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

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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 2024 R1 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 2024 R1

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.

Advantages of Turbo Chargers:

- Improved torque at low rpm in the case of diesel engines and over a whole speed range in the case of petrol engines.
- Better mixing of air and petrol in the case of petrol engine resulting in effective pollution control.
- The engine runs smoother and quieter
- Reduces diesel knock.

Purpose of Turbocharger using IC Engine:

- To reduce weight per horse power of the engine as required in aero engines.
- To reduce the space occupied by the engine as required in marine engines
- To have better turbulence and this ensures more complete combustion giving greater power and low specific fuel consumption

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 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.

Scope of Work:

The scope of this study involves designing a CI engine turbocharger turbine wheel using SolidWorks 2024 and conducting structural analysis with ANSYS 2024 R1. The study will evaluate four materials—Titanium Aluminide (TiAl), Aluminum Alloy, Inconel 718, and Silicon Carbide (SiC)—under varying loads of 40 N. Key performance parameters such as deformation, von Mises stress, and strain distribution will be analyzed to assess each material's durability and performance under high-stress conditions. The study aims to identify the most suitable material for ensuring the optimal performance and longevity of the turbocharger turbine wheel in CI engine applications.

Objectives:

- To design and analyze a CI engine turbocharger turbine wheel using Different materials
- To evaluate their performance under varying loads of 40 N, focusing on key parameters (deformation, von Mises stress, and strain distribution)
- To determine the most suitable material that ensures optimal strength, durability, and performance in the high-stress conditions of a turbocharger turbine wheel

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.

As CI engine efficiency and turbocharging technologies continue to evolve, researchers are focusing on hybrid materials and nano-coatings that combine the best properties of multiple materials to enhance performance. For example, ceramic coatings applied to nickel-based alloys could offer enhanced oxidation resistance at high temperatures. **Ghosh and Saini (2024)** proposed the use of nanostructured coatings to reduce wear and tear, thus extending the service life of turbine wheels. The next generation of turbine materials will likely involve further advancements in smart materials that adapt to changing conditions for enhanced performance. **D. Ramesh Kumar et, al., (2017)** in their study to conducted research using ANSYS and CATIA software and utilized several materials for the turbine and compressor impeller in this work. By utilizing the ANSYS software, we were able to ascertain the fluctuation of stresses, strains, and deformation profiles of the turbine and compressor impeller. **Shujie Liu, et, al., (2016) researched** the fatigue life evaluation of centrifugal compressor impeller is an important matter for both automotive and industrial applications. In this study, the impeller life was analyzed using finite element analysis (FEA), taking into account both centrifugal load and aerodynamic load. The impeller is subjected to both static and dynamic loads, including centrifugal, aerodynamic, exciting, and other types of loads, while it operates. **CH. Satya sai et, al. (2016)** analyzes the turbocharger impeller's structure by analyzing stress, strain, and deformation ranges in various materials under static and dynamic conditions. The authors of this study take the impeller's design for 30,000 rpm into account. The primary goal of the design was to minimize the blade size in accordance with the specifications, and this turbocharger impeller was created using geometrical modeling.

3.Methodology

The methodology 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. This chapter also details the experimental setups, simulations, and analysis methods used in the study

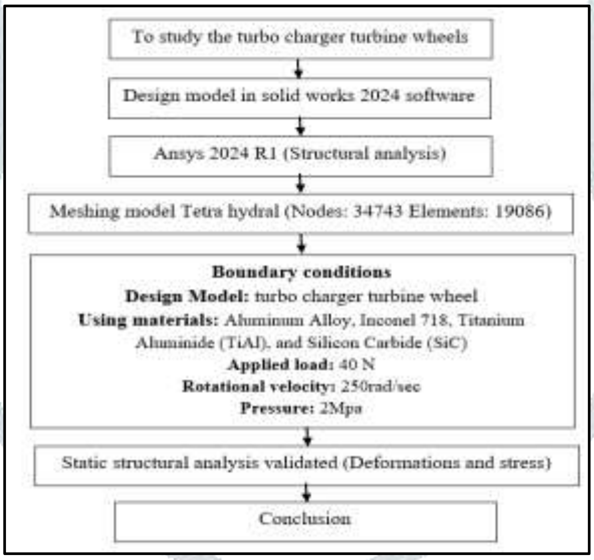

Figure 1: Design flow chart

Working principal of IC Engine Turbo charger

A turbocharger in an internal combustion (IC) engine works by using exhaust gas energy to increase the engine's power output. The exhaust gases produced during combustion spin a turbine connected to a compressor via a shaft. As the turbine rotates, it drives the compressor, which draws in and compresses air before sending it into the engine's intake system. This compressed air, which is denser and contains more oxygen, allows for more fuel to be burned in the combustion chamber, resulting in increased power. The turbocharger system is regulated by a wastegate that controls the exhaust gas flow, preventing over boost and ensuring safe operation. In addition, the compressed air is often cooled by an intercooler to improve efficiency. This process allows a turbocharged engine to produce more power without significantly increasing its size, improving both performance and fuel efficiency

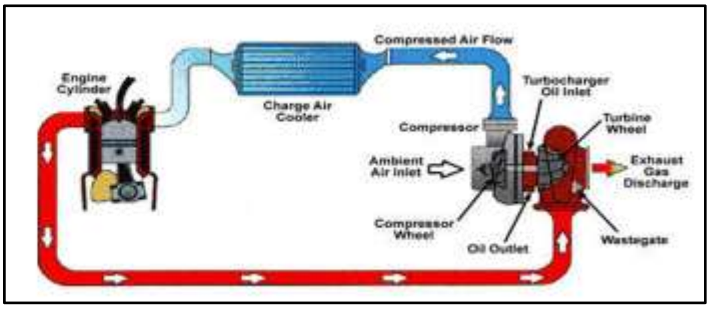

Figure 2: working of turbo charger

Table 1: Engine parameters

Type	Parameters
Engine	Six-cylinder, four-stroke
Fuel type	Diesel
Number of valves	Four
Bore diameter × Stroke length (mm)	126 × 130
Displacement	9.73 L
Calibration power	130 kw
Maximum Torque	950 Nm

Figure 3: Turbo charger turbine Compressor wheel

Using materials Turbo charger:

Turbochargers utilize a variety of materials carefully selected to withstand the extreme conditions they operate in, including high temperatures, pressures, and rotational speeds. n turbocharger wheels, structural steel offers excellent mechanical strength and durability under moderate thermal conditions.

