Thermal analysis of Turbocharger Impeller.

Sunil Shinde[1], Atharv Sangale[2], Kajal Sargar[3], Sarthak Balel[4], Siddhesh Rithe[5], Zaki Sange[6]
[1,2,3,4,5,6] *Vishwakarma Institute of Technology, Pune*

Abstract: Turbochargers play a pivotal role in enhancing the performance and efficiency of internal combustion engines. Among their critical components, the impeller, subjected to high rotational speeds and exhaust gas temperatures, is susceptible to thermal stresses and deformations. This research presents a comprehensive thermal analysis of a turbocharger impeller to investigate the thermal behaviour under varying operating conditions.

Keywords: **Turbocharger, Impeller, Thermal Analysis, Finite Element Analysis, Heat Transfer, Structural Integrity, Internal Combustion Engines.**

Objective: The primary objective of this study is to assess the thermal performance and integrity of a turbocharger impeller by analyzing its temperature distribution, thermal stresses, and deformations.

INTRODUCTION

In the realm of internal combustion engines, turbocharging stands as a cornerstone technology for achieving increased power output and improved efficiency. Turbochargers leverage exhaust gas energy to compress intake air, bolstering engine performance while striving to meet stringent emissions standards. At the core of these ingenious devices lies the impeller—a meticulously designed, high-speed rotating component tasked with the arduous mission of air compression.

The performance of turbochargers, vital in a range of applications from automotive engines to industrial power plants, hinges significantly on the effectiveness and durability of the impeller. However, this pivotal component operates in an environment fraught with challenges, including intense thermal stresses. The impeller's relentless rotation and its direct exposure to high- temperature exhaust gases engender substantial heat generation and intricate thermal phenomena.

Understanding and effectively managing the thermal behavior of turbocharger impellers is paramount for achieving optimal performance, durability, and efficiency. Thermal analysis emerges as a crucial tool in this endeavor, offering insights into temperature distribution, thermal stresses, and deformations that affect the impeller's structural integrity and longevity.

This research embarks on a comprehensive exploration of the thermal dynamics of turbocharger impellers. Utilizing advanced analytical techniques, including Finite Element Analysis (FEA) and computational simulations, we delve into the intricacies of impeller thermal behavior under real-world operating conditions. Our objectives are to elucidate temperature patterns, quantify thermal stresses, and scrutinize deformations that impact impeller performance.

The outcomes of this investigation hold the potential to propel advancements in turbocharger technology. By gaining a deeper understanding of the thermal challenges faced by impellers, we aim to pave the way for innovative design optimizations, material selection strategies, and cooling solutions. In doing so, we anticipate contributing to the sustained evolution of turbocharging systems, fostering enhanced engine performance, reduced emissions, and increased sustainability across diverse industries.

In the subsequent sections of this paper, we outline our research methodology, present our critical findings, and engage in discussions that illuminate the implications of our discoveries. Through this study, we endeavor to advance the knowledge base surrounding turbocharger impellers and catalyze progress toward more efficient and resilient internal combustion engines.

LITERATURE REVIEW

The paper titled "Design and Analysis of an Impeller of a Turbocharger" (N. Sathishkumar, 2020) presents a study on the design and analysis of an impeller of a turbocharger using three different materials (Nickel, Structural Steel, and Titanium). The study involved creating models of the impeller and performing static structural analysis and thermal analysis using ANSYS software. The principal stress and strain conditions were analysed, along with heat flux properties. The results of the analysis were compared for the three materials, and the key findings were presented. The study concludes that the use of Nickel alloy in the impeller design can lead to a reduction in specific fuel consumption and an increase in overall efficiency. The research methodology and analysis techniques used in this study can also be applied to other mechanical engineering applications to improve the design and performance of various components.

The paper titled “Effect of temperature on the strength of centrifugal compressor impeller for a turbocharger.” (Zheng, Jin, Du, & Gan, 2013) investigates the effect of temperature on the strength of a centrifugal compressor impeller for a turbocharger. The authors used a solid-fluid coupling analysis method to study the effects of temperature distribution on the reliability of the impeller under different pressure ratio conditions. The results show that the strength of the impeller decreases with increasing temperature, and the thermal load has a significant effect on the stress distribution of the impeller. The authors suggest that the solid-fluid coupling method is necessary to obtain the impeller temperature at high pressure ratios. The study provides a better understanding of the impeller's behaviour under thermal and centrifugal loads and identifies the critical factors that affect its reliability.

