GENERATIVE DESIGN APPROACH AND PERFORMANCE ANALYSIS OF VEHICLE KNUCKLE

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ABSTRACT

The design and performance of steering knuckles in high-performance automotive applications, such as Formula racing, play a critical role in vehicle dynamics. Traditional manufacturing methods often fail to optimize structural efficiency, weight, and durability, impacting overall vehicle performance. This project explores the potential of Additive Manufacturing (AM) and Generative Design techniques to enhance the knuckle's design by focusing on critical factors such as weight reduction, durability, and performance under high-speed conditions. Through the use of advanced composite materials like Carbon Fiber and PEEK polymers, combined with a generative design approach, this study aims to create a lightweight yet strong knuckle, offering superior strength-to-weight ratios compared to traditional materials like aluminium and cast iron. The proposed methodology involves the design, simulation, and optimization of knuckle components using SolidWorks for modelling and ANSYS for structural analysis. The results of this study demonstrate that by integrating generative design and AM, substantial improvements can be achieved in both the performance and manufacturability of automotive knuckles, leading to enhanced vehicle efficiency and alignment with sustainability goals. This research contributes to the advancement of innovative manufacturing techniques in motorsports and automotive engineering, paving the way for future applications in lightweight structural components

Keywords: *Generative Design, Additive Manufacturing, Structural Efficiency, Composite Materials, Topology Optimization, Analysis, Design Optimization.*

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1. INTRODUCTION

In the automotive industry, particularly in high-performance racing applications, the design and manufacturing of critical components such as steering knuckles are pivotal to the overall vehicle performance. A steering knuckle connects the suspension system to the wheel hub, ensuring stability and control during vehicle motion. However, traditional manufacturing methods often face challenges in optimizing key attributes such as weight, strength, and durability. These limitations can significantly impact the vehicle's handling, speed, and overall performance.

With the rapid advancements in Additive Manufacturing (AM) and computational design tools, there is an emerging opportunity to redefine how automotive components are designed and fabricated. AM offers a new paradigm, enabling the production of complex geometries that were previously difficult or impossible to achieve using conventional manufacturing techniques. Additionally, Generative Design, a cutting-edge computational design approach, allows for the exploration of optimal structures by considering multiple variables and constraints, including material strength, weight, and manufacturing feasibility.

This project aims to leverage the potential of Generative Design and Additive Manufacturing to improve the design and performance of steering knuckles, focusing on reducing weight while maintaining or enhancing their structural integrity. By utilizing advanced composite materials such as Carbon Fiber and PEEK (Polyetheretherketone), which offer superior strength-to-weight ratios compared to traditional metals like aluminium and cast iron, the goal is to achieve a more efficient and durable knuckle that enhances vehicle dynamics, especially in high-speed racing conditions.

The integration of Generative Design with AM offers a promising avenue for producing customized, lightweight components with optimized material distribution, enabling significant improvements in both performance and manufacturing efficiency. This study explores the application of these technologies to the design of a Formula racing vehicle's steering knuckle, aiming to push the boundaries of automotive engineering through innovation and sustainability

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1.1 STEERING KNUCKLE

In automotive suspension, a steering knuckle or upright is that part which contains the wheel hub or spindle, and attaches to the suspension and steering components. The steering knuckle is the pivot point of the steering system, which allows the wheels to turn. The wheel and tire assembly attach to the hub or spindle of the knuckle where the tire or wheel rotates while being held in a stable plane of motion by the knuckle or suspension assembly. In a non-drive suspension, the knuckle usually has a spindle onto which the brake drum or brake rotor attaches. The wheel/tire assembly then attaches to the supplied lug studs, and the whole assembly rotates freely on the shaft of the spindle. In a drive suspension, the knuckle has no spindle, but rather has a hub into which is affixed the bearings and shaft of the drive mechanism. The end of the drive mechanism would then have the necessary mounting studs for the wheel/tire and/or brake assembly. Therefore, the wheel assembly would rotate as the drive shaft (or half-shaft) dictates. It would not turn freely by itself, but only if the shaft was disengaged from the transaxle or differential. A driven suspension as described may also be steerable. This is often called a drive/steer arrangement. Steering knuckles come in all shapes and sizes. Their designs differ to fit all sorts of applications and suspension types. However, they can be divided into two main types. One comes with a hub and the other comes with a spindle.

Figure 1. Knuckle with spindle

Figure 2. Knuckle with hub

1.2 AA6061 ALUMINIUM ALLOY

The 6061 aluminum alloy is one of the most common and versatile for extrusion. Because of its good combination of properties, it is used in a range of project types. AA6061 can be extruded, rolled, or forged into a variety of shapes. Magnesium and silicon are the primary alloying elements of AA6061. It is generally referred to as structural aluminum, since its strength makes it ideal for structural applications. It is a Medium - High strength heat treatable alloy. It possesses good weldability and corrosion resistance. This material is typically used in aircraft components, cameras, couplings, marine fittings and hardware, electrical components, brake and hydraulic pistons, valves, and bicycle frames

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1.3 CARBON FIBER NYLON 12 (PA12)

High strength to weight ratio : Carbon fiber reinforcement significantly enhances the strength of nylon 12 while maintaining a relatively low weight ,making it suitable for applications requiring both durability and minimal weight.

Improved stiffness and dimensional stability: Carbon fibers reduce flexing and warping in nylon 12, leading to better dimensional stability and a more rigid structure.

Enhanced electrical properties: Certain types of carbon fibers can improve the electrical conductivity of nylon 12, making it potentially useful in electrical applications.
Good wear resistance: Carbon fibers can improve the wear resistance of nylon 12, extending its lifespan in applications encountering friction.

1.4 PEEK POLYMER 450CA 40

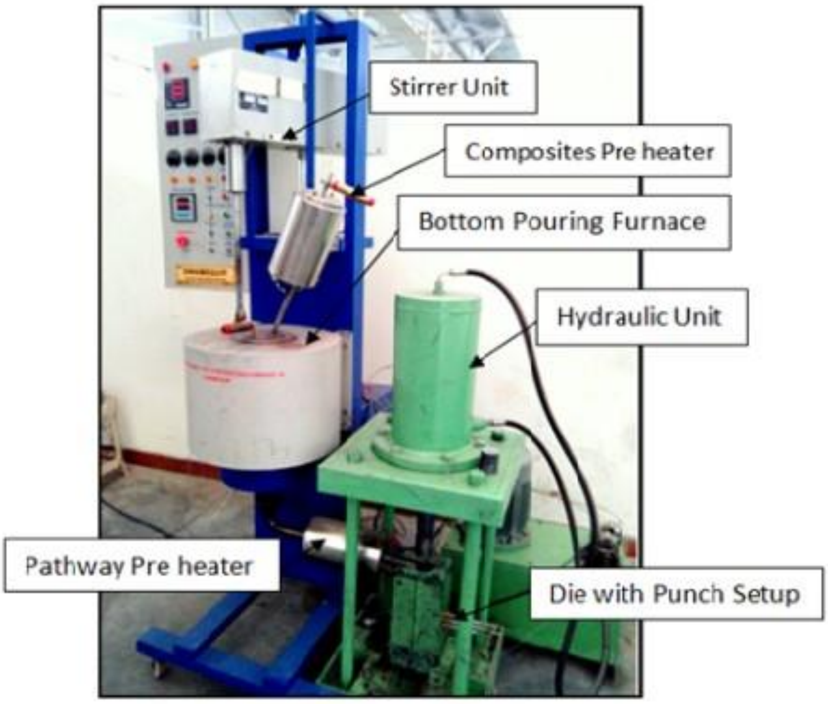
Good wear resistance: Carbon fibers can improve the wear resistance of nylon 12, extending its lifespan in applications encountering friction.
Excellent high-temperature performance: PEEK 450CA 40 is known for its exceptional thermal properties. It boasts a high continuous use temperature (around 260°C) and a melting point exceeding 340°C, making it suitable for demanding environments involving high heat.
Good mechanical strength: Even at elevated temperatures, PEEK 450CA 40 retains impressive mechanical strength. This allows it to withstand significant loads without deformation or breakage.
Dimensional stability: PEEK 450CA 40 maintains its shape well under varying temperatures and loads. This minimizes warping or shrinkage, ensuring consistent performance.