Table 2: Material properties

Property	Aluminum Alloy	Inconel 718	TiAl	SiC
Density (g/cm³)	2.7	8.19	4.0	3.21
Tensile Strength **(**MPa)	240	1,290	140	450
Yield Strength (MPa)	205	1030	350	360
Elastic Modulus (GPa)	69	207	160	340
Thermal Conductivity **(**W/m·K)	150	11.4	30	130
Melting Point **(**°C)	660	1300	1400	2700
Hardness (Brinell) **(**HB)	95-105	95	250	2800

Introduction to Solid works: SolidWorks is a powerful 3D CAD (Computer-Aided Design) software developed by Dassault Systems. It is widely used in industries for product design, mechanical engineering, and simulation. SolidWorks offers intuitive tools for designing, analyzing, and visualizing 3D models, making it an essential software for engineers, designers, and manufacturers.

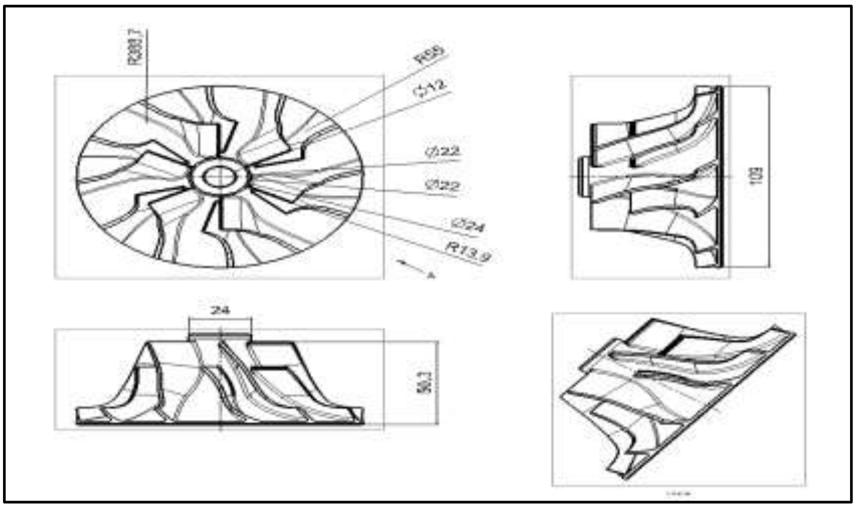

Figure 4: Geometry model in NX 12.0

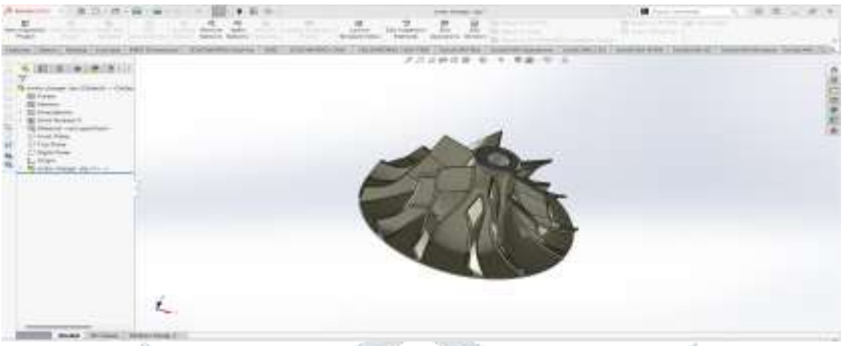

Figure 5: Turbine wheel for turbocharger Model in SW 2024.

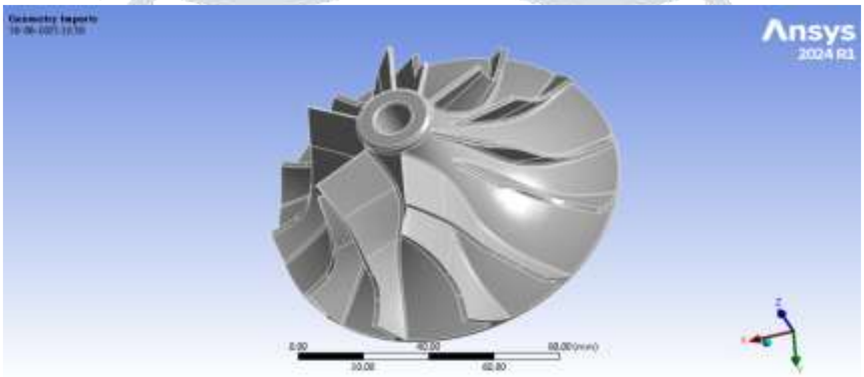

Figure 6: Imported model

This is an imported model of a turbocharger turbine wheel, shown in the software Ansys 2024 R1. The image displays a detailed 3D representation of the turbine wheel, which is a critical component of a turbocharger used in internal combustion engines. The measurements at the bottom indicate the size in millimeters, with a scale from 0 to 80 mm.

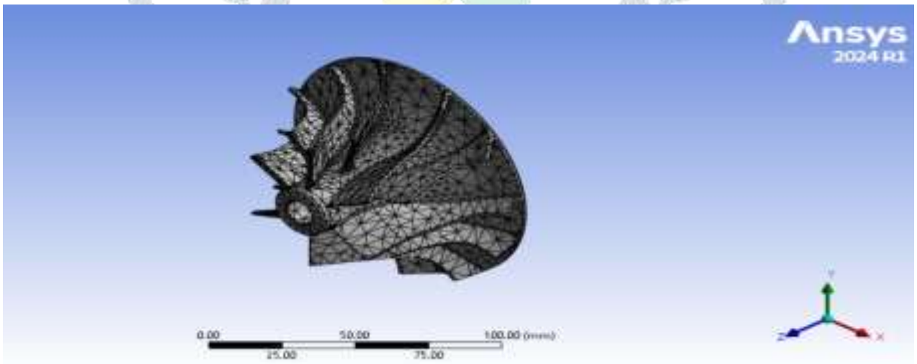

Figure 7: Meshed model

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 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

