International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 08 Issue: 05 | May - 2024 SJIF Rating: 8.448 ISSN: 2582-3930

FEA-Based Camshaft Design and Analysis on a Range of Heat-Treated Materials

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Abstract - Camshafts play a critical role in internal combustion engines, dictating the timing and duration of valve opening and closing events. To ensure optimal engine performance and longevity, camshaft design must balance factors such as strength, durability, and weight. Finite Element Analysis (FEA) offers a powerful tool for evaluating camshaft designs under varying operating conditions. This paper presents a comprehensive study on the design and analysis of camshafts using FEA, focusing on the influence of different heat-treated materials. The study begins with an overview of material selection criteria for camshaft applications, considering factors such as strength, fatigue resistance, and wear characteristics. Various materials high-performance alloys are investigated for their suitability and performance enhancements through heat treatment processes such as carburizing, quenching, and tempering. A detailed 3D CAD model of the camshaft geometry is developed, capturing key features such as lobes, journals, and bearings. Finite element meshing techniques are employed to ensure accurate representation of the geometry and precise stress analysis. Boundary conditions are defined to simulate realistic operating conditions, including forces exerted by cam followers and valve springs. Material properties are assigned to finite elements based on the selected materials and heat treatment parameters. Static and dynamic FEA analyses are conducted to evaluate stress distribution, deformation, fatigue life, and natural frequencies of the camshaft under varying load scenarios. The results of the FEA analyses are used to optimize the camshaft design iteratively, considering factors such as weight reduction, performance enhancement, and durability improvement. Validation of FEA results is performed through physical testing and comparison with empirical data. Overall, this paper provides valuable insights into the design and analysis of camshafts using FEA, highlighting the importance of material selection and heat treatment processes in optimizing camshaft performance and reliability in automotive engine applications.

***Key Words*:** Design, Analysis, geartrain, idler gear, FEA, reciprocating motion, Solid works, CAD, ANSYS, efficiency, IC engines, camshaft.

I.INTRODUCTION

Camshafts serve as the mechanical heart of internal combustion engines, orchestrating the precise timing and duration of valve opening and closing events. This pivotal role places significant demands on camshaft design, necessitating a delicate balance between strength, durability, and weight. In pursuit of enhanced engine performance and longevity, engineers have turned to advanced computational methods, notably Finite Element Analysis (FEA), to scrutinize and optimize camshaft designs under diverse operating conditions. This paper embarks on a comprehensive exploration of camshaft design and analysis using FEA, with a specific focus on the influence of various heat-treated materials. Material selection forms the bedrock of camshaft engineering, with critical considerations encompassing mechanical properties, thermal stability, and resistance to wear and fatigue. To this end, a spectrum of steel alloys, including industry standards like SAE 8620 and 9310, as well as high-performance variants, are scrutinized for their suitability and potential for enhancement through tailored heat treatment processes. Central to our investigation is the development of a detailed 3D CAD model encapsulating the intricate geometry of the camshaft, encompassing lobes, journals, and bearings. This model serves as the foundation for subsequent FEA analyses, necessitating meticulous attention to meshing techniques to ensure fidelity and accuracy in stress prediction. Boundary conditions are meticulously defined to emulate real-world operating environments, encompassing the dynamic interplay of forces exerted by cam followers and valve springs. With the material properties elucidated and the finite element mesh meticulously crafted, the camshaft undergoes rigorous scrutiny through static and dynamic FEA analyses. These simulations afford insights into stress distribution, deformation patterns, fatigue life expectancy, and resonant frequencies under varying loading scenarios, laying bare the intricacies of camshaft behavior and performance. Armed with these insights, the iterative optimization process ensues, leveraging FEA results to fine-tune the camshaft design. Paramount among the objectives is the pursuit of weight reduction without compromising structural integrity, alongside enhancements in performance and durability. Validation of FEA findings is conducted through empirical testing, ensuring alignment between computational predictions and real-world performance benchmarks. Usually, camshafts have variable speeds that adjust to the engine's speed. The majority of contemporary cars are equipped with two overhead camshafts, one for the intake and one for the exhaust valves. Smaller inline 4- or 6-cylinder engines have a single overhead camshaft, but V-6 and V-8 engines typically have two overhead camshafts. The engine can have more valves thanks to dual camshafts, which improves the flow of exhaust and intake gasses. The engine's power is increased by this higher flow.

