INTERNATIONAL JOURNAL OF AUTOMOTIVE SCIENCE AND TECHNOLOGY

2025, VOL. 9, NO:2, 259-*268*

www.ijastech.org

e-ISSN: 2587-0963

Numerical Investigation on Material Optimization of Turbocharger

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Research Article

Abstract

This research investigates about a critical area of turbocharger failure and tends to study the impacts of stresses on turbine wheel. As the turbine wheel of a turbocharger is one of the highly stressed components in automotive engines, it is commonly subjected to creeps and deformations which lead to the failure of the turbocharger and, in turn, damages the engine. Hence, to study these phenomena and to identify the regions of failure, a 3D model of a Turbocharger is designed in Creo 8.0, followed by a comprehensive Thermo-Structural analysis conducted using Ansys 2023 R1. This coupled Finite Element Analysis proved to be instrumental in accurately determining the thermal stress induced warpage due to heat transfer, enabling the consideration of this factor in evaluating three critical mechanical characteristics - Total Maximum Deformation, Equivalent Strain and Equivalent Stress. The localization of stress-induced failures is validated by comparing the numerical results with real-world observed failures as well as aligning them with existing research. The derived data were then subsequently compared across three different materials that are commonly used in the manufacturing of turbine wheels. The unique chemical composition of Mar-M246, featuring 10% Cobalt, 10% Tungsten, and a higher proportion of Carbon content compared to Inconel 713C and Inconel 783, contributes to its impressive high temperature strength, lower ductility, enhanced hot hardness, improved creep and oxidation resistance. This formulation results in minimal deformation of just 0.648 mm in turbine wheel when the turbocharger is operating at 95,000 rpm. On the basis of the comparison deduced, this study concludes that Mar-M246 outperforms the other two materials.

Keywords: Finite Element Analysis; Optimal Material Investigation; Thermo-Structural Analysis; Turbocharger

History
Received 16.10.2024
Revised 21.04.2025
Accepted 02.06.2025

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To cite this paper: Sinha, K.B., Saxena, R.R., Numerical Investigation on Material Optimization of Turbocharger. International Journal of Automotive Science and Technology. 2025; 9 (2): 258-269. https://doi.org/10.30939/ijastech..1568643

1. Introduction

Internal Combustion (IC) Engine serves as the primary power source in automobiles. Its purpose is to generate mechanical power from the chemical energy contained in the fuel through fuel combustion. Turbocharger is a type of forced induction system whose function is to enhance the engine's efficiency by increasing the density of the intake air, thereby allowing more power per engine cycle. Turbocharger utilizes a series of blades to convert the kinetic energy from the flow of exhaust gases to mechanical energy of a rotating shaft which is used to power the compressor section. The compressor impeller is responsible for compressing the ambient air before it enters the engine's combustion chamber. This compressed air offers a greater mass of oxygen per cycle to support combustion than available to a naturally aspirated engine. Hence, turbocharging makes it possible for more fuel to be burnt and more work to be done per combustion cycle, which increases the power produced by the engine.

This automotive enhancement was pioneered by a Swiss engineer Alfred Büchi, who patented his idea in 1905. He successfully installed the first exhaust gas turbocharger system to a marine diesel engine in 1925, boosting its power reportedly by 40%. Following this milestone, turbochargers were introduced in automobiles in 1962-63 in the US, but faced some resistance initially. They gained wider acceptance in commercially used diesel vehicles only after the oil crisis in 1973. On the contrary, petrol engine manufacturers rejected the idea of turbocharging due to concerns about the ability of lighter parts used in petrol engines to sustain the rise of pressure caused by the turbocharger. Additionally, the materials used in early turbochargers were not robust enough to handle the high exhaust gas temperatures produced by petrol engines. Nevertheless, making certain modifications such as introducing intercooler and selecting smaller compressor wheel allowed for greater adoption of turbochargers on petrol engines from the 1980s onwards as a mean to increase the performance of smaller displacement engines.

Apparently, with more than a decade of history, the issue of material selection for turbo core still persists. Optimal material selection stands on top among other parameters in determining the overall efficiency of a turbocharger. Since the turbine wheel is directly exposed to the exhaust gas, it must endure the highest temperature and maximum pressure. The repeated stress on the turbocharger rotating components is a major factor contributing to degradation in turbomachinery. There are three typically recognized forms of fatigue – Thermal-Mechanical Fatigue (TMF), High Cycle Fatigue (HCF) and Low Cycle Fatigue (LCF). The continuous operation under fatigue stress caused due to variations in cyclic mechanical load leads to creep growth, fracture and ultimately turbine wheel failure [14]. Therefore, selecting the most appropriate material for turbine wheel becomes a matter of significant concern. The present research focuses on identifying the region undergoing maximum deformation and experiencing maximum stress caused due to Thermo-Mechanical loading. Furthermore, this research extends its objective to make a modest contribution towards the investigation of material optimization for the turbocharger turbine wheel. In order to achieve this, three widely used materials for the manufacturing of turbine wheel are chosen – Inconel 713/K-18/K-418, Inconel 783 and Mar-M246. These particular materials are considered for this study owing to their superior properties such as excellent corrosion resistance, better fatigue characteristics and high temperature strength over other conventional metals like Structural Steel, Aluminium Alloys and Titanium Alloys.

