Structural Analysis of Compressor Blades for Turbocharger by Using the Different Materials

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ABSTRACT

A structural analysis has been carried out to investigate the Von-Mises stresses, effective strains and total deformation of the compressor blades of the turbocharger in locomotive diesel engines. An investigation in the usage of new materials is required. In this research, compressor blades are designed with three different materials. The modeling of the compressor is drawn by using SolidWorks (2016) software and analysis is done in ANSYS (17.0). The design speed of the compressor is considered 68,000 rpm. An attempt is also made to suggest the suitable material for the compressor blades of a turbocharger by comparing the results obtained for three different materials (Aluminum Alloy (7050-T7651), AISI 4340 Steel and Inconel Alloy (718)) for the compressor. The Aluminum Alloy (7050-T7651) for the compressor blades of a turbocharger is recommended on the suitable results than the other two materials

Key Words: *Compressor Blades, Effective Strain, Total Deformation, Turbocharger, Stress Analysis, Material.*
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1. INTRODUCTION

   Turbochargers are a class of turbo machinery these are to increase the power of internal combustion engines. This is working by increasing the pressure of intake air, allowing more fuel to be combusted. Rudolf Diesel and Gottlieb Daimler experimented with pre-compressing air to increase the power output and fuel efficiency in the late 19th century. The first exhaust gas turbocharger was done completely in 1925 by the Swiss engineer Alfred Buchi who introduced a prototype to increase the power of a diesel engine by a reported 40%. At that time, the idea of turbo charging was not widely accepted [1].

   A turbocharger consists of a compressor with impeller and turbine with impeller operating on a single common shaft. These are often investigated for use on automobile internal combustion engines. The hot exhaust gases exiting the cylinders pass through the turbine side of the turbocharger, tunning the turbine blades, and thus the shaft. The shaft then generated power to drive the compressor. The exhaust gases then continue out to the exhaust manifold and continue as usual. As the compressor turns, it raises the pressure of the incoming air from the air intake. The high pressure air is often allowed through a charged air cooler (also known as an intercooler) to further raise the density of the air [5]. Figure 1 shows the operation of turbocharger.
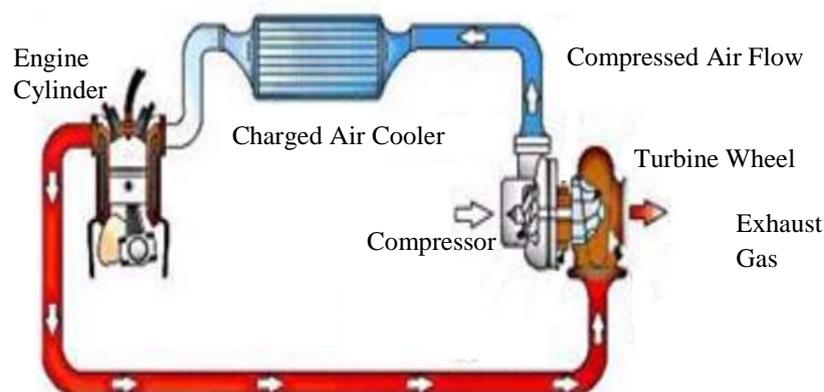
Figure 1. Operation of Turbocharger [5]

2. DESIGN OF COMPRESSOR IMPELLER FOR TURBOCHARGER

Consider a design of centrifugal compressor impeller, the shape of an impeller is the most important for optimum efficiency. Computational procedure is based on the specified parameters.

2.1 Design Procedure for Centrifugal Compressor

In this research, the design parameter of impeller is pitched up at 'Diesel Locomotive Workshop (YWAHTAUNG)'. The centrifugal compressor of the station has the following parameter;

Power	=	810kW
Outlet Temperature, T_2	=	408 K
Capacity, Q	=	0.19 m³/sec
Outlet Pressure, P_2	=	500 kPa
Air mass flow rate, m°	=	1.6 kg/sec
Slip factor, σ	=	0.85

Ambient pressure and ambient temperature is 1.2 bars and 30° C. Figure 2 shows entry and exit velocity triangles for impeller.

