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Integrated thermal and modal analysis of turbocharger with 3D Printed Prototype

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Abstract

Turbochargers improve engine performance and fuel efficiency by raising air intake pressure, but they encounter issues such as thermal deformation and vibrational instability under high stress. This paper does a combined thermal and modal analysis of a turbocharger system utilizing computational simulations and experimental validation with a 3D-printed prototype. Finite element methods (FEM) evaluate temperature distribution, heat transmission, and thermal loads to detect overheating concerns and critical fatigue zones. Modal analysis assesses vibrational activity, identifying natural frequencies and resonance circumstances that may lead to mechanical failure. The interplay of thermal expansion and vibration is investigated to forecast and reduce failure scenarios.

A 3D-printed prototype is tested in controlled environments to confirm simulations and ensure correct performance predictions. This comprehensive method optimizes turbocharger design to increase longevity, efficiency, and dependability. The findings assist the development of more durable turbochargers that can resist harsh automotive conditions, improving engine performance while lowering maintenance costs. The study emphasizes the need of addressing both thermal and vibrational concerns by combining advanced models and actual prototyping. The findings open the way for future advancements in vehicle engineering, allowing for the development of more durable and high-performance turbocharger systems.

Thermal and modal study were conducted to compare three materials for 3D-printed turbochargers: Silicon Carbide exhibited higher heat resistance (4446.8°C), but Molybdenum had higher thermal conductivity (15440 W/m^2) and vibration stability (11.474 Hz). Ni Resist Cast Iron underperformed Molybdenum, making the latter preferable despite Silicon Carbide's thermal advantages, subject to further structural validation.

Keywords: Thermal analysis; Modal analysis; Additive Manufacturing; 3D Printing Technology; Rapid Prototyping

1. Introduction

A turbocharger is a forced induction device that increases engine power and efficiency by compressing intake air, which allows for more fuel combustion without increasing engine displacement. It is made up of three major sections: the turbine (powered by exhaust gases), the compressor (which pressurizes intake air), and the middle housing (which houses bearings and lubrication). It has heat-resistant housings, lightweight compressor wheels, and precision-balanced shafts to withstand harsh circumstances, including temperatures up to 1000°C and speeds exceeding 200,000 RPM. Wastegates, intercoolers, and blow-off valves improve performance by controlling boost pressure and cooling air.

Turbochargers, which are widely used in automotive, aerospace, and marine applications, benefit from sophisticated technologies such as variable geometry turbos (VGT) and electric turbocharging in order to reduce latency and increase efficiency. However, issues such as turbo lag, heat soak, and bearing problems due to oil hunger necessitate proper

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cooling and maintenance. Material innovations, 3D printing, and hybrid electrification continue to improve turbocharger performance, making them essential for modern high-efficiency engines.

By enabling complicated geometries, weight reduction, and material efficiency through layer-by-layer fabrication, additive manufacturing, or AM, has revolutionized industrial production. AM is used in the medical industry for patient-specific implants and porous prosthetics, and in aerospace for lightweight, high-strength parts like turbine blades with internal cooling channels. Customized tooling, heat exchangers, and on-demand spare parts are examples of industrial applications that lower waste and inventory costs. Using technologies like FDM, SLA, and DMLS, rapid prototyping speeds up product development in the consumer electronics, automotive, and medical industries by enabling functional testing and iterative design modifications prior to mass manufacturing. With its use in the aerospace, medical, automotive, and energy sectors for supply chain resilience, distributed manufacturing, and optimized components, 3D printing has progressed from prototyping to full-scale production.

AM has transformed the manufacturing of turbochargers by combining DMLS and EBM with cutting-edge metals such as Inconel to produce lightweight, aerodynamically efficient designs with complex cooling channels. Faster validation and performance improvement are made possible by rapid prototyping methods like SLA and metal 3D printing. For final turbocharger components, industry titans like GE Aviation and BMW are increasingly using AM to create high-strength, topology-optimized parts with excellent thermal management. Future developments will lead to lighter, more effective, and environmentally friendly turbochargers for automotive applications. These developments include high-temperature materials, AI-driven generative design, hybrid manufacturing, and on-demand spare part production