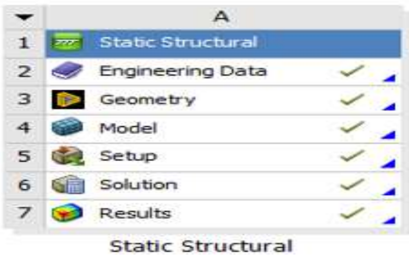

Figure 8: Static structural analysis solver layout

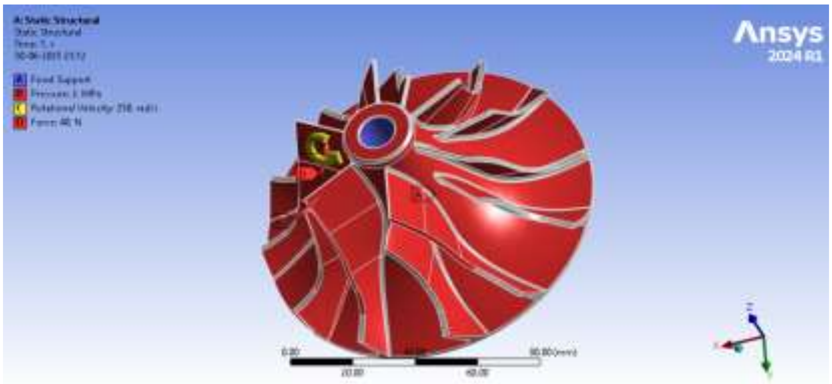

Figure 9: Applied boundary conditions

The image shows a fixed support condition applied to a portion of the turbocharger model. This constraint restricts the movement of the supported region in all directions (X, Y, and Z). It simulates a fixed attachment point or a rigid support for the component.

Turbo charger turbine wheel using Aluminum alloy at 40 N

In the static structural analysis of the turbocharger turbine wheel made from Aluminum Alloy under a 40 N load, the material's response to applied forces and boundary conditions was assessed. The analysis considered a fixed support at the base of the turbine wheel, with a pressure of 2 MPa and a rotational velocity of 250 rad/s, simulating real-world operational conditions. The results showed how the Aluminum Alloy turbine wheel deformed under the applied load and evaluated key performance metrics such as von Mises stress, total deformation, and strain distribution.

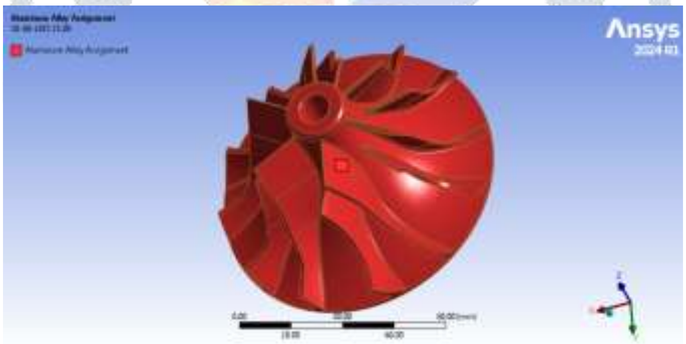

Figure 10: Aluminum alloy Material Assignment

The figure indicates that the material "Aluminum Alloy" has been assigned to the entire turbocharger model the stress and strain levels in the turbocharger to ensure that they remain within acceptable limits and that the turbocharger does not fail due to fatigue, creep, or other mechanisms.

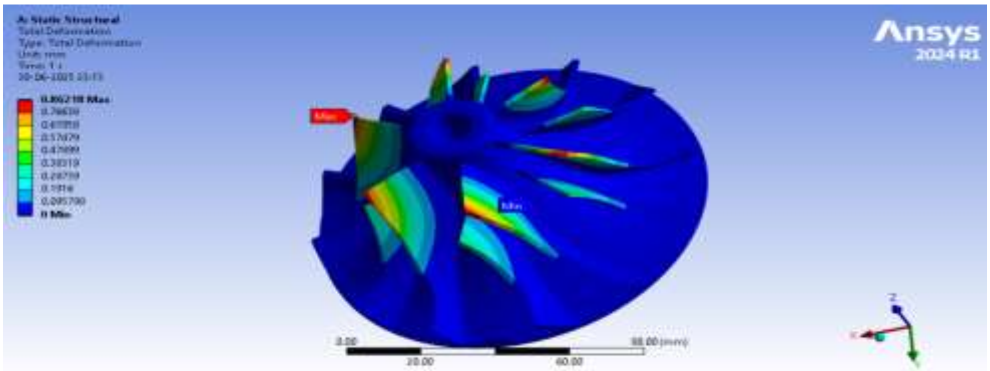

Figure 11: Total Deformation

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.

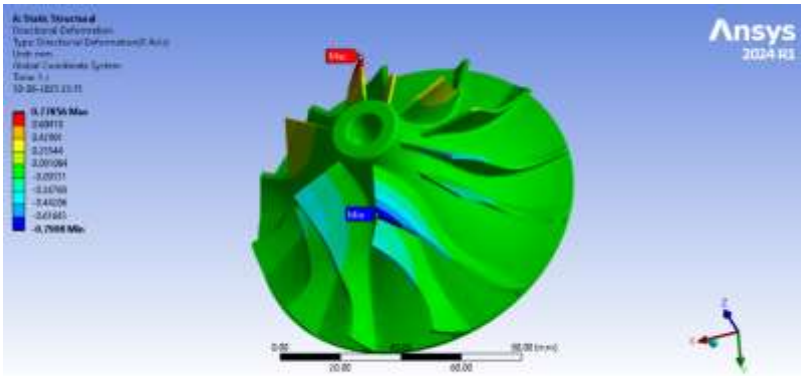

Figure 12: Directional Deformation

Above figure to analyze the stress distribution in the turbocharger alongside the directional deformation results to understand how stress contributes to the deformation in the X-direction. The maximum deformation in the positive X-direction is 0.77856 mm.