(a) Absolute Velocity as Sum of Velocity Relative to Blade

(b). Inlet Velocity Component

(c) Outlet Velocity Component
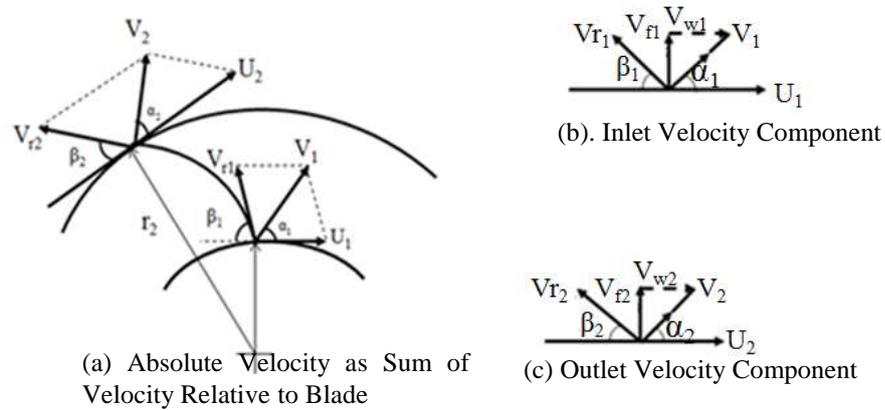
Figure 2. Entry and Exit Velocity Triangles for Impeller

Design calculation divided into five main parts for turbocharged compressor. There were

(i)   Calculation of Impeller Inlet Dimensions
(ii)   Calculation of Impeller Outlet Dimensions
(iii)   Efficiency of Compressor
(iv)   Calculation of Stress on Compressor Impeller
(v)   Calculation of Strain on Compressor Impeller

2.2.1   Calculation of Impeller Inlet Dimensions

Impeller inlet and outlet pressure ratio,

$$r_P = \frac{P_2}{P_1} \tag{1}$$

Shaft Diameter, D_s (Aluminum Alloy (7050-T7651))
Standard shaft diameter is up to 25 mm [13].

$$D_S = \sqrt[3]{\frac{16T}{\pi \times S_s}} \tag{2}$$

Impeller Inlet Velocity and Inlet Blade Angle
The air enters the impeller eye to tip in the axial direction. The prewirl angle is zero so that $V_1 = V_{f1}$.

$$D_1 = 1.025 \times D_0 \tag{3}$$

Inlet Absolute Velocity, U_1

$$U_1 = \frac{\pi D_1 N}{60} \tag{4}$$

Inlet Blade Angle, β_1

$$\beta_1 = \tan\frac{V_1}{U_1} \tag{5}$$

2.2.2 Calculation of Impeller Outlet Dimensions

Impeller Outlet diameter, D_2

Assume K' = 0.55

$$D_2 = \frac{60\sqrt{H_p g}}{\pi N \sqrt{K'}} \tag{6}$$

K' is the pressure coefficient which has a value between 0.5 and 0.65 depending on the type of impeller.

The Outlet Peripheral Velocity, U_2

$$U_2 = \frac{\pi D_2 N}{60} \tag{7}$$

2.2.3 Efficiency of Compressor

Compressor Efficiency, η_c is

$$\eta_c = \frac{\text{Output}}{\text{Input}} = \frac{\rho g Q H}{C_p(T_{02} - T_{01})} \tag{8}$$

2.2.4 Calculation Stress on Compressor Impeller

There are two forces on the compressor impeller. The centrifugal force, F_c

$$F_c = m r \omega^2 \tag{9}$$

The gas bending force, F_b

$$F_b = m^{\circ} V_{\omega 2} \tag{10}$$

The most important components of static stresses are centrifugal stress and gas bending stress. The centrifugal stress can be determined as follows. The centrifugal stress, σ_c

$$\sigma_c = \frac{\rho \omega^2}{2}\left(r_t^2 - r_r^2\right) \tag{11}$$

The gas bending stress can be calculated as follows;

$$\sigma_{gb} = \frac{m^{\circ}\left(C_{w\text{-}in} + C_{w\text{-}out}\right) \times h_R}{2 \times n_R \times z \times c_R^3} \tag{12}$$

In the principle stress theory, failure will occur when the principle stress in the complex system reaches the value of the maximum stress at the elastic limit in simple tension. The principal stresses are determined by the following equation.

$$\sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_y}{2} \pm \frac{1}{2}\sqrt{\left(\sigma_x - \sigma_y\right)^2 + 4\tau_{xy}^2} \tag{13}$$

The von-Mises stress is calculated by the following equation;

$$\sigma_v = \frac{1}{\sqrt{2}}\sqrt{\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2} \tag{14}$$

