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Design and Analysis of a CI Engine Turbocharger Turbine Wheel Using Different Materials

A CHENNA REDDY[1], PUNAGANI ANIL KUMAR[2], CHEDIKA SATISH[3], G VAMSI REDDY[4], YAKA JAGADEESH KUMAR[5], KONANGI JAYA VARDHAN[6]

[1] Assistant Professor, Department of Mechanical Engineering, ABR College of Engineering and Technology, Andhra Pradesh- 533437

[2,3,4,5,6] Students, Department of Mechanical Engineering, ABR College of Engineering and Technology, Andhra Pradesh- 533437

Abstract:

A CI (Compression Ignition) Engine Turbocharger is a crucial component designed to improve engine efficiency and performance by utilizing exhaust gases to compress incoming air before it enters the combustion chamber. The present study focuses on the design and structural analysis of a CI (Compression Ignition) engine turbocharger wheel using multiple materials Aluminum Alloy, Inconel 718, Titanium Aluminide (TiAl), and Silicon Carbide (SiC). The turbocharger wheel plays a critical role in enhancing engine performance by improving air intake efficiency, necessitating robust material selection to ensure durability and performance under high-stress conditions. The wheel design was developed using SolidWorks 2024, and structural analysis was conducted in ANSYS 2025 R2 to assess its behavior under varying loads of 40 N. Key parameters such as total deformation, von Mises stress, and strain distribution were examined to evaluate the performance of each material.

Keywords: Turbocharger wheel, SW 2024, Static structural, Ansys 2025 R2

1. INTRODUCTION

A turbocharger is a turbine driven forced induction device that increases an internal combustion engines efficiency and power output by forcing extra air into the combustion chamber. This improvement over a naturally aspirated engines power output is due to the fact that the compressor can force more air and proportionately more fuel into the combustion chamber than atmospheric pressure. Turbochargers were originally known as turbo superchargers when all forced induction device classified as superchargers. Nowadays the terms supercharger applied only to mechanically driven forced induction device. The difference between a turbocharger and a conventional supercharger is that a supercharger is mechanically driven by the engine, often through a belt connected to the crankshaft, whereas a turbocharger is powered by a turbine driven by the engine’s exhaust gas. Turbochargers are commonly used on truck, train, car, aircraft, and construction equipment engines. Turbocharger are widely used in car and commercial vehicles because they allow smaller capacity engines to have improved fuel economy, reduced emission, higher power and considerably higher torque.

Turbo charger: Turbocharger will provide boost more quickly and at lower engine speeds, but may not be able to provide much boost at higher engine speeds when a really large volume of air is going into the engine.

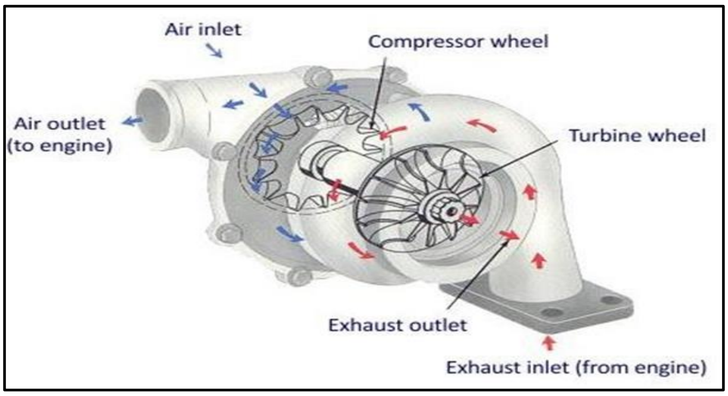

Figure 1: Schematic diagram of Turbo charger

Problem Statement:

The performance and efficiency of a CI (Compression Ignition) engine are significantly influenced by the turbocharger, particularly the turbine wheel, which compresses incoming air using exhaust gases before it enters the combustion chamber. The turbine wheel operates under extreme conditions, including high temperatures and mechanical stresses, making material selection critical to ensure optimal performance and durability. The challenge lies in selecting the most suitable material that can withstand these harsh conditions while maintaining strength, resistance to deformation, and long-term reliability. Common materials like Titanium Aluminide (TiAl), Aluminum Alloy, Inconel 718, and Silicon Carbide (SiC) are potential candidates, but their performance under specific loading conditions has yet to be comprehensively analyzed. This study seeks to evaluate and compare these materials to determine the best option for enhancing the turbine wheel's performance in CI engine applications, ensuring both durability and efficiency under high-stress conditions.

2. Literature Review

Recent studies have highlighted that geometric design and material properties are interrelated when optimizing turbocharger turbines. The turbine wheel needs to be designed to handle high rotational speeds, withstand centrifugal forces, and manage heat dissipation effectively. Researchers, such as Zhang et al. (2024) and Singh and Kumar (2023), emphasized using 3D design tools like Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) to predict performance and stress distribution, leading to more efficient designs with minimal material usage.

