FEA Analysis and Fatigue Life Prediction of Aircraft Turbine Disk
Muhammad Adnan¹, Liu Shujie¹

¹ School of Mechanical Engineering, Dalian University of Technology, Dalian 116024 China

ABSTRACT

This paper represents the fatigue life Prediction of aircraft turbine disk. Low-cycle fatigue of remanufactured turbine disk has been carried out through finite element simulation analysis. First establish the remanufactured turbine disc finite element Model, considering its service characteristic load, through simulation to calculate the stress and strain distribution results at its maximum speed and slow speed. The life of an aircraft turbine disk at a critical stage can be effectively calculated using the finite element analysis method. Aircraft turbine disk have been designed and simulated by abacus. The material properties of Inconel 718 alloy have been used. By applying load and boundary condition on the turbine disk simulation results have been calculated. Different results such as maximum principal stress, minimum principal stress, nodal temperature, pressure, spatial distance and heat flux have been calculated out. Secondly, critical point has been pointed out on the turbine disk having maximum stress effect such as disk bore, fir tree area and assembly holes. After calculation results show that turbine disk bore has maximum stress and its critical point. Fatigue life has been calculated at the turbine disk bore by morrow equation.

Keywords: TURBINE DISK, FATIGUE LIFE ESTIMATION, INCONEL 718 ALLOY, FINITE ELEMENT ANALYSIS, MORROW EQUATION

1. Introduction

The aerospace industry has always a great significance to support area for the country. Every government has focused on making policies to promote the development of the aerospace industry. Recently aerospace industry gains much importance because of their significance and to and to manufacture costly aerospace parts and to remanufacture (1). Aircraft Turbine Disk is the main component of the aero engine. It has been working under extreme conditions for a long time, and has high requirements for materials, design, manufacturing and maintenance. Each aero engine has hundreds of blade and disks components, and the failure of the disk creates an extremely serious hazard, which can cause huge economic losses and casualties.
if it is dangerous. Nowadays, the failed disks are replaced and repaired. Because of high cost of blade manufacturing, the economic benefits of direct replacement after failure are too low, so the remanufacturing is very important.

Alloy 718, also known as Inconel 718, is a nickel-iron-based superalloy with a high strength. Where high temperature strength, fatigue resistance, and oxidation resistance are needed, this material is used. In addition, the aircraft industry, medical tooling, jet engines, and gas turbines are also popular applications. “Alloy 718 was a natural candidate material for many gas turbine applications due to its unusual property balance, ability to be treated as both a wrought and cast component, and weldability.

Many researchers have worked on the fatigue life Prediction of aircraft turbine disk. Z. Zhang (2) has proposed the creep life prediction model of the aircraft turbine disk alloy and then he combine the test data result with finite element result. J.L. Wang (3) Has predicted the fatigue life model by the analysis of fatigue failure. He has also proposed a life prediction model by surface roughness of the material. S.P. Zhu (4) Proposed a probabilistic procedure of fatigue life Prediction and reliability analysis of a high-pressure Turbine disk by using finite element analysis with the effect of variation of load. In working conditions, the P-S-N curve of the high-pressure turbine is plotted against the P-S-N curve of GH4169 and then the fatigue life is measured. M.N. Menon (5) Established a lifting criteria for turbine disc bore by multiracial state of stress. M.N. Menon has presented a method to determine the minimum low cycle fatigue life of disc bore by won mises stress distribution by using Inconel 718 material for testing. L. Witek (6) have performed a failure analysis of aero engine turbine by fine element analysis. By calculating the von mises stress lucijan pointed out the critical region of failure such as third lower slot of turbine disc. S.P. Zhu (7) proposed a life prediction model of aircraft turbine disk using Bayesian theorem and to check the feasibility LCF test data were compared with the predicted result.

The main objective of this paper is to design the simulation model of aircraft turbine disk by using solid works and Abaqus for analysis. Material property of Inconel 718 alloy will be used. After applying load on the turbine disk their effecting parameters such as stress strain, temperate, pressure, and Nodel displacement will be calculated. The critical point of the turbine disk will be pointed out having maximum stress such as Disk bore, web and assembly holes area. At critical point fatigue life of the turbine disk can be estimated by using morrow equation.