2.2.5 Calculation Strain on Compressor Impeller

If three principle stresses are applied simultaneously, each causes Poisson strains in the directions and the three dimensional form of Hook's law would show that,

$$\varepsilon_1 = \frac{1}{E}\left[\sigma_1 - \upsilon\left(\sigma_2 + \sigma_3\right)\right] \tag{15}$$

$$\varepsilon_2 = \frac{1}{E}\left[\sigma_2 - \upsilon\left(\sigma_1 + \sigma_3\right)\right] \tag{16}$$

$$\varepsilon_3 = \frac{1}{E}\left[\sigma_3 - \upsilon\left(\sigma_1 + \sigma_2\right)\right] \tag{17}$$

For the von-Mises criterion, the effective strain is given by;

$$\bar{\varepsilon} = \left[\frac{2}{3} \left(\varepsilon_1^{\ 2} + \varepsilon_2^{\ 2} + \varepsilon_3^{\ 2} \right) \right]^{1/2} \tag{18}$$

Table 1.Results Data of Compressor (Aluminum Alloy)

No.	Name	Value	Units
1	Pressure ratio, r_p	4.167	-
2	Shaft Diameter, D_s	12	mm
3	Inlet Blade Angle, β_1	33	degree
4	Outlet Blade Angle, β_2	65	degree
5	Number of blades, n	14	-
6	Impeller Inlet Diameter, D_1	51.1	mm
7	Impeller Outlet Diameter, D_2	169.8	mm
8	Compressor Efficiency, η_c	92.58	%
9	Centrifugal Force, F_c	10491	N
10	Gas Bending Force, F_{gb}	790.54	N
11	The Centrifugal Stress, σ_c	110.71	MPa
12	The Gas Bending Stress, σ_{gb}	3.4859	MPa
13	von-Mises Stress, σ_v	59.93	MPa
14	Effective Strain,	7.52×10^{-4}	-

Table 1 describes results data of compressor for Aluminum Alloy (7050-T7651).

3. STRUCTURAL ANALYSIS OF COMPRESSOR

The analysis involved in the use of ANSYS (17.0) software. The model is created using SolidWorks (2016) and analyzed using ANSYS (17.0) for compressor impeller with different materials. In this paper, it is investigated the variation of von-Mises stress and effective strain for three materials of compressor impeller. There is in the following steps

(i)   Selecting analysis system to be used for modeling after starting ANSYS (17.0).
(ii)   Selection the material of rotor blade in engineering data
(iii)   Adding geometry to read into the design modeler
(iv)   Meshing
(v)   Static Structural Analysis

Table 2 Properties of Materials

Properties	Aluminium Alloy(7050-T7651)	AISI (4340) Steel	Inconel Alloy (718)	Units
Elastic Modulus (E)	72	205	205	GPa
Poisson's ratio (υ)	0.33	0.32	0.284	-
Density (ρ)	2830	7850	8190	kg/m^3
Yield Strength (σ_y)	490	710	827	MPa
Ultimate Strength(σ_u)	550	1110	1120	MPa

3.1 Analysis System
The static structural simulation was performed on compressor blade by using ANSYS 17.0 software.

3.2 Material Selection

Three types of materials are chosen for the material selection. They are aluminum alloy (7050-T7651) with yield strength 490 MPa, AISI (4340) steel with yield strength 710 MPa and Inconel alloy with yield strength 827MPa.

3.3. Geometry

In this simulation, the SolidWorks (2016) software is used of the design of solid model as an external geometry file to import into the ANSYS 17.0. Two types of geometry are used for compressor blade. One is for the flow analysis using CFX-Pre and other is for static structural analysis. Results data from the CFX-Pre are imported to the structural analysis as input data to get the stress distribution of compressor blade. Figure 3 shows the geometry model of the blade for CFX-Pre which was drawn in SolidWorks software and imported to ANSYS (17.0).
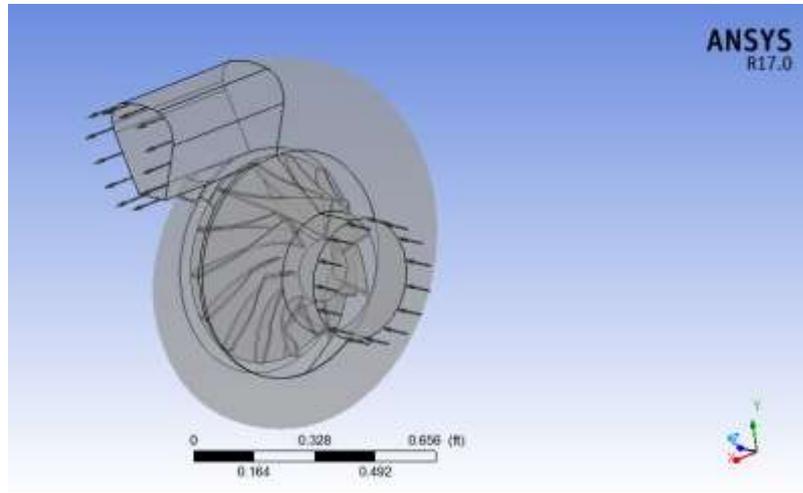
Figure 3. Geometry Model of the Compressor for CFX-PRE