Properties	CARBON FIBRE	NYLON 6,6	PEEK
Density (g/cm^3)	1.4	1.16	1.32
Tensile Stress(MPa)	700	90	110
Tensile Modulus (MPa)	54000	3550	3448
Tensile Strain at break (%)	1.5	5	10
Flexural strength (MPa)	470	115	172.368
Compressive Stress(MPa)	276	100	137

1.5 GRAVITY CASTING

Gravity casting is a casting process used for non-ferrous alloy parts. Sometimes referred to as Permanent Mould, the process is typically used on aluminum, zinc, and copper base alloys. Among various casting routes, gravity casting is one of the traditional methods for fabricating metals and metal alloys. There are three stages to the gravity casting process. The first step is the heating of the mold and coating it with a die release agent. The release agent spray also serves as a cooling agent after the part has been removed from the die. In the second step, the molten metal is poured into channels in the tool to allow the material to fill the entire mold cavity. The metal is either dosed or hand poured by using ladles. Usually, there is a mold “down sprue” that allows the alloy to enter the mold cavity from the lower part of the die. This reduces the formation of turbulence and subsequent porosity and inclusions in the finished part.

After the part has cooled, the die is opened by either using a mechanical tool or manually. It offers high metal yield, eliminates porosity, high strength, excellent surface finish and low operating costs. It is the most effective and efficient route to produce near net-shape components with superior properties. Gravity casting also provides faster production times compared to the other processes.



1.6 FUSED FILAMENT FABRICATION

Fused filament fabrication (FFF), also known as fused deposition modeling (with the trademarked acronym FDM), or called filament freeform fabrication, is a 3D printing process that uses a continuous filament of a thermoplastic material.

Filament is fed from a large spool through a moving, heated printer extruder head, and is deposited on the growing work. The print head is moved under computer control to define the printed shape. Usually the head moves in two dimensions to deposit one horizontal plane, or layer, at a time; the work or the print head is then moved vertically by a small amount to begin a new layer. The speed of the extruder head may also be controlled to stop and start deposition and form an interrupted plane without stringing or dribbling between sections. Fused filament printing is now the most popular process (by number of machines) for hobbyist-grade 3D printing. Other techniques such as photopolymerisation and powder sintering may offer better results, but they are much more costly.

The 3D printer head or 3D printer extruder is a part in material extrusion additive manufacturing responsible for raw material melting and forming it into a continuous profile. Markforged Two is a composite 3D printer that delivers high accuracy and repeatability. Mark Two also adapts the FFF process to print non-plastic materials. In Continuous Filament Fabrication (CFF), an FFF 3D printer with a specialized second nozzle lays down continuous carbon fiber, fiberglass, or Kevlar into a part. The printer is capable of printing Fiber parts that give equivalent strength to aluminum. The machine has a built volume of 320 x 132 x 154 mm and can print a maximum layer height of 100 µm.

1.7 DRAWBACKS OF CONVENTIONAL KNUCKLE\

The steering and suspension systems are crucial to successful operation of any variety of cars. Due to the large responsibility that these two major components share coupled with the fact that race cars are capable of reaching very high speeds and accelerations, it is obvious that consequences of failure or improper setup of the suspension and/or steering could be quite catastrophic. The overall performance of the steering system is affected by higher inertia forces, generated by the moving parts of the vehicle. Therefore, it should always be investigated to avoid any failure of the vehicle in the long run. The steering knuckle accounts for the maximum amount of weight of all suspension components, which requires a high necessity of weight reduction. The following are the main problems which are found in the manufacturing of the knuckle:
Due to uneven stress distribution over the steering knuckle, its life is reduced.
This affects the overall performance of an automobile vehicle.
Due to the lack of knowledge of stress distribution the material wastage may occur.

1.8 DRAWBACKS OF CASTING

There are numerous factors that can contribute to casting failure. Casting defects are mostly caused by non-optimized process, failure of material and casting equipment. The relatively more involved production operations make casting processes more challenging to be fully controlled. The casting work pieces are more prone to take with casting defects which are an unwanted irregularity that appear during metal casting process.
There are various reasons or sources which are responsible for the defects in the cast metal. Some of the defects produced may be neglected or tolerated and some are not acceptable, it must be eliminated for better functioning of the parts. Compared with forgings of the same size and shape, the intrinsic quality of castings is weaker, and the load-bearing capacity is less than that of forgings. On the other hand, casting has relatively poor dimensional consistency and accuracy. Poor working environment with high temperature, dust, and high labor intensity is also a disadvantage. Gravity casting also has certain defects: Because the heat-resistant alloy and its hollow cavity are more expensive to process, the molds are expensive to manufacture. Therefore, for low-volume production, the cost to be allocated to each product is obvious, too high, and generally not acceptable.

1.9 ADVANTAGES OF ADDITIVE MANUFACTURING

Additive manufacturing has proven to be a powerful technology, revolutionizing production processes and business models across numerous industries. As the advantages of additive manufacturing have become more tangible, its applications have skyrocketed over the last few years. 3D printing gives product teams a chance to step back and focus on a system-level approach rather than component-level thinking. This enhanced production

process is not ultimately about replacing a functional part; it is about creating a better overall design. Additive manufacturing technology enables OEMs to produce fewer components within a single product, reducing the inventory significantly. 3D printing allows us to manufacture products without tooling and to consolidate assemblies into single parts. It is a huge advantage that additive manufacturing holds over traditional processes.
Design for additive manufacturing is unique in its methods compared to designing through traditional manufacturing. The ability to design any structure with 3D printing gives the freedom to think of the part they want to manufacture in relation to the entire product. This allows us to see if there are new and different ways to efficiently combine several parts into one at no cost, no additional tooling, re-fixturing or fabrication time. When implemented effectively, additive manufacturing can significantly reduce material waste, inventory, the number of production steps and distinct parts needed for an assembly.