Materials Used in Turbocharger Turbine Wheels

- Titanium Alloys: Titanium alloys like Ti-6Al-4V have been frequently studied due to their excellent combination of high strength-to-weight ratio, oxidation resistance, and good thermal stability at high temperatures. According to Patel et al. (2023), these alloys have gained popularity in turbochargers operating at extreme conditions (high RPM and elevated temperatures).
- Nickel-Based Alloys: Inconel 718 is often considered the industry standard due to its high-temperature strength and corrosion resistance, making it ideal for CI engine applications. Wang et al. (2022) conducted a study showing that Inconel 718 provides an optimal balance of high-temperature resistance and mechanical strength.
- Aluminum Alloys: Lightweight alloys such as AlSi10Mg have been studied for their lower thermal expansion and better fuel efficiency at lower rotational speeds. However, their performance decreases at higher temperatures, limiting their use. Cheng et al.

(2022) demonstrated that aluminum alloys are effective for smaller engines but may not be ideal for high-performance turbochargers.

- Ceramics and Ceramic Matrix Composites (CMCs): Emerging research indicates the potential of ceramic materials like silicon carbide (SiC) and carbon composites for their superior thermal properties and low thermal expansion coefficients. Sahu and Singh (2023) showed that CMCs outperform metal alloys in terms of heat resistance, making them suitable for next-generation turbochargers with higher efficiency and reduced thermal fatigue.

3.Methodology

The methodology chapter in a study focused on the design and analysis of a CI engine turbocharger turbine wheel using different materials outlines the process, tools, and techniques employed to achieve the study's objectives. It explains the approaches taken to design the turbine wheel, select materials, and assess their performance under different operational conditions.

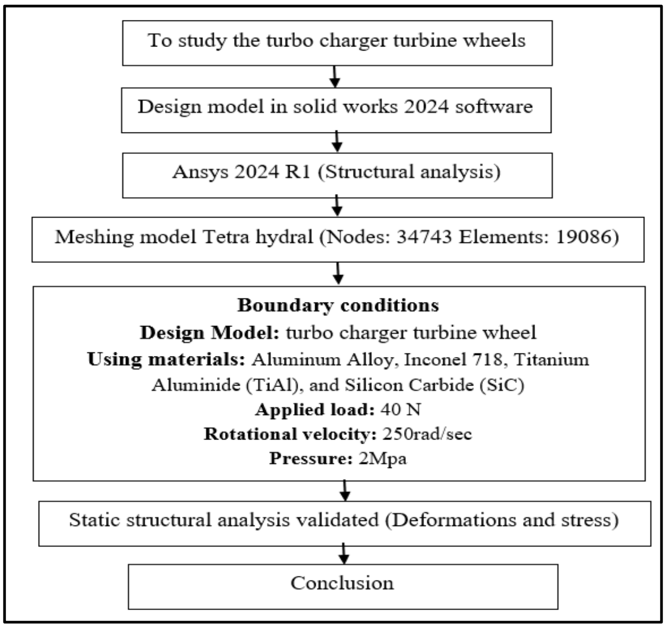

Figure 2: Design flow chart

Working principal of IC Engine Turbo charger

A turbocharger is composed of 3 basic parts, a compressor, a turbine, and center housing. The turbine is the section of the turbocharger where the exhaust gases of the engine are forced through to cause the turbine wheel to spin. This rotation energy is then transferred through the center housing and into the compressor by means of a stainless steel, or sometimes Inconel, shaft. This center housing is comprised of journal or ball bearings, depending upon the application, as well as oil lubrication ports and drains. This allows the bearings to well lubricated, as well as cooled, to handle the immense rotational speeds and heat that they have to endure. Some center housings have integrated coolant passages to provide supplemental cooling. This is not always required, but it does drastically improve a turbochargers life, as well as protect it in circumstances where it is put under high or prolonged demand. The compressor does exactly what it’s named for, it compresses air.

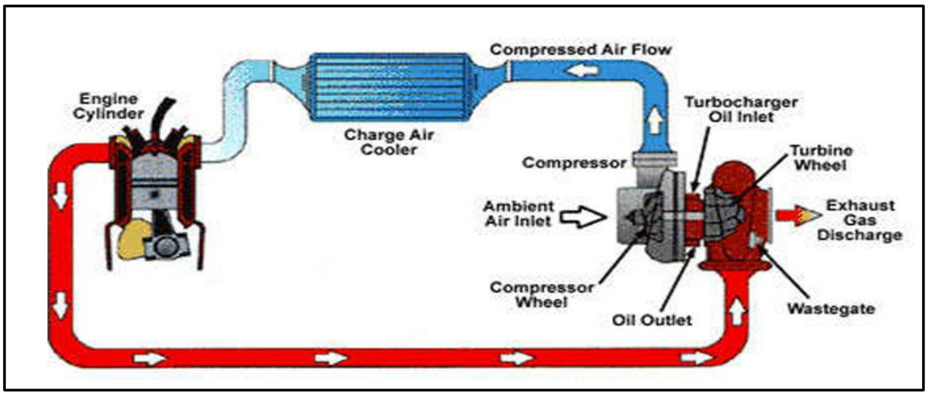

Figure 3: working of turbo charger

Although not utilized in all cases, most turbocharged platforms utilize an intercooler to cool the compressed air back down to the ambient air temperature. This is due to the fact that heat is transferred from the turbine of the turbocharger to the compressor by of the exhaust gases flowing through it.