3.4 Meshing

Meshing of the compressor has been done using ANSYS 17.0. There are three types of mesh namely Coarse, Medium and Fine. Figure 4 shows the fine meshed model of the compressor blades for CFX-Pre. This mesh model has 66003 nodes and 344759 elements.
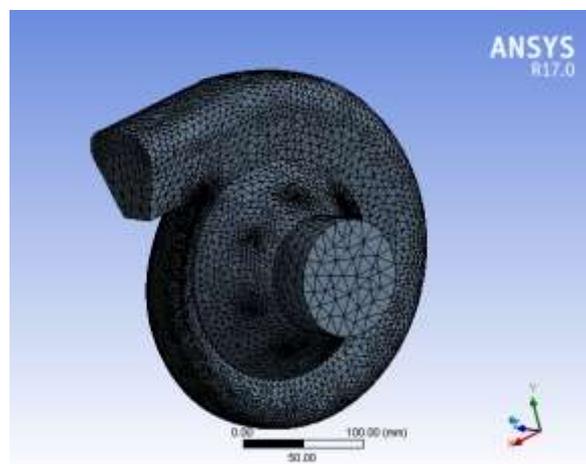
Figure 4. Meshed Model of the Compressor Blades for CFX-Pre

3.5 Static Structural Analysis

A static structural analysis determines the von-Mises stresses, strains, and total deformation in structures or components caused by loads that do not induce significant inertia and damping effects. A model of compressor blade was imported to ANSYS 17.0 and setting up the boundary conditions for static structural. There are three important boundaries for structural; imported pressure (result data from the CFX), the centrifugal force and fixed support. Figure 5 shows the project schematic for static structural of compressor blades.
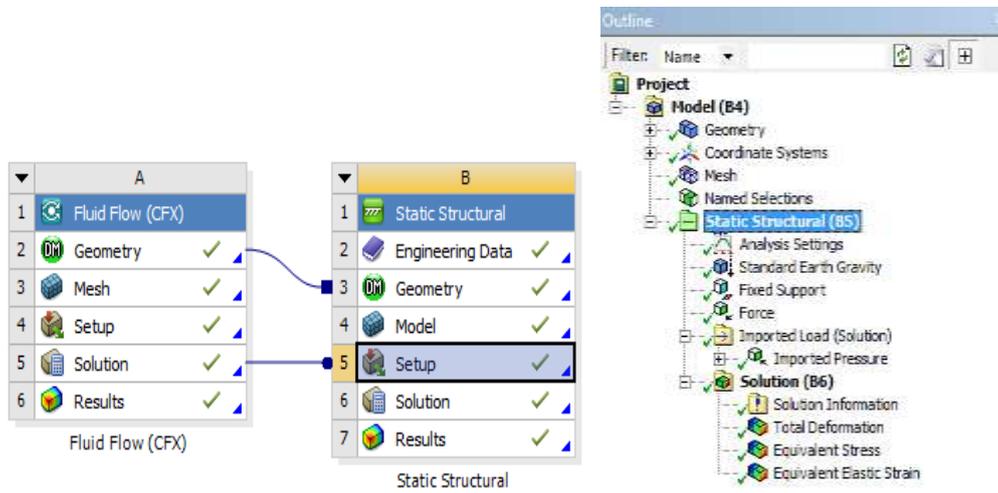
Figure 5. Project Schematic for static structural of compressor blades