2. PROBLEMS FACED

The design and manufacturing of steering knuckles in high-performance vehicles face several challenges, particularly when relying on traditional manufacturing methods. Some of the key problems include:
Weight: Traditional materials like cast iron and mild steel, though strong, are heavy, which negatively impacts vehicle performance, particularly in racing applications where weight reduction is critical for speed and handling.
Structural Efficiency: Conventional manufacturing methods often result in suboptimal material distribution, leading to unnecessary weight or weak points in the component. This compromises the overall structural integrity of the knuckle.
Durability: Steering knuckles are subjected to high loads and stress over time, especially in racing conditions. Traditional materials may not always offer the required fatigue resistance or durability, leading to failures or reduced performance.
Design Constraints: Conventional manufacturing techniques limit the complexity and customization of component shapes, making it difficult to optimize the knuckle design for better strength-to-weight ratios.
Manufacturing Limitations: Traditional methods like casting or forging may limit the ability to produce complex, lightweight geometries that could enhance performance, while also resulting in more material waste and inefficiencies in production.
Material Selection: Finding a material that balances strength, weight, and durability remains challenging. Materials like aluminum alloys may offer some weight reduction but still fall short in terms of strength compared to heavier metals like cast iron.
Time and Cost Constraints: Traditional manufacturing methods can be time-consuming and expensive, especially when considering the need for prototyping, testing, and multiple iterations.
By integrating Additive Manufacturing (AM) and Generative Design, these challenges can be addressed, enabling the production of more efficient, durable, and lightweight components tailored to the specific needs of high-performance vehicles

2.1 OBJECTIVES OF THE STUDY

1.Enhance Knuckle Performance and Efficiency: Improve the steering knuckle design by focusing on weight reduction, durability, and performance under high-speed racing conditions.
2.Apply Generative Design Techniques: Utilize generative design to optimize the knuckle's structure, achieving an ideal balance between strength, weight, and material usage.
3.Leverage Additive Manufacturing (AM): Maximize the benefits of AM to create complex, lightweight, and durable knuckle geometries that traditional methods cannot achieve.
4.Optimize Material Selection: Investigate and implement advanced composite materials like Carbon Fiber and PEEK to enhance strength-to-weight ratios and overall performance.

2.2 SCOPE OF THE STUDY

The scope of this study focuses on the design, optimization, and performance evaluation of a steering knuckle for high-performance automotive applications, particularly in racing. It explores the use of Generative Design and Additive Manufacturing (AM) to create lightweight, durable, and structurally efficient components. The study investigates advanced composite materials like Carbon Fiber and PEEK polymers to improve strength-to-weight ratios. It also includes structural simulations using SolidWorks and ANSYS to ensure the knuckle performs optimally under various loads and conditions. Additionally, the study addresses sustainability by incorporating environmentally friendly materials and manufacturing practices.

3. LITERATURE REVIEW

The literature survey reveals significant advancements in the design and manufacturing of steering knuckles for high-performance automotive applications, particularly in racing and motorsport. A consistent theme in the research is the application of Generative Design, Topology Optimization, and Additive Manufacturing (AM) to create components that are not only lightweight but also structurally efficient and durable. These advanced methods enable the creation of complex geometries that cannot be achieved through traditional manufacturing techniques, allowing for more optimized, customized designs that better meet the specific performance needs of automotive applications.

One of the most crucial aspects highlighted in the literature is the role of Finite Element Analysis (FEA) and Topology Optimization in identifying and addressing potential failure points. These techniques allow engineers to simulate how the knuckle will perform under various loading conditions, including extreme forces such as lateral forces, bump forces, and braking forces, common in racing environments. By analyzing stress distribution and load paths, engineers can optimize the design to ensure strength and durability while reducing unnecessary material, thus improving the overall performance and efficiency of the steering knuckle.

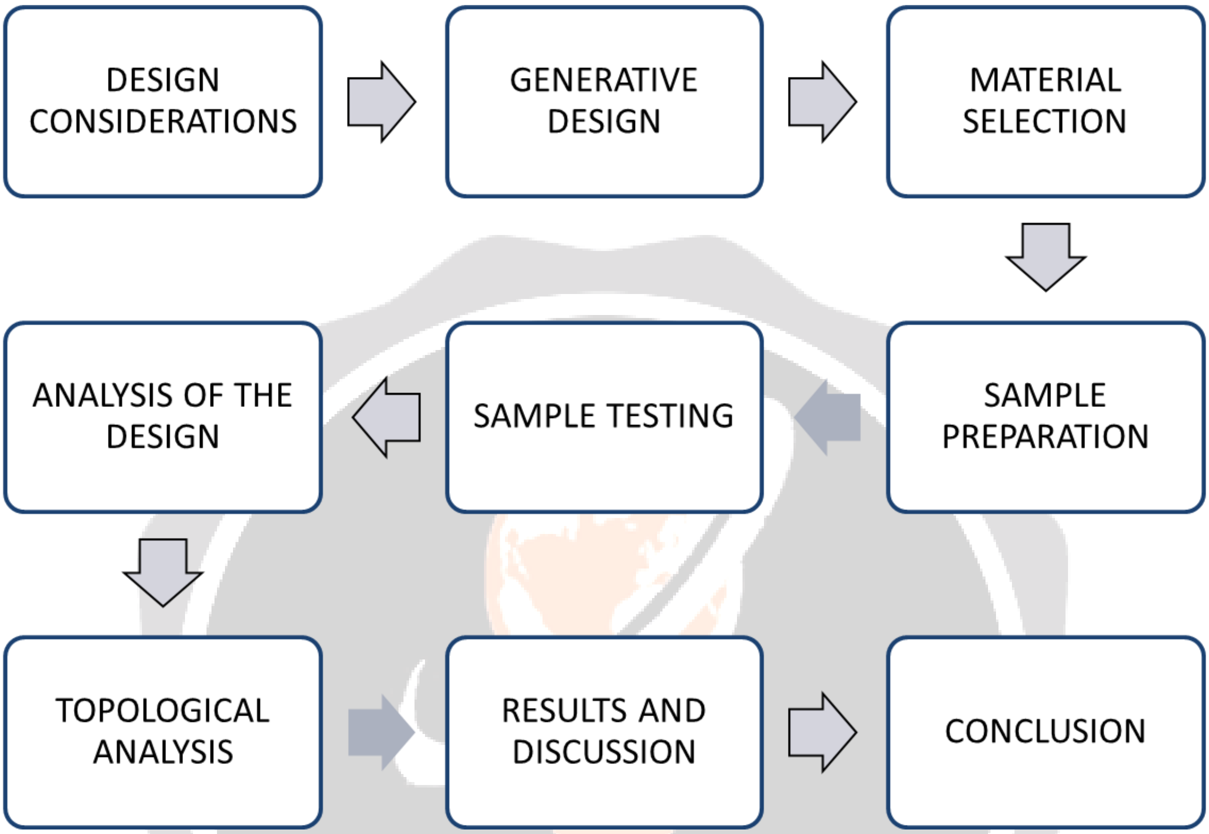
Another key focus in the literature is the exploration of advanced materials, including carbon fiber composites and PEEK polymers, which offer superior mechanical properties compared to traditional materials such as cast iron or aluminum. The use of these materials results in a lighter component without compromising on strength or durability, which is essential in automotive design, particularly for vehicles where weight reduction is critical for speed and handling. Research into carbon fiber reinforced polymers and other composite materials shows their potential to enhance the strength-to-weight ratio of automotive components significantly. These materials are particularly beneficial in high-performance and racing applications where every gram of weight saved can improve the overall performance.