In this comprehensive study titled "The Analysis of Heat Transfer in Automotive Turbochargers," (Nick Baines, 2010) authors Nick Baines, Karl D. Wygant, and Antonis Dris aimed to develop a one-dimensional heat transfer network model capable of accurately simulating heat fluxes and heat transfer coefficients within turbochargers. To achieve this, three commercially available turbochargers were meticulously outfitted with thermocouples, strategically placed on all accessible external and internal surfaces. These instruments facilitated extensive temperature surveys, capturing data under various conditions of turbine inlet temperature and external ventilation. The results of the study indicated that, by employing conventional convective heat transfer correlations, a set of heat transfer coefficient values could be derived, demonstrating a notable independence from the specific turbocharger model. The authors concluded that their model exhibited a high level of predictive capability, a confidence substantiated through thorough comparisons between the simulated heat transfers and the actual temperatures measured during the experiments. This research contributes valuable insights into understanding and predicting heat dynamics in automotive turbochargers, offering potential advancements in the optimization and performance of these critical components.

In the pursuit of enhancing the efficiency of diesel engines, the research paper titled "Design and Analysis of Impeller of Turbocharger for Diesel Engine" (V.R.S.M Kishore Ajjarapu, 2012) sets out to achieve multiple objectives. The primary goal is the design of a turbocharger impeller to elevate its potential efficiency, with a particular focus on comparing the performance of 6-blade and 12-blade compressors against an 8-blade variant. Additionally, the paper delves into a comparative analysis of various materials for both compressor and turbine impellers, examining the effects of temperature, pressure, and induced stresses on the impeller. The methodology employed encompasses structural and model analysis for the compressor impeller, while the turbine impeller undergoes structural, model, and thermal analyses. The investigation includes the evaluation of von Mises stresses, von Mises strain, deformation, frequency, and deflection for different materials. Results highlight the impact of these factors on both compressor and turbine impellers, offering insights into their structural integrity and thermal performance. The materials considered for the compressor impeller include wrought aluminium alloy, Incoloy alloy 909, and wrought aluminum copper alloy, while the turbine impeller explores Inconel alloy 740, Inconel alloy 753, and wrought aluminum alloy 2219. The culmination of the study involves identifying the best-performing material based on the obtained results. For the compressor, it is found that Incoloy alloy 909 exhibits the minimum von Mises stresses and maximum frequency. In contrast, for the turbine, Inconel alloy 740 demonstrates the minimum von Mises stresses. The conclusion underscores the resilience of the materials under various conditions, noting that the compressor material, specifically Incoloy alloy 909, withstands up to 482.62 Hz with a minimum stress of 32.981 MPa, while the turbine material, Inconel alloy 740, endures up to 773.58 Hz with a minimum stress of 171.01 MPa. These findings contribute valuable insights into optimizing turbocharger design for diesel engines, balancing material considerations with structural and thermal performance.

The research paper titled "Stability Analysis of Turbocharger Impeller: A Review," (B.P.Terani, 2015) authored by B.P. Terani, Dr. K.S. Badarinarayan, and Prakasha.A.M., undertakes a comprehensive exploration of impeller stability through structural, modal, and thermal analyses, considering various boundary conditions and blade parameters. The primary objectives encompass the optimization of compressed air and fuel mixer for enhanced engine power efficiency and power-to-weight ratio. Notably, the turbocharger's remarkable rotational speed, reaching up to 15000 revolutions per minute, is emphasized, highlighting its significance in comparison to the car engine. Acknowledging the limitations of conventional turbocharger systems, the paper delves into the advantages of Variable Geometric Turbocharger (VGT), which adapts its nozzle geometry based on engine speed. The methodology involves an examination of oxygen saturation levels before and after the use of an after cooler, revealing the potential for faster and more efficient combustion with increased oxygen saturation. Results showcase the design details and engine bench testing outcomes for various vane variations, ultimately leading to the development of the most suitable assembly nozzle with two separate vanes. Despite the inherent complexities of heat transfer processes, the compressor demonstrates adiabatic behavior at high rotation speeds, and the study indicates that an insulated casing significantly reduces turbo lag. Experiments with the new Turbocharger illustrate its efficacy in expanding the effective torque band and reducing fuel consumption. In conclusion, the paper emphasizes the utility of Computer-Aided Engineering (CAE) in analyzing turbocharger difficulties related to manufacturing and testing. Various iterations of the turbine impeller, featuring diverse blade thickness and blade numbers, are manufactured and compared with the stock model. The research encompasses structural analysis to discern stress deformation and strain, modal analysis to identify natural frequencies, and thermal analysis to evaluate the impact of exhaust gases on the turbine impeller. This comprehensive approach contributes valuable insights into the stability and performance optimization of turbochargers, addressing critical aspects of their design and operation.

Design of Impeller: -

The investigation involves utilizing the dimensions of the impeller sourced from an actual diesel engine turbocharger. Accurate measurements were taken and subsequently employed in developing a 3D model through Solidworks software. Figure 1 displays a visual representation of the impeller under consideration for this research.