There are three boundary conditions for static structural; imported pressure which is the result data of CFX, the centrifugal force and fixed support .The imported pressure is subjected to four walls and fixed support is subjected to top of the compressor. Figure 6 shows the boundary conditions for static structural analysis of compressor blades.
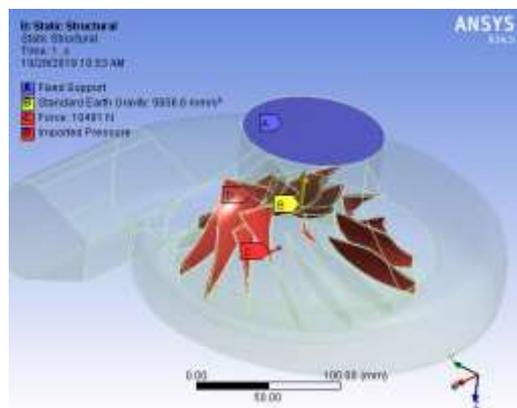
Figure 6. Boundary Conditions for Static Structural Analysis of Compressor Blades

3.5.1. Numerical Results of von-Mises Stress on Compressor Blades

Figure 7 shows the equivalent (von-Mises) stress on blade using Aluminum Alloy (7050-T7651). The equivalent (von-Mises) stress on blade is 28.66 MPa while the yield strength of the Aluminum Alloy (7050-T7651) is 490 MPa. The blade will work safely at this stress.
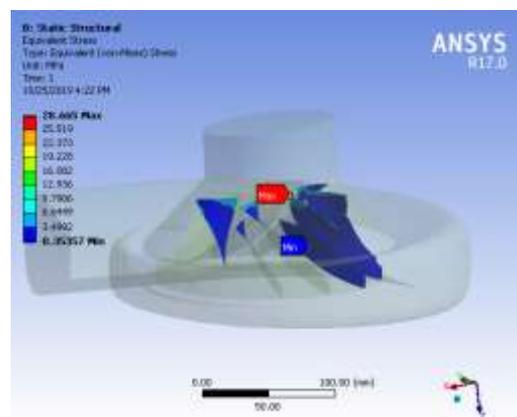
Figure 7. Equivalent (von-Mises) Stress on Compressor Blades using Aluminum Alloy (7050-T7651)
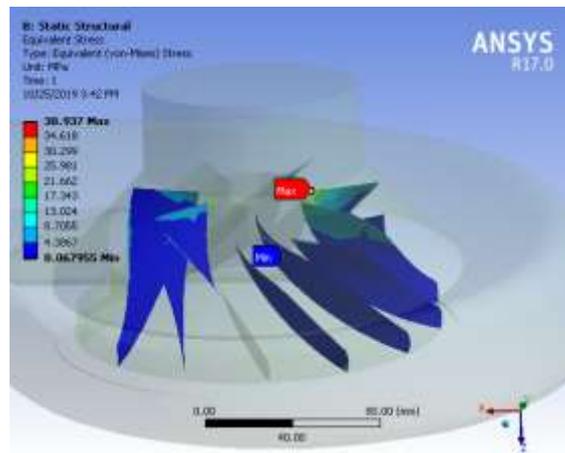
Figure 8. Equivalent (Von-Mises) Stress on Compressor Blades Using AISI (4340) Steel

Figure 8 shows the equivalent (von-Mises) stress on blade using AISI (4340) steel. The equivalent (von-Mises) stress on blade is 38.94 MPa while the yield strength of the AISI (4340) steel is 710 MPa. The blade will work safely at this stress.
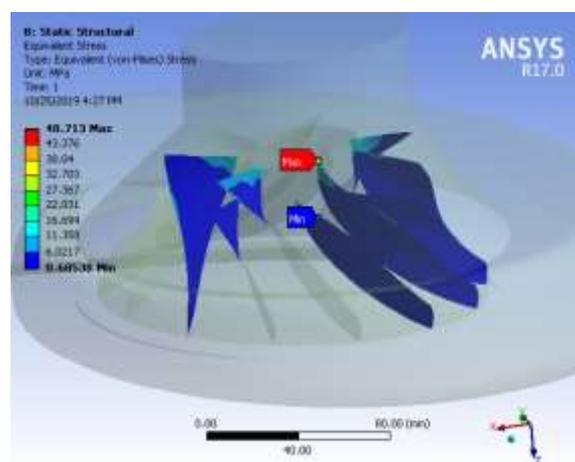
Figure 9. Equivalent (von-Mises) Stress on Compressor Blades Using Inconel Alloy (718)

Figure 9 shows the equivalent (von-Mises) stress on compressor blades using Inconel alloy (718). The equivalent (von-Mises) stress on blade is 48.71 MPa while the yield strength of the Inconel alloy (718) is 827 MPa. The blade will work safely at this stress.