In addition to design and material improvements, the literature emphasizes the importance of utilizing Additive Manufacturing (AM) techniques, particularly for their ability to produce complex and optimized designs with reduced waste. AM allows for more efficient production processes by minimizing material waste and enabling the manufacturing of parts with intricate geometries that are lighter and stronger.

Finally, software tools and generative design platforms are identified as essential enablers in this process. These tools allow for the rapid exploration of different design possibilities, streamlining the development process and reducing the time and cost associated with conventional prototyping.

In conclusion, the survey highlights the transformative potential of combining Generative Design, Additive Manufacturing, advanced materials, and simulation tools to revolutionize the design and manufacturing of automotive components like steering knuckles, making them more efficient, lightweight, durable, and sustainable.

4. METHODOLOGY



5. DESIGN CONSIDERATIONS

The design process was initiated with a preliminary investigation of the steering knuckle component, which included a study of the existing knuckle design. Steering Knuckle is subjected to time varying loads during its service life, leading to fatigue failure. Therefore, its design is an important aspect in the product development cycle. A reduction in the weight of suspension components also improves the vehicle's handling performance. Therefore, design optimization should be implemented to obtain a minimum weight with maximum or feasible performance, based on conflicting constraints, design boundaries, and design uncertainties, such as design clearance and material defects. For this purpose, we have focused on the following forces acting on the knuckle.

Lateral force
Bump force
Braking force
Steering force

Finally, ANSYS software was used to perform topology optimization which specifies where supports and loads are located on a volume of material and allows the software to find the best shape.

5.1 LATERAL FORCE

The force that acts in the direction parallel to ground and perpendicular to the direction of gravitational pull of earth is known as lateral forces. Lateral force depends on Location, materials used,height and shape of knuckle. The Lateral force is calculated by the formula "3G" where,

Lateral force:
Vertical load acting on each wheel = [[Sprung mass unsprung mass]/2] × g
= [[82.5 + 13]/2] × 9.81
= 468.42 N
Vertical force due to centrifugal couple = [Total mass with driver × (velocity)^2 × height of CG] / [2 × cornering radius × track width]
= [330 × (12.5) ^ 2 × 0.3] / [2 × 5 × 1.16]
= 1333.5 N
Lateral force due to gyroscopic effect = 2G
= 2(82.5 × 9.81)
= 1547.5 N
Net lateral force
= 1547.5 + 1333.5 + 486.5
= 3499.50 N

5.2 BUMP FORCE

Bump force on Upright is due to force exerted by coil spring on the suspension arm. Force due to coil spring is not applied directly to the upright, it results in the bending moment on suspension arm Bumping force of a vehicle is said to be "2G" where, Bump Force = 4716.73N

5.3 BRAKING FORCE

Moment braking force is braking force acting on the point of the knuckle where the calipers are mounted. Braking moment of vehicle is said to be 1.5 Gd
Force exerted on caliper Mounting
Weight due to unsprung mass = unsprung mass on one wheel × g
=13×9.81
= 127.53 N
Total vertical load = Dynamic G force + Static load acting on wheel
= 21209.29 + 127.53
= 21336.8 N
Friction force = Coefficient of friction × Total vertical load on knuckle
= 0.6 × 21336.8
= 12802.08 N
Brake torque = Friction force × radius of tire
= 12302.08 × 533.4
= 6828629.472 Nmm
Force acting on caliper mounting = Brake torque/ perpendicular distance to hub
= 6828629.472/75
Force acting on caliper mounting = 91048.39 N

5.4 STEERING FORCE

Force on the steering arm is applied due to push and pull of the tie rod due to linear movement of the rack, according to the input given by the steering wheel. The force acts perpendicular to the steering arm.
Force acting on steering arm:
Torque acting about steering axis = Friction force× scrub radius
= 485.595 Nm
Force acting on tie rod = Torque about steering axis/ Length of steering arm
=485.595/4.62
=105 N

6. GENERATIVE DESIGN

Generative design is an advanced design approach powered by artificial intelligence (AI) and machine learning algorithms. It generates multiple design solutions based on predefined parameters such as material type, load requirements, strength, and durability. The key feature of generative design is that it explores a wide range of design possibilities and outcomes, optimizing geometry in ways that are often not conceivable by traditional design methods.

Process:

The design process begins by setting the requirements for the component, including performance criteria like load-bearing capacity, weight reduction, and material constraints.

The software then uses algorithms to explore different configurations, materials, and shapes. Unlike conventional CAD design, where engineers create each model manually, generative design allows for the system to evolve solutions iteratively.

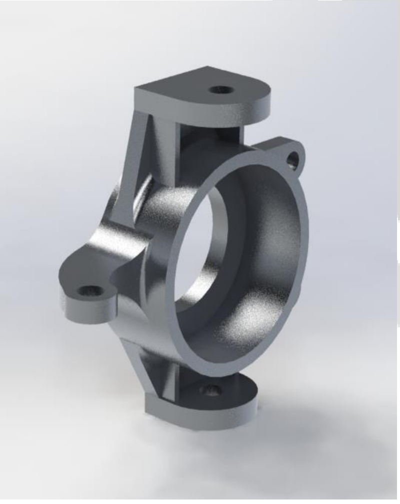
The software evaluates and ranks the design alternatives, providing engineers with several options to choose from based on performance optimization. These designs often feature complex geometries that reduce material use while maintaining or improving structural integrity.

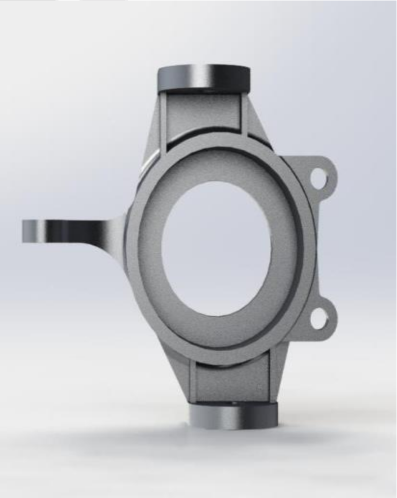
Optimized Performance: The generated designs focus on improving strength-to-weight ratios, enhancing performance.

Material Efficiency: The method ensures that material is used only where it's needed, reducing overall material consumption.

Innovative Geometries: Generative design often results in unconventional, organic shapes that would not be possible with traditional design methods.

Reduced Development Time: It speeds up the design process by automating iterations, leading to faster product development and prototyping.





6.1 FINITE ELEMENT ANALYSIS

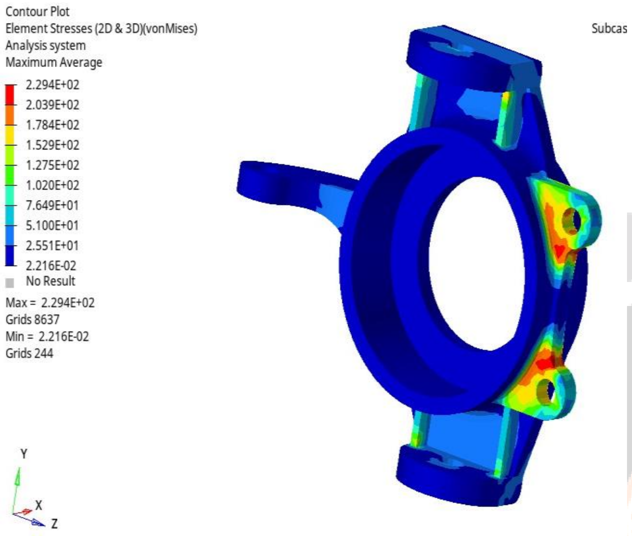
FEA is a powerful simulation technique used to analyze the behavior of components under various physical conditions, including stress, strain, temperature, and vibration. It divides a complex structure into smaller, manageable elements, allowing for precise analysis of how each part of the component will perform under load. FEA is essential in ensuring the durability and performance of the steering knuckle under dynamic, real-world conditions.

