Analysis of Stress and Parameters on Back Face of Turbine Wheel

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Abstract: The output power of engine is increased by use of turbochargers which employ exhaust gases from engine to rotate the turbine wheel and in turn the compressor wheel coupled with the shaft. The turbocharger turbine wheels possess high possibility of imbalance as they are manufactured by casting process. High stresses are created around the rotor due to uneven mass distribution. To identify the location and amount of imbalance, the balancing machines are used. But the challenge is to use this information to correct the imbalance. Significant correction is made on the back face using two planes balancing. Additional stresses are induced in the wheel due to the balancing cut and it depends on various parameters. A trial and error method is used currently which is a time consuming process involving lot of iterations. The intent of this paper is to identify critical parameters contributing to the rise in stress at balance cut, the variation in their behavior and identify location to remove material on back face of turbine wheel where the stresses are within acceptable limits.

***Keywords*: balancing, turbine wheel, imbalance, stress analysis, FEA**

I. INTRODUCTION

The turbine wheel is rotated by the waste exhaust gases coming from the engine which in turn rotates the compressor wheel coupled to it by a shaft. The material used for the turbine wheels is Inconel, which has properties like withstanding high temperatures and pressures. The wheels are manufactured by casting process, and mostly include defects. The most prominent defect is mass imbalance which may lead to various failures of the turbine wheel. To eliminate this defects, the balancing of the turbine wheel is needed to be done. The balancing of turbine wheel can be done by three different methods. The methods are material addition, material removal and material adjustment. The material adjustment is used when the amount of imbalance is insignificant. The material addition leads the system to become bulky and induces cost. Also its stiffness is increased. The removal of material on other hand reduces the weight of the component, thus reducing the cost factor but acts as a stress raiser thus hampering the load bearing capacity of the component. The removal of material causes stress generation on the back face of the wheel. There are various parameters which affect the stress values. The three main parameters considered in this paper are the cut distance, the grinding equipment distance and the arc angle. The effect of this parameters on the stress value is studied to understand location for balance cut and also to consider additional parameters in future. The stress analysis is carried out and the results are validated by mathematical calculations.

1. Objective:

The objective of this paper is to carry out the stress analysis of turbine wheels and understand the variation in stress and also the effect of various parameters on the wheel stress.

2. Literature Review:

The study of an integrated optimized design for a radial turbine wheel with of a turbocharger is conducted. The behaviour of stress variation and the factors that affect it are also taken into consideration. The balance cut and containment method is studied and implemented to carry out the analysis of the wheel. The cutting tool used to create the balance cut being grinding equipment, its characteristics, compositions and dimensions are explained.

3. Literature Gap:

The references studied in literature do not mention or explain the procedure for stress analysis of a turbocharger turbine wheel by considering the parameters: cut distance, grinding equipment distance and arc angle.

The methodology in this paper can be used as a reference for the stress calculations of turbine wheels considering effect of the parameters on stress. Also there are no fixed parameters or their effects explained particularly. The parameters are selected based on the variation of stress and its behaviour when the dimensional and loading aspects of the wheel are changed. The literature explains the balancing method and optimization of the turbine wheels.

Table 1.Comparison of balancing methods

S.N.	Parameters	Material Addition	Material Removal
1	Load bearing Capacity	↑	↓
2	System bulkiness	↑	↓
3	Stiffness	↑	↓
4	Vibration	↓	↑
5	Time consumed	↑	↓
6	Cose	↑	↓

Increase	↑
Decrease	↓

II. METHODOLOGY

A. Balancing Machines

The comparison of balancing method from Table 1 indicates material removal to be the best method for balancing. The balancing of turbine wheel is done in a balancing machine. The machine consists of a loading unit, grinding unit, display unit and unloading unit. The wheels undergo stress analysis procedure.The turbine wheel is first loaded into the machine through the loading unit and is checked for imbalance. If the imbalance exists in the wheel then grinding of the wheel is done with the help of grinding equipment of a specific diameter and material is removed from the back face of the grinding equipment. If the imbalance is within the tolerance limits, then the grinding equipment is unloaded and if it is not within the limit, then the wheel is reloaded and grinding operation is performed again to balance the wheel. Once in balance the wheel is unloaded from the machine. The display unit shows the amount and location of imbalance on a screen which can be used to operate the grinding equipment accordingly.