Design model of Turbo charger turbine Compressor wheel In SW 2024

- **Dimensions and Specifications:** Obtain specific dimensions like diameter, blade thickness, number of blades, hub diameter, and angles.
- Open SW 2024, and create a new file for the compressor wheel.
- Use the *Sketch* tool to draw the air foil cross-section of the blade.
- Define the blade curvature and leading/trailing edges using spline curves.
- Create 3D Blade Profile Use the *Revolve* or *Sweep* command to create the initial blade
- Draw the hub profile using the *Sketch* tool (circular or conical shape).
- Revolve the sketch to create a 3D model of the hub.
- Use the *Pattern* tool to replicate the blade around the hub.
- Use built-in SW 2024 simulation tools or export to third-party software for CFD (Computational Fluid Dynamics) or structural analysis.
- Ensure all dimensions and features align with the specifications.
- Save the file in the desired format (e.g., STEP, IGES) for manufacturing.

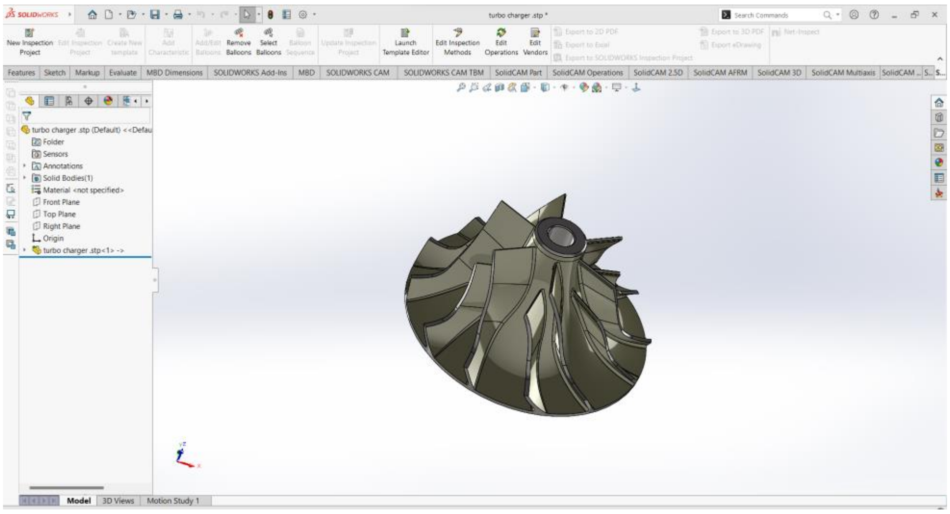

Figure 4: Turbine wheel for turbocharger Model in SW 2024.

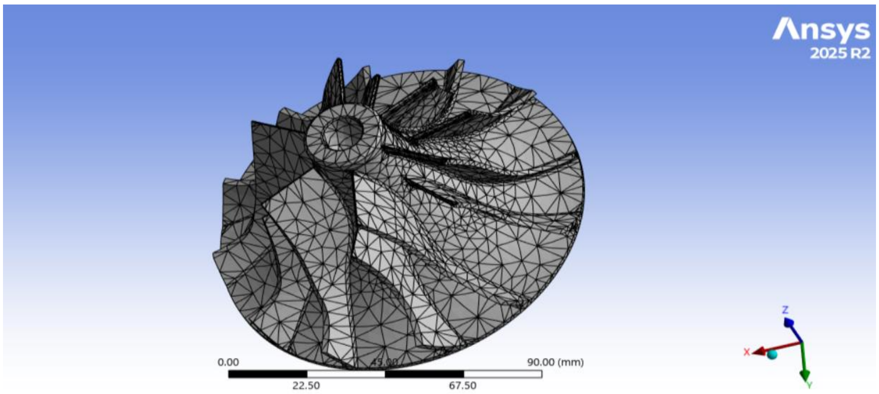

Figure 5: Meshed model

The turbocharger model appears to be meshed, which means it has been divided into a finite number of smaller elements.The statistics indicate that the model has 34,743 nodes and 19,086 elements, which are part of the finite element analysis process. This mesh quality ensures a balance between computational efficiency and accuracy for simulations.

4. Results and Discussions

In this chapter to discuss the static structural analysis Turbo charger to significant centrifugal forces and gas bending forces during operation. To ensure their structural integrity and prevent failures, it is crucial to perform a static structural analysis using different materials Titanium Aluminide (TiAl), Aluminum Alloy, Inconel 718, and Silicon Carbide (SiC). This analysis helps in assessing the stress, strain, and deformation of the wheel under operating conditions

Turbo charger turbine wheel using Aluminum alloy at 40 N

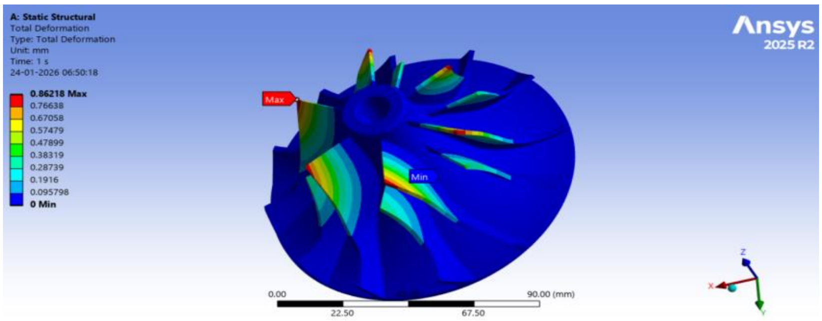

Figure 6: Total Deformation

The deformation pattern reveals how the turbocharger deforms under the applied 40 N force. It highlights areas of significant deformation and areas that remain relatively rigid. The maximum deformation is 0.86218 mm.