3.5.2. Numerical Results of Effective Strain on Compressor Blades

The numerical results of effective strain on blade are analyzed with static structural on ANSYS 14.5 by changing three different materials namely aluminum alloy (7050-T7651), AISI (4340) steel and Inconel alloy (718).
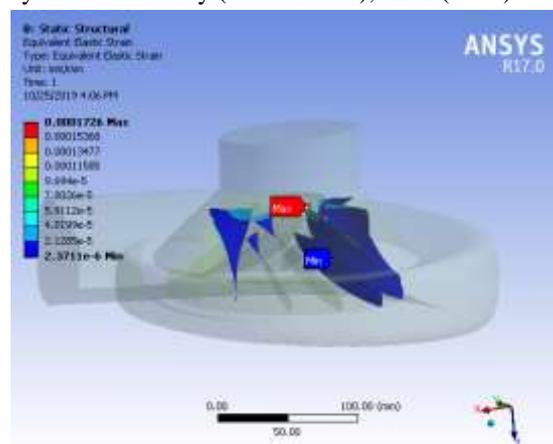
Figure 10. Effective Strain on Compressor Blades using Aluminum Alloy (7050-T7651)

Figure 10 shows the effective strain on blade with aluminum alloy (7050-T7651). The elastic strain on blade using Aluminum Alloy (7050-T7651) was 1.72×10^{-4} at inlet potion of the blades. In the inlet potion of the blades, the effective strain was increased by the forces.
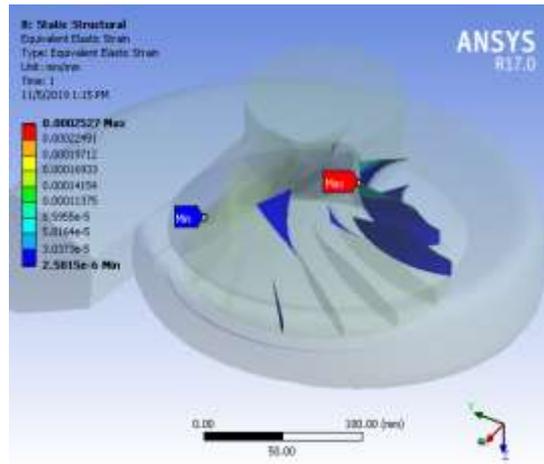
Figure 11. Effective Strain on Compressor Blades using AISI (4340) Steel

Figure 11 shows the effective strain on blade with AISI (4340) Steel. The elastic strain on blade using aluminum alloy (7050-T7651) was 2.53×10^{-4} at inlet potion of the blades. In the inlet potion of the blades, the effective strain was increased by the forces.
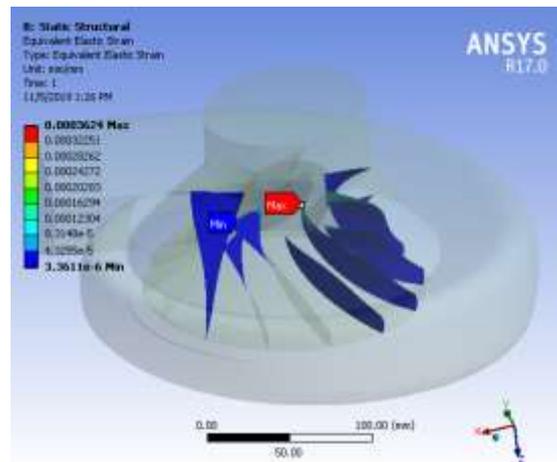
Figure 12. Effective Strain on Compressor Blades using Inconel Alloy (718)

Figure 12 shows the effective strain on blade with Alloy (718). The elastic strain on blade using aluminum alloy (7050-T7651) was 3.62×10^{-4} at inlet potion of the blades. In the inlet potion of the blades, the effective strain was increased by the forces.