Fig-1: Cam and Camshaft

In summation, this paper endeavors to unravel the complexities of camshaft design and analysis using FEA, underscoring the pivotal role of material selection and heat treatment processes in sculpting camshaft performance and reliability in automotive engine applications. Camshafts are crucial components in internal combustion engines, responsible for controlling the timing and duration of valve opening and closing events. Over the years, researchers have extensively explored various aspects of camshaft design and analysis using Finite Element Analysis (FEA), aiming to optimize performance, durability, and efficiency. Several studies have investigated the influence of material selection and heat treatment processes on camshaft performance. For instance, Bhojwani and Pandey (2018) conducted Finite Element Analysis to optimize camshaft profiles, considering different material properties and heat treatment effects. Similarly, Reddy et al. (2012) explored FEA analysis and optimization of camshafts for diesel engines, emphasizing the importance of material properties in design. FEA has been extensively used to analyze the structural integrity and dynamic behavior of camshafts under various loading conditions. Chong and Kim (2016) conducted a study on camshaft design and analysis using FEA, focusing on both static and dynamic performance. Their research highlighted the significance of accurate boundary conditions and meshing techniques in predicting stress distribution and fatigue life. Dorninger and Eichlseder (2015) employed simulation-based optimization to refine camshaft profiles for passenger car applications. By integrating FEA with optimization algorithms, they achieved improved performance and reduced weight while maintaining structural integrity. This highlights the potential of FEA-driven optimization in enhancing camshaft design. Validation of FEA results through experimental testing is crucial for ensuring the accuracy and reliability of simulation predictions. Perisic et al. (2011) conducted design and FEA analysis of camshafts for internal combustion engines, followed by experimental validation. Their research demonstrated good correlation between simulation and test results, validating the effectiveness of FEA in camshaft design. Recent studies have explored advanced FEA techniques, such as coupled fluid-structure interaction (FSI) analysis, to capture the interaction between camshaft dynamics and engine performance. Huang and Zhu (2008) investigated FEA on camshaft structures, paving the way for future research into FSI-driven optimization for improved engine efficiency and emissions control. In summary, existing literature demonstrates the widespread application of FEA in the design and analysis of camshafts, encompassing material selection, static and dynamic analysis, optimization techniques, and validation through experimental testing. Future research directions may focus on integrating advanced FEA methods with emerging technologies to further enhance camshaft performance and efficiency in internal combustion engines.

2. MATERIALS AND METHODOLOGY

2.1 Materials Selection: The selection of materials for camshaft construction is critical to ensure optimal performance, durability, and reliability under varying operating conditions. Common materials used for camshaft manufacturing include steel alloys such as Mild Steel (EN08), Grey Cast Iron (CI), and high-performance variants like maraging steel or titanium alloys. The choice of material depends on factors such as mechanical properties, thermal stability, wear resistance, and cost considerations.

2.2 Heat Treatment: After material selection, appropriate heat treatment processes are employed to further enhance the mechanical properties of the chosen material. Typical heat treatment processes for camshaft materials include carburizing, quenching, and tempering. Carburizing increases surface hardness and wear resistance, while quenching and tempering improve strength and toughness, respectively. The specific heat treatment parameters are determined based on the material composition and desired mechanical properties.

2.3 Finite Element Analysis (FEA): Finite Element Analysis (FEA) serves as the primary methodology for the design and analysis of camshafts. FEA allows for the simulation of complex structural behavior and performance under various loading conditions. The following steps outline the FEA methodology for camshaft design and analysis:

I. **CAD Modeling:** Develop a detailed 3D CAD model of the camshaft geometry, including lobes, journals, bearings, and other features. Ensure accuracy and completeness in capturing the geometric details of the camshaft.

II. **Mesh Generation:** Generate a finite element mesh of the camshaft model using appropriate meshing techniques. Pay attention to mesh quality and density, especially in critical regions such as fillets and stress concentration areas.

III. **Material Properties Assignment:** Assign material properties to the finite elements based on the selected material and heat treatment parameters. Material properties include Young's modulus, Poisson's ratio, yield strength, ultimate tensile strength, and thermal expansion coefficients.

IV. **Boundary Conditions:** Define boundary conditions to simulate realistic operating conditions of the camshaft. This includes fixing one end of the camshaft and applying loads and constraints to simulate forces exerted by cam followers, valve springs, and other components of the valve train system.