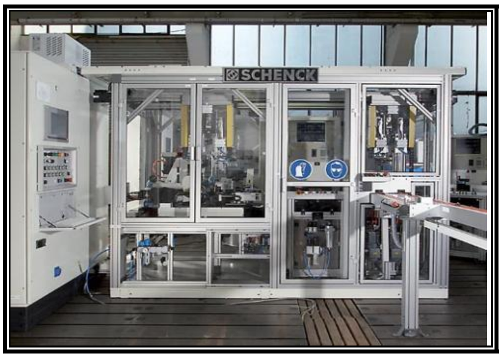

FIG.1BALANCING MACHINE WITH GRINDING UNIT

B. Parameters for balance cut:

The effect of various parameters is studied on the stress at the cut location on back face of the wheel. The parameters considered are-

1. Cut Distance
2. Grinding equipment diameter
3. Arc angle

The cut distance defines the distance up to which the material is removed from the back face surface. The grinding equipment diameter changes from maximum to minimum as it wears out during its use. The arc angle is the angle between the two ends of the balance cut. Figure 2 explains about the parameters considered.

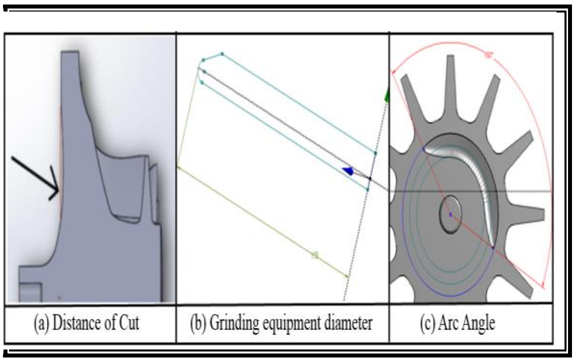

FIG.2PARAMETERS TO STUDY THE EFFECT ON STRESS

C. Effects of Parameters on turbine wheel stress:

1. The cut distance is the distance up to which the material is removed from the wheel back face. This parameter defines the amount of material that will be removed up to a certain depth and is measured in millimetres. It has an effect on stress value of wheel such that if the cut distance is increased, more amount of material is removed leading to mass imbalance and discontinuity which leads to increase in the stress of the turbine wheel.

2. The second parameter defined as the grinding equipment distance can be referred to as the diameter of the wheel. The value of diameter is being measured in millimetres. When the value of the equipment distance is increased it creates a cut occupying more area. The area of cut decreases accordingly with decrease in the value of equipment distance. The change in area is inversely proportional to the value of the stresses acting on the turbine wheel.

3. Arc angle is the value of angle created between the two ends of the balance cut created on the turbine wheel back face. The ideal value is between 150°-180° depending upon the application. Since the outer limits of the balance cut along with the cut distance determine the stress values, the arc angle is independent of the turbine stress.

D. Analysis

The balancing of turbine is simulated analytically before performing actual on field analysis. ANSYS workbench is used to carry out the balance cut analysis of the turbine wheel. Since the wheel geometry is replicated with slight modifications from original one, only the effect can be understood.

1) *Geometry creation*: The geometry of the grinding equipment is created by the specific dimensions and moved through various planes to finally approach the turbine wheel and to create a cut on its back face. Five different planes are created for the movement of the grinding equipment. Figure 3 shows the geometry of turbine wheel on which the balance cut is created.

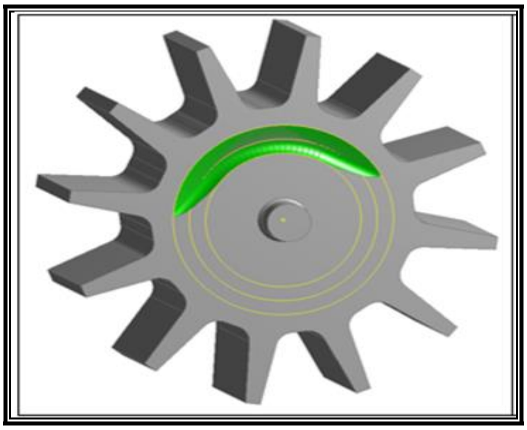

FIG. 3TURBINE WHEEL WITH BALANCE CUT

2) *Meshing:* The model undergoes meshing, succeeded by application of boundary conditions and loads. The following figures show the wheel mesh model where the sizing used is about 0.3-0.7 mm for different features of the turbine wheel. The meshed model of the turbine wheel can be seen in below figure 4.

