Numerical Analysis of Fracture In Locomotive Turbocharger Blades
And estimating The Effective Life of Blade

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Abstract: Report of turbine periodical inspection has shown the increasing growth of fracture in
blades due to some phenomenon which causes decreasing the blade service life and serious damages to
turbine disk. In this article, the main aim of study is to find out the cause of failure in turbocharger
blade from the mechanical and metallographic points of view. Therefore non-destructive test (NDT)
was carried out on the blades to show the critical zones for accumulation of periodic fatigue cracks.
Furthermore, the chemical and metallographic analysis has been done on a new blade and some broken
blades. Finally, the service life of a turbo blade, with assumption of having an oval superficial crack
has been assessed through stress intensity factor by using Walker-Paris equations and finite element
method under periodic fatigue conditions in airfoil. Also, the cause of blade fracture has been
identified by making a comparison between numerical and experimental results.

Key words: Turbocharger blade - Non-destructive test - Periodic fatigue - Crack propagation - Stress
intensity factor

INTRODUCTION

The blades used in a locomotive turbocharger are failed to different extent with respect to working
conditions. This causes serious damages to turbine disc and finally stops locomotive. Failure investigation of
blade turbines has been conducted in different articles. In 2007 and 2008; Xiao-lei Xu and Zhi-wei Yu (2007)
and (Zhi-wei Yu, Xiao-lei Xu 2009) have conducted an experimental survey on turbine blades which failed in
airfoil and root areas. These investigations have revealed that corrosion and appearance of fine cracks in radial
& axial directions on airfoil are the root cause of fracture. In 2006, Kyo-Soo Song and Seon Gab Kim (Kyo-Soo
Song et al., 2007) dealt with analysis of fracture of a turbine blade on a turbo jet engine. They found that the
fractured turbine blade did not suffer any damages by foreign objects. But, turbine blade had initially cracked
by a fatigue mechanism on airfoil and fractured by overload to turbine blade owing to vibrations and gas
emission. In 2010, Jiang-Jiang Zhu and Zi-Chun Yang (Jiang-JiangZhu and Zi-chun Yang 2010), computed the
thermo-elasto-plastic stress by using finite element method and found effective parameters used in life
prediction formula which can be used to estimate fatigue life in gas turbine blade. In 2001, Myounggu Park,
Young-Ha Hwang, Yun Seung Choi and Tae-Gu-Kim (Myounggu Park 2002) have analyzed J69-T-25 engine
and found cracks on its turbine blades. They believe that those cracks are due to over loading the engine. In
1997, Yuh J., Chao and Shuliu (1997), investigated failure of cracks under mixed mode loads on turbine blades
and found that in similar structure with certain ductility, crack propagation initiates based on maximum hoop
stress criterion in mode (I) and on maximum shear stress criterion in mode (II). In 2009, Kamran Moghadam
and Mohammad Sadeghi (2009) used new method of reverse engineering including construction geometry and
made a 3D model of turbine blade.

Traction Division in railway, have given high priority to numerical simulation and analysis together with
experimental studies. In this research work, fatigue cracks and propagation rate in cracks have been predicted.
Finally, criteria for critical crack length and also crack propagation life were found in accordance with working
conditions of the assembled parts.

Experimental Tests:

Figure 1, shows a typical damaged turbine disc. Five specimens which have been selected for tests are
indicated in figure 2. Statistical study in Iranian railway has shown that, about 85% of the turbine blades were
damaged in service duration seriously, in the form of fracture, crack and plastic deformation in concave and
convex areas of airfoil surfaces.
Chemical composition of turbine blades is given in table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Fe</th>
<th>Si</th>
<th>P</th>
<th>Mn</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Wt %)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.160</td>
<td>79.60</td>
<td>0.74</td>
<td>0.065</td>
<td>0.72</td>
<td>1.28</td>
</tr>
<tr>
<td>Cr</td>
<td>12.21</td>
<td>0.046</td>
<td>0.02</td>
<td>0.005</td>
<td>0.018</td>
<td>S</td>
</tr>
<tr>
<td>Al</td>
<td>0.001</td>
<td>0.00</td>
<td>0.042</td>
<td>0.001</td>
<td>0.071</td>
<td>W</td>
</tr>
</tbody>
</table>

The hardness measurement test was carried out within 15 seconds and a load of 150 kg was utilized by tapered diamond (acc. to ASTM E 18). The test result is given in table 2:

<table>
<thead>
<tr>
<th>Parts No.</th>
<th>Hardness (on average)</th>
<th>Limits</th>
<th>Number of measured points</th>
<th>Average of equivalent harness (Vickers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample1</td>
<td>38</td>
<td>37-38</td>
<td>5</td>
<td>370</td>
</tr>
<tr>
<td>Sample2</td>
<td>34.5</td>
<td>33-36</td>
<td>7</td>
<td>350</td>
</tr>
</tbody>
</table>

With respect to metallographic illustration of samples, the materials used in blades are stainless steel with martensite structure and equivalent to (DIN 1.4024) X 15 Cr 13 alloy (Ahmad Saatchi and Hosein Edris).