V. **Analysis Type:** Choose appropriate analysis types based on the objectives of the study. Static analysis is typically used to evaluate stress distribution and deformation under steady-state loading conditions, while dynamic analysis may be employed to assess dynamic behavior, including fatigue life and natural frequencies.

VI. **FEA Solving:** Solve the finite element model using FEA software such as ANSYS, Abaqus, or COMSOL Multiphysics. Perform iterative analyses to refine the model and obtain accurate results.

VII. **Post-Processing:** Analyze the results obtained from FEA to evaluate key performance metrics such as stress distribution, deformation, fatigue life, and natural frequencies. Compare results against design criteria and standards to assess the performance of the camshaft design.

VIII. **Optimization:** Iteratively optimize the camshaft design based on FEA results to improve performance, durability, and efficiency. This may involve adjusting geometric parameters, material selection, or heat treatment processes to meet design objectives.

By following this methodology, engineers can effectively design and analyze camshafts using Finite Element Analysis, ensuring optimal performance and reliability in automotive engine applications.

2.4 Classification of Cams

Cams are classified in three ways:

a) In terms of their shape, such as wedge, radial, cylindrical, globoidal, conical, spherical, or Three-dimensional.
b) In terms of the follower motion, such as dwell-rise-dwell (DRD), dwell-rise-return-dwell (DRRD), or rise-return-rise (RRR).
c) In terms of the follower constraint, which is accomplished by either positive drive or spring load as mentioned previously.

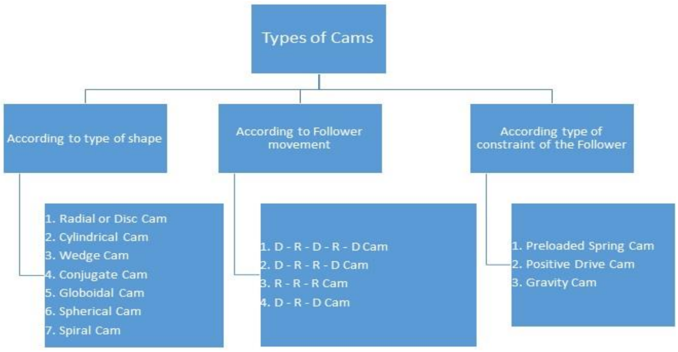


Fig-2: various types of cams

2.4 Cam Terminology

Here are some key terminologies related to camshaft design and analysis:

I. **Camshaft:** A shaft with one or more eccentric lobes used in internal combustion engines to control the opening and closing of valves.

II. **Lobe:** The raised portion of the camshaft responsible for actuating valves or other components. It determines the valve lift and duration.

III. **Base Circle:** The smallest diameter of the camshaft around which the lobe is formed. The cam profile starts and ends at the base circle.

IV. **Flank:** The sloping portion of the cam profile between the base circle and the peak of the lobe.

V. **Dwell:** The portion of the cam profile where the follower remains stationary at its highest or lowest position, typically representing a period of valve closure or opening.

VI. **Lift:** The maximum displacement of the follower from its rest position, measured perpendicular to the camshaft axis. It determines the maximum valve opening.

VII. **Duration:** The angular distance or time interval during which the follower remains above a certain lift threshold, typically representing the duration of valve opening or closing.

VIII. **Follower:** A component that rides on the surface of the cam lobe and transmits motion to the valves or other components. It can be in the form of a flat tappet, roller tappet, or rocker arm.

IX. **Valve Timing:** The relationship between the position of the camshaft and the opening and closing of engine valves relative to the piston position. It influences engine performance, fuel efficiency, and emissions.

X. **Valve Overlap:** The period, during which both the intake and exhaust valves are partially open at the same time, allowing for scavenging of exhaust gases and improved engine performance.

XI. **Valve Lift Profile:** The graphical representation of the lift versus crank angle for each valve, indicating the motion imparted by the camshaft.

XII. **Acceleration and Deceleration Ramps:** The portions of the cam profile where the slope changes abruptly, affecting the rate of change of lift and valve motion.

Understanding these terminologies is crucial for designing, analysing, and optimizing camshafts for internal combustion engines, ensuring optimal engine performance, efficiency, and reliability.