2. **Turbine Disk model**

2.1. **Design of disk**

For the designing of aircraft turbine disc finite element analysis is performed using Abacus 6.14 to determine the distribution of stress and their deformation at the critical region. A 2D model of turbine disc have been generated on abacus which is shown in Figure 1 and their measuring parameters have been taken from the reference paper (8). We assumed plane stress condition acting on its diversity basis. Inconel 718 alloy is used as a material for aircraft turbine disc because it has good chemical and mechanical property,
good corrosion resistance.

![Figure 1. A 2D model of turbine disk](image)

2.2. Properties of disc

2.2.1. Chemical properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical composition</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inconel 718 alloy</td>
<td>55Ni18Cr14.8Co3Mo1.25W5Ti2.5Al0.035C</td>
<td>Nickel-base super alloy, ingot metallurgy / powder metallurgy route</td>
</tr>
<tr>
<td></td>
<td>0.033B0.03Zr</td>
<td></td>
</tr>
</tbody>
</table>

2.2.2. Mechanical properties

A turbine disc having 41 mortises have been generated on abacus. Having axially symmetric structure and blades are uniformly distributed on the rim. Since meshing the entire turbine disc is complicated, 1/41 of the turbine disc is chosen by considering the axial symmetry of the turbine disc to construct a finite element model and test the fatigue life longevity in this study. 1/41 model meshing of geometric structural is used for a multizone method and free mesh type hexagonal dominant. We got a statistics node at 11126 and elements at 2594. Figure 2 illustrates properly where (a) 3D model of Disk and (b) 1/41 part of disk.
2.3. Load

In fact, on the turbine disc there are various kinds of loads acting on it. The dynamic loads that aircraft turbine disc bear predominantly include temperature load, assembly load, centrifugal load.

Moreover, sometimes blades failure can also affect the disc, bending, twisting and vibrating load can also be transmitted to the bore of the disc. Among these loads we will consider only few types of loads such as centrifugal load, temperature load. Table 2 demonstrates the load level and rotational speed.

Three kinds of load have been applied on the turbine disc such as temperature load, centrifugal load and shrink fitted load. These loads will affect on the turbine disk.

Table 2 load level and rotational speed

<table>
<thead>
<tr>
<th>Cyclic load level</th>
<th>Cycle</th>
<th>Rotational speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>1278</td>
<td>0-12300-0</td>
</tr>
<tr>
<td>Level 2</td>
<td>1936</td>
<td>3800-12300-3800</td>
</tr>
</tbody>
</table>

2.4. Boundary conditions

Three-dimensional model of turbine disc is used in finite element analysis and for computation 1/41 part of the model chased because of their symmetry. Add axis symmetrical boundary condition to constraint the turbine disc in the axial direction and circumferential direction. Make sure there is no any circumferential
deformation. The general form of the constraint is given in Eq.1.

\[ CONST = \text{Sum}\ of\ \left( COEF_1 \cdot U_1 \right) \]  \hspace{1cm} (1)

The radial and circumferential rotational constraints are denoted in Eq.2.

\[ U_r = U_{r1} \hspace{1cm} U_\theta = U_{\theta1} \hspace{1cm} U_z = U_{z1} \]  \hspace{1cm} (2)

3. Numerical simulation

3.1. Finite Element result of aircraft turbine disk

The turbine disk revolves at 3800 to 123000 rpm, according to the finite element analysis. Stress and strain results of turbine disk are very important throughout this work. The stress distribution on the turbine disk by maximum principal stress and minimum principal stress is considered diverse. The bore of the turbine disk, the assembly cavity, and the third lower corner of the fir tree turbine disc has the highest stress levels. Their maximum value is 7.141e2 while minimum is -6.88e+1. On the other hand, minimum principal stresses are shown in figure 3(b). These stresses are maximum at disk web area while minimum at disk fir tree area.