Experimental investigations for 3075 blades which carried out in the workshop have indicated that, the most cracks are appeared in the location as recorded in table 3:

<table>
<thead>
<tr>
<th>Item</th>
<th>Classification of crack</th>
<th>Statistics of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Crack in upper surface of airfoil (thermal stresses)</td>
<td>57.5%</td>
</tr>
<tr>
<td>2</td>
<td>Crack in lower surface of airfoil (fatigue stresses)</td>
<td>41%</td>
</tr>
<tr>
<td>3</td>
<td>Crack in root area</td>
<td>1.5%</td>
</tr>
</tbody>
</table>

Examination of Fractured Surfaces:

According to the investigations on the broken blades, particularly around crack initiation area, a sign of corrosion, detachment, pitting and grain boundary cracks was not noticed. Therefore, it can be concluded that, the appearance of initial cracks and propagation in longitudinal and transverse directions are due to collision of the gases emitted from engine, which directed at blade concave side through turbocharger inlet nozzle (figure 3). Fig. 4 shows an overall illustration of fractured surface on blade 1.

With respect to figure 4, it can be considered that, the first region is the location which a crack begins to occur and it propagates towards the second region in the form of semi-oval profile shaped.

To find out more details about the fractured surface, the blade was observed under a scanning electron microscopy (SEM). The details of metallographic obtained by SEM is indicated in figures 5 and 6.

Finite Element Modeling:

For modeling of crack in airfoil area, commercial finite element software (ABAQUS, version 6-10) was used. For geometric modeling, first, coordinates of a new blade were measured by a CMM with accuracy of 0.001mm. Then, by using these coordinates, a model was developed in CATIA package.

Three main stresses found in turbocharger blades are as follows:

A) Tension stresses obtained due to turbine disk centrifugal forces.
B) Bending stresses obtained due to engine exhaust gases.
C) Bending stresses obtained due to turbine disk centrifugal forces.

With respect to working conditions, items A) & B) are the most important stresses imposed on the rotating blades (A. Kostyuk and V. Frolov 1988). To determine the amount of centrifugal force and tension stresses on blades, the equations 1, 2 and 3 were used respectively (www.specialsteel-jy.com/403html).

\[
\sigma(r) = \frac{F_{bl}(r)}{S(r)}
\]

Where, \(F_{bl}(r)\) is centrifugal force in airfoil which acts on the surface between \(R_t\) and \(r-R_h\) and \(S(r)\) is the cross sectional area of airfoil at the distance \(r\) and \(\sigma(r)\) is the normal stress on each section of the blade.

Fig. 3: Appearance of initial cracks in airfoil end side

Fig. 4: the examined fracture surface.

Fig. 5: Beach marks in fractured surface

Fig. 6: Closed and protrudent areas of fracture grain boundary in turbine blade

Fig 7: Parameters of tension stress and centrifugal force formula.
Where “L” is airfoil length and equal to “L=RTip - RHub”

\[ S(\xi) \] is the current cross sectional area of the selected section along the airfoil length.

\[
\sigma_{(\xi)} = \frac{1}{S(\xi)} \int_{R_{hub}}^{R_{tip}} \rho \omega^2 S(\xi) \left[ \frac{L}{L} \right] d\xi
\]

Where, \( m_b = 38 \text{ g, } \delta = 0.003 \text{ m, } \rho = 7800 \text{ Kg/m}^3, R_{tip} = 0.075 \text{ m, } R_{hub} = 0.022 \text{ m, } \omega \) can be obtained by equation (4):

\[
\omega = \left[ \frac{2\pi \rho L}{60} \right] = \frac{2\pi \times 17000}{60} = 1780 \text{ rad/s}
\]

After calculating cross sectional area of airfoil at distance of 1, 10, 20, 30 and 40 mm from root of the blade, the amount of stresses were determined (table 4).

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Centrifugal force (N)</th>
<th>Cross sectional Area (mm²)</th>
<th>Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16789.54</td>
<td>266.67</td>
<td>62.96</td>
</tr>
<tr>
<td>10</td>
<td>12610.16</td>
<td>228.72</td>
<td>55.62</td>
</tr>
<tr>
<td>20</td>
<td>8151.34</td>
<td>190.63</td>
<td>42.76</td>
</tr>
<tr>
<td>30</td>
<td>3970.98</td>
<td>159.03</td>
<td>24.97</td>
</tr>
<tr>
<td>40</td>
<td>297.39</td>
<td>133.36</td>
<td>2.23</td>
</tr>
</tbody>
</table>

For computer simulation, the stress was selected according to value given in table 4 and oval crack profile diameters were selected 1.2 mm and 0.50 mm respectively. The blade material has been assumed elastic-plastic, homogenous, and isotropic. Then, for analysis, the mechanical properties given in table 5 were used as input data.

