \( \delta_{\text{min}} = 0.19 \text{mm} \). The tool path of each process and tool path simulation which was designed by applying the non-uniform allowance strategy and the process parameters in Table 3 is shown in Fig.5.

| Tool Type          | Machining Content                  | Spindle speed (r/min) | First cut feed (mm/min) | Cut feed (mm/min) | Cut depth (mm) |
|--------------------|------------------------------------|-----------------------|-------------------------|-------------------|----------------|
| \( \Phi 6_{-8^\circ} \) taper rose cutter | Layered rough finish of channel    | 16000                 | 1000                    | 4000              | 2.5            |
| \( \Phi 5_{-6^\circ} \) taper rose cutter | Leading edge fine finish           | 20000                 | 3000                    | 5000              | 0.15           |
| \( \Phi 5_{-6^\circ} \) taper rose cutter | Trailing edge fine finish          | 20000                 | 3000                    | 5000              | 0.15           |
| \( \Phi 5_{-6^\circ} \) taper rose cutter | Blade fine finish                  | 20000                 | 3000                    | 5000              | 0.15           |
| \( \Phi 5_{-6^\circ} \) taper rose cutter | Channel fine finish                | 20000                 | 1000                    | 5000              | 0.3            |

Figure 5. Tool Path Planning and Simulation Based on NX.

Figure 6. The cutting test.

The tool path was converted into NC code for the cutting experiment on the MIKRON UCP800 cradle type high speed five-axis machining center. The forged blank of 6061 after finish turning and distressing was clamped on workbench by three-jaw chuck and alignment mandrel. The alignment of the radial run-out of \( \geq 0.02 \text{mm} \) was performed by two dial gauges. Then a lot of coolant was used to
flushing and cleaning the chip in order to ensure the force directivity, well cutting performance and the life of cutting tools. The experiment method is shown in Fig.6.

The reverse modeling was done by Geomagic software after 3d scanning, the surface contour model of which was compared to that of the tool path planning. Thus the manufacture error of the integral impeller could be obtained, which was compared with that of the original process. Results show that the maximum error of curve manufacturing has been decreased from 0.311mm to 0.118mm and the average error has been decreased from0.128mm to 0.057mm as well, the maximum error optimization rate is 62.06% and the average error optimization rate is 55.47%.

| Table 4. max error before optimization and after optimization. |
|---------------------------------------------------------------|
| Name                           | Value   |
| Maximum error before optimization          | 0.311 mm |
| Average error before optimization         | 0.128 mm |
| Maximum error after optimization          | 0.118 mm |
| Average error after optimization          | 0.057 mm |
| Maximum error optimization rate           | 62.06%  |
| Average error optimization rate           | 55.47%  |

SUMMARY

1) The deformation law of the blade with complex curve was obtained by using FEA analysis on the ultrathin blade of axial flow shaped impeller.

2) The non-uniform allowance strategy was designed, and the blade was thickened by layer in the height direction and cut by area in cross section direction.

3) The integral impeller is taken as an object in cutting experiment, the NC program of which is produced after tool path planning by optimized process. The results were compared with that of the original manufacturing method that the strategy proposed in this paper could effectively reduce the manufacturing error of ultrathin blade.

4) The error optimization effectivity is especially outstanding for front blade and tail blade with weak rigidity. The results are of significant to the manufacture of the similar blade of the integral impeller with complex curve. Otherwise the strategy is also suitable for manufacturing the unusual shaped blade with extended front and tail.

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