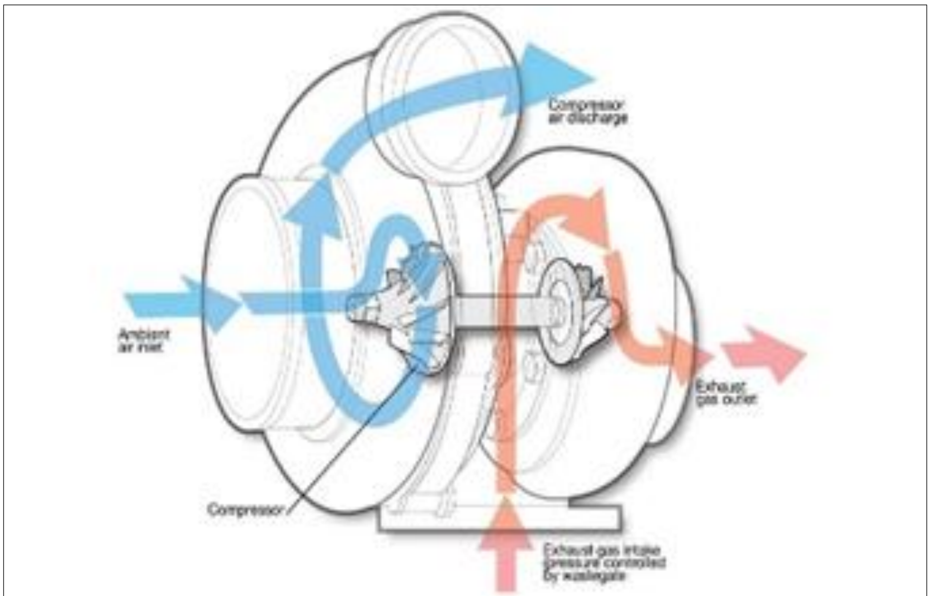

Figure 1 Turbocharger

1.1. Objectives of Integrated Thermal and Modal Analysis of Turbochargers with 3D Printed Prototype

- **Validate a high-performance turbocharger design** balancing thermal resilience, vibrational stability, and manufacturability.
- Conduct thermal and vibrational analysis to assess performance and durability under operational conditions.
- Simulate temperature distribution, heat transfer, and thermal stresses in turbocharger components.
- Perform modal analysis to study natural frequencies, resonance, and vibrational behaviour.
- Analyse thermal-vibration interactions to identify failure risks from thermal-induced resonances.
- Develop a 3D-printed prototype for experimental validation of simulation results.

2. Literature Review

Recent developments in thermal-mechanical analysis and additive manufacturing (AM) have greatly improved turbocharger design and performance optimization. A computational and multi-objective optimization study on 3D-printed conformal cooling channels was carried out by Shen et al. Reference [1], who showed enhanced thermal management in high-temperature applications. Similar to this, Basir et al. Reference [2] used infrared thermography to examine the thermal behaviour of turbochargers, confirming heat dispersion models experimentally. For turbochargers to be reliable, vibration and structural integrity are essential. Multibody simulations were used by Armentani et al. Reference [3] to evaluate the vibrations of turbocharged diesel engines and identify important resonance modes that impact durability. Jagatheesh kumar et al. Reference [4] devised a simulation-driven approach for distortion prediction in laser powder bed fusion (LPBF)-manufactured compressor blades, highlighting the role of residual stresses. In order to facilitate quick thermal analysis under automobile operating conditions, Gil et al. Reference [5] devised a fast 3D heat transfer model for turbocharger bearing housings.In order to prevent failures, thermal and vibrational interactions are essential. Using surrogate modelling, Mutra & Srinivas Reference [6] improved fatigue resistance by optimizing turbocharger rotor design under exhaust emission loads. In their investigation of forced and free vibrations in 3D-printed bioinspired structures, Gunasegeran & Sudhagar Reference [7] provided information on damping properties. Rajkumar Reference [8] used experimental modal analysis to examine how infill patterns affected mechanical qualities, highlighting the importance of AM parameters for dynamic performance. Historical and contemporary thermal studies further refine turbocharger efficiency. Romagnoli & Martinez-Botas Reference [9] combined experimental and computational methods to evaluate turbine heat transfer, establishing benchmarks for thermal modelling. Alaviyoun et al. Reference [10] developed a conjugate heat transfer model for turbine housings, enhancing accuracy in 3D thermal simulations. Collectively, these studies underscore the importance of integrated thermal and modal analysis in advancing turbocharger design and durability.