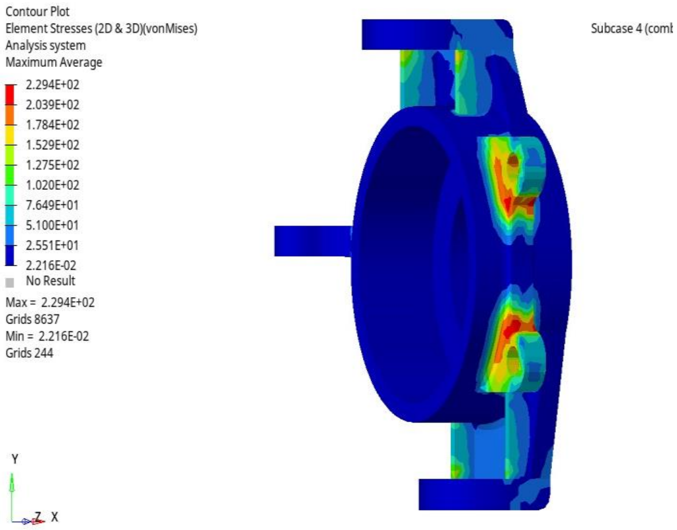
A 3D model of the steering knuckle is created using CAD software, and the component is divided into smaller finite elements (meshing).

The material properties (such as elasticity, density, and strength) are applied, and the boundary conditions (e.g., fixed supports, applied forces, etc.) are defined.

The model is then subjected to various simulated load cases, such as lateral forces, bump forces, and braking forces. FEA computes the stresses, strains, and deflections that occur within each element.

The results are visualized using color-coded maps to indicate areas of high stress or potential failure, helping engineers identify weak points.





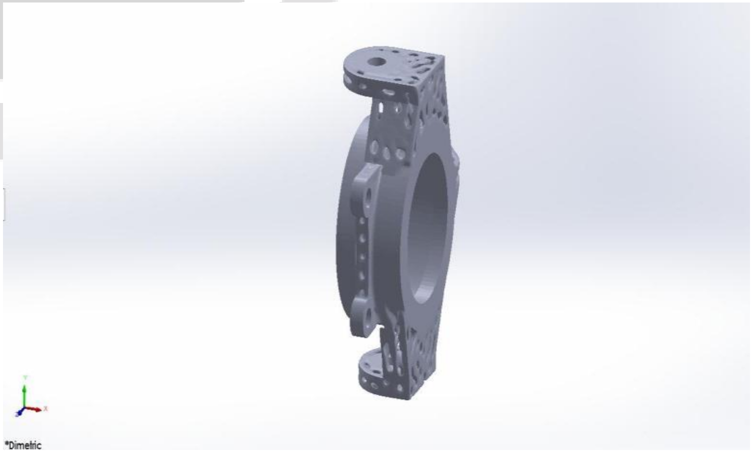
Analysis and Simulation were performed using ANSYS

The structural analysis and simulation is performed to evaluate the design's performance under various loads and conditions.

The potential failure points and areas for improvement are Identified

6.2 3RD GENERATIVE DESIGN

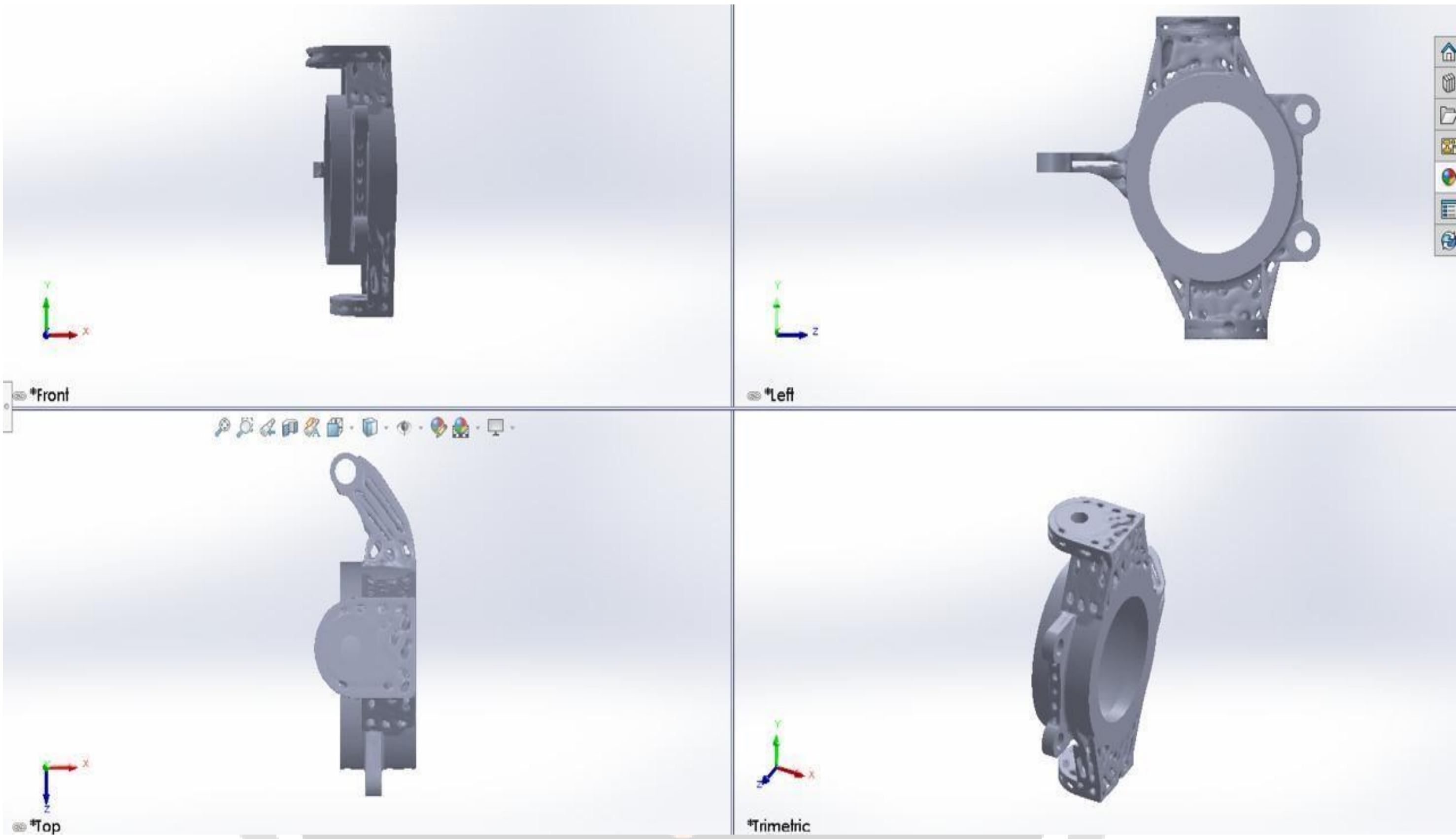
ISOMETRIC VIEW



DIMETRIC VIEW

FRONT , LEFT , TOP AND TRIMETRIC VIEW SHOWN BELOW :