2. Literature Review

Numerous endeavors have been made in the past to dissect the impact of temperature, heat exchange and structural loading on different turbocharger components. One such enlightening works incorporate the think about made by Hamed Basir and Marc A. Rosen [1]. They made an attempt to study the temperature distribution in a turbocharger body experimentally using a thermal camera and then compared it with a one-dimensional simulation of a turbocharger developed for the temperature distribution. The experiment was conducted on two different engines to observe whether or not the derived outcomes conform to numerical investigation. The comparison of the experimental and numerical results showed that the maximum error observed was acceptable. Elena Zadorozhnaya, Vlad Hudyakov and Sergey Sibiryakov [2] aimed at developing a formulation for evaluating the heat transfer in the turbocharger bearing housing in order to examine the impact of thermal distortions on the rotor dynamics and the hydromechanical characteristics of the bearing. It was concluded that with an increment in the rotor speed, the radial bearing assembly was exposed to the most significant increase in the value of heat exchange coefficient. Alessandro Romagnoli and Ricardo Martinez-Botas [3] examined the performance of a turbocharger under non-adiabatic conditions to determine the effect of heat transfer. A commercial turbocharger was introduced on a 2.0liter diesel engine and estimations were conducted for a range of engine speeds and loads. On measuring the surface temperatures of three primary bodies constituting the turbocharger (turbine and compressor casing, bearing housing), it was observed that the engine has a huge effect on surface temperature of the turbine and compressor casing and moreover that the surface temperatures of both the turbine and the compressor change linearly with the temperature of the flue gasses. B. James Prasad Rao, E. Venkata Reddy and V. Mallikarjuna [4] made an endeavor to propose the best material for turbocharger impellers by comparing the comes about obtained from three diverse analyses. The comparison was done on the basis of effects such as stress, deformation and heat flux to conclude the study. Another set of Indian analysts [5] carried out an identical numerical study by modelling an impeller of a turbocharger with three distinctive materials. They examined the impact of temperature, pressure and induced stresses on the impeller considering certain different constraints. G.R. Krishna Prasad Reddy and D. Jakeer Hussain [6] compared composite materials for turbine wheel under two different fluid flow conditions (i.e., laminar and turbulent flow). The results compared the structural and thermal properties across the three materials on typical and optimized models of turbine wheels. Dr. Htay Htay Win and Tin Ni Lar Win [7] analyzed the stress on the turbine blade of turbocharger. The calculation of turbine design included determining the values of pressure, blade parameters, mass flow rate, tangential and radial force on turbine blade. The stress on turbine blade was evaluated both theoretically and numerically. For this investigation, the turbine inlet and outlet temperature were measured by using Infrared thermometer BM-380. Upon applying the above stated boundary conditions, turbine wheels with 3 different number of blades (11, 12, and 13) were analyzed to determine the stress and strain. The minimum von-Mises stress and effective strain were found in blade numbers 13 and the most suitable material was Structural Steel. A similar work was carried out by Aye Aye Thet et al. [16]. The group analyzed the most apt material for turbine wheel by comparing the outcomes procured numerically with the analytical calculation. The study went on to determine the appropriate number of blades for optimal performance. M. Cormerais, J. F. Hetet, P. Chesse and A. Maiboom [9] analyzed heat transfer in a turbocharger compressor. This turbocharger test bench allowed to measure: turbine, compressor and oil inlet and outlet temperatures with thermocouples and Turbine and compressor inlet and outlet pressures with piezoresistive sensors. To estimate heat flux from the turbine to the compressor, three methods had been tested. The first one consisted to consider that the heat fluxes from the turbine to the compressor depend only on the difference between the turbine inlet temperature and the compressor inlet temperature for a constant turbocharger speed. The second method was based on a Nusselt number correlation proposed by Bohn to determine heat fluxes from the turbine to the compressor. In the third method, the central housing was supposed to be a flat plate of uniform thickness and of constant section. In this case, the heat transfer was calculated using convective heat transfer equation in steady state. The results obtained by the direct use of the maps were found in average 30% higher than those provided by the three methods. Paulson Ouseph A. et al. [11] aimed to evaluate the critical thermal stresses in turbine housing of a turbocharger subjected to thermo-mechanical stresses. The researches compared the FEA results with the scanned on-road data to locate the regions exposed to thermo-mechanical fatigue in order to compute the components' fatigue life cycle. A strength test of the turbine wheel blades was carried out by T. Kalaczyński et al. [20]. They compared the effects of stress and strain on the deformation of blades of the turbine wheel operating at a specific angular velocity by varying the turbine wheel sizes across three different vehicle types. The FEA turn-outs deduced that the stresses and deformation on the rotor blades grew as the overall dimension of the model was reduced. Doncasters Superalloys [22] studied the turbocharger turbine wheel design requirements and how this affects material property and chemical composition requirements by performing various mechanical testing across a few industrially used alloys. Based on the outcomes, it was deduced that Mar M-246 is suitable for high temperature applications. Shaik Mohammed Shafi et al. [13] performed FEA on a turbocharger casing by to determine the best material across the chosen four by comparing the thermal properties. In the subsequent stage, CFD was conducted to examine the drop in pressure, temperature, density and kinetic energy in order to evaluate cycle life of the turbine and compressor housing. Many of the previously mentioned research works primarily concentrate on the temperature distribution in turbocharger casings or the stress experienced by compressor impellers. Additionally, there has been limited analysis on the stress distribution within turbine wheels. Notably, there is a gap in studies that examine commonly used industrial materials for turbine manufacturing. The current study seeks to address this gap by focusing on material optimization specifically for turbine wheel applications, thereby contributing valuable insights to the field.