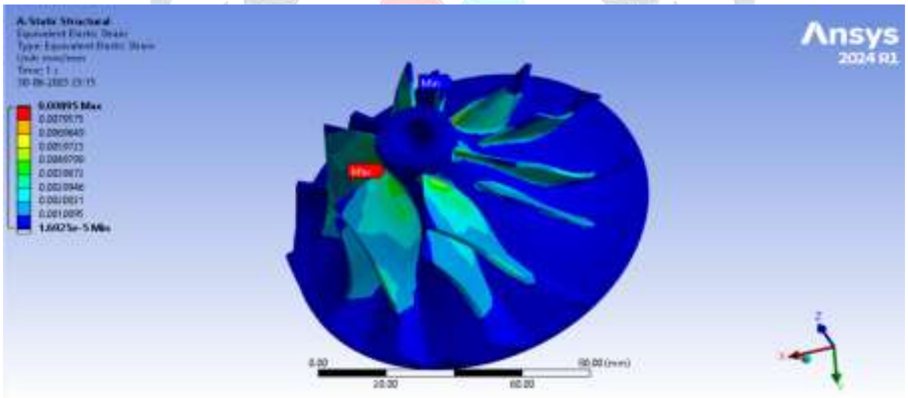

Figure 13: Equivalent Elastic strain

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

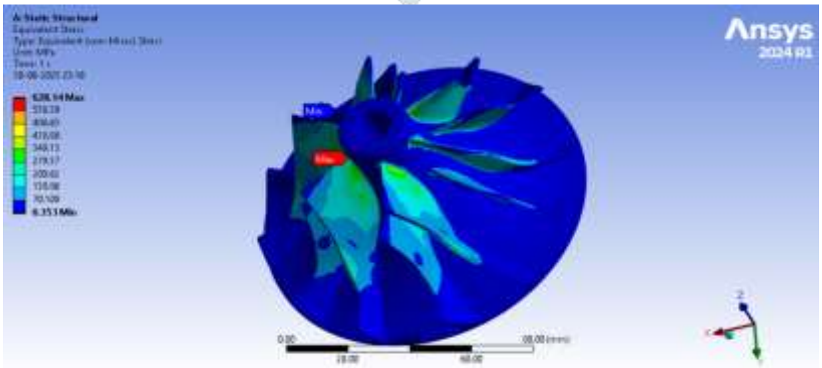

Figure 14: Equivalent Stress

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

To analyze the case of a turbocharger compressor wheel made of Inconel 718 subjected to a 40 N load. a suitable material for turbocharger compressor wheels due to its high-temperature strength, creep resistance, and corrosion resistance.

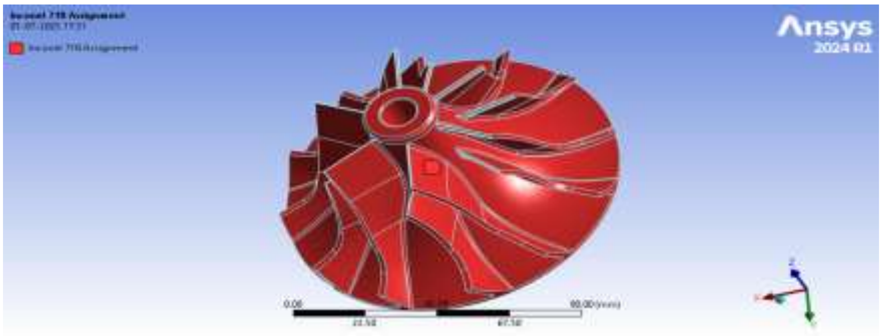

Figure 15: Inconel 718 material Assignment

The figure indicates that the material "Inconel 718" has been assigned to the turbocharger model. Define the boundary conditions, such as constraints and supports, to simulate the actual operating environment of the turbocharger.

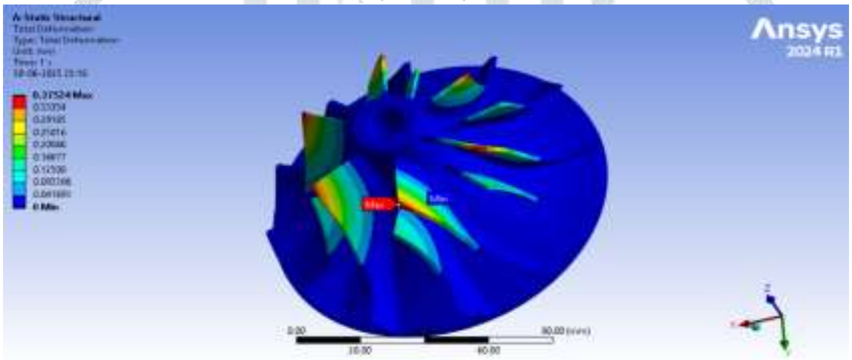

Figure 16: Total Deformation

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

- Max Deformation: The maximum deformation is 0.37524 mm.
- Min Deformation: The minimum deformation is 0 mm.

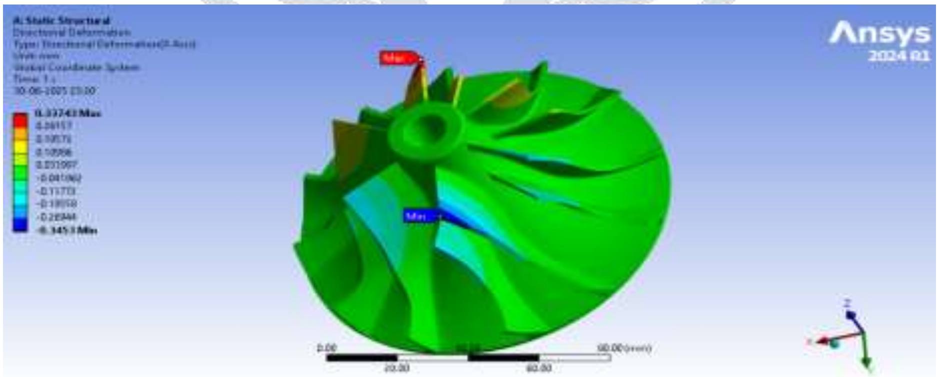

Figure 17: Directional Deformation

This image shows the results of a static structural analysis for a turbocharger component, specifically examining Directional Deformation (X-Axis)

- Maximum Value: 0.33743 mm
- Minimum Value: -0.3453 mm

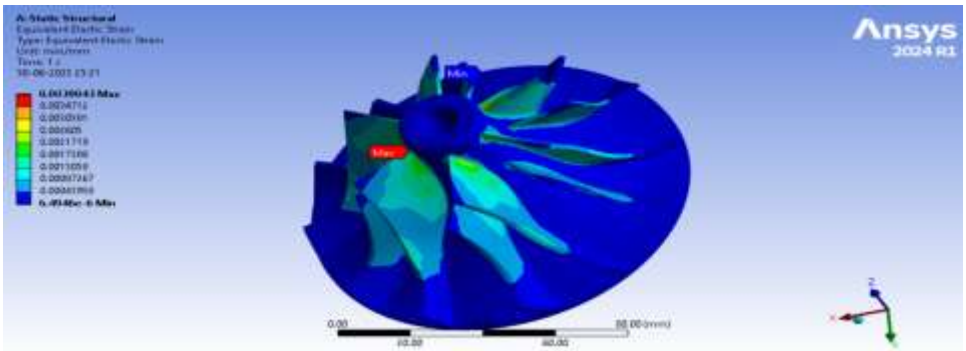

Figure 18: Equivalent Elastic strain

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.