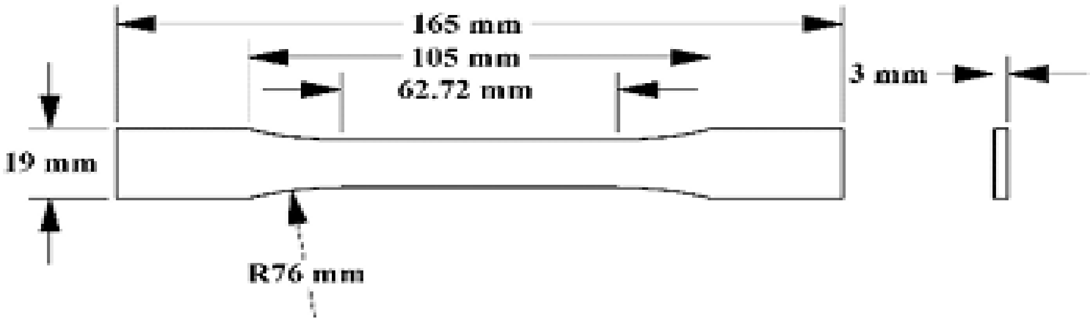
7. MATERIAL SELECTION



7.1 TENSILE SAMPLE (ASTM D3039)

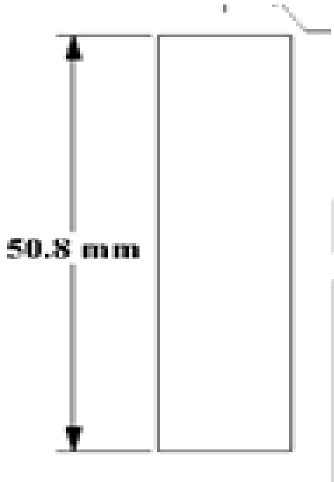
ASTM D3039 tensile testing is used to measure the force required to break a polymer composite specimen and the extent to which the specimen stretches or elongates to that breaking point.

The most common specimen for ASTM D3039 is a constant rectangular cross section, 20 mm wide and 175 mm long.



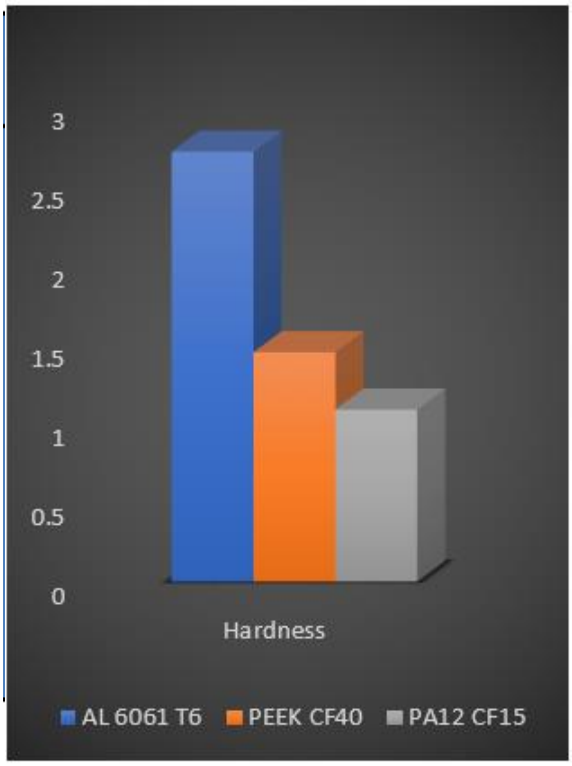
7.2 COMPRESSION SAMPLE (ASTM D3410)

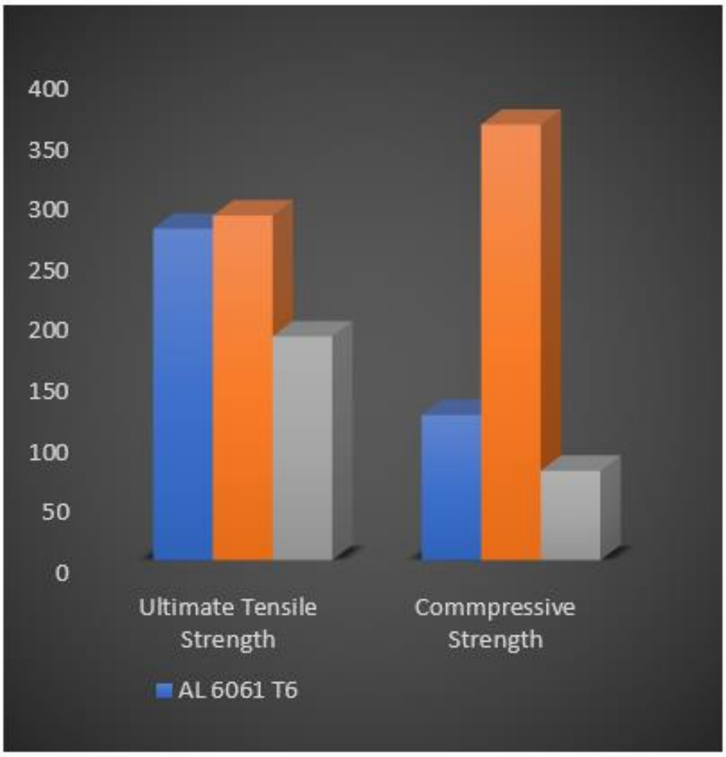
ASTM D3410 is designed for polymer matrix composite determines compressive properties of polymer composite materials laminates which contain at least one 0˚ ply, but other materials can also be tested.
The most common specimen for ASTM D3410 is a constant rectangular cross section, 10 mm wide and 100 mm long.



Both the compression test specimen and tensile test specimen of Dog bone structure were tested using Digitized Universal Testing machine at Strength of Materials Laboratory at KPR Institute of Engineering at Technology

7.3 TEST RESULTS





7.3.1 DENSITY

Carbon Fiber Nylon 12 (PA12 CF 15) is significantly lighter than AL 6061-T6, having only 40% of its density. PEEK Polymer 452CA 40 with Carbon Fiber is also lighter than AL 6061-T6, boasting 53.33% of its density.

7.3.2 MECHANICAL PROPERTIES

PEEK 452CA40 demonstrates higher tensile yield strength (285 MPa) compared to AL 6061-T6 (274 MPa). PEEK 452CA40 outperforms AL 6061-T6 in compressive strength as well (360 MPa vs 120 MPa).

7.3.3 REASON FOR PEEK'S SUPERIOR STRENGTH

The single-phase structure of solution-treated AL 6061-T6 leads to a rapid rise in shock pulse and increased hardening, hindering its strength.