3. Methodology

This study attempts to analyze the effects of thermo-mechanical loads acting upon the turbine wheel operating in a turbocharger. The primary objective of this research is to evaluate the levels of stress, strain and deformation developed in the turbine wheel blade and to locate them. Moreover, the examination extends to propose an optimal material for the afore-said application by comparing the derived results across three selected materials. In order to accomplish the above objectives, thermo-structural simulation is performed using Ansys 2023 R1.

3.1. Design Considerations

Garrett GTB 2056V Turbocharger model is recreated as a 3D model to be studied in this research paper using PTC Creo 8.0. The dimensions of the turbocharger turbine wheel considered for this investigation are tabulated below.

Table 1. Turbine Wheel Geometry

Inducer Diameter (mm)	47
Exducer Diameter (mm)	43
No. of Blades	9
Blade Angle (°)	40

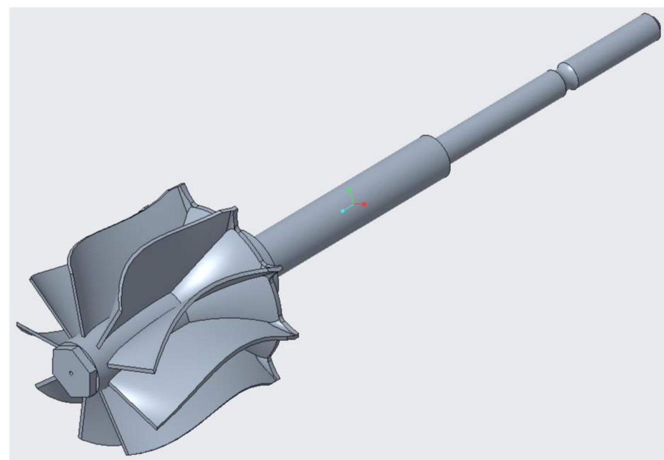

Figure 1. Cad Model of Turbocharger Turbine Wheel

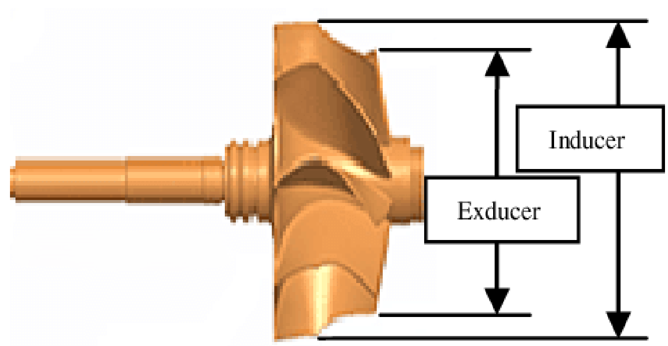

Figure 2. Design Parameters of Turbine Wheel

3.2. Material Assignment and Properties

Turbocharger turbine wheel material is selected based on its ability to withstand high temperatures, resist corrosion and resist thermal fatigue. Other factors that affect the life of a turbocharger include thermal cracking, stress induced fatigue and creep. The turbocharging application demands the material to operate under excessive temperatures, high pressures and variations in rotational speed. Therefore, taking into consideration the above-mentioned criteria and studying the latest turbocharging trend, the following three materials are selected for further analysis. The properties of each material are tabulated below.

Table 2. Material Assignment for Turbine Wheel

Material	Inconel 713C / K-18 / K-418	Inconel 783	Mar-M246
Density (kg/m³)	7910	7810	7800
Young's Modulus (GPa)	193	180	200
Poisson's Ratio	0.3	0.31	0.3
Thermal Conductivity (W/mK)	28.5	10.1	16.2
Specific Heat (J/kgK)	792	317	500
Tensile Strength (MPa)	856	1194	515
Yield Strength (MPa)	698	779	275
Melting Point (K)	1533-1561	1609-1680	1493-1623

3.3. Mesh Generation and Grid Independence Test

The complex geometry of the turbine wheel is broken down into fine individual computational elements to execute further simulations using meshing. Taking into consideration the intricacies of the model, tetrahedral meshing is chosen for its ability to provide better solutions for the surface and boundary features. Subsequently, Grid Independence Test is conducted as it offers a scope to determine the optimal mesh size at which accurate result is obtained. This study uses Mesh Element Size as the input parameter, varying it to assess Total Deformation of the turbine wheel by assigning it Inconel 713C/K-18/K-418 material. Figure 3. depicts the discretization of the model into meshed geometry. The value of Mesh Element Size is steadily reduced from coarse (0.75 mm) to fine (0.3 mm).