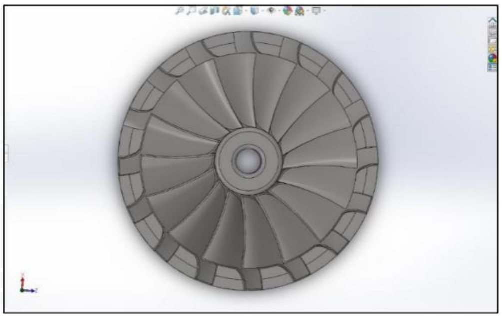

Fig. 1.1

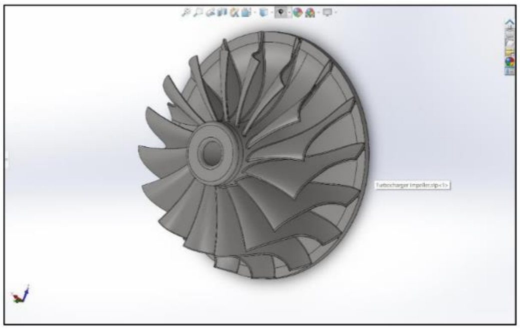

Fig. 1.1 & 1.2 geometry of Turbocharger Impeller.

Experimentation: -

Table 1, 2, and 3 outline the respective properties of the structural steel, titanium alloy, and Incoloy800 materials chosen for examination. Employing Solidworks software, dimensions were designed based on assumed material properties. Stringent checks for geometrical file errors, such as facet overlap, geometrical data redundancy, and adherence to vertex-to-vertex rules, were meticulously carried out. Following the confirmation of geometrical accuracy, the solid model underwent calculations for mass properties, including mass, volume, and density.

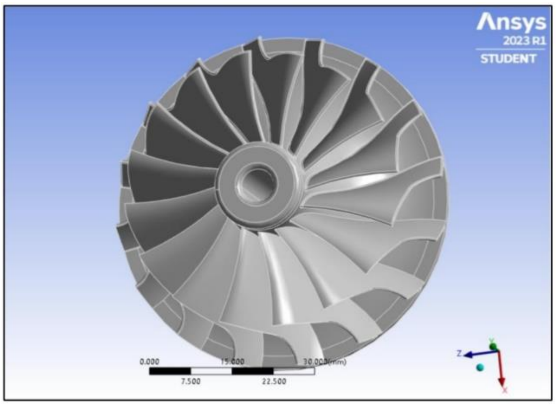

Fig. 2 Design Modeller of Ansys.

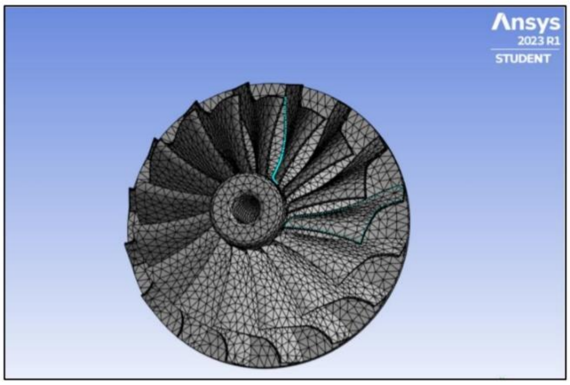

Fig. 3 Tetrahedral Meshing.

After a thorough analysis of mass properties, the 3D models were exported to a neutral file format, facilitating smooth file transfer across various vendor software. Subsequent to this, finite element analysis was conducted separately for the three assumed materials, encompassing static structural, steady State thermal analyses and transient thermal analysis using ANSYS version 2023 R1 software. The detailed results of finite element analysis for each material are presented in subsequent figures. Figure 2 illustrates the impeller model loaded into ANSYS version 2023 R1, and Figure 3 depicts the meshing process with Tetrahedral elements to ensure precision in results. And size was 2mm for each element.

Table 1. Properties of Incoloy.

Sr No.	A	B	C
	Property	Value	Unit
1.	Material Field variables	--	--
2.	Density	7.94	G cm^-3
3.	Isotropic Secant Coefficient of Thermal Expansion	--	--
4.	Isotropic Elasticity	--	--
5.	Strain Life Parameters	--	--
6.	S N Curve	--	--
7.	Tensile Yield Strength	276	Mpa
8.	Compressive Yield Strength	207	Mpa
9.	Tensile Ultimate strength	586	Mpa
10.	Compressive Ultimate Strength	552	Mpa
11.	Isotropic Thermal Conductivity	15	W m^-1 K^-1
12.	Specific Heat Constant Pressure, C.	0.5	J g^-1 K^-1

Table 2. Properties of Titanium.

Sr No.	A	B	C
	Property	Value	Unit
1.	Material Field variables	--	--
2.	Density	4620	Kg m^-3
3.	Isotropic Secant Coefficient of Thermal Expansion	--	--
4.	Isotropic Elasticity	--	--
5.	Tensile Yield Strength	9.3E + 08	Pa
6.	Compressive Yield Strength	9.3E + 08	Pa
7.	Tensile Ultimate strength	1.0E + 09	Pa
8.	Compressive Ultimate Strength	0	Pa
9.	Isotropic Thermal Conductivity	21.9	Wm^-1 C^-1
10.	Specific Heat Constant Pressure, C.	522	J kg^-1 C^-1

Table 3. Properties of Titanium.