3. Materials

High-performance materials are required because turbochargers operate in harsh environments with temperatures above 1000°C, fast thermal cycling, and rotational speeds exceeding 200,000 RPM. Silicon carbide (SiC), Ni-Resist Cast Iron, and molybdenum (Mo) are the three main materials employed; each has special benefits in terms of durability, strength, and heat resistance. A thorough comparison of their characteristics and uses in turbocharger systems may be found here.

Table 1 Material Properties

Material	Density	Young's Ratio	Poisson's Ratio	Bulk Modulus	Shear Modulus	Isotropic thermal conductivity
Molybdenum	10280 kgm^3	3.4E+11 pa	0.29 pa	2.6984E+11 pa	1.3178E+11 pa	1.38Wm^-1c^-1
Ni Resist Cast Iron	7500 kgm^3	1.7E+11 pa	0.3 pa	1.4167E+11 pa	6.5385E+10 pa	0.3Wm^-1c^-1
Silicon Carbide	4.84E-06 kgm^3	1.37E+11 pa	0.37 pa	1.7564E+11 pa	5E+10 pa	0.207Wm^-1c^-1

3.1. Modelling of turbocharger

The study analyses turbocharger performance using a combination of computational and experimental methods. SOLIDWORKS is used to create a parametric CAD model, which is then meshed using FEA with fine-tuned elements in key areas. In addition to applying operating boundary conditions (thermal/mechanical stresses), material attributes are assigned to the components (cast iron case, Inconel impeller). While modal analysis assesses natural frequencies to avoid resonance, coupled thermal analysis determines heat flux and stress concentrations. For experimental validation, a working prototype is 3D printed using FDM (PLA/ABS), considering scaling for heat testing. In order to correlate and optimize the design, the process consists of the following steps: (1) component modelling (air foil blades, reinforced casings), (2) virtual assembly and interference checks, (3) Multiphysics simulation, and (4) prototype testing. This comprehensive methodology improves turbocharger durability and thermal management by bridging the gap between simulation and physical validation.

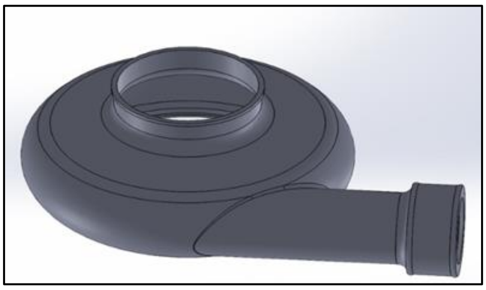

Figure 2 Turbocharger- Front Cover

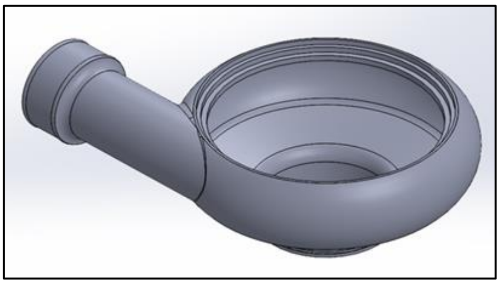

Figure 3 Turbocharger- Back Cover

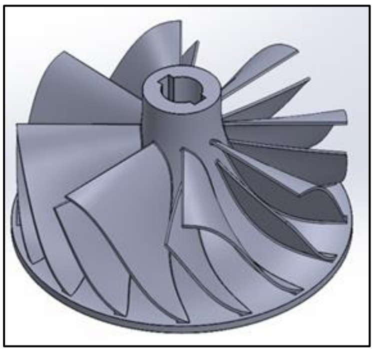

Figure 4 Turbocharger- Impeller

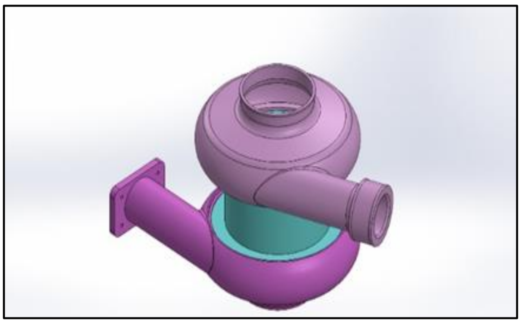

Figure 5 Turbocharger- Assembled View

4. Experimental analysis

Turbocharger casing design relies heavily on thermal and modal analyses to ensure dependability at high operating speeds (200,000+ RPM) and extreme temperatures (>1000°C). By assessing heat distribution, thermal stresses, and material behaviour—such as the heat resistance of Ni-Resist cast iron—thermal analysis using FEA helps to avoid deformation or cracking and directs cooling techniques like thermal coatings. By identifying natural frequencies and vibration modes, modal analysis helps prevent fatigue caused by resonance. It also shifts crucial frequencies by adjusting stiffness or damping, such as with SiC composites. When integrated, these assessments guarantee structural integrity under combined mechanical and thermal loads, improving endurance under harsh circumstances.