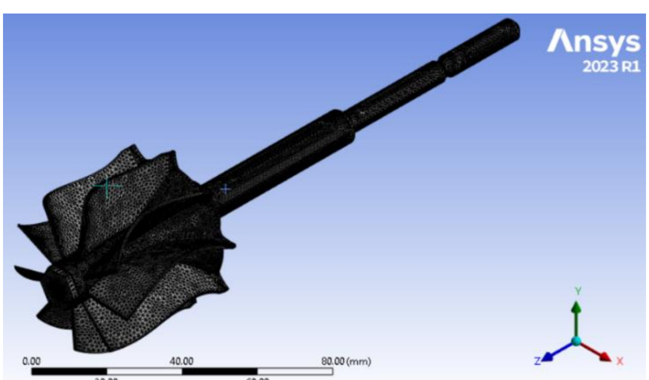

Figure 3. Mesh Geometry

Table 3. given below depicts that as the Mesh Element Size was progressively decreased, more accurate Total Maximum Deformation results were obtained, with element size 0.3 mm yielding excellent result. Upon evaluation, the amount of Total Deformation appears to plateau at a Mesh Element Size of 0.45 mm, showing minimal variation beyond this point. Therefore, it is deemed optimal for further analysis. Additionally, a high-quality mesh is achieved at this element size, as over 90% of the elements have a Jacobian ratio close to 1. This ratio indicates that the majority of the elements align well with the ideal geometric shape, ensuring an effective balance between accuracy and computation time. Consequently, opting for a finer element size, such as those below 0.45 mm, is not advisable, as it would unnecessarily increase computational costs and extend solution times.

Table 3. Turbine Wheel Geometry

Mesh Element Size (mm)	Total Maximum Deformation (mm)	Mesh Nodes	Mesh Elements
0.75	0.66937257	326845	182579
0.7	0.670933984	371819	208602
0.65	0.671762478	428642	240807
0.6	0.673165822	505393	285049
0.55	0.674255634	596881	337608
0.5	0.675739555	724771	410945
0.45	0.679846071	894125	510360
0.4	0.680121711	1148071	660666
0.35	0.680838846	1540872	892850
0.3	0.681224	2099329	1217942

3.4. Boundary Conditions

The current work benefits from the research conducted by Elena Zadorozhnaya, Vlad Hudyakov and Sergey Sibiryakov [2]. The boundary conditions to be applied on the geometry are derived from the experimental setup and data accuracy of their study. The high temperature exhaust gases are incident on the inner surfaces of the turbine blades, while the entire turbine blade geometry contributes to convectional heat transfer as depicted in Figure 4. The examination of the impacts of mechanical loads involves applying a rotational velocity of 95,000 rpm to the turbine wheel while constraining its displacement with a cylindrical support applied to the shaft as shown in Figure 5. This coupled analysis is instrumental in accurately determining the thermal stress induced warpage due to heat transfer, allowing for the consideration of this effect in the analysis system of stress and deformation of the model. Below is the tabulated data from their study.

Table 4. Boundary Conditions

Angular Speed (rpm)	Parameter	Turbine Inlet	Turbine Outlet
95,000	Pressure (Pa)	2,63,445	1,01,325
	Temperature (K)	926	796

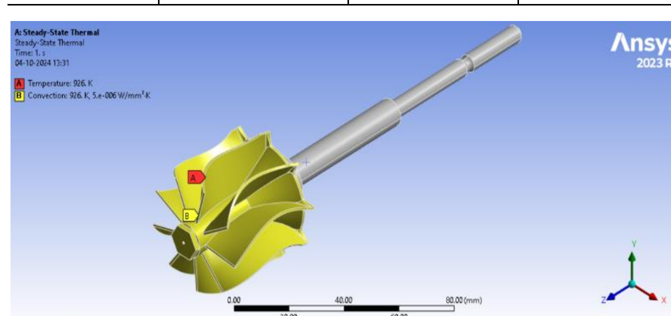

Figure 4. Thermal Boundary Conditions

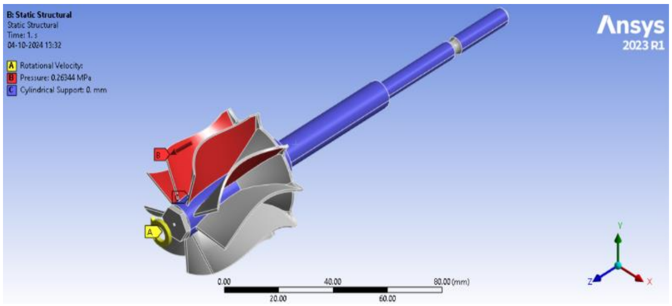

Figure 5. Structural Boundary Conditions

4. Results and Discussion

Turbine rotors exhibit cyclic symmetry, indicating that the behavior of one blade can be representative of the others. Additionally, because a similar stress distribution is observed in all blades, analyzing a single blade allows for a clearer and more detailed examination of critical stress impingements and locating potential hotspots.