Sr No.	A	B	C
	Property	Value	Unit
1.	Material Field variables	--	--

2.	Density	7850	Kg m^-3
3.	Isotropic Secant Coefficient of Thermal Expansion	--	--
4.	Isotropic Elasticity	--	--
5.	Strain Life Parameters	--	--
6.	S N Curve	--	--
7.	Tensile Yield Strength	2.5E + 08	Pa
8.	Compressive Yield Strength	2.5E + 08	Pa
9.	Tensile Ultimate strength	4.6E + 08	Pa
10.	Compressive Ultimate Strength	0	Pa
11.	Isotropic Thermal Conductivity	60.5	Wm^-1 C^-1
12.	Specific Heat Constant Pressure, C.	434	J kg^-1 C^-1

Boundary Conditions: -

In this project, we conducted thermal analysis on three distinct materials, utilizing identical boundary conditions for all. These boundary conditions are as follows: fig. 5, fig 6, fig 7,The uniformity in boundary conditions allows for a comparative study of how each material responds thermally under the same external influences.

1) The turbocharger impeller rotates at a speed 2000 Rad/sec.

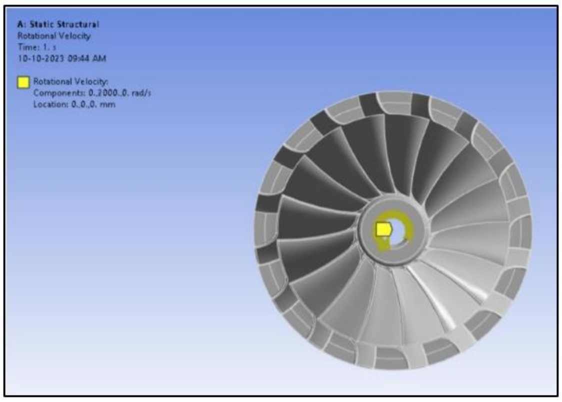

Fig. 5. Rotational Velocity.

2) Fixed support is given to hub of the Impeller, and this hub is attached to Turbine shaft.

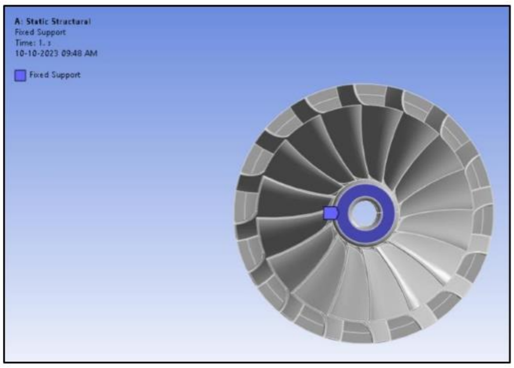

Fig. 6. Steady Face.

3) 1500 MPa Pressure is applied only to the impeller Blades.

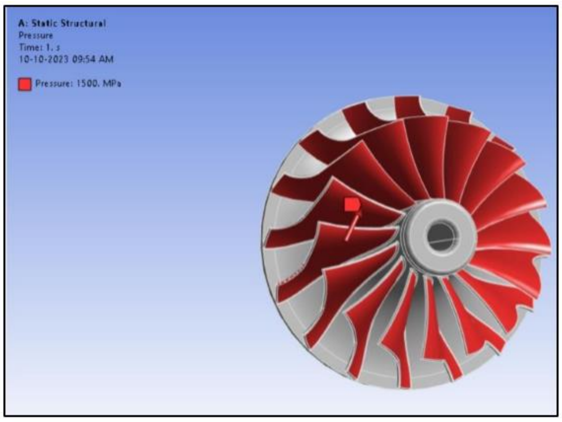

Fig. 7. Pressure of hot air flow.

RESULT AND DISCUSSION

The Incoloy underwent finite element analysis to scrutinize two vital properties: static structural and both steady state and transient thermal characteristics. Figures 8 through 12 illustrate the results, showcasing total deformation, equivalent stress analysis, and equivalent strain analysis. These visuals offer a comprehensive understanding of how Incoloy responds across different conditions.

The figure, Fig. 8, illustrates the overall deformation of Incoloy 800. The highest total deformation is concentrated along the edges of the impelle.

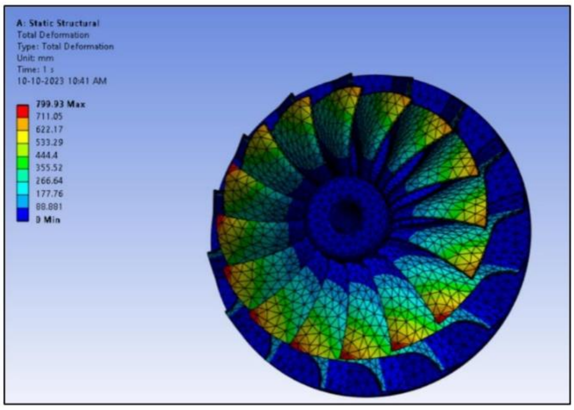

Fig. 8 Total deformation of Incoloy 800.