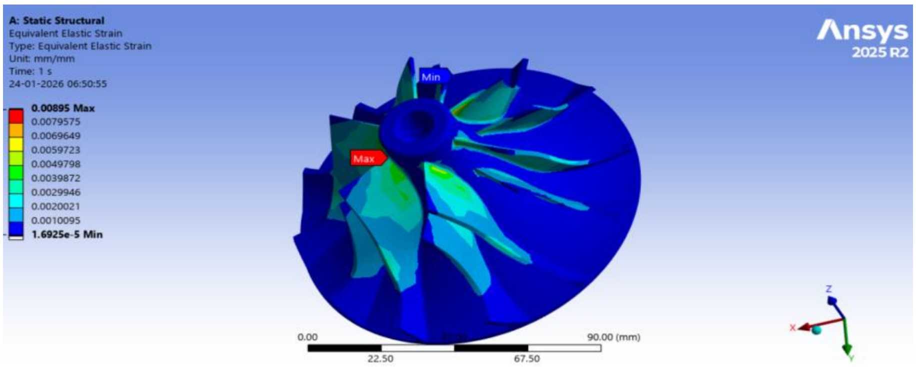

Figure 7: Equivalent Elastic strain

The image shows the equivalent strain distribution. This likely represents the von Mises equivalent strain, which is a measure of the combined effect of normal and shear stresses on the material The maximum equivalent strain is 0.00895

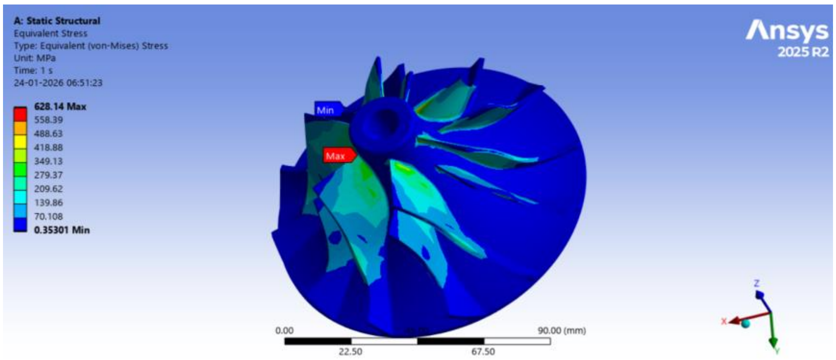

Figure 8: Equivalent Stress

The image shows the equivalent (von Mises) stress distribution. This is a commonly used stress measure that combines the effects of normal and shear stresses to give a single value that predicts the onset of yielding in ductile materials The maximum equivalent stress value is 628.14 MPa

Turbo charger compressor wheel using Inconel 718 at 40 N

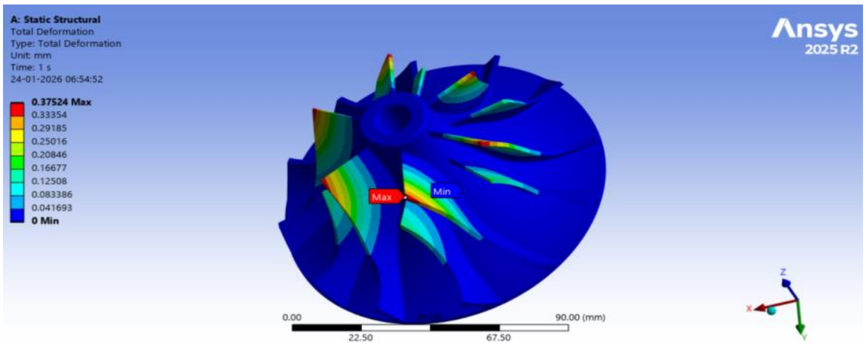

Figure 9: Total Deformation

The deformation pattern reveals how the turbocharger deforms under the applied loads. It highlights areas of significant deformation and areas that remain relatively rigid. The maximum deformation is 0.37524 mm.

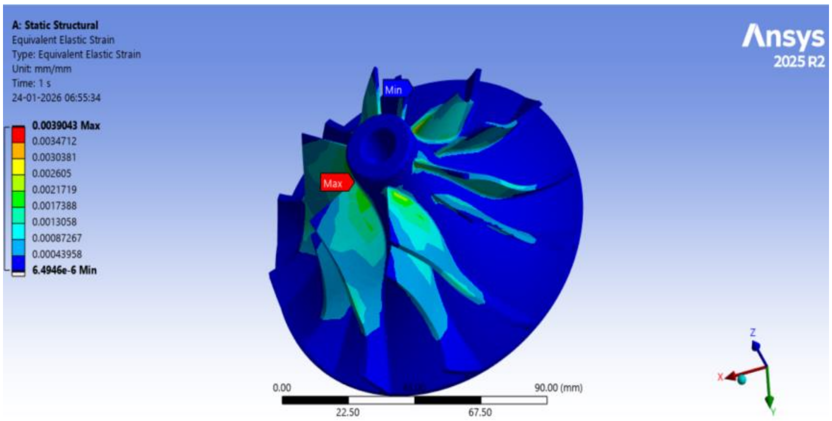

Figure 10: Equivalent Elastic strain

The maximum value of the Equivalent Elastic Strain in the turbocharger turbine wheel made from Inconel 718 shown in the static structural analysis is 0.0039043 mm/mm. This value corresponds to the areas of the turbine wheel that experience the highest strain under the applied loading conditions (40 N load, 2 MPa pressure, and 250 rad/s rotational velocity).