<table>
<thead>
<tr>
<th>Stress(MPa)</th>
<th>Yield stress(MPa)</th>
<th>Tension stress (MPa)</th>
<th>Elastic Modulus(GPa)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>62.96</td>
<td>275</td>
<td>485</td>
<td>200</td>
<td>0.29</td>
</tr>
</tbody>
</table>

In this research work, three dimensional dynamic analysis was performed using 3D hexagonal elements (C3D20R) with 18288 elements and 83797 nodes.

Fig. 8: Max. Plastic zone of crack area.

With respect to the output results, the maximum Von Mises stress was equal to 288 MPa (figure 9):

In this research, Tanaka model has been used to estimate crack propagation.

Tanaka equation of equivalent stress intensity factor is as follows (Farhad javiedrad 2009).

\[
\Delta K_{eq} = \left[ \Delta K' + 8\Delta K_{n} + \frac{8\Delta K_{m}}{(1-\nu)} \right]^{10.25}
\]
This equation calculates the equivalent stress intensity factor for crack tip. This factor has a considerable value in mode I, and for modes II and III is negligible. So, based on Tanaka model (5), considering \(\nu = 0.29\), value of \(\Delta K_{eq}\) nearly equals to 9.94 MPa m\(^{1/2}\).

**Fig. 9:** Crack distribution in cracked turbine blade.

### 5. Estimation Of Blade Life:

Diagram of fatigue crack propagation rate per stress intensity factor of mode I, consists of 3 regions (fig 10):

- **Region A:** Threshold crack propagation
- **Region B:** Stable crack propagation
- **Region C:** Unstable crack propagation

**Fig. 10:** Schematic diagram to show fatigue crack propagation rate (Farhad javiedrad 2009).

For \(\Delta K_I > (8.32 \text{ MPa.m}^{1/2})\), which is limit of region II, crack propagation rate per stress intensity factor amplitude in log coordinates was liner, which is presentable by Paris equation (6):

\[
\frac{da}{dN} = C(\Delta K)^M
\]

Where \(da/dN\) is crack propagation rate, \(\Delta K\): stress intensity factor of mode I (in combined mode, equivalent stress intensity factor) and \(C\) (width from direct line initiation in region II) and \(M\) (line slop of region II) are material constants. In Paris equation, it is supposed stress ratio, which is defined as \(R = K_{Imin} / K_{Imax}\), to be zero (Farhad javiedrad 2009; Yung-Lilu, Jwo Pan, Richard Hathaway).

The constant values for steel in Paris formula (6) are according to table 6:

**Table 6:** Typical values of material constants \(C\) and \(M\) in the Paris law for \(R = 0\) (Yung-Lilu, Jwo Pan, Richard Hathaway).

<table>
<thead>
<tr>
<th>Material</th>
<th>(C)</th>
<th>(M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Martensitic Steel</td>
<td>(1.36 \times 10^{-7})</td>
<td>2.25</td>
</tr>
<tr>
<td>Ferritic-Pearlitic</td>
<td>(6.89 \times 10^{-7})</td>
<td>3</td>
</tr>
<tr>
<td>Austentic Steel</td>
<td>(5.61 \times 10^{-7})</td>
<td>3.25</td>
</tr>
</tbody>
</table>

With respect to martensitic structure of turbo blade and by placing constant values (table 5) in formula (6),
the value of \( \frac{da}{dN} \) was determined.

\[
\frac{da}{dN} = 1.36 \times 10^7 (\Delta k)^{2.25}
\]  

(7)

By integrating formula 7, crack propagation life is calculated. The critical \( K_c \) for fracture initiation is 9.94 MPa m^{-1/2}. Where, \( K_c = K_e \) at the final half crack length \( a_f \) under the maximum applied stress \( \sigma_{\text{max}} \) formula (8) is obtained:

\[
k_e = \sigma_{\text{max}} \sqrt{\pi a_f}
\rightarrow
a_f = 1.51 \text{ mm}
\]  

(8)

It can be seen that, the crack critical length is remarkable. Before researching to this value, the crack would be created and causes a fracture. Experimental observations and the inspection made in this research work confirms these results.

To estimate the blades life, the following formula is used (equation 9):

\[
N_{ef} = \frac{1}{C(\Delta \sigma \sqrt{\pi})^m (\frac{m}{2} - 1) a_f^{\frac{m}{2}-1}}
\]  

(9)

![Fig. 11: Estimation of the turbocharger blade service life (cycles verses of crack lengths “a_i”).](image)

**Conclusion:**

With respect to the results obtained in this research work, the following points were concluded:

1. According to two distinctive regions (initiation and propagation of crack), cyclic fatigue is the main reason of blade fracture. This is due to abnormal working conditions like, vibrations, over temperature of engine emitted gases, inappropriate compositions in the emitted gases (too much sulfur in gas oil fuel) and inadequate combustion have been led to over temperature of turbo blade during operation especially around airfoil.

2. Alloy properties and characteristics of a blade in all sections and airfoil were maintained identical throughout their service life.

3. Many fatigue cracks with abundant ratio appeared in concave and convex sides of airfoil surfaces, which are remarkable in airfoil end side. Existence of semi-oval fatigue cracks in airfoil end side and close to blade root indicates the additional effective bending stress which causes the fracture in blade.

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