3.5.3. Numerical Results of Total Deformation on Compressor Blades

The numerical results of total deformation on blade are analyzed with static structural on ANSYS 14.5 by changing three different materials namely Aluminum Alloy (7050-T7651), AISI (4340) steel and Inconel alloy (718).
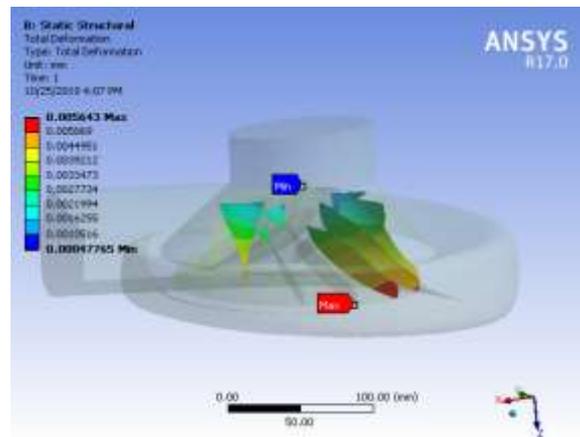
Figure 13. Total Deformation on Compressor Blades using Aluminium Alloy (7050-T7651)

Figure 13 shows the total deformation on blade with Aluminum Alloy (7050-T7651). The total deformation on blade using Aluminum Alloy (7050-T7651) was 0.0056 mm at outlet potion of the blades. In the outlet potion of the blades, the total deformation was increased by the output air pressure.
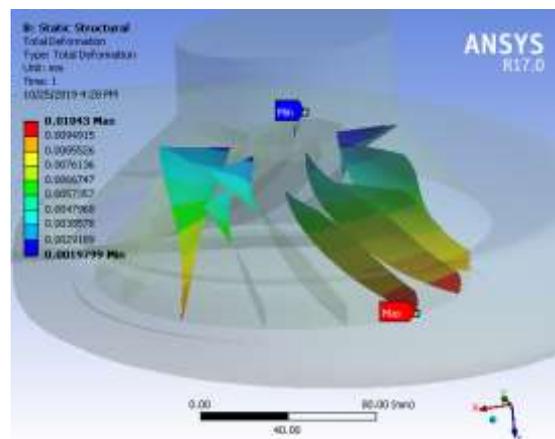
Figure 14. Total Deformation on Compressor Blades using AISI (4340) Steel

Figure 14 shows the total deformation on blade using AISI (4340) steel. The total deformation on blade using AISI (4340) steel was 0.0104 mm at outlet potion of the blades. In the outlet potion of the blades, the total deformation was increased by the output air pressure.
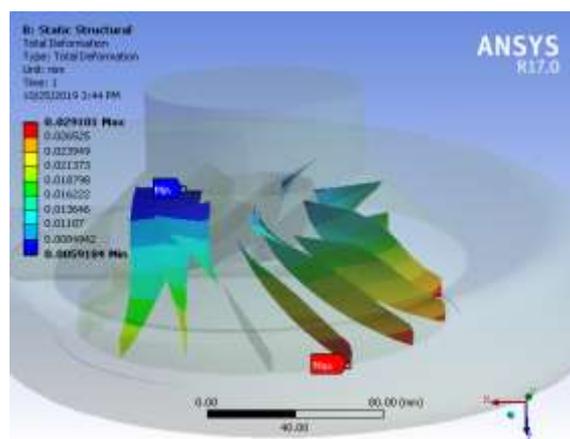
Figure 15. Total Deformation on Blade using Inconel Alloy (718)

Figure 15 shows the total deformation on blade using Inconel alloy (718). The total deformation on blade using Inconel alloy (718) was 0.0291 mm at outlet potion of the blades. In the outlet potion of the blades, the total deformation was increased by the output air pressure.

4. RESULTS AND DISCUSSION

Comparative study on static structure analysis has been carried out on compressor blades made of different materials namely Aluminum Alloy (7050-t7651), AISI (4340) steel and Inconel alloy (718) which are suitable for compressor blades. Table 3 shows von-Mises stress, effective strain and total deformation on compressor blades with three types of materials.

Table 3 von-Mises Stress, Effective strain and Total Deformation on Compressor Blades with Three Types of Materials