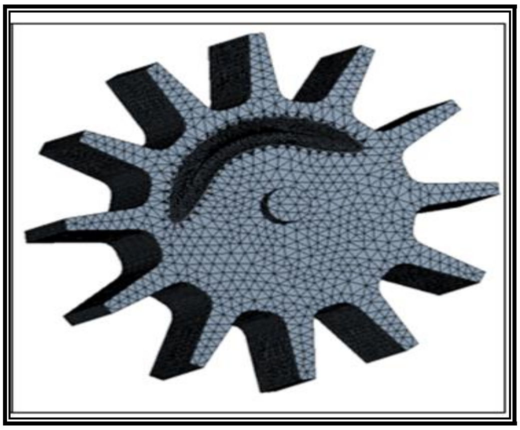

FIG. 4MESHED MODEL OF TURBINE WHEEL

3) *Boundry Conditions and Loads*:After the meshing of the wheel is done, the boundry conditions are applied to the face of the wheel attached to the shaft. The displacement is given to that face and cylindrical support is given to the surface of the shaft which is cylindrical. After the boundary conditions are given, load is applied in the form of rotational speed. The speed is defined by the co-ordinates, wherein the value of rotational speed is input in the x-coordinate. The rotational speed is given either in terms of rpm (Rotations per minute) or Radian/ sec. Figure 5 shows the boundry conditions and loads.

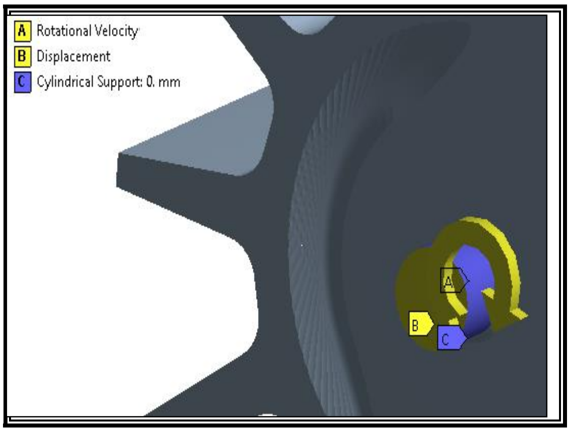

FIG. 5 BOUNDARY CONDITIONS AND LOAD APPLICATION

4*) Solution*: The analysis is given a solve input, to obtain the output in the form of stress and deformation plot. The radial stress at cut location and the back face of the wheel are obtained. The displacement plot of the entire wheel has also been captured and validated simultaneously. Figure 6 shows the cut radial stress plot with a maximum stress value of about 722 MPa at the cut location due to the material discontinuity caused on the wheel back face due to the cut. The Figure 7 shows the back face stress plot with a maximum stress value of about 713 MPa at the center of the turbine wheel. The area at the centre being minimum, the stress is comparatively higher at that location. The discontinuity of material due to cut creation further leads to the elevation of stress value. The table 2 shows maximum stress at cut and wheel back face.

Table 2. Maximum stress at different locations

Locations	Maximun Stress
Cut radial Stress	722 MPa
Back face Stress	713 MPa

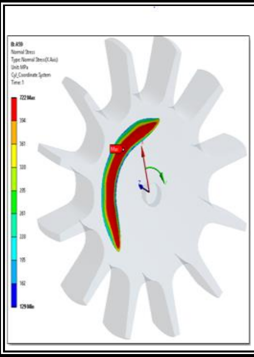
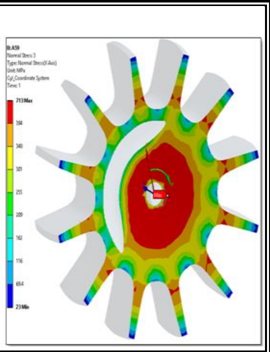

FIG 6.CUT RADIAL STRESS FIG. 7 BACK FACE STRESS

The deformation of the wheel can be seen in Fig.8. The deformation of the wheel is about 0.065 mm.