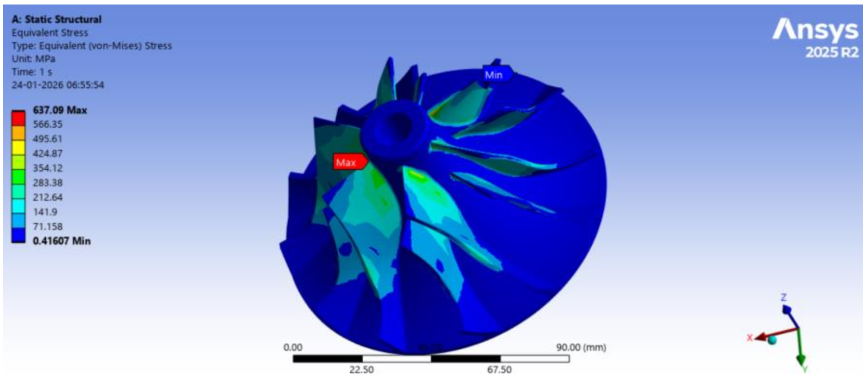

Figure 11: Equivalent Stress

This image shows the Equivalent (von-Mises) Stress distribution in a turbocharger component from an analysis performed using Ansys 2025 R2. The peak stress recorded is 637.09 MPa, concentrated near the central hub region (highlighted in red). This area experiences the highest load concentration due to torque transmission and rotational forces

Turbo charger compressor wheel using Titanium Aluminide (TiAl) at 40 N

Titanium Aluminide (TiAl) for a turbocharger compressor wheel at 40 N refers to employing a lightweight, high-strength alloy in the construction of the compressor wheel, which is the part of the turbocharger responsible for compressing air. TiAl is known for its exceptional strength-to-weight ratio and resistance to high temperatures, making it ideal for high-performance applications like turbochargers that experience intense heat and pressure

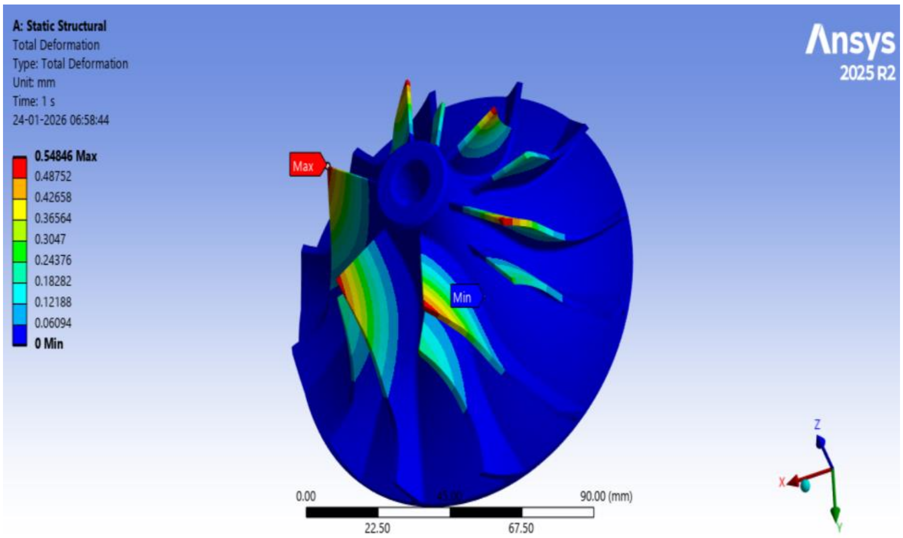

Figure 12: Total deformation in mm

This figure shows the Total Deformation of the turbocharger turbine wheel in Ansys 2025 R2, based on a Static Structural analysis. The deformation is visualized using a color map, where the maximum deformation is represented in red (0.54846 mm) and the minimum deformation in blue (0.00694 mm).