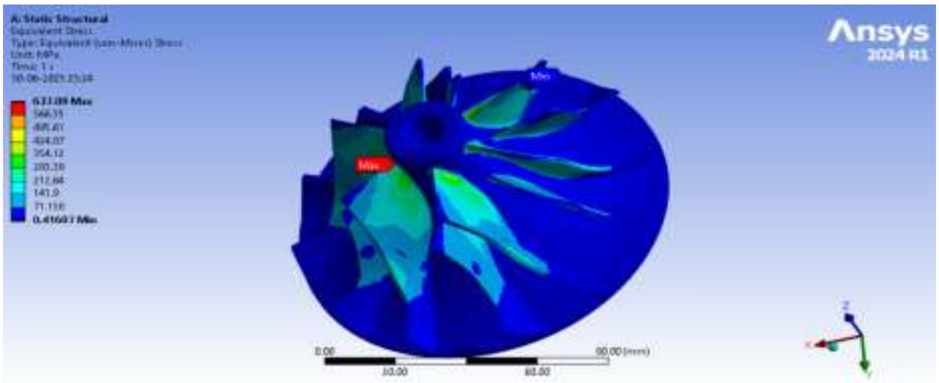

Figure 19: Equivalent Stress

This image shows the Equivalent (von-Mises) Stress distribution in a turbocharger component from an analysis performed using Ansys 2024 R1. 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.

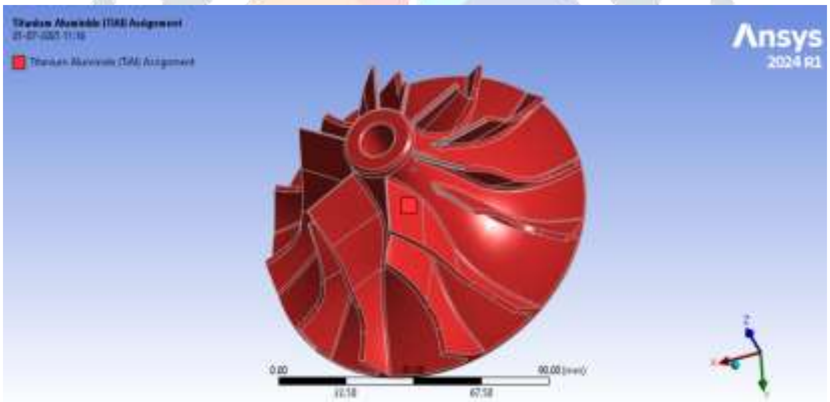

Figure 20: Titanium Aluminide (TiAl) material assignment

This figure shows the material assignment for the turbocharger turbine wheel, specifically Titanium Aluminide (TiAl), applied in Ansys 2024 R1. The entire model is colored red, indicating that the material TiAl has been assigned to the geometry.

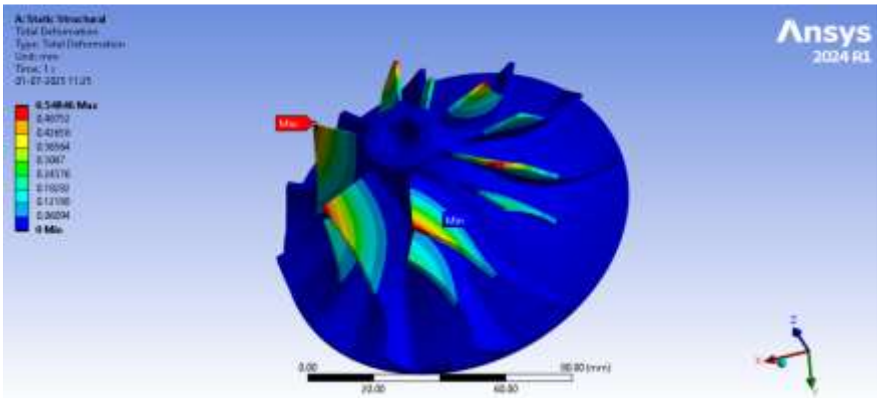

Figure 21: Total deformation in mm

This figure shows the Total Deformation of the turbocharger turbine wheel in Ansys 2024 R1, 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).

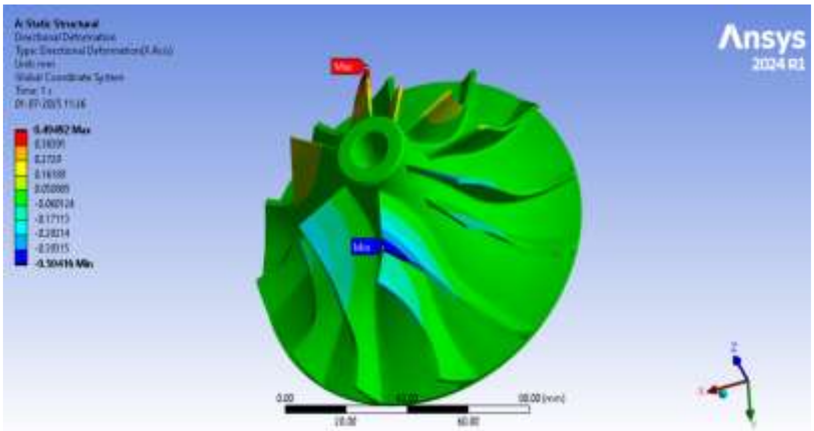

Figure 22: Directional Deformation

This figure displays the Directional Deformation along the X-Axis for the turbocharger turbine wheel, obtained from a Static Structural analysis in Ansys 2024 R1. the maximum deformation (0.49 mm) marked in red at the most stressed areas of the wheel, while the minimum deformation (-0.504 mm) appears in blue, indicating the regions with the least movement.