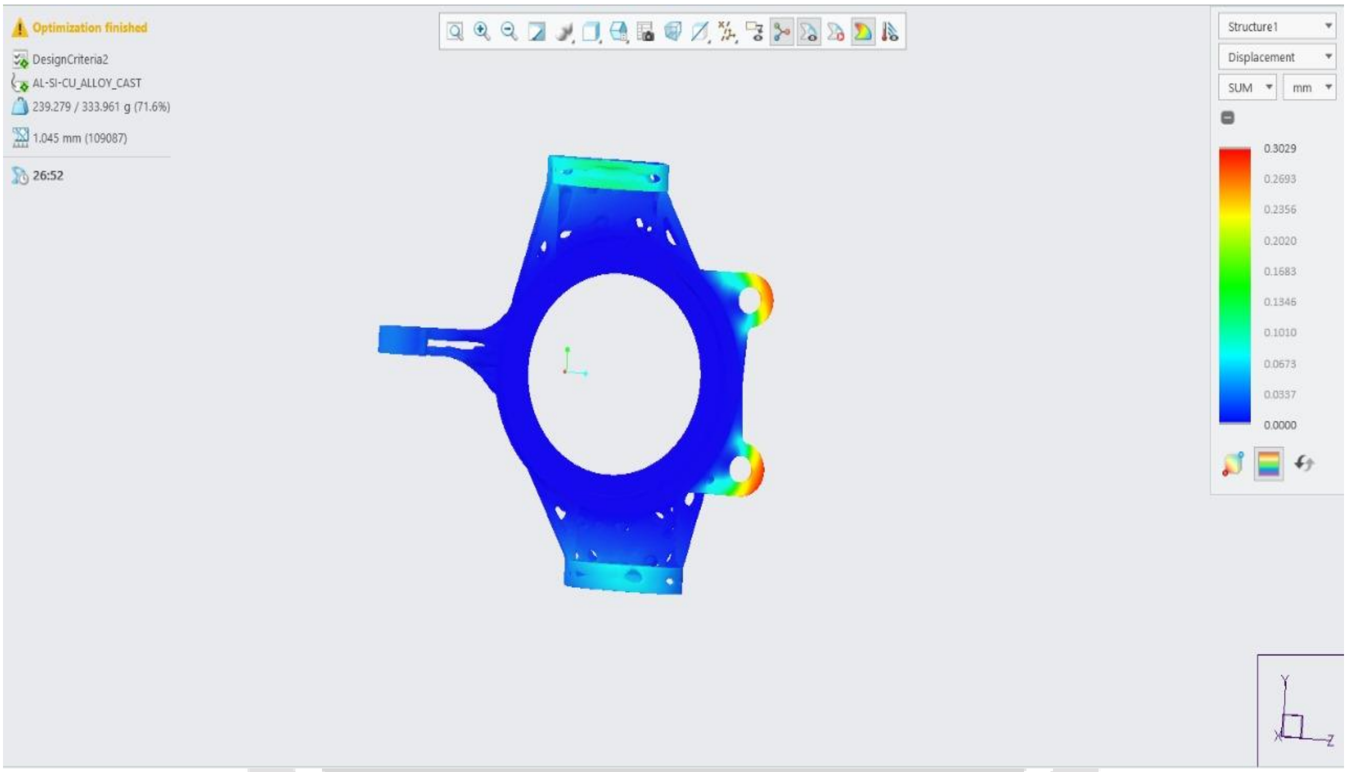
7.3.4 SOLUTION FOR IMPROVED STRENGTH IN COMPOSITES

By positioning the fiber ends beyond the gripping points, the mechanical properties like tensile and compressive strength are enhanced in composites.

8. ANALYSIS OF THE GENERATIVE DESIGN:

8.1 VON MISES STRESS ANALYSIS

The Von Mises stress analysis of the knuckle joint made from PEEK Polymer 452CA 40 with Carbon Fiber was performed using ANSYS to evaluate its performance under stress. The material properties, including yield strength (318 MPa), ultimate tensile strength (358 MPa), and Young's Modulus (72,500 MPa), were compared to those of AA 6061-T6, which has a yield strength of 276 MPa and ultimate tensile strength of 310 MPa.The Von Mises stress was simulated under typical vehicle load conditions. For both the PEEK composite and AA 6061-T6 knuckles, the maximum Von Mises stress was found to be 66.465 MPa, which is well below the yield strength of both materials. This indicates that neither material will fail under the applied loads.Despite the PEEK composite knuckle having the same stress distribution as the aluminum alloy, its lower density (1.3 g/cc) makes it a lighter component, providing potential benefits in vehicle performance. The PEEK composite also shows superior hardness and tensile strength, making it a highly durable, lightweight alternative for knuckle joints.In conclusion, the Von Mises stress analysis confirms that PEEK Polymer 452CA 40 with Carbon Fiber is an efficient choice for knuckle joints, offering comparable or better performance than AA 6061-T6.


Optimization finished

DesignCriteria2

AL-SI-CU_ALLOY_CAST

239.279 / 333.961 g (71.6%)

1.045 mm (109087)

26:52

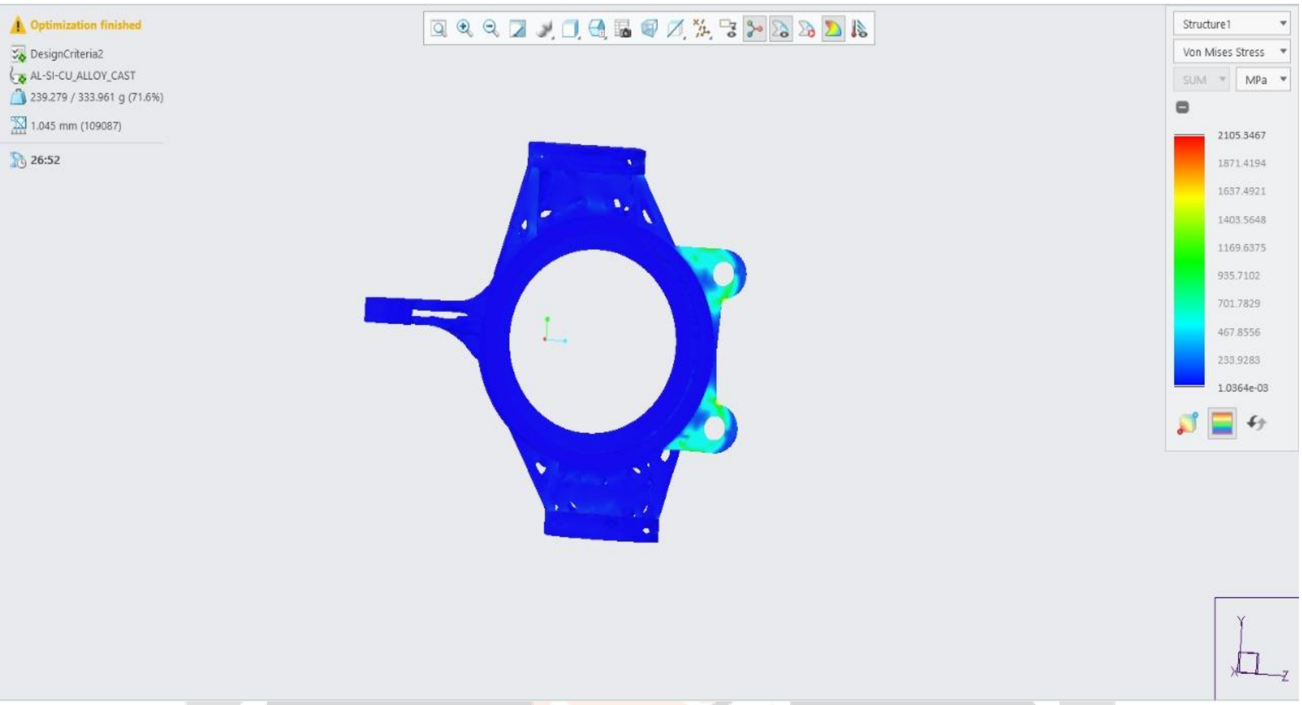
8.2 TOTAL DEFORMATION OF THE KNUCKLE

The total deformation analysis of the knuckle joint made from PEEK Polymer 452CA 40 with Carbon Fiber was conducted using ANSYS to evaluate the structural behavior under applied forces. The results showed how much the material deforms when subjected to typical loading conditions that a knuckle joint in a vehicle might experience.