4.1. Deformation across all Materials

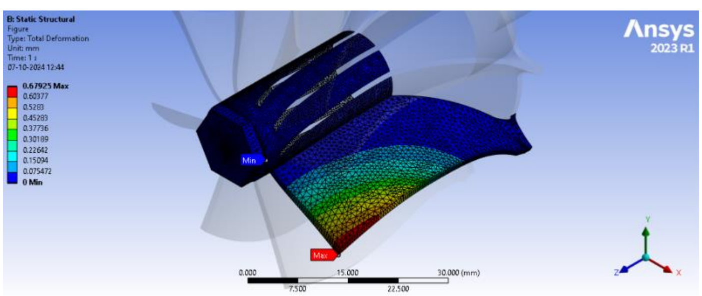

Figure 6. Deformation in Inconel 713C/K-18/K-418

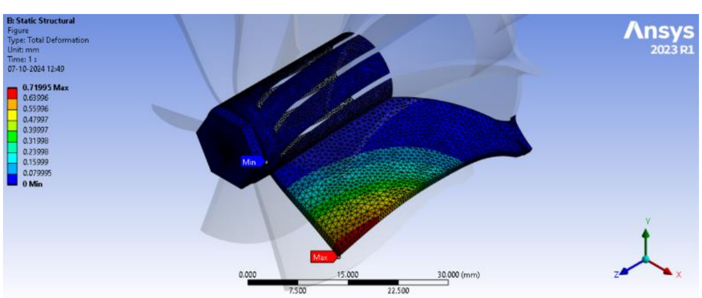

Figure 7. Deformation in Inconel 783

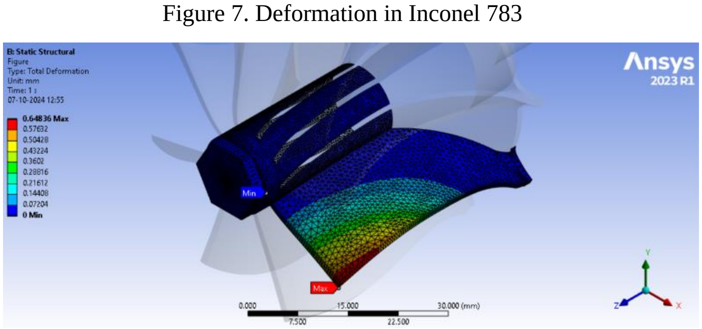

Figure 8. Deformation in Mar-M246

The provided figures illustrate the deformation experienced by the turbine wheel blade when constructed from three different materials. Notably, Mar-M246 exhibits the least deformation at 0.648 mm, highlighting its superior performance, while Inconel 783 shows the highest deformation at 0.719 mm. These findings suggest that Mar-M246 may be the more effective choice for applications requiring minimized deformation.

4.2. Equivalent Strain across all Materials

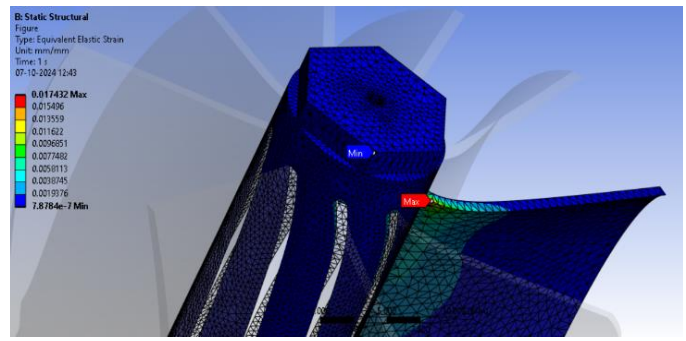

Figure 9. Equivalent Strain in Inconel 713C/K-18/K-418

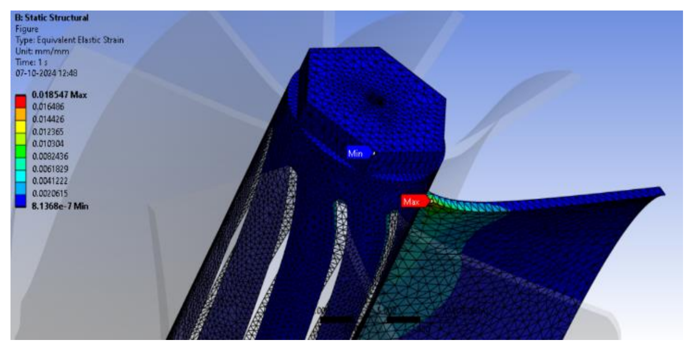

Figure 10. Equivalent Strain in Inconel 783

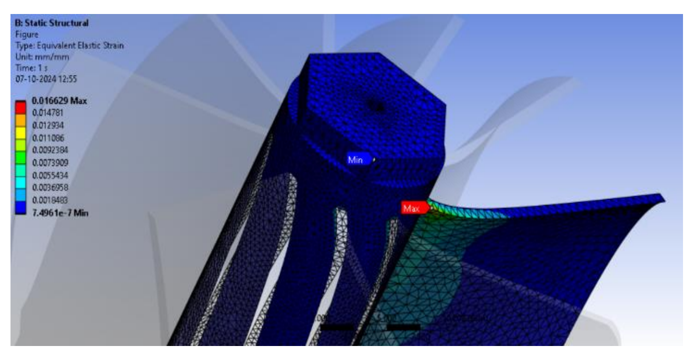

Figure 11. Equivalent Strain in Mar-M246

The analysis of the provided figures indicates that the blade made from Mar-M246 experiences the lowest equivalent strain, measured at 0.016. In contrast, Inconel 783 exhibits the highest level of strain at 0.018. This information highlights the relative performance of these materials under stress, suggesting that Mar-M246 may be a more favorable choice for applications requiring lower strain.