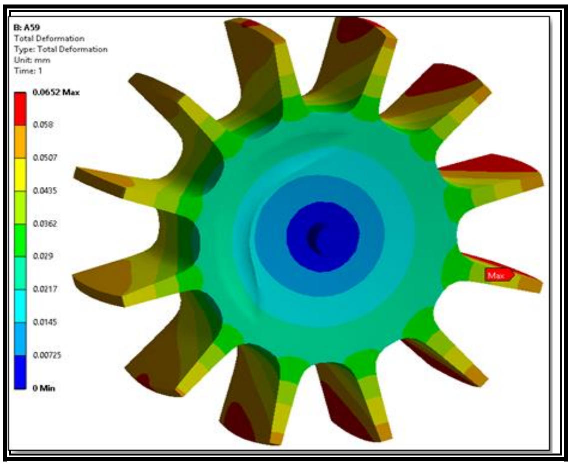

FIG. 8 DEFORMATION PLOT

III. CALCULATIONS

A. *Stress Calculations*: The analysis results carried out for the turbine wheel are validated by the following mathematical calculations. The theoretical stress analysis of the turbine wheel is carried out using dimensions of an onboard wheel. The dimensional and operational details of the wheel are as given below: The principal stress can be calculated by using the following formula:

$$\sigma_0 = \gamma\,\omega^2 r_e{}^2 \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where,

- σ_0 = Principal Stress
- γ = Density of Wheel = M/V
- ω = Rotational Speed = 18000 rad/ sec.
- Re = Cut location radius= 25.75 mm

Now substituting all the values in equation (1)

σ_0= [(8.05 x 10^{-9}) ×18000^2 × 25.75^2]
σ_0=1729.39 MPa

Now the radial stress (σ_r) needs to be calculated to determine stress at the location of placing the cut on the wheel back face. The principal stress calculated above is needed to determine the radial stress value. The formula for calculating radial stress is as below:

$$\sigma_r = \left(\frac{3+\nu}{8}\right)\ \sigma_0\ (1-\rho^2) \ldots\ldots\ldots\ldots\ldots (2)$$

Where,

- ν = Poisson' ratio= 0.3
- ρ = Radial distance from the center of the wheel

Now the stress at radial locations on cut can be found out by substituting the known values in above equation (2), the solution is as below:

σ_r= (3.3/8) × 1729.39× (1- 0^2)
σ_r=713 MPa

The analysis of the turbine wheel for which the theoretical calculations have been done shows results which highly correspond with each other. The stress plot for the wheel back face location and the balance cut are shown in the following figures. The stress plots show that the cut stress is about 722 MPa whereas the back face stress is 713 MPa which highly coincide with the results obtained through theoretical calculations. The tangential stress (σ_t) needs to be calculated to determine stress at the tangential location of the wheel back face. The formula for calculating stress at tangential location is as below-

$$\sigma_t = \left(\frac{3+\nu}{8}\right) \sigma_0 \left(1 - \frac{1+3\nu}{3+\nu}\rho^2\right) \ldots\ldots\ldots (3)$$

σ_t= (0.4125 ×1729.39 × 0.3030)
σ_t= 300 MPa

B. *Deformation Calculation:* The next step in the process of calculations is the determination of the displacement of the turbine wheel. The formula used for calculating the displacement is:

$$u = \left(\frac{r_e}{E}\right)\ \rho\ \left(\frac{3+\nu}{8}\right) \sigma_0\ \left(1 - \frac{1+3\nu}{3+\nu}\rho^2\right) \ldots\ldots\ldots (4)$$

u = 0.00209 ×1×0.4125×1729.39×0.3030
u = 0.0657 mm

IV. RESULTS

The simulation of stress analysis is validated by the mathematical calculations for the turbine wheel cut and the back face. The trend of stress variation is same for the original wheel.