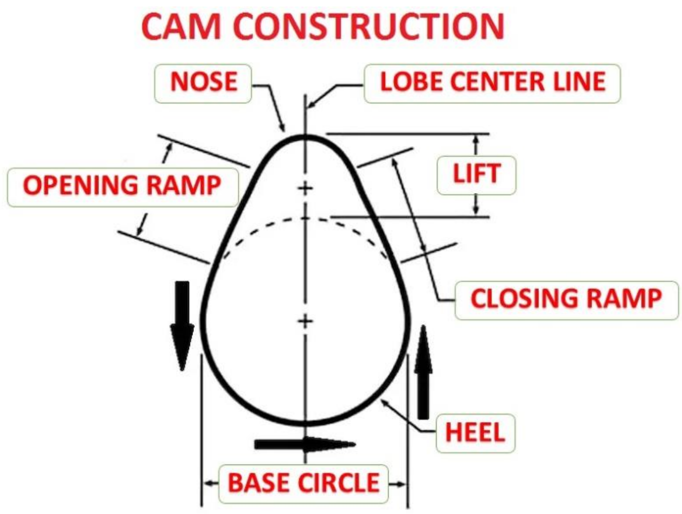


Fig-3: cam Geometry

2.5 Finite Element Analysis (FEA)

Finite Element Analysis (FEA) is a computational technique used to analyse and solve complex engineering problems related to structural mechanics, heat transfer, fluid dynamics, and electromagnetics, among others. It's based on the concept of dividing a complex structure or system into smaller, simpler elements called finite elements, which are interconnected at discrete points called nodes. By solving mathematical equations governing the behaviour of these elements, FEA enables engineers to simulate and predict the response of a system to various loading and boundary conditions.

Here's an overview of the key components and steps involved in Finite Element Analysis:

A. **Pre-processing:**
   a. **Modeling:** Develop a geometric representation of the structure or system to be analyzed using computer-aided design (CAD) software.
   b. **Meshing:** Divide the model geometry into finite elements and assign appropriate properties such as material properties, element type, and boundary conditions.
   c. **Boundary Conditions:** Define constraints and loads applied to the model to simulate real-world operating conditions.

B. **Analysis:**
   a. **Discretization:** Formulate mathematical equations governing the behavior of each finite element based on principles of continuum mechanics, such as stress-strain relationships.
   b. **Assembly:** Combine individual element equations into a system of algebraic equations representing the entire model.
   c. **Solution:** Solve the system of equations using numerical methods, such as the finite element method (FEM) or the boundary element method (BEM), to obtain the response of the model.

C. **Post processing:**
   a. **Visualization:** Interpret and visualize the results of the analysis, including stress distribution, displacement, temperature, and other relevant parameters.
   b. **Validation:** Compare analysis results with experimental data or analytical solutions to validate the accuracy and reliability of the model.
   c. **Optimization:** Modify the model parameters, such as geometry, material properties, or boundary conditions, to optimize the design and improve performance.

Finite Element Analysis is widely used across various industries, including automotive, aerospace, civil engineering, mechanical engineering, and biomedical engineering, to solve a wide range of engineering problems. It allows engineers to explore multiple design iterations, evaluate the performance of different configurations, and make informed decisions early in the design process, ultimately leading to more efficient and cost-effective engineering solutions.

2.6 Heat Treatment of Camshafts

The heat treatment of camshafts is crucial for enhancing their mechanical properties, including hardness, strength, and wear resistance, to ensure optimal performance and durability under demanding operating conditions. Common heat treatment processes applied to camshafts include the following:

A. **Carburizing:**
   a. **Process:** Carburizing involves introducing carbon into the surface layer of the camshaft by heating it in a carbon-rich atmosphere, typically containing carbon monoxide or methane. The carbon diffuses into the steel,

forming a hardened case with increased carbon content while maintaining a softer core.

b. **Benefits:** Carburizing increases the surface hardness and wear resistance of the camshaft, reducing wear and extending its service life in high-contact areas such as the cam lobes and followers.

B. **Quenching:**

a. **Process:** After carburizing, the camshaft is rapidly cooled, or quenched, in a suitable quenching medium such as oil, water, or polymer solution. Quenching arrests the diffusion of carbon atoms, locking them into the crystalline structure and forming a hardened surface layer.

b. **Benefits:** Quenching further increases the hardness and toughness of the camshaft surface, enhancing its resistance to wear, abrasion, and plastic deformation.