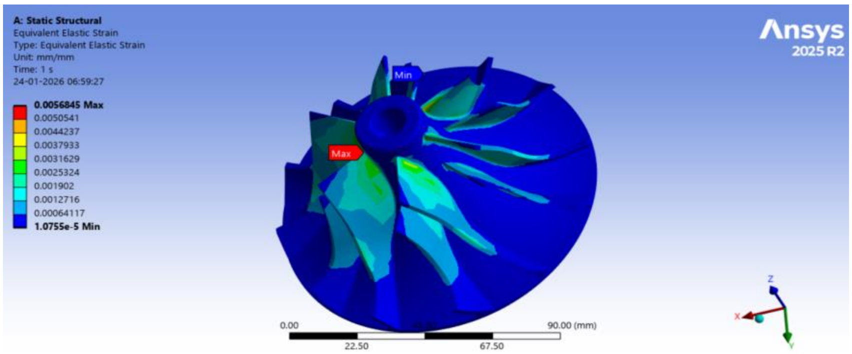

Figure 13: Equivalent Elastic Strain

This figure presents the Equivalent Elastic Strain distribution on the turbocharger turbine wheel from a Static Structural analysis in Ansys 2025 R2. The results are shown using a color map, with the maximum equivalent strain in red (0.0056845 mm/mm) and the minimum strain in blue (1.0755e-5 mm/mm).

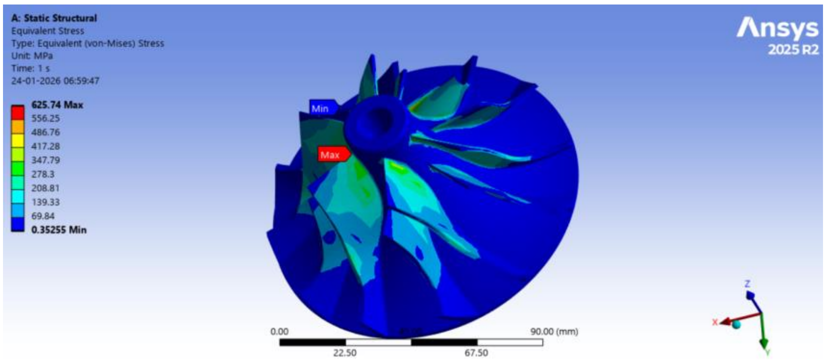

Figure 14: Equivalent Stress

This figure shows the Equivalent Stress distribution on the turbocharger turbine wheel, based on a Static Structural analysis in Ansys 2025 R2. The results are presented using a color map, with the maximum equivalent stress value indicated in red (625.74 MPa) and the minimum in blue (0.35255 MPa).

Turbo charger compressor wheel using SiC at 40 N

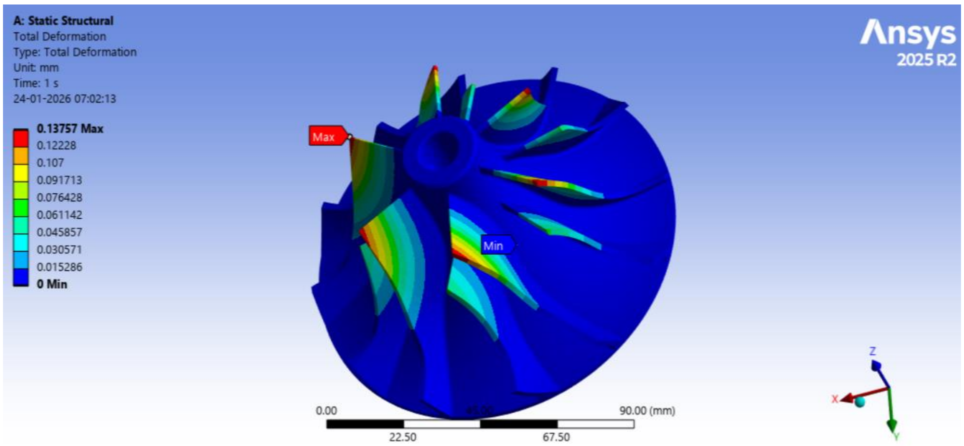

Figure 15: Total deformation in mm

This figure shows the Total Deformation of the turbocharger turbine wheel, visualized in Ansys 2025 R2 based on a Static Structural analysis. The deformation is represented in millimeters (mm), with the maximum deformation of 0.13757 mm shown in red, indicating the areas with the highest displacement under the applied forces. The minimum deformation is shown in blue (0 mm), representing areas that experience no movement.