(1) The effect of parameters like distance of cut and the grinding equipment diameter are shown in the following graphs:

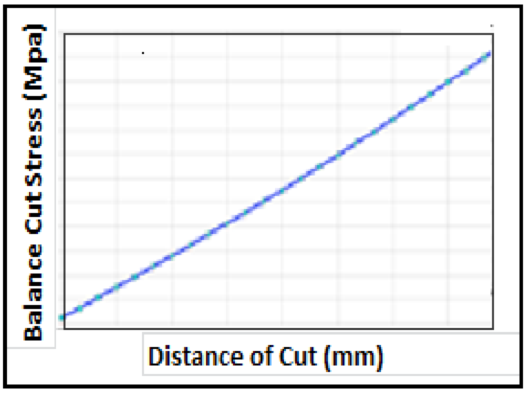

FIG. 9 CHANGE IN BALANCE CUT STRESS WITH CHANGE IN DISTANCE OF CUT

Figure 9 indicates that the distance of cut is directly proportional to the value of balance cut stress. Thus, increase in distance cut acts as a stress raiser.

(2) The increase in diameter of the grinding equipment decreases the value of balance cut stress. Hence it is recommended to use lower diameters in order to reduce the stress. Figure10 shows the inverse relation between the two parameters.

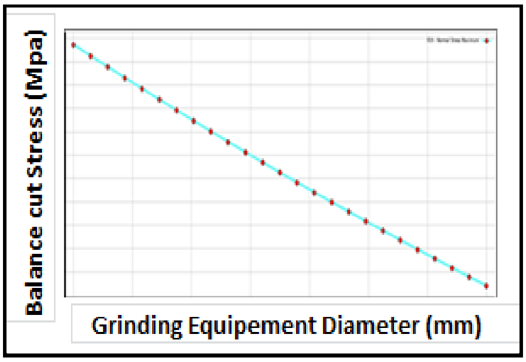

FIG. 10 CHANGE IN BALANCE CUT STRESS WITH CHANGE IN GRINDING EQUIPMENT DIAMETER

Thus from Figure10, we can conclude that to achieve lower stress values, we should increase the value of the grinding equipment distance accordingly.

(3) The arc angle between the two ends of the balance cut does not seem to affect the value of balance cut stress. Thus we can conclude that change in arc angle doesn't affect the balance cut stress value. The following Figure11 shows the relation between the two parameters.

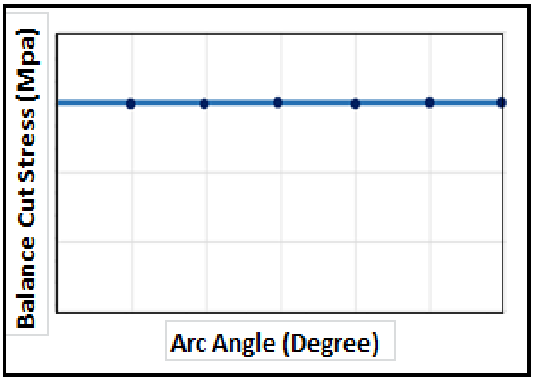

FIG. 11 CHANGE IN BALANCE CUT STRESS WITH CHANGE ARC ANGLE

- **Effects of parameters on turbine wheel stress:**

The effect of the various parameters on the turbine wheel stress is obtained through simulations and is represented above graphically. The way in which every parameter contributes to the turbine wheel stress is explained above in the section 'C' of the methodology. The effect of parameters on stress is tabulated below in Table 3.

Table 3. Effect of parameters on wheel stress

	Parameters	Effect On Stress
1	Cut distance	Increase
2	Grinding equipment distance	Decrease
3	Arc Angle	Neutral

V. CONCLUSIONS

The balancing procedure is adopted for the mass balancing of turbine wheels which possess imbalance by removing the material from the back face of the wheel. The strength and load bearing capacity of the wheel are not to be affected by removal of material. Also the stresses generated on the wheel should be within acceptable limits. The rotating wheel is already subjected to high centrifugal forces and creating a balance cut adds to the stress. The data can be used further to understand the placement of the balance cut in order to lower the stresses and maintain them in tolerance limits to avoid failures of the component. The study of effect of parameters on the balance cut stress shows that:
i) The balance cut stress increases with increase in distance of cut.
ii) The balance cut stress decreases with increase in grinding equipment diameter.
iii) The balance cut stress is independent of change in arc angle.

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