C. **Tempering:**

a. **Process:** Following quenching, the camshaft is heated to a lower temperature and held for a specified time before being cooled gradually. This process, known as tempering, relieves internal stresses induced during quenching and imparts the desired balance of hardness and toughness to the camshaft.

b. **Benefits:** Tempering reduces the brittleness of the hardened surface layer, improving the camshaft's resistance to impact loading and fatigue failure while maintaining adequate hardness and wear resistance.

D. **Shot Peening:**

a. **Process:** Shot peening involves bombarding the surface of the camshaft with high-velocity spherical or irregularly shaped shot particles. This induces compressive residual stresses in the surface layer, improving fatigue strength and resistance to stress corrosion and fretting.

b. **Benefits:** Shot peening enhances the fatigue life and performance of the camshaft by mitigating the initiation and propagation of fatigue cracks, particularly in regions subjected to cyclic loading.

E. **Nitriding:**

a. **Process:** Nitriding involves diffusing nitrogen into the surface layer of the camshaft at elevated temperatures in a nitrogen-rich atmosphere. This forms a hardened surface layer consisting of nitrides, which enhances wear resistance and fatigue strength.

b. **Benefits:** Nitriding improves the surface hardness, wear resistance, and corrosion resistance of the camshaft, particularly in high-temperature and high-load applications.

The selection of heat treatment processes for camshafts depends on factors such as the material composition, desired mechanical properties, application requirements, and manufacturing constraints. By carefully tailoring the heat treatment regimen, engineers can optimize the performance, longevity, and reliability of camshafts in automotive and industrial applications.

In this study of camshaft we use Quenching processes for various material Mild Steel (EN08), Grey Cast Iron (CI), and high-performance variants like titanium alloys.

3. RESULTS AND DISCUSSION

The Static structural analysis is mainly done by performing following steps,

3.1 Creating a model: A three dimensional modeling software is required in order to make model of camshaft. Solid-works is one of the most commonly used 3D modeling software used by modern industries. The basic geometry can be identified by means of visualizing the model in solid-works. Below figure shows the modeled camshaft with the help of solid-works.

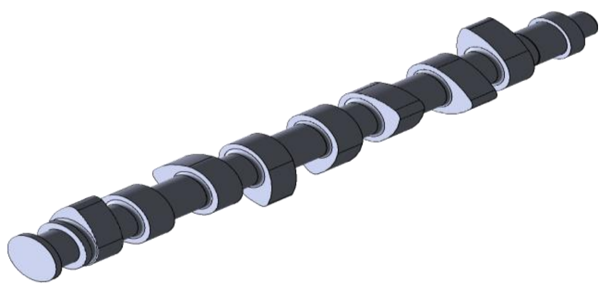


Fig-4: 3D model of Camshaft

3.2 Material properties: After creating a 3D model in solid-works, the model is going to import in analysis software. Ansys R 19.2 is going to be used as analysis software. Material properties like Modulus of Elasticity, Poisson's ration, density, etc. needs to be inputted in the software for better results.

Table-1: Properties of Materials

Materials	Density (Kg m^-3)	Elasticity (Pa)	Poisson's Ratio
Mild Steel (EN08)	7850	2E + 11	0.3
Grey CI	7200	1.1E + 11	0.28
Titanium alloy	7900	2.2E + 11	0.31

3.3 Mesh generation: In finite element analysis, mesh generation is the concept in which the model is divided into number of discrete parts known as elements which is connected by means of point said to be Nodes. Mesh size is directly proportional to the accuracy of result. Big size of nodes sometimes gives unexpected results which can lead to failure of the actual product.

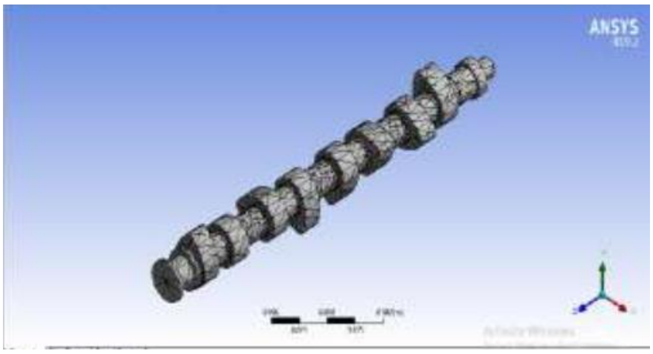


Fig-5: Mesh Generation

3.4 Applying Boundary Conditions: After completing of mesh generation proper constrain must be applied to the model in order to set the limiting point. Load of turning moment is applied to the camshaft as it is a rotating member in IC engine. Proper ID must be given to loads and constrain so that it could be easy to identify the load.