In Fig. 9, the Von Mises strain of Incoloy 800 is depicted. The maximum strain recorded is 4.75, concentrated at the root of the blade. Conversely, the minimum strain observed is 0.010363, located at the end of the blades.

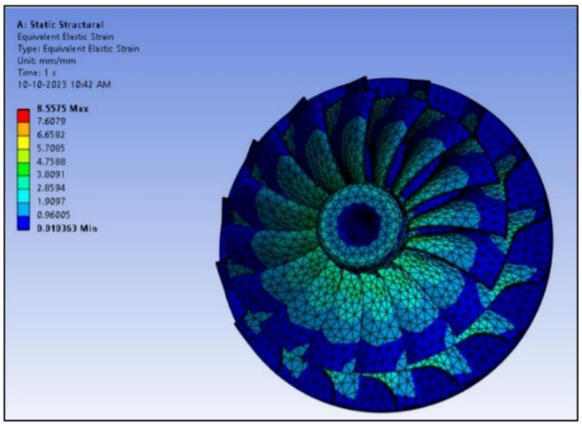

Fig. 9 Von misses' strain of Incoloy 800.

Fig. 10 displays the equivalent Von Mises stress of Incoloy 800. The maximum stress recorded is 7.59 * 10^5 MPa, situated at the root of the blades. In contrast, the minimum stress observed is 652.45 MPa, found at the base and edges of the blades.

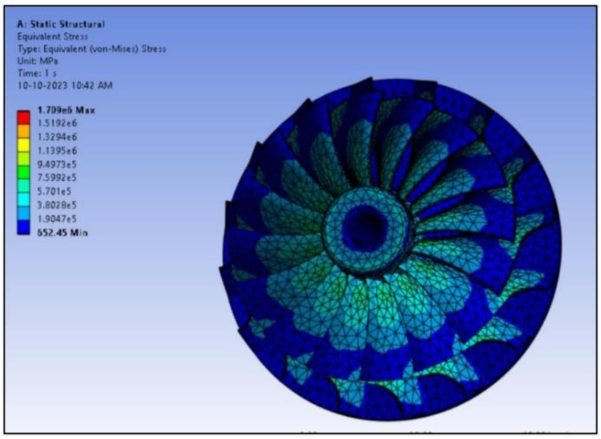

Fig. 10 Equivalent von mises stress of Incoloy 800.

The temperature distribution of Incoloy 800 is illustrated in Fig. 11. The highest temperature is observed at the edges of the blades, while the minimum temperature is registered at the base plate of the turbine wheel.

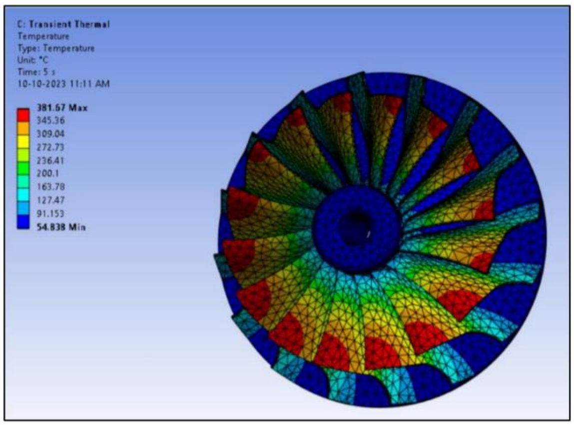

Fig. 11 Temperature distribution of Incoloy 800.

Fig. 12 presents the distribution of total heat flux. The maximum heat flux, reaching 1.35 W/mm2, is located near the blade roots. On the other hand, the minimum heat flux, at 0.00014579 W/mm2, is observed at the edges and base plate.

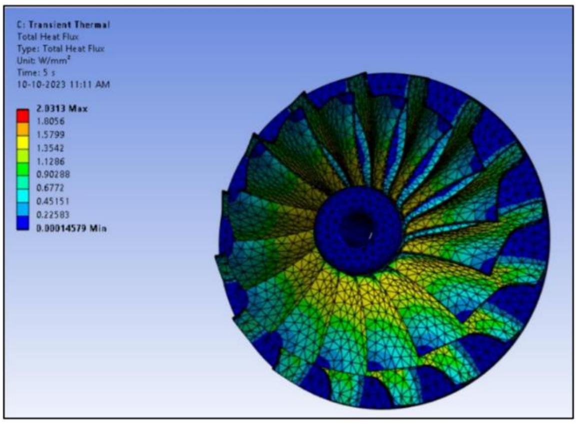

Fig. 12, Total heat flux of Incoloy 800.