4.1. Meshing of Turbo Charger Casing

Using meshing, CFD/FEA simulations can break down physical geometries into discrete computational components. In ANSYS, Mechanical manages FEA meshing, striking a balance between accuracy and efficiency using hybrid approaches and techniques include sliding mesh/MRF for transient analyses, whereas Fluent/ICEM CFD creates structured/unstructured meshes with inflation layers and refinements.

- Details for meshing
- Mesh type -medium
- Type of element-triangle
- Nodes- 25850
- Elements-12690

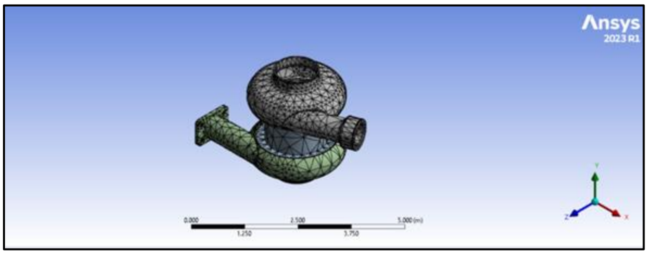

Figure 6 Turbocharger- Meshed View

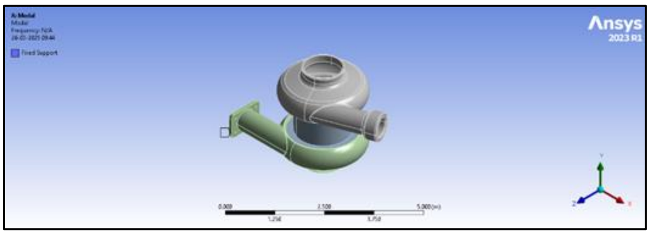

Figure 7 Boundary Conditions-Modal

Fixed support

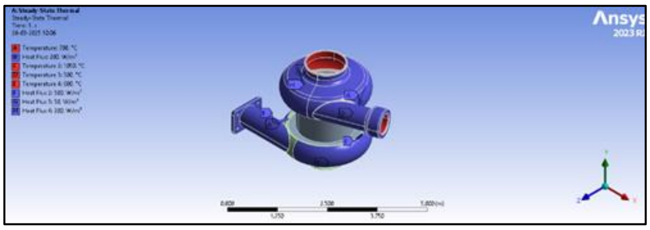

Figure 8 Boundary Conditions- Thermal

Temperature -700°c -1050°c, Heat flux -200-500w/m^2

5. Results and discussions

5.1. Thermal Analysis: Turbocharger Casing

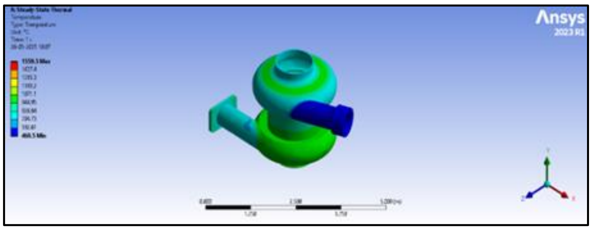

Figure 9 Temperature: Molybdenum

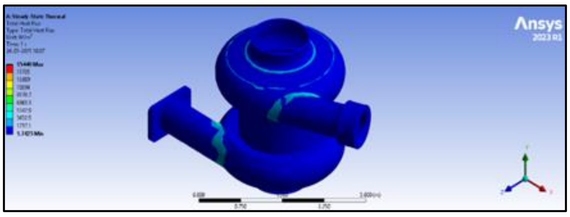

Figure 10 Heat Flux: Molybdenum

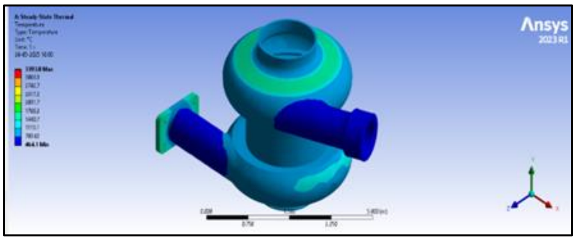

Figure 11 Temperature: Ni-Cast Iron

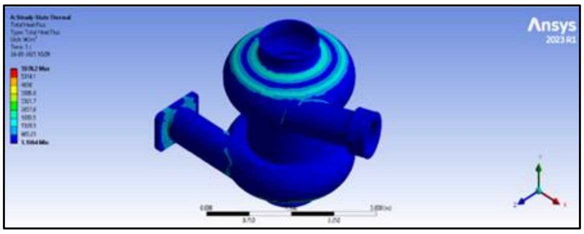

Figure 12 Heat Flux: Ni-Cast Iron

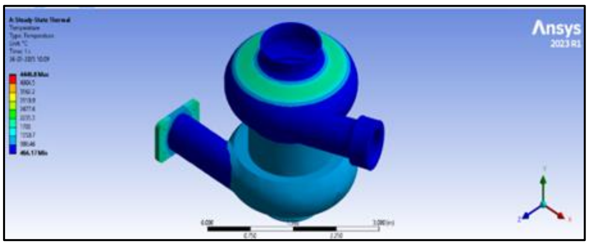