3.5 Solution: After applying the loads and defining the boundary condition, according to the defined problem, Solution phase deals with model. In this analysis the main concern is Total deformation, von mises stress and von mises strain.

3.6 Post Processing: The last step in Static structural analysis is post processing. With the help of different color graphics post processing program shows us the values of different factors varying from high to low. Clear idea of failure of material can be observed from the graphics.

Material: Mild Steel Grade EN08

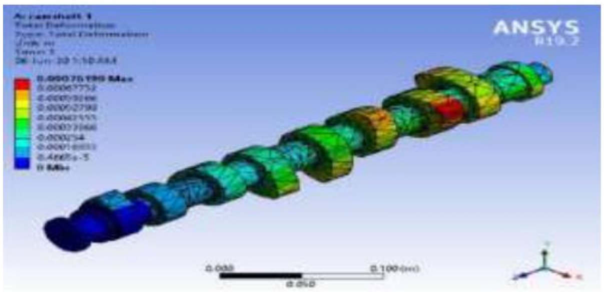


Fig-6: Total Deformation

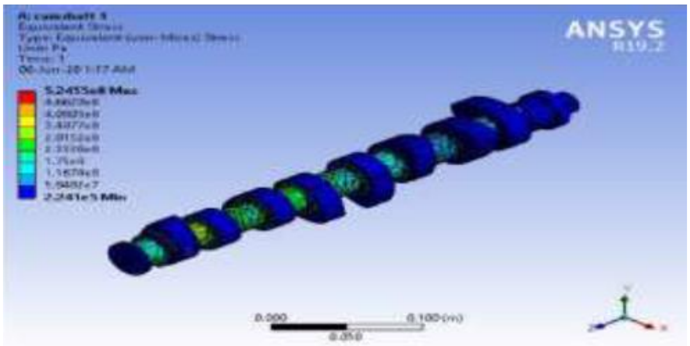


Fig-7: Equivalent Stress

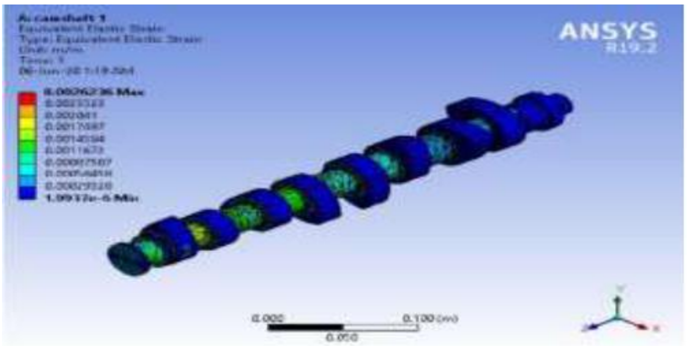


Fig-8: Equivalent Strain

Material: Grey Cast iron

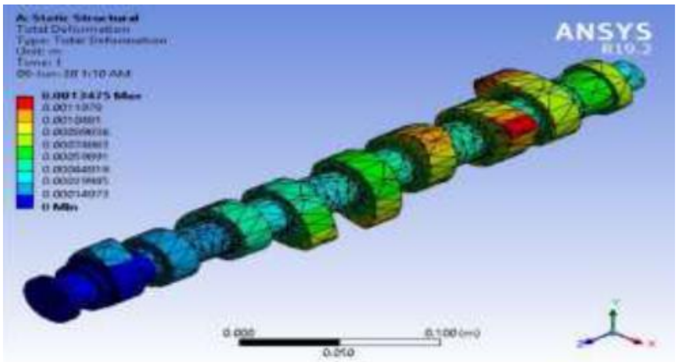


Fig-9: Total Deformation

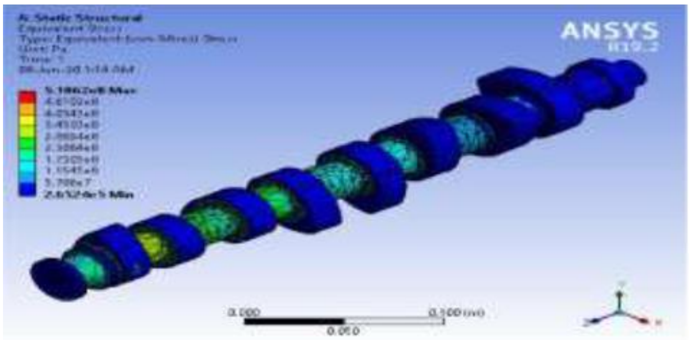


Fig-10: Equivalent Stress

Volume: 08 Issue: 05 | May - 2024 SJIF Rating: 8.448 ISSN: 2582-3930

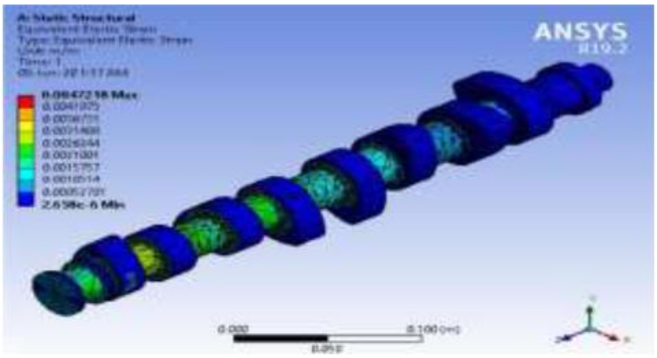


Fig-11: Equivalent Strain

Material: Titanium Alloy

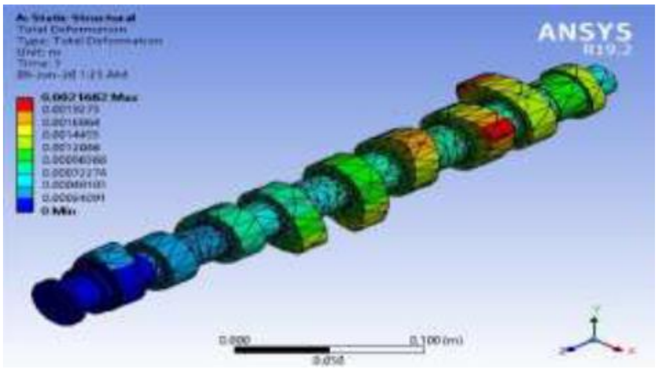


Fig-12: Total Deformation

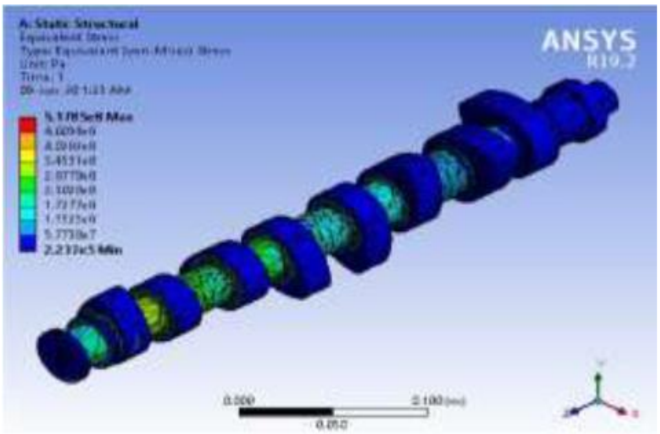