Now, Structural Steel was subjected to finite element analysis to examine two crucial attributes: static structural behaviour and both steady-state and transient thermal characteristics. Results, depicted in Figures 13 to 17, present insights into total deformation, equivalent stress analysis, and equivalent strain analysis. These graphical representations provide a thorough comprehension of Structural Steel material response under varied conditions.

Figure 13 depicts the overall deformation of Structural Steel, showcasing a maximum total deformation of 800 mm concentrated along the edges of the impeller.

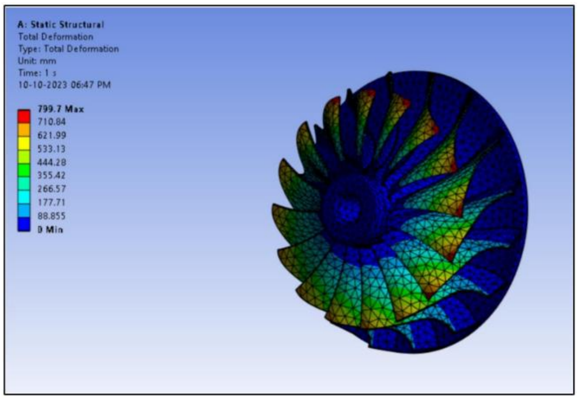

Fig. 13, Total Deformation of Structural Steel.

Figure 14 displays the Von Mises strain of Structural Steel. The highest recorded strain is 4.7495, concentrated at the root of the blade. In contrast, the minimum observed strain is 0.010325, situated at the end of the blades.

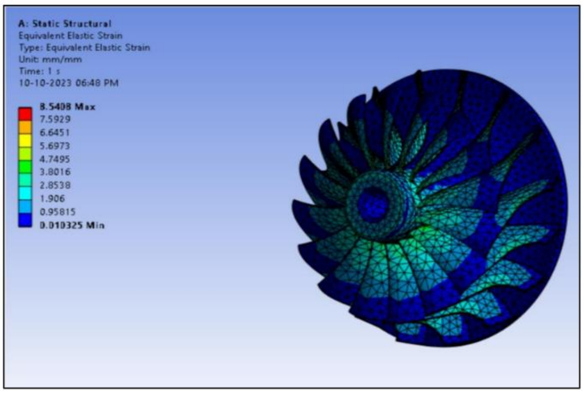

Fig. 14, Equivalent Elastic Strain of Structural Steel.

In Figure 15, the equivalent Von Mises stress of Structural Steel is presented. The maximum recorded stress is 7.58 * 10^5 MPa, concentrated at the root of the blades. Conversely, the minimum observed stress is 630.66 MPa, located at the base and edges of the blades.

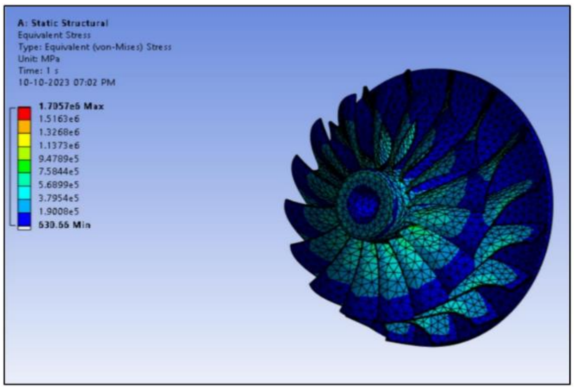

Fig. 15, Equivalent Von-Mises Stress of Structural Steel.

Figure 16 illustrates the temperature distribution of Structural Steel. The highest temperature, 383.88 degrees Celsius, is observed at the edges of the blades, while the minimum temperature, 55.56 degrees Celsius, is registered at the base plate of the turbine wheel.

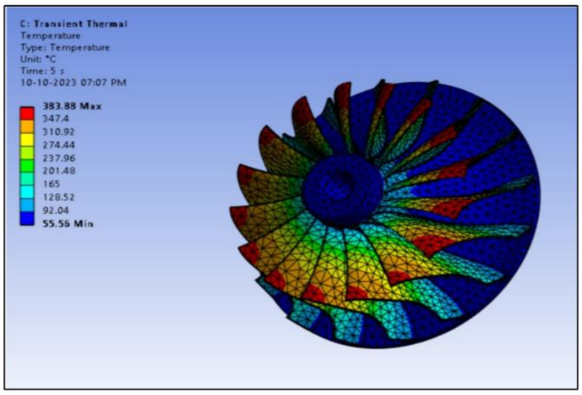

Fig. 16, Temperature Distribution of Structural Steel.

In Figure 17, the distribution of total heat flux is showcased. The maximum heat flux, reaching 1.80 W/mm2, is concentrated near the blade roots. Conversely, the minimum heat flux, at 0.00014579 W/mm2, is observed at the edges and base plate.