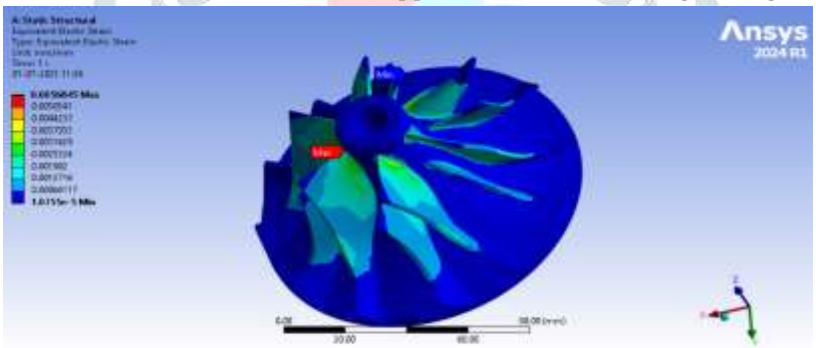

Figure 23: Equivalent Elastic Strain

This figure presents the Equivalent Elastic Strain distribution on the turbocharger turbine wheel from a Static Structural analysis in Ansys 2024 R1. 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).

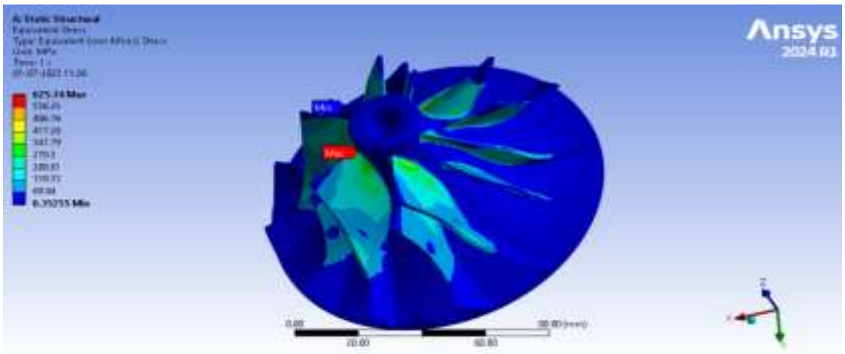

Figure 24: Equivalent Stress

This figure shows the Equivalent Stress distribution on the turbocharger turbine wheel, based on a Static Structural analysis in Ansys 2024 R1. 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

Silicon Carbide (SiC) for a turbocharger compressor wheel at 40 N indicates that the wheel is made from a material known for its extreme hardness, thermal stability, and resistance to wear. Silicon Carbide is often chosen for applications that require high strength and durability, especially in high-temperature and high-stress environments, like in a turbocharger.

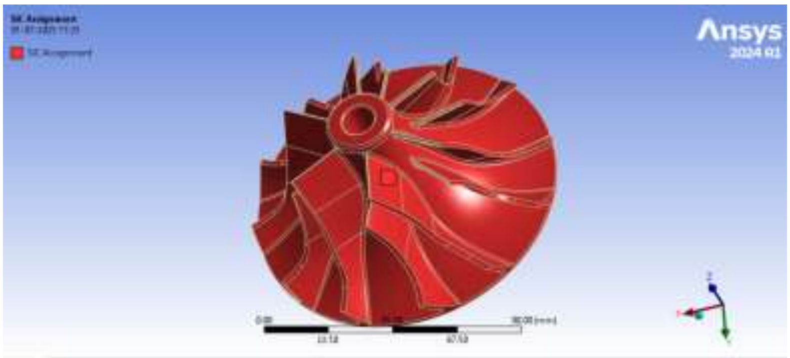

Figure 25: material assignment SiC

This figure shows the material assignment for the turbocharger turbine wheel, specifically Silicon Carbide (SiC), applied in Ansys 2024 R1. The red color represents the assignment of Silicon Carbide, a high-performance ceramic material known for its excellent thermal conductivity, strength at high temperatures, and resistance to wear and oxidation.

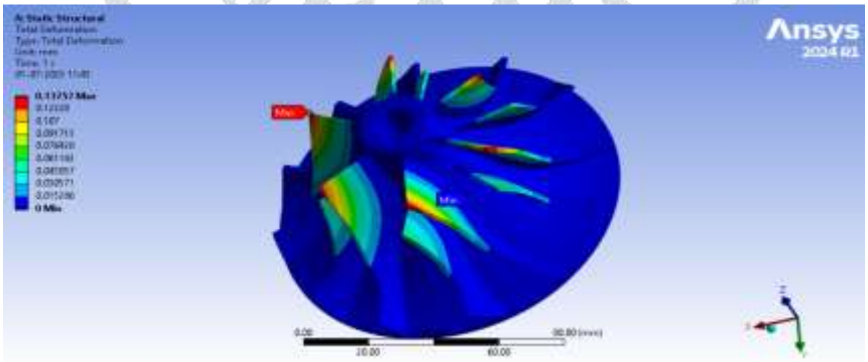

Figure 26: Total deformation in mm

This figure shows the Total Deformation of the turbocharger turbine wheel, visualized in Ansys 2024 R1 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.

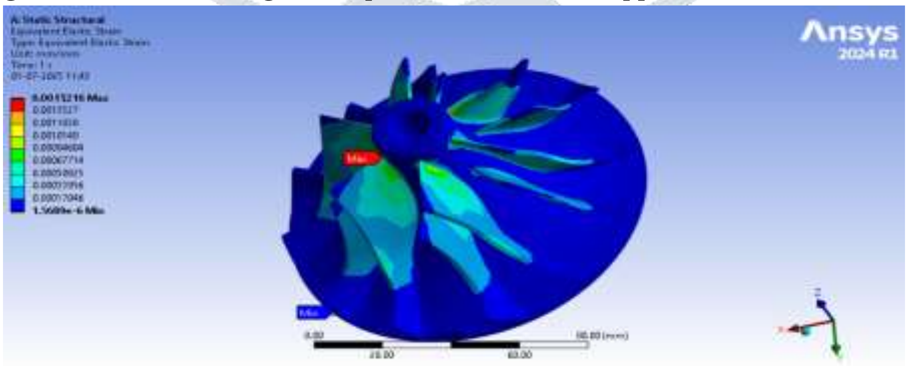

Figure 27: Equivalent Elastic Strain

This image shows the Equivalent Elastic Strain distribution on the turbocharger turbine wheel, obtained from a Static Structural analysis in Ansys 2024 R1 the maximum strain of 0.0012516 mm/mm shown in red, indicating the areas that experience the highest elastic deformation. The minimum strain of 1.5689e-6 mm/mm is shown in blue, highlighting regions with minimal deformation.