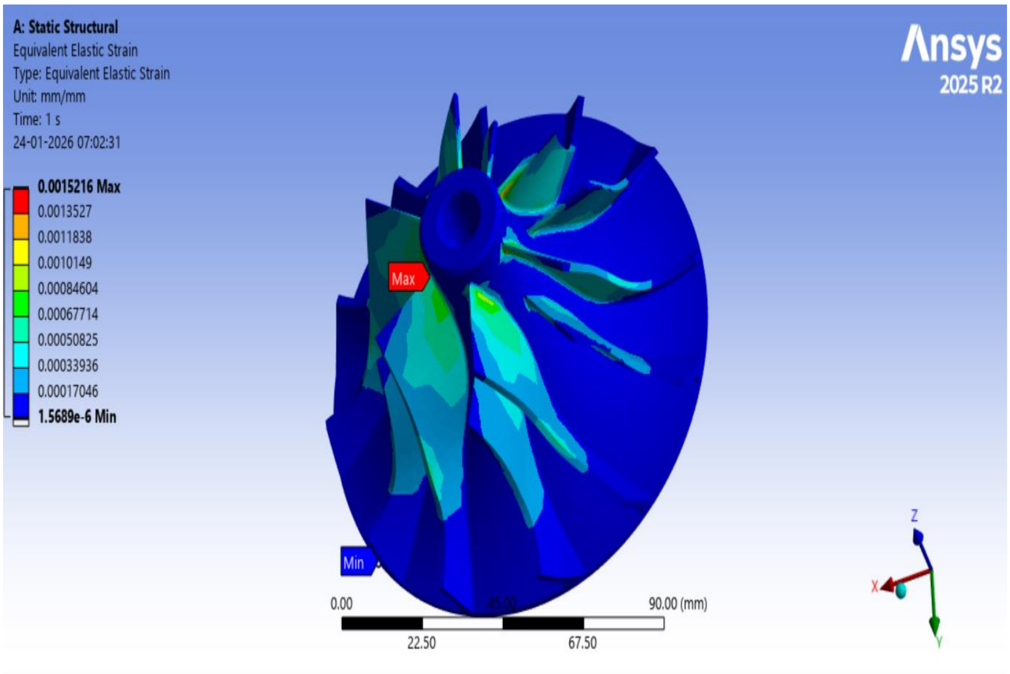

Figure 16: Equivalent Elastic Strain

This image shows the Equivalent Elastic Strain distribution on the turbocharger turbine wheel, obtained from a Static Structural analysis in Ansys 2025 R2. The strain is represented in millimeters per millimeter (mm/mm), with the maximum strain of 0.0012516 mm/mm shown in red, indicating the areas that experience the highest elastic deformation.

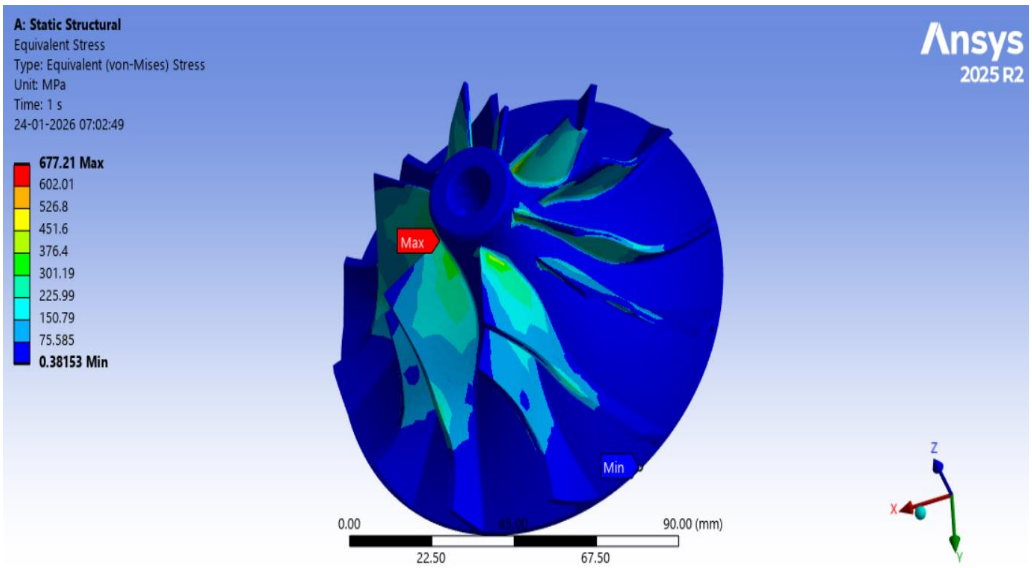

Figure 17: Equivalent stress

This figure presents the Equivalent Stress distribution on the turbocharger turbine wheel, based on a Static Structural analysis in Ansys 2025 R2, with the material set as Silicon Carbide (SiC). The stress is measured in MPa with the maximum equivalent stress of 677.21 MPa shown in red, indicating the regions of the wheel that are experiencing the highest stress. The minimum stress value of 0.38153 MPa is shown in blue, highlighting areas of lower stress.