Fig-13: Equivalent Stress

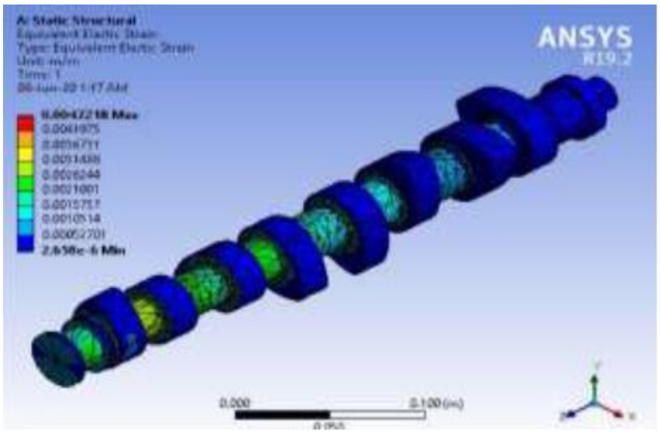
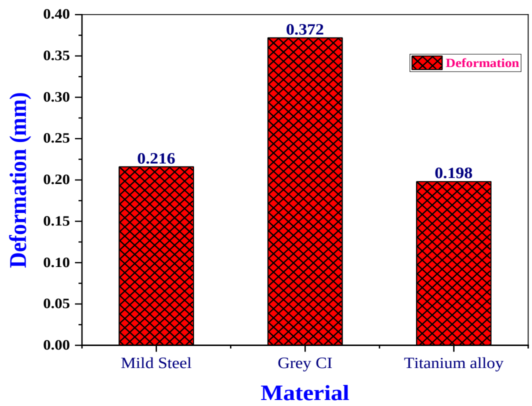
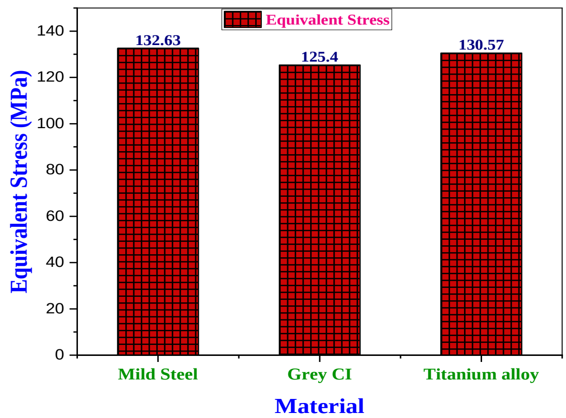
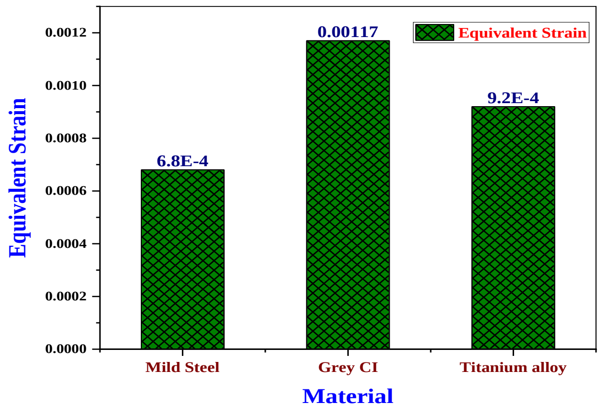


Fig-14: Equivalent Strain

From the result we plotted graphs:







4. CONCLUSION

In conclusion, the deformation characteristics of titanium alloys significantly surpass those of mild steel and grey cast iron. Titanium alloys exhibit higher ductility and toughness, allowing them to endure greater deformation under stress before failure. In contrast, mild steel, while also ductile, does not reach the same levels of deformation as titanium alloys. Grey cast iron, known for its brittleness, exhibits the least deformation among these materials, fracturing under relatively lower stress levels. This hierarchy in deformation capacity underscores the suitability of titanium alloys for applications demanding high resilience and deformation tolerance, whereas mild steel and grey cast iron are more appropriate for applications where brittleness and rigidity are acceptable or desirable.

The equivalent stress of titanium alloy exhibits a unique position when compared to grey cast iron and mild steel. Titanium alloy demonstrates higher equivalent stress than grey cast iron, making it more resilient and suitable for applications requiring greater strength and durability. However, its equivalent stress is lower than that of mild steel, indicating that while it is strong, it does not surpass the robust performance of mild steel under similar conditions. This balance of properties makes titanium alloy an attractive choice for specialized applications where its superior strength over cast iron is beneficial, yet the extreme robustness of mild steel is not necessary.

The analysis of Equivalent Strain for various materials reveals that titanium alloy exhibits a lower Equivalent Strain compared to grey cast iron but a higher Equivalent Strain than mild steel. This positioning indicates that titanium alloy offers a favourable balance of strength and ductility, making it a versatile choice for applications where both mechanical performance and material resilience are critical. Its superior performance relative to grey cast iron and mild steel highlights titanium alloy's suitability for demanding engineering applications, where material behaviour under strain is a crucial consideration.

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