4.3. Equivalent Stress across all Materials

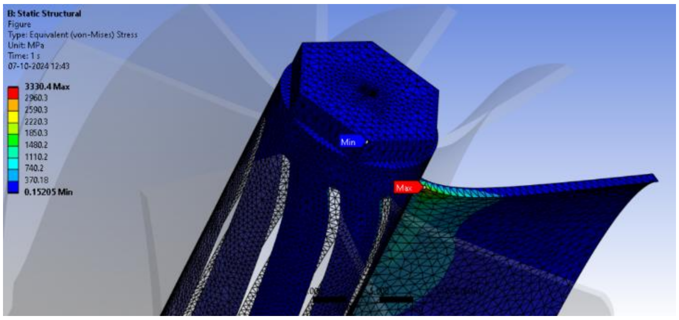

Figure 12. Equivalent Stress in Inconel 713C/K-18/K-418

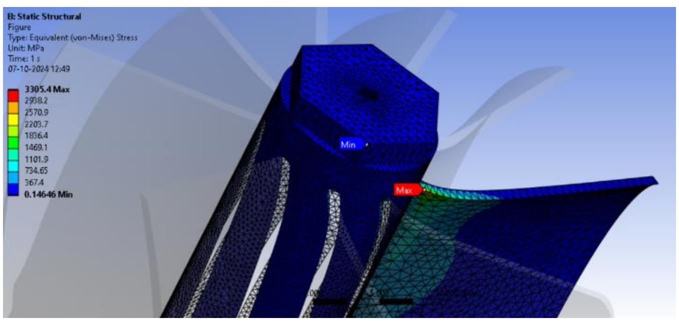

Figure 13. Equivalent Stress in Inconel 783

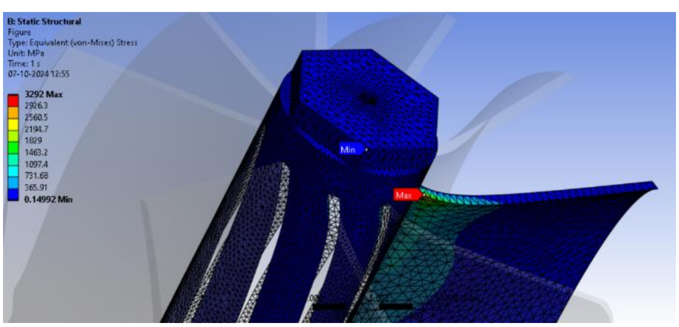

Figure 14. Equivalent Stress in Mar-M246

The afore-given figures depict that Mar-M246 experiences the lowest levels of stress, demonstrating its advantageous performance under the given conditions (3292 MPa). In contrast, the blade made from Inconel 713C/K-18/K-418 exhibits the highest stress levels, suggesting a need for further evaluation or potential enhancements in its design or material composition (3330 MPa).

Table 5. Material Comparison based on FEA Results

Material	Total Maximum Deformation (mm)	Maximum Equivalent Strain	Maximum Equivalent Stress (MPa)
Inconel 713C/ K-18/K-418	0.679	0.0174	3330.4
Inconel 783	0.719	0.0185	3305.4
Mar-M246	0.648	0.0166	3292

The above figures derived from the Ansys finite element analysis depict that the tip of the turbine blade undergoes greatest deformation, whereas the maximum stress and strain are concentrated near the roots on the convex side of the blades regardless of the assigned materials. Furthermore, the derived data presents a comparison of three essential structural properties among three different materials. It is conspicuous from the analysis that Mar-M246 demonstrates superior performance compared to the other materials. It undergoes the least amount of deformation (0.648 mm) under the specified boundary conditions. While the deformation results for Inconel 713C (0.719 mm) and Inconel 783 (0.679 mm) show minimal variation, with the latter exhibiting slightly better properties. Additionally, least value of equivalent stress (3292 MPa) and strain (0.0166) are induced in blade assigned with material Mar-M246. On the other hand, the turbine blades assigned with Inconel 783 are subjected to Maximum Equivalent Strain (0.0185) and with Inconel 713C/K-18/K-418 are subjected to Maximum Equivalent Stress (3330.4 MPa).