Figure 13 Temperature: Silicon Carbide

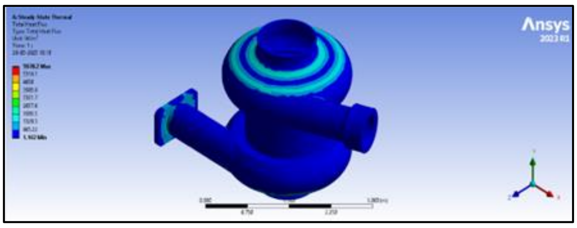

Figure 14 Heat Flux: Silicon Carbide

5.2. Modal Analysis: Turbocharger Casing

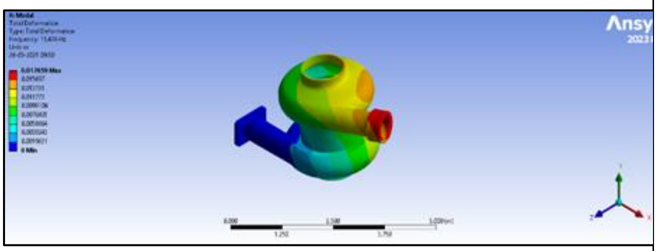

Figure 15 Total Deformation1 - Molybdenum

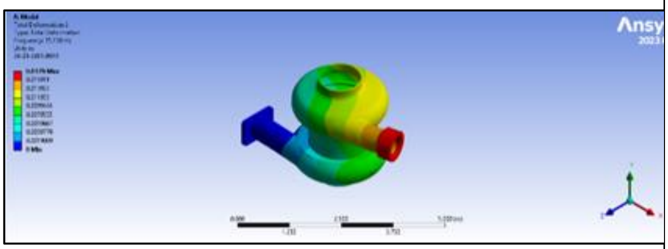

Figure 16 Total Deformation2 - Molybdenum

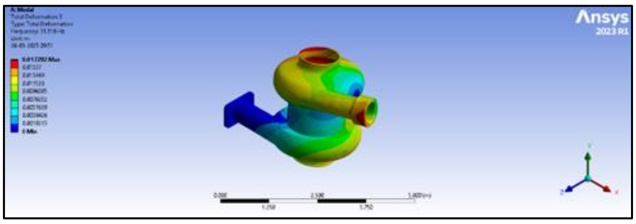

Figure 17 Total Deformation3 - Molybdenum

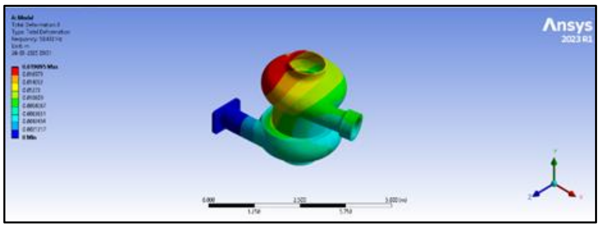

Figure 18 Total Deformation4 - Molybdenum

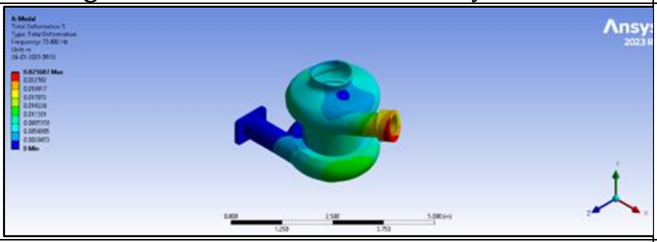

Figure 19 Total Deformation5 - Molybdenum

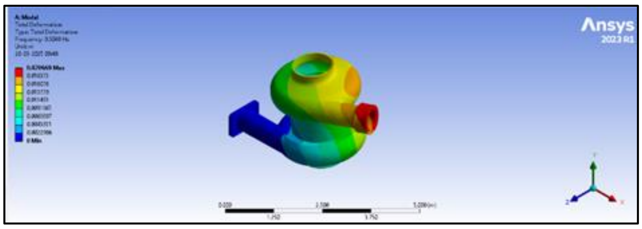

Figure 20 Total Deformation1 - Ni-Cast Iron

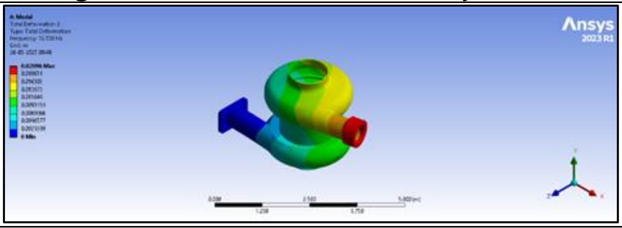

Figure 21 Total Deformation2 - Ni-Cast Iron

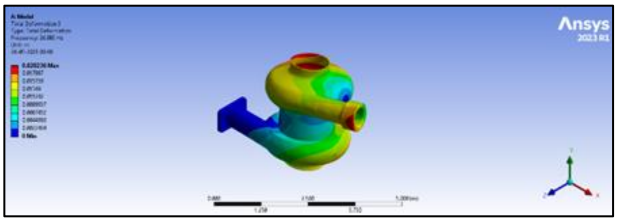

Figure 22 Total Deformation3 - Ni-Cast Iron

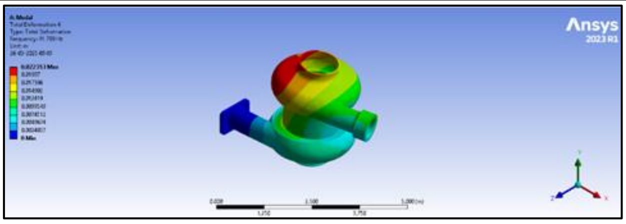

Figure 23 Total Deformation4 - Ni-Cast Iron

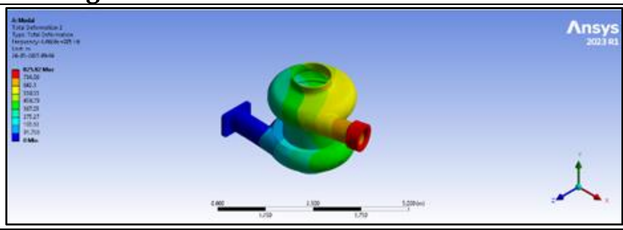

Figure 24 Total Deformation5 - Ni-Cast Iron

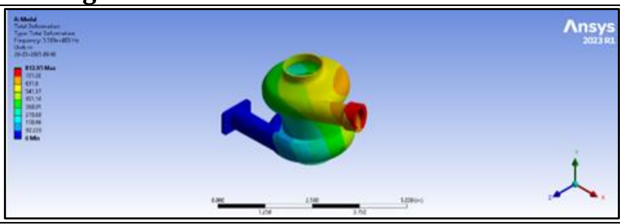

Figure 25 Total Deformation1 - Silicon Carbide

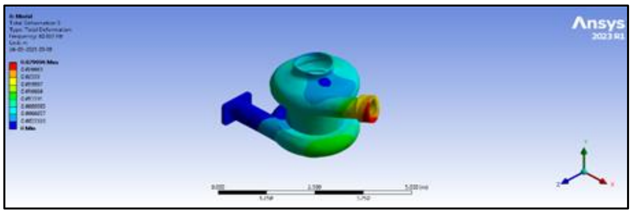

Figure 26 Total Defrormation2 - Silicon Carbide

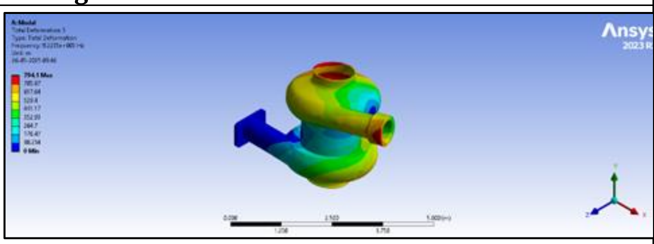

Figure 27 Total Defrormation3 - Silicon Carbide