![Image of stress distribution](image_url)

**Figure 3.** a) maximum principle stress b) Minimum principle stress

Figure 4(a) show the pressure effect on the turbine disk. Pressure have the maximum effect on the turbine disk as turbine disk are working at extreme pressure. As fir tree area of the turbine disk face maximum pressure so it have maximum effect and its value is 1.057e+2 while turbine disk bore and assembly hole area have minimum effect so their value is -3.230e+2. Their maximum value is 1.032e+2 while their minimum value is -3.247e+2.

Figure 4(b) shows the spatial displacement (U) at nodes of turbine disc. The displacement represents maximum magnitude at rim of turbine disc and its magnitude decrease gradually from rim to bore area.
Temperature has the main effect on the turbine disk. As the aircraft working at high temperature and high pressure so the temperature effect cannot be neglected. Figure 5(a) represents the effect of temperature on the turbine disk. Temperature has different effects on different parts of the turbine disk. It is maximum at the rim of the disk and decrease gradually from rim to the bore of the disk. Its maximum value is 4.51e+2 while its minimum value is 3.00e+2. Figure 5(b) represents the heat flux resultant. Where the temperature is maximum, the HFL value will also have maximum value so at the rim fir tree area the HFL value is maximum and it decrease gradually from rim to the bore of the disk. The results generated from HFL are maximum 6.395e+1 while for minimum value is 2.69e-01.

**Figure 4.** a) Pressure b) U spatial distance magnitude

**Figure 5.** a) Nodel temperature b) heat flux resultant
The results generated are given significantly in table 3.

<table>
<thead>
<tr>
<th>Result</th>
<th>Nodel temperature (NT)</th>
<th>Heat flux magnitude (HFL)</th>
<th>Max principal stress</th>
<th>Spatial displacement (U)</th>
<th>Pressure p</th>
<th>Minimum principal stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal</td>
<td>4.51 e+2</td>
<td>6.395 e+1</td>
<td>7.12 e+2</td>
<td>3.065 e-1</td>
<td>1.057 e+2</td>
<td>1.032 e+2</td>
</tr>
<tr>
<td>Minimal</td>
<td>3.0 e+2</td>
<td>2.69 e-1</td>
<td>-6.69 e+1</td>
<td>2.597 e-2</td>
<td>3.203 e+2</td>
<td>-3.247 e-3</td>
</tr>
</tbody>
</table>

### 3.2. Aeroengine remanufacturing turbine disc LCF life predictions

In the service state of the remanufactured turbine disk, although most of the positional deformation is in an elastic deformation state, elastoplastic deformation will occur in the dangerous area. As a result, using finite element analysis with maximum tension, the critical points have been identified. From figure 6 it shows that turbine disk bore, its assembly hole area and first tree area of the rim have maximum stress. After calculation it shows that turbine disk bore has maximum stress 692Mpa which is more critical point. It has maximum chances of failure. At this critical point fatigue life will be calculated out. Miner’s rule is used to overcome the low cycle fatigue life of the remanufactured turbine disk based on the material's fatigue.

![Figure 6 critical points location on the turbine disk](image_url)

According to the results of finite element analysis, the dangerous point of the remanufactured turbine disk is the turbine disk bore and third lower corner. Under working conditions, the biggest here and minimum the local strain values are shown significantly in the following table 4. These are valuable parameters as discussed in details. The material's fatigue is efficiency parameter throughout this numerical simulation process in this existing study.
Table.4 Local stress-strain data in the bore of remanufactured turbine disk

<table>
<thead>
<tr>
<th>status</th>
<th>Peak/rpm</th>
<th>Wave /rpm</th>
<th>(\varepsilon_{\text{max}}/%)</th>
<th>(\varepsilon_{\text{min}}/%)</th>
<th>(\Delta\varepsilon_{\ell}/%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brake-max-stop</td>
<td>0</td>
<td>12300</td>
<td>0.5843</td>
<td>0</td>
<td>0.5843</td>
</tr>
<tr>
<td>Local-Max-local</td>
<td>3800</td>
<td>12300</td>
<td>0.5843</td>
<td>0.05621</td>
<td>0.5281</td>
</tr>
</tbody>
</table>

Inquire literature Know the temperature of 650°C under the low-cycle fatigue performance parameters of the turbine disc forgings are shown in the following table.