4.4. Deductions

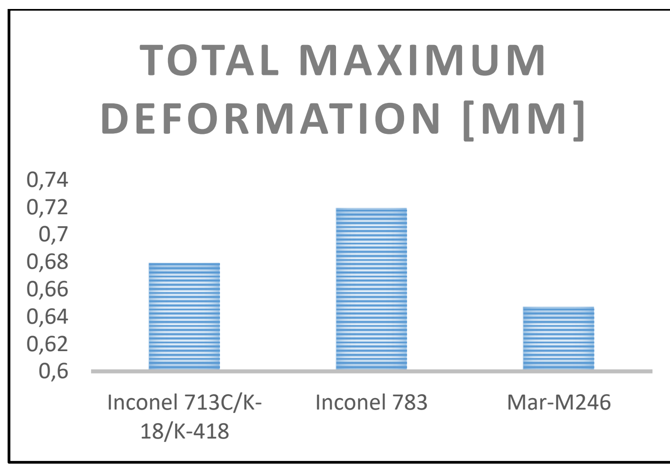

Figure 15. Total Maximum Deformation [mm]

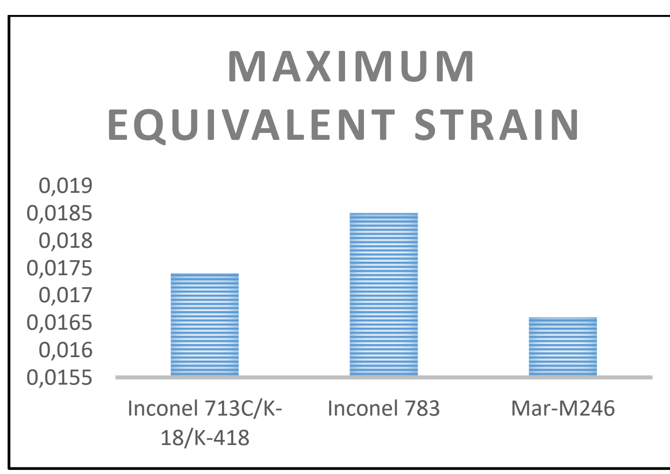

Figure 16. Maximum Equivalent Strain

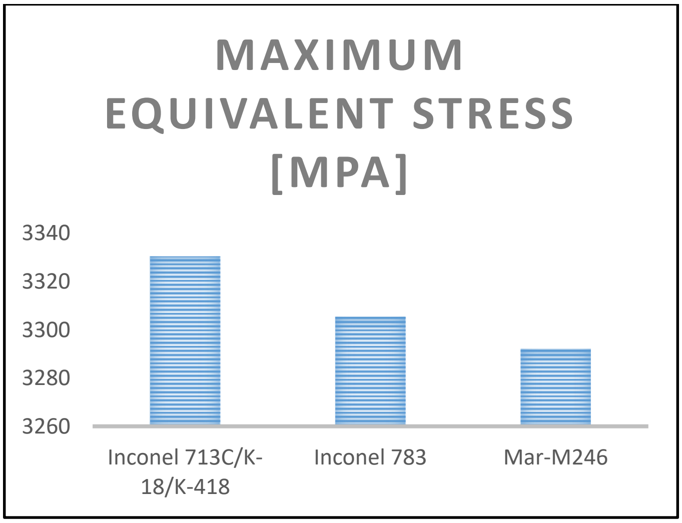

Figure 17. Maximum Equivalent Stress [MPa]

The afore-derived line graphs depict the difference in performance of the three materials considered in this research work. One of the various reasons why Mar-M246 seems to outperform the other two materials is because of its better high temperature strength and creep resistance. The theoretical bearing temperature of Inconel 713C as well as Inconel 783 is around 950°C, whereas Mar-M246 can be used in applications where the temperature of exhaust gases exceeds 1000°C. Mar-M246 contains 10% Cobalt and 10% Tungsten, and higher composition of Carbon than Inconel 713C and Inconel 783. This unique chemical composition imparts higher strength, lower ductility and enhanced hot hardness. Furthermore, Mar-M246 contains a higher proportion of Tantalum and a smaller proportion of Aluminium compared to the other two materials under study. This optimized microstructure of Mar-M246 contains a fine dispersion of strengthening precipitates that contribute to its high creep and oxidation resistance. These properties conform to the study carried out in alloy development research [22]. Therefore, the above-mentioned reasons make Mar-M246 an excellent choice for applications demanding exceptional high-temperature resistance, strength and resistance to creep and fatigue.

5. Validation

To validate the legitimacy of the deductions made from this research on material optimization of turbine wheel, it is essential to compare these results with the observations made from real-world problems. To achieve this, the components of a turbocharger were dismantled to examine the turbine wheel failure caused by the spinning of the turbocharger above the permissible rpm. As shown in Figures 19 and 20, the turbine wheel showed deformations in the tip region as well as the blade profile was distorted.

Figure 18. Failed Turbine Wheel (Author’s Image)

Figure 19 (a). Blade Tip Deformation (Author’s Image)

Figure 19 (b). Blade Tip Deformation (Author’s Image)

Figure 20 (a). Blade Profile Distortion (Author’s Image)

Figure 20 (b). Blade Profile Distortion (Author’s Image)

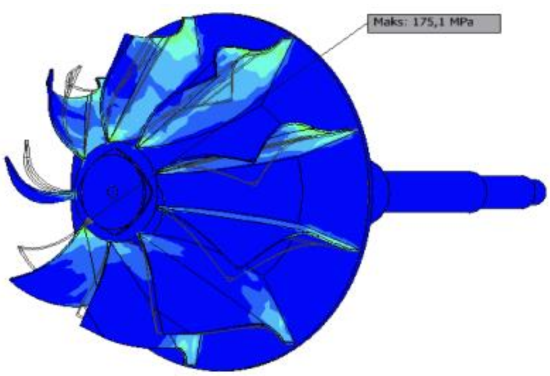

Figure 21 (a). Localization of Maximum Stress near the Root (Cited Image)