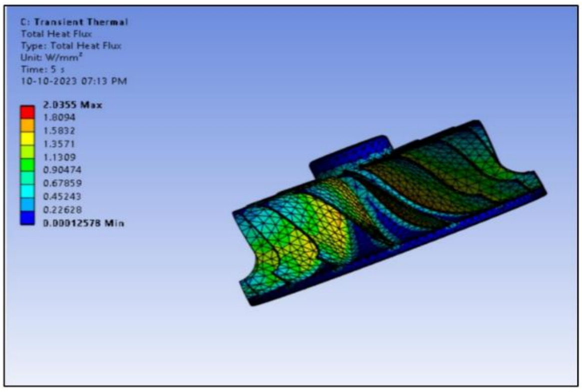

Fig. 17, Total Heat flux of Structural Steel.

Now, the Third material was Titanium underwent finite element analysis to scrutinize two vital properties: static structural and both steady state and transient thermal characteristics. Figures 18 through 22 illustrate the results, showcasing total deformation, equivalent stress analysis, and equivalent strain analysis. These visuals offer a comprehensive understanding of how Structural Steel responds across different conditions.

Figure 18. depicts the overall deformation of Titanium, showcasing a maximum total deformation of 1658.8 mm concentrated along the edges of the impeller.

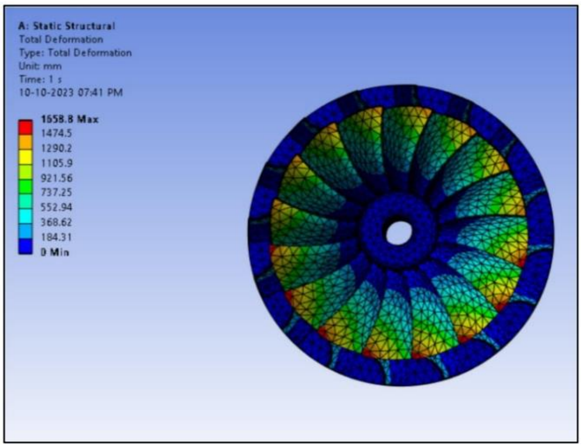

Fig. 18, Total Deformation of Titanium.

Figure 19. displays the Von Mises strain of Titanium. The highest recorded strain is 9.64, concentrated at the root of the blade. In contrast, the minimum observed strain is 0.025937, situated at the edge of the blades.

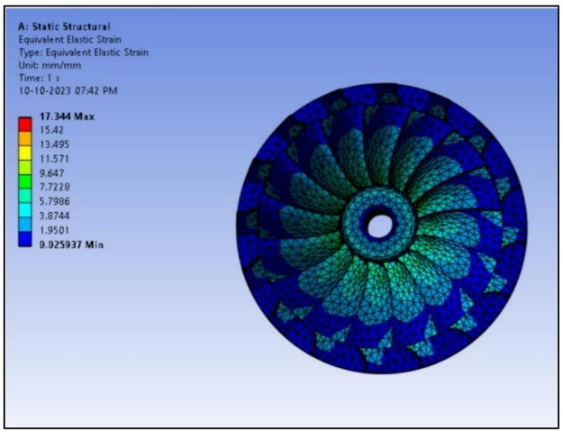

Fig. 19, Equivalent Elastic Strain.

In Figure 20, the equivalent Von Mises stress of Titanium is presented. The maximum recorded stress is 7.39 * 10^5 MPa, concentrated at the root of the blades. Conversely, the minimum observed stress is 561.62 MPa, located at the base and edges of the blades.

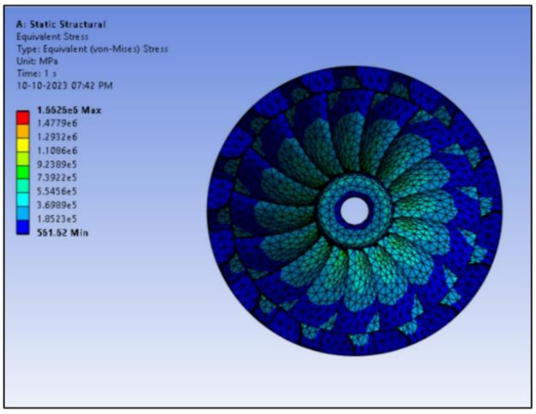

Fig. 20, Equivalent Stress.

Figure 21 illustrates the temperature distribution of Titanium. The highest temperature, 654.65 degrees Celsius, is observed at the edges of the blades, while the minimum temperature, 43.431 degrees Celsius, is registered at the base plate of the turbine wheel.