Table.5 Strain fatigue parameter of Inconel alloy forged disk pieces

<table>
<thead>
<tr>
<th>(\Theta/\degree\text{C})</th>
<th>(\sigma'_f/M\text{pa})</th>
<th>(\varepsilon_f'/%)</th>
<th>(K'/M\text{pa})</th>
<th>(n')</th>
<th>(b)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>1163</td>
<td>29.8</td>
<td>1356</td>
<td>0.096</td>
<td>-0.059</td>
<td>-0.681</td>
</tr>
</tbody>
</table>

There are many types of fatigue life prediction models based on the local stress-strain method. Because the material stress-strain life curve is usually obtained from the fatigue test under the action of symmetrical cyclic load, the service load of remanufactured turbine disk is asymmetrical cyclic load, so the belt The Morrow elastic stress correction formula with average stress correction is used to predict the low-cycle fatigue life of remanufactured turbine disks. Morrow elastic stress correction formula is:

\[
\frac{\Delta\varepsilon_{\ell}}{2} = \frac{\sigma'_f - \sigma_m}{E} \left(2N_f\right)^b + \frac{\varepsilon'_f}{(2N_f)^c} \tag{3}
\]

Where is \(\Delta\varepsilon_{\ell}\) Total strain range, \(\sigma'_f\) the fatigue strength coefficient, \(\varepsilon'_f\) is the fatigue ductility coefficient, \(b\) is the fatigue strength index, \(c\) is the fatigue ductility index, \(E\) is the elastic modulus, is the average value of the static stress components, and is the fatigue life \(\sigma'_f\varepsilon'_f/\sigma_m N_f\).

Substitute the data in Table 4 and Table 5 into the formula (3), the table can be obtained by iterative solution. The low-cycle fatigue life Prediction of the remanufactured turbine disk is mentioned.

Table.6 Result of life Prediction using Morrow modifying formula.

<table>
<thead>
<tr>
<th>status</th>
<th>Peak/rpm</th>
<th>Wave valley/rpm</th>
<th>(\varepsilon_{\text{max}}/%)</th>
<th>(\varepsilon_{\text{min}}/%)</th>
<th>(\Delta\varepsilon_{\ell}/%)</th>
<th>(\sigma_m/M\text{pa})</th>
<th>(N_f/\text{e}+4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brake-max-stop</td>
<td>0</td>
<td>12300</td>
<td>0.5843</td>
<td>0</td>
<td>0.5843</td>
<td>692</td>
<td>1.6558</td>
</tr>
<tr>
<td>Local-Max-local</td>
<td>3800</td>
<td>12300</td>
<td>0.5843</td>
<td>0.05621</td>
<td>0.5281</td>
<td>692</td>
<td>2.5182</td>
</tr>
</tbody>
</table>

It concluded that the total fatigue life of the turbine disk at critical point is 1.6568e+4 when their speed is from 0 to 12300 rpm while the fatigue life of the disk is 2.5282e+4 when their speed is in between 3800rpm
4. Conclusion

In this study finite element analysis of the aircraft turbine disk and their fatigue life have been studied. A geometrical FEA model of aircraft turbine disk has been designed and analyzed for fatigue life estimation. From calculation it shows that there are two critical areas on the turbine disk having maximum stress. The first critical is disk bore while the second critical point is fir tree area where the maximum stress have been calculated out. From the result it also concluded that environmental effects such as temperature, pressure and heat flux also effect on the turbine disk. It also concludes that stress variation exists at the contact region and the low thickness area region. Inconel 718 alloy have good mechanical properties and is best suitable for the manufacturing of aircraft turbine disk. The observations and explanations provided in this analysis contribute in a deeper understanding of the mechanical phenomena that exist in the turbine disks of aero engines.

References