Results	Aluminium Alloy (7050-T7651)	AISI (4340) Steel	Inconel Alloy (718)	Unit
Equivalent von-Mises Stress	28.52	42.71	59.88	MPa
Effective Strain	1.72×10^{-4}	2.53×10^{-4}	3.62×10^{-4}	-
Total Deformation	0.0056	0.0104	0.0291	mm
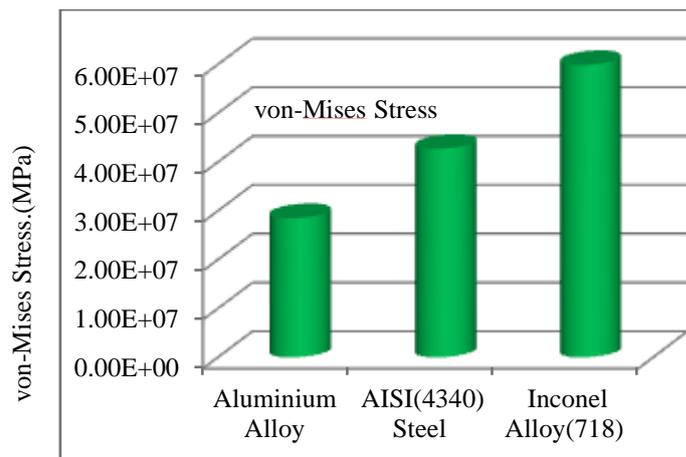
Figure 16. Comparison Results for von-Mises Stress

Figure 16, Figure 17 and 18 show comparison results for von-Mises stress, elastic strain and total deformation. The resulted data for static structural analysis with three types of materials are compared with von-Mises stress, effective strain and total deformation. The maximum von-Mises stress on compressor blades are 28.66 MPa, 38.94 MPa and 48.71 MPa, effective strain are 1.72×10^{-4}, 2.53×10^{-4} and 3.62×10^{-4} and maximum displacement on compressor blades are 0.0056 mm, 0.0104mm and 0.0291 mm, respectively. From the structural contours of ANSYS, it can be observed that the total deformation is maximum at outlet end portion of the blade. The von-Mises stress and effective strain on the compressor blades are the minimum value than other two materials. The deformation analysis by using aluminum alloy (7050-T7651) on the compressor blades has minimum values and chooses the aluminum alloy (7050-T7651) for suitable material in this designed compressor blades.
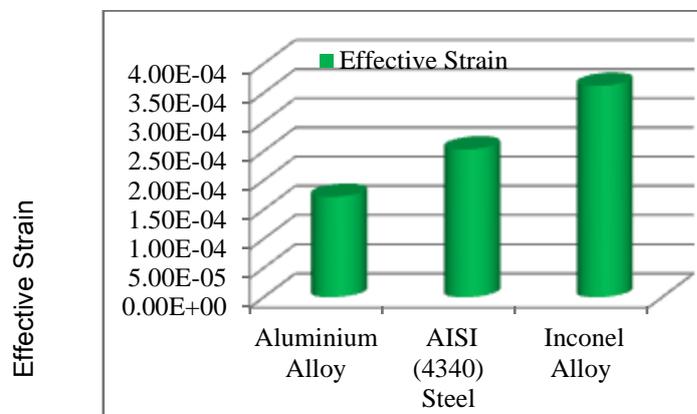
Figure 17. Comparison Results for Effective Strain
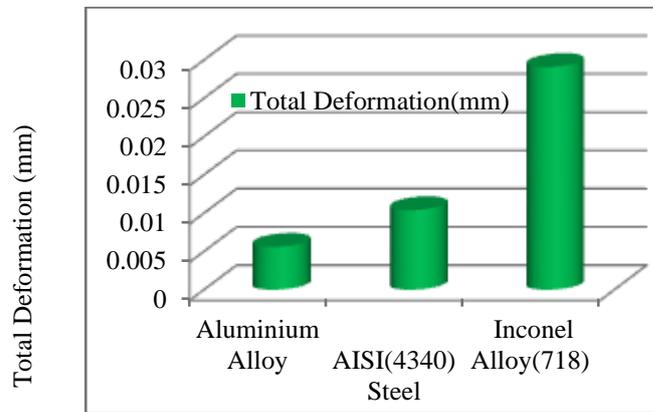
Figure 18. Comparison Results for Total Deformation

5. CONCLUSION

The design of the compressor impeller was carried out. The model of the turbocharger compressor was drawn using SolidWorks 2016 and was analyzed by using ANSYS 17.0. The analysis is carried out with three different materials and the results are compared. From the above results summary table, we concluded that the minimum von-Mises stress and effective strain of Aluminum Alloy (7050-T7651) are found better results than other two materials, AISI(4340) steel and Inconel Alloy (718).

The other components such as casing and diffuser are should be designed and analyzed for the future study. The casing should be analyzed to increase the efficiency by decreasing the clearance. The compressor blade design should be modified because it influences in its performance.

ACKNOWLEDGMENT

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