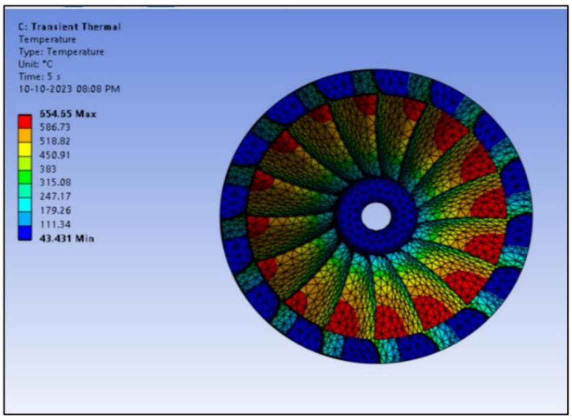

Fig. 21. Temperature Distribution of Turbocharger Impeller.

In Figure 22, the distribution of total heat flux is showcased. The maximum heat flux, reaching 1.67 W/mm2, is concentrated near the blade roots. Conversely, the minimum heat flux, at 0.0002494 W/mm2, is observed at the edges and base plate.

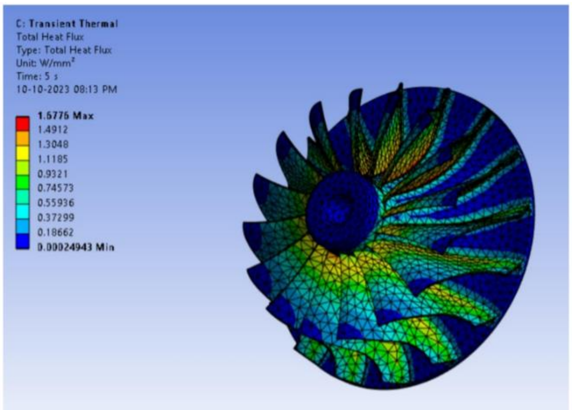

Fig. 22. Total Heat Flux of Titanium.

Table 4 provides a comprehensive overview, juxtaposing the results of static structural analysis and transient thermal analysis for the three materials under examination in this study.

Table 4. Comparison of Analysis Results of Three Materials.

Sr. no.	Parameter	Incoloy 800	Structural Steel	Titanium
1.	Total deformation.	799.93 mm	799.70mm	1658.8mm
2.	Von mises Strain.	4.75	4.7995	9.64
3.	Von mises Stress.	$7.59 * 10^5$ Mpa	$7.58 * 10^5$ Mpa	$7.39*10^5$ Mpa
4.	Temperature.	381.67 Degree Celsius	383.88 Degree Celsius	654.65 Degree Celsius
5.	Heat Flux.	1.35 W/mm^2	1.80 W/mm^2	1.67 W/mm^2

Table 4 reveals a distinct comparison in the analysis results for three materials. Notably, Titanium exhibits higher deformation than Incoloy and Structural Steel. Moreover, Titanium demonstrates the lowest stress values when compared to the other two materials. Conversely, Incoloy 800 exhibits minimal values in terms of stress, temperature, and heat flux as opposed to Structural Steel and Titanium.

CONCLUSION

The analysis focused on the turbo charger impeller, utilizing ANSYS. Initial steps involved creating the impeller model in SolidWorks, saving files in STEP format and importing them into ANSYS. Subsequent analysis was conducted on the redesigned model, employing different materials (Structural Steel, Incoloy and titanium), with the results being compared.

Upon examining the data presented in table.4 It is evident that incoloy 800 outperforms structural steel, Titanium. The findings indicate that the incoloy 800 exhibits minimal stress and deformation. Additionally, the total thermal flux affecting the impeller is lower for incoloy 800. This suggests that incoloy 800 can withstand higher stress and temperature levels. In conclusion, Incoloy 800 emerges as the most suitable material among the three choices for the turbocharger impeller.

REFERENCES

[1] N. Sathishkumar,P. Premkumar, A. Ruskin Bruce, K. Pravinkumar, P.L. Sudharsan , Design and Analysis of an Impeller of a Turbocharger, 2020. Department of Mechanical Engineering, St.Joseph’s College of Engineering, Chennai.

[2] V.R.S.M. Kishore Ajjarapu, K.V.P.P Chandu, D.M. Mohanthy Babu, Design and analysis of the Impeller of a turbocharger for a diesel Engine. 2012, Vishakhapatnam.

[3] B.P.Terani, Dr. K.S.Badarinarayan, Prakasha.A.M., Stability Analysis of Turbocharger Impeller: A Review, MS Engineering College ,Bangalore, Karnataka.

[4] Baines, Nick; Wygant, Karl D.; Dris, Antonis (2010). The Analysis of Heat Transfer in Automotive Turbochargers. Journal of Engineering for Gas Turbines and Power, 132(4), 042301–. doi:10.1115/1.3204586

[5] Zheng, X.; Jin, L.; Du, T.; Gan, B.; Liu, F.; Qian, H. (2013). Effect of temperature on the strength of a centrifugal compressor impeller for a turbocharger. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 227(5), 896– 904. doi:10.1177/0954406212454966