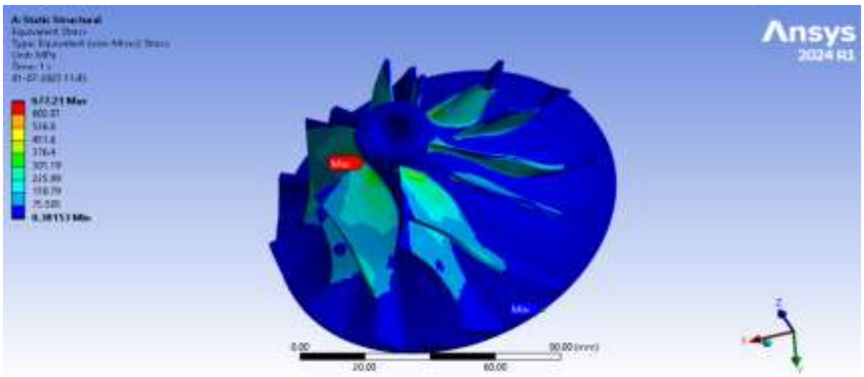

Figure 28: Equivalent stress

This figure presents the Equivalent Stress distribution on the turbocharger turbine wheel, based on a Static Structural analysis in Ansys 2024 R1, with the material set as Silicon Carbide (SiC). 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.

Table 3: Structural analysis of Turbo charger turbine wheel using different materials at 40 N Force

Materials	Total Deformation (mm)	Directional Deformation (mm)	Equivalent Elastic strain	Equivalent Stress (Mpa)
Aluminum alloy	0.862	0.778	8.95	628.14
Inconel 718	0.375	0.337	3.904	637.09
Titanium Aluminide (TiAl)	0.548	0.494	5.684	625.74
SiC	0.136	0.124	1.521	677.21

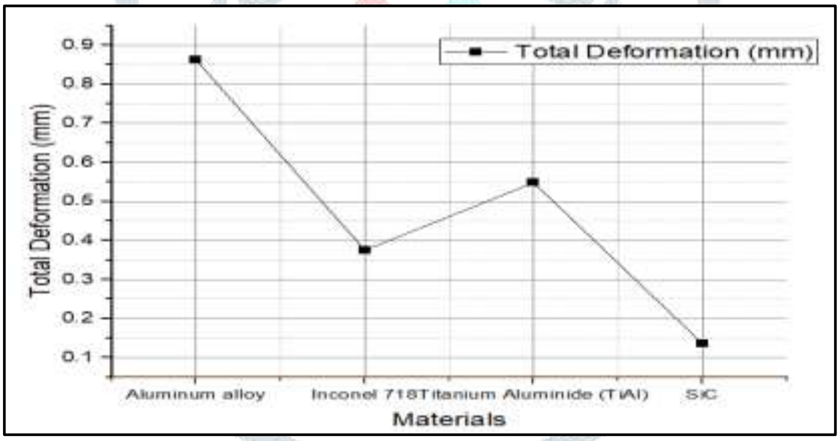

Figure 29: Validation of total deformation at 40 N Load

The figure above compares the total deformation of different materials—Aluminum alloy, Inconel 718, Titanium Aluminide (TiAl), and Silicon Carbide (SiC)—under a 40 N load. It clearly shows that Aluminum alloy undergoes the highest deformation, reaching about 0.9 mm, indicating it is less resistant to stress compared to the other materials. Inconel 718 and Titanium Aluminide (TiAl) experience moderate deformation, around 0.5 mm, reflecting their better ability to resist deformation than aluminum.

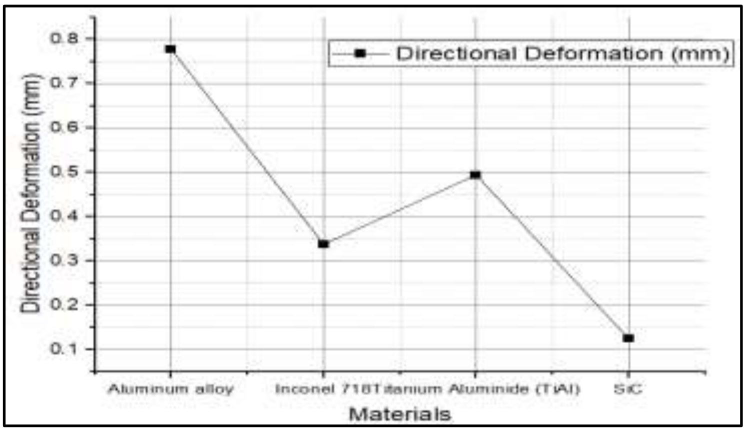

Figure 30: Validation of directional deformation at 40 N Load

The figure above shows the directional deformation of different materials—Aluminum alloy, Inconel 718, Titanium Aluminide (TiAl), and Silicon Carbide (SiC)—under a 40 N load. It reveals that Aluminum alloy experiences the highest directional deformation at approximately 0.8 mm, indicating it is the least resistant to directional displacement when stressed. Inconel 718 and Titanium Aluminide (TiAl) show moderate deformation around 0.5 mm, reflecting their better resistance to directional strain compared to aluminum. Silicon Carbide (SiC) exhibits the lowest directional deformation, with a minimal value of just 0.1 mm, showcasing its outstanding strength and stability under directional forces.

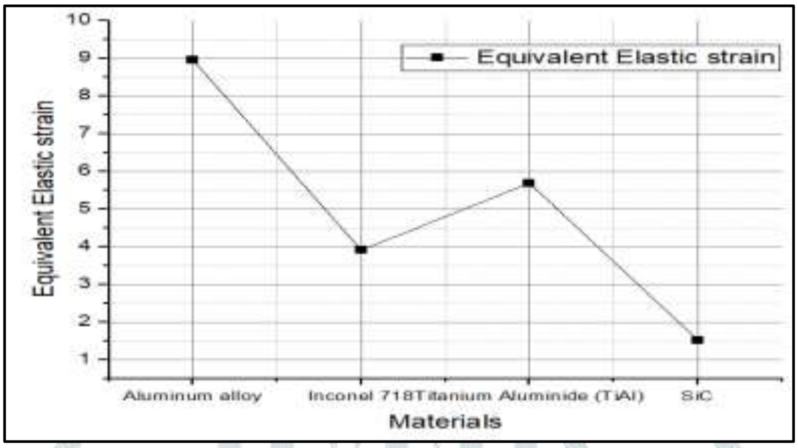

Figure 31: Validation of equivalent elastic strain at 40 N Load

The figure presents the validation of equivalent elastic strain at a 40 N load for various materials, including Aluminum Alloy, Inconel 718, Titanium Aluminide (TiAl), and Silicon Carbide (SiC). The graph shows that Aluminum Alloy experiences the highest equivalent elastic strain, indicating greater deformation under load. In contrast, SiC demonstrates the lowest strain, suggesting better resistance to deformation. Inconel 718 and Titanium Aluminide show moderate strain levels, reflecting their balance between flexibility and rigidity. This comparison helps assess the material's performance under load in terms of deformation.