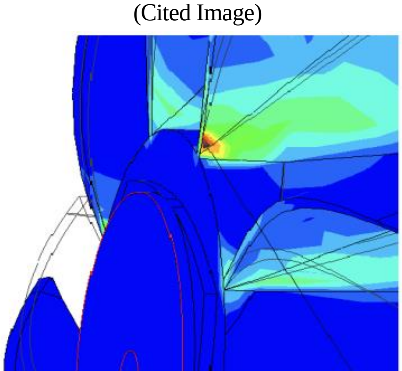

Figure 21 (b). Localization of Maximum Stress near the Root (Cited Image)

The failure of blades occurred due to exposure to high pressure and elevated exhaust gas temperature. Over-speeding induced internal stresses in the rotor material, leading to the deterioration of the turbine wheel’s performance. These findings stand in accordance with the investigations of a failed turbocharger turbine blade [21]. Additionally, similar kind of failure pattern obtained from Ansys FEA, as depicted in Figures 6-14, is observed in the developed numeric models [20] as shown in Figures 21 and 22, and in the study carried out to investigate a failed turbine wheel [21] as depicted in Figures 23 and 24.

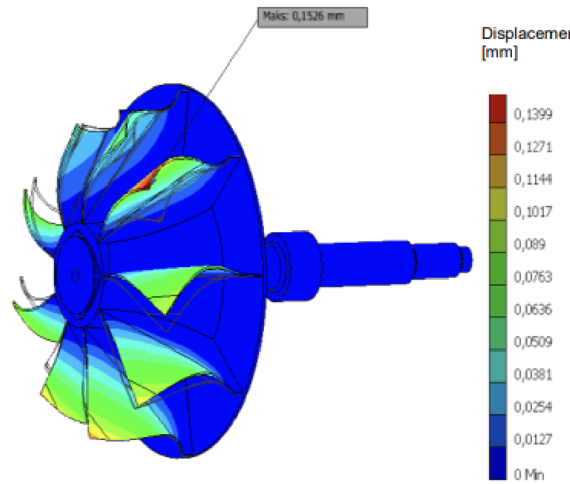

Figure 22 (a). Deformation of Blade Tip (Cited Image)

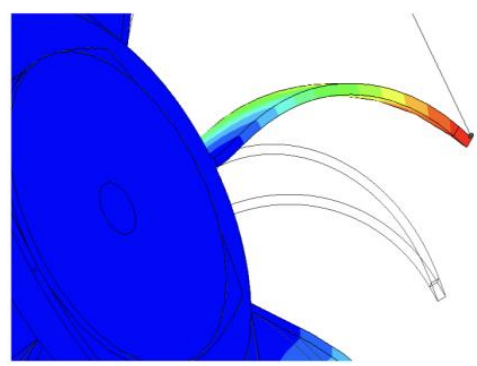

Figure 22 (b). Deformation of Blade Tip (Cited Image)

Figure 23. Damaged Blade Tip (Cited Image)

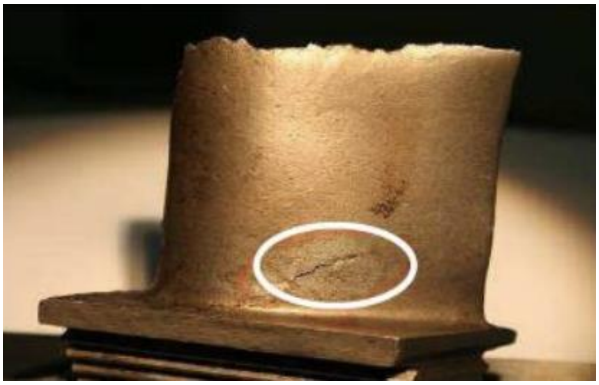

Figure 24. Crack Propagation near the Blade Root (Cited Image)

6. Conclusion

This research paper thoroughly investigates the thermo-structural characteristics of a turbocharger's turbine wheel using FEA under several experimental boundary conditions [2]. The study aims to determine the levels of stress and deformation, to locate the regions subjected to maximum stress and deformation occurred due to exposure to high pressure and elevated exhaust gas temperature, and to identify the most suitable material for the turbine wheel by comparing the FEA results across three different materials. The results drawn from the study illustrate that the maximum distortion is witnessed on the tip of the turbine wheel blades, while the maximum stress and strain is concentrated near the blade's root. On the basis of the investigation findings, Mar-M246 outperforms the other two materials owing to its better high temperature strength, lower ductility, enhanced hot hardness, improved creep and oxidation resistance. Therefore, Mar-M246 has been conclusively identified as the optimal material for producing turbine wheels for Turbocharger applications.

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Keval B. Sinha: Conceptualization, Methodology, Resources, Formal analysis, Data curation, Investigation, Writing-original draft
Rishi R. Saxena: Project administration, Supervision, Resources, Validation

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