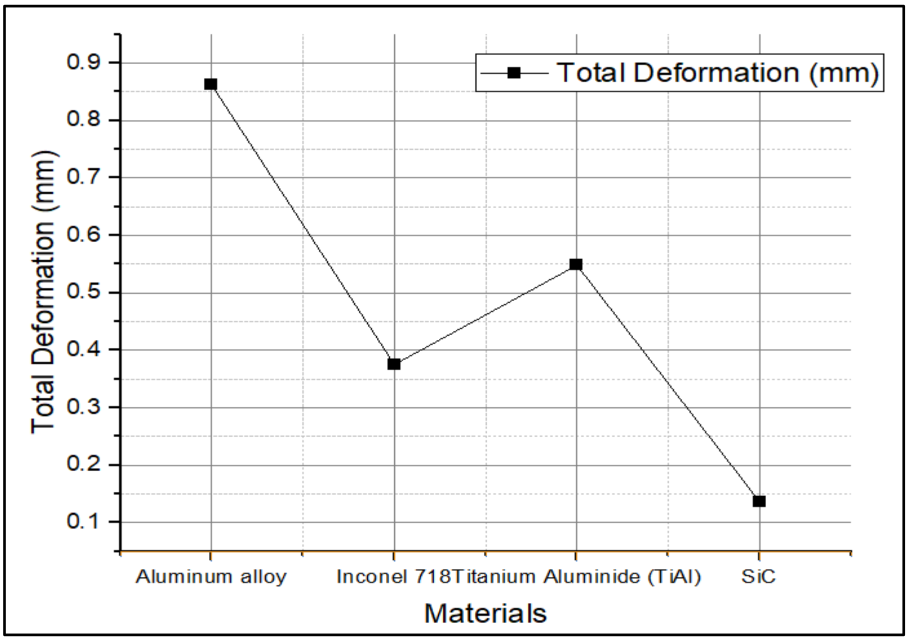

Figure 18: Validation of total deformation at 40 N Load

The figure illustrates the varying deformation of materials under a 40 N load, revealing that Silicon Carbide (SiC) exhibits the least deformation, making it highly suitable for high-performance applications. In contrast, Aluminum alloy shows the highest deformation, emphasizing its lower resistance to stress compared to Inconel 718 and Titanium Aluminide (TiAl).

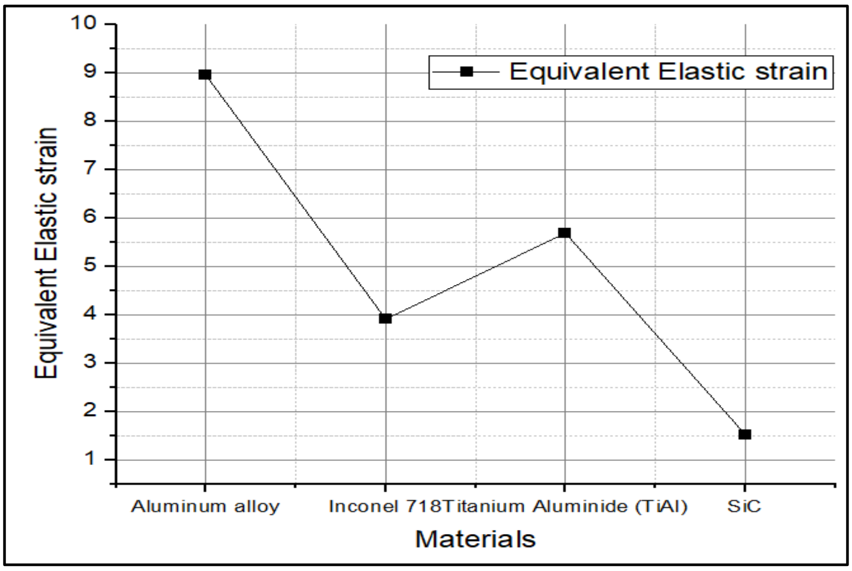

Figure 19: Validation of equivalent elastic strain at 40 N Load

The figure demonstrates that Silicon Carbide (SiC) exhibits the lowest equivalent elastic strain, highlighting its exceptional resistance to deformation, ideal for high-performance applications. In contrast, Aluminum alloy shows the highest strain, indicating its higher susceptibility to elastic deformation under stress.

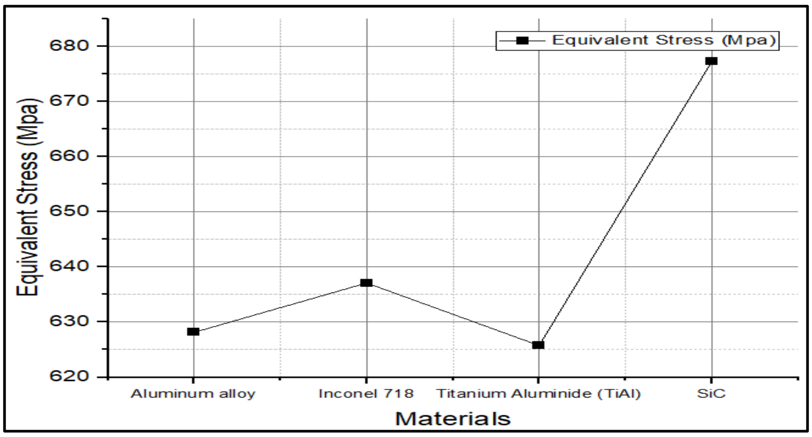

Figure 20: Validation of equivalent stress at 40 N Load

The figure shows that Aluminum alloy has the lowest equivalent stress, indicating its lower resistance to stress compared to other materials. Inconel 718 and Titanium Aluminide (TiAl) offer better stress resistance, with values around 640 MPa. Silicon Carbide (SiC) stands out with a significantly higher stress value of 680 MPa, demonstrating its exceptional strength and suitability for high-stress applications.

Conclusion

In the design and structural analysis of the CI engine turbocharger turbine wheel under 40 N load conditions, the materials tested Aluminum Alloy, Inconel 718, Titanium Aluminide (TiAl), and Silicon Carbide (SiC) show distinct performance characteristics. Silicon Carbide (SiC) emerges as the most suitable material for turbocharger turbine wheels, outperforming Aluminum alloy, Inconel 718, and Titanium Aluminide (TiAl) under a 40 N load. While Aluminum alloy exhibits the highest deformation and elastic strain, making it unsuitable for high-stress applications, Inconel 718 and TiAl offer better performance but still experience more deformation than SiC. exceptional strength, minimal deformation, and superior resistance to stress and strain make it the ideal choice for high-performance applications like turbocharger turbine wheels, where durability and integrity are critical for long-term operation.

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