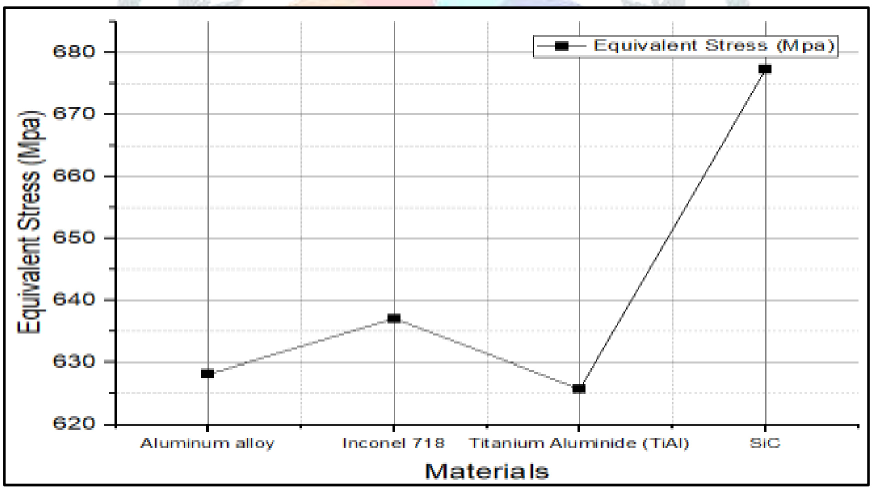

Figure 32: Validation of equivalent stress at 40 N Load

The figure above shows the Equivalent Stress for different materials—Aluminum alloy, Inconel 718, Titanium Aluminide (TiAl), and Silicon Carbide (SiC)—under a 40 N load. Aluminum alloy experiences the lowest equivalent stress, around 630 MPa, indicating it is the least resistant to stress. Inconel 718 and Titanium Aluminide (TiAl) show moderate stress values, approximately 640 MPa, suggesting they offer better stress resistance than aluminum. However, Silicon Carbide (SiC) exhibits a significantly higher stress value of 680 MPa, reflecting its exceptional strength and ability to withstand high-stress conditions. This validation highlights SiC's superior performance in high-stress applications, such as turbine wheels, where resistance to deformation and stress is critical.

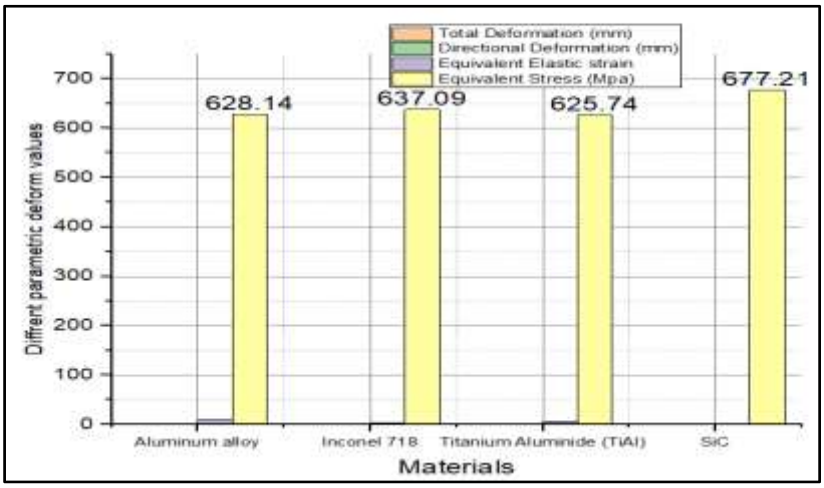

Figure 33: Comparison of turbocharger turbine wheel using different materials at 40 N Load condition

The figure illustrates the validation of total deformation for different materials—Aluminum alloy, Inconel 718, Titanium Aluminide (TiAl), and Silicon Carbide (SiC)—under varying load conditions. The chart shows that Aluminum alloy, Inconel 718, and Titanium Aluminide (TiAl) all experience similar amounts of deformation, with values ranging from 625 MPa to 637 MPa, indicating their relatively moderate resistance to deformation. Silicon Carbide (SiC), on the other hand, shows a significantly higher value of 677.21 MPa, reflecting its superior strength and minimal deformation under load. This comparison highlights the effectiveness of SiC in high-performance applications where minimal deformation is critical, making it an optimal material for components exposed to significant stress, such as turbocharger turbine wheels.

Conclusion:

In the design and structural analysis of the CI engine turbocharger turbine wheel under 40 N load conditions, the materials tested—Aluminium Alloy, Inconel 718, Titanium Aluminide (TiAl), and Silicon Carbide (SiC)—show distinct performance characteristics. Aluminium Alloy demonstrates the highest total deformation and elastic strain under the applied load, making it the least suitable for high-stress applications like a turbocharger turbine wheel. Its relatively low strength results in significant deformation, which can lead to failure under operating conditions. Inconel 718 and Titanium Aluminide **(**TiAl**)** offer better performance than aluminium, with moderate deformation and elastic strain values. These materials are known for their high-temperature resistance, making them suitable for turbocharger applications. However, they still exhibit more deformation compared to SiC under the same load conditions. Silicon Carbide **(**SiC**)** stands out as the best material for the turbocharger turbine wheel. It exhibits the least total deformation and elastic strain, with significantly higher resistance to equivalent stress. SiC's superior thermal and mechanical properties make it the most durable and reliable material under extreme conditions. It maintains its integrity better than the other materials, making it the ideal choice for high-performance turbocharger wheels, where minimal deformation and maximum strength are essential for long-term operation. Among the tested materials, Silicon Carbide **(**SiC**)** is the best option for the turbocharger turbine wheel under 40 N load conditions due to its excellent strength, minimal deformation, and superior performance in high-stress environments.

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