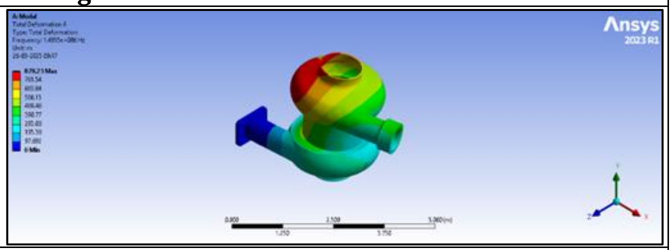

Figure 28 Total Deformation4 - Silicon Carbide

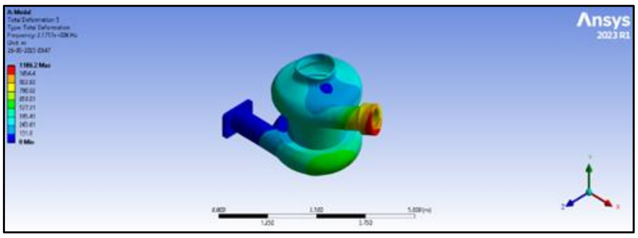

Figure 29 Total Deformation 5 – Silicon Carbide

Figure 30 3D-Prototype

Table 2 Results- Thermal Analysis

S.no.	Material	Temperature	Heat Flux
1	Molybdenum	Max: 1559.5°c Min: 460.5 °c	Max: 15440w/m^2 Min:1.7425 w/m^2
2	Ni Resist Cast Iron	Max: 3393.8°c Min: 464.1°c	Max: 5978.2w/m^2 Min:1.1064 w/m^2
3	Silicon Carbide	Max:4446.8°c Min: 466.17°c	Max: 5978.2w/m^2 Min:1.102 w/m^2

Table 3 Results- Modal Analysis

S no.	Material	Frequency	Total deformation 1	Total deformation 2	Total deformation 3	Total deformation 4	Total deformation 5
1	Molybdenum	11.474Hz	Min-0 Max-0.017659m	Min-0 Max-0.0179m	Min-0 Max-0.017292m	Min-0 Max-0.019095m	Min-0 Max-0.025607m
2	Ni Resist Cast iron	9.5049Hz	Min-0 Max-0.020669m	Min-0 Max-0.02096m	Min-0 Max-0.020236m	Min-0 Max-0.022353m	Min-0 Max-0.029996m
3	Silicon Carbide	3.383e+005Hz	Min-0 Max-812.05m	Min-0 Max-825.82m	Min-0 Max-794.1m	Min-0 Max-879.23m	Min-0 Max-1186.2m

6. Conclusions

- According to the study, which used 3D printed prototypes to test silicon carbide, molybdenum, and nickel-resist cast iron for turbochargers, silicon carbide had the best heat dissipation (15,440 W/m2) and the best thermal resistance (4446.8°C).
- The best balance of structural stability was found in molybdenum (11.474 Hz natural frequency, 0.025607 m deformation), whereas nickel-resist cast iron performed adequately and silicon carbide produced dubious findings (3.383×10^5 Hz, >1000 m deformation), according to modal analysis.
- Even though silicon carbide performed exceptionally well thermally, its severe deformation values point to possible simulation mistakes that need more research before being used in real-world applications.
- With its exceptional heat conductivity and robust vibrational stability for turbocharger applications, molybdenum turned out to be the most promising material overall.
- The study highlights the usefulness of integrated thermal-modal analysis in material evaluation and the efficiency of 3D printing for developing intricate turbocharger components.

- Adoption of innovative materials and additive manufacturing for next-generation turbochargers is supported by the findings, with molybdenum exhibiting particular promise despite the need for additional research on the structural behaviour of silicon carbide.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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