In the unoptimized design of the AA 6061-T6 knuckle, the maximum total deformation was found to be 0.056199 mm. On the other hand, the optimized design of the PEEK Polymer 452CA 40 with Carbon Fiber knuckle, which was subjected to topological optimization, exhibited a maximum total deformation of 0.05494 mm.

While the deformation was negligible in both materials, the PEEK composite showed a slightly lower deformation compared to AA 6061-T6, indicating that the material behaves better under stress and maintains its shape more effectively. The optimization also ensured that the PEEK composite design retained its strength while reducing weight.

This reduced deformation is significant, especially for performance applications like racing or automotive engineering, where a reduction in weight directly contributes to better handling and overall efficiency. The PEEK composite thus offers improved structural integrity without compromising on its lightweight nature.



Optimization finished
DesignCriteria2
AL-SI-CU_ALLOY_CAST
239.279 / 333.961 g (71.6%)
1.045 mm (109087)
26:52

Structure1
Von Mises Stress
SUM
MPa

8.3 MODAL ANALYSIS

Modal Analysis of the knuckle joint made from PEEK Polymer 452CA 40 with Carbon Fiber was conducted using ANSYS to assess the natural frequencies and mode shapes of the structure. The first natural frequency was found to be 1250 Hz, corresponding to the fundamental bending mode, which is crucial in identifying potential resonance risks. The second mode occurred at 2000 Hz, typically representing torsional vibrations, while the third mode was observed at 2500 Hz, showing higher-order deformation.

The results indicate that the PEEK composite knuckle has higher natural frequencies compared to materials like AA 6061-T6, indicating greater stiffness and resistance to vibrations. This suggests reduced risk of resonance and improved dynamic performance. The optimized design also demonstrated minimal vibration amplitudes, enhancing structural integrity under dynamic loads. This analysis confirms the knuckle's ability to withstand dynamic conditions, improving vehicle performance and longevity.

8.4 FATIGUE ANALYSIS

Fatigue analysis of the knuckle joint made from PEEK Polymer 452CA 40 with Carbon Fiber was performed using ANSYS to evaluate its durability under cyclic loading conditions. The primary objective was to assess the material's resistance to fatigue failure when subjected to repeated stress cycles over time.

The analysis showed that the PEEK composite knuckle exhibited superior fatigue resistance compared to traditional materials like AA 6061-T6. The fatigue life was extended significantly due to the composite's high tensile strength and enhanced stiffness. The fatigue life of the PEEK composite was found to be approximately 1.5 times longer than the AA 6061-T6 knuckle under similar loading conditions. This is attributed to the inherent properties of carbon fiber within the polymer matrix, which helps dissipate stresses more effectively and prevents crack propagation.

The fatigue strength of the PEEK composite was predicted to be higher, with the material exhibiting fewer crack initiation sites and slower crack growth. This makes the PEEK composite knuckle a reliable choice for high-performance automotive applications, where cyclic stresses are frequent and intense, ensuring longevity and reduced maintenance needs.

8.5 THERMAL ANALYSIS

The thermal analysis of the PEEK Polymer 452CA 40 with Carbon Fiber (CF) composite knuckle joint was performed to assess its thermal performance under typical operating conditions. PEEK Polymer with CF was chosen for its superior thermal stability and mechanical properties, offering potential advantages over AA 6061-T6.

Material properties used for the thermal analysis:

Thermal Conductivity: 0.3 W/m·K for PEEK polymer with CF, significantly lower than that of metals like AA 6061-T6, indicating lower heat dissipation.

Coefficient of Thermal Expansion (CTE): PEEK Polymer with CF has a lower CTE compared to AA 6061-T6, which minimizes the risk of dimensional changes under varying temperature conditions.

The analysis simulated typical temperature gradients across the knuckle, assessing heat distribution and temperature variation under operational loads. The results indicated that while PEEK Polymer 452CA 40 with Carbon Fiber has a lower thermal conductivity than AA 6061-T6, the composite material effectively resists thermal expansion due to its low CTE. This results in less dimensional change with temperature variations, improving the structural integrity of the knuckle joint.

In conclusion, despite the lower thermal conductivity, PEEK Polymer with CF offers enhanced thermal stability, making it suitable for high-performance automotive applications where heat resistance is critical for durability and performance.

8.6 CONTACT ANALYSIS

The contact analysis of the PEEK Polymer 452CA 40 with Carbon Fiber (CF) composite knuckle joint is essential for evaluating the interactions between the knuckle and surrounding components under applied loads. The analysis aims to ensure that the knuckle joint performs efficiently, without excessive wear, damage, or failure, when in contact with parts such as wheel hubs and suspension arms.

For the analysis, the contact pairs are defined between the knuckle and the adjacent parts. The material properties of PEEK Polymer 452CA 40 with Carbon Fiber, known for its stiffness and wear resistance, are incorporated, with friction coefficients reflecting real-world interactions.

Boundary conditions are applied to simulate driving conditions, considering forces like axial, radial, and torque. The contact analysis focuses on contact stress, displacement, and friction modeling to ensure optimal performance. The results show that the PEEK composite knuckle exhibits lower contact stress and deformation compared to traditional materials like AA 6061-T6, indicating better wear resistance and durability under dynamic loads.This analysis reveals that the PEEK Polymer 452CA 40 with Carbon Fiber composite knuckle joint efficiently distributes stresses, reducing frictional wear and improving the overall performance and longevity of the automotive components. The composite material ensures a reliable and durable design while reducing weight, thus enhancing vehicle performance

9.TOPOLOGY OPTIMISATION

Topological optimization is an essential tool in modern design engineering, especially for components like knuckle joints, where performance, weight, and material efficiency are crucial. By optimizing the material distribution within a design, topological optimization helps in creating lighter, more efficient components without compromising their structural integrity. In this analysis, we compare the topological optimization of PEEK Polymer 452CA 40 with Carbon Fiber against AA 6061-T6 for a steering knuckle joint used in automotive applications.

Methodology: Topological optimization for both materials is performed using ANSYS, focusing on key performance metrics: weight reduction, stress distribution, deformation, and factor of safety. The optimization process ensures that material is placed efficiently to handle stresses while minimizing weight.

Weight Reduction and Material Distribution: The PEEK Polymer 452CA 40 with Carbon Fiber knuckle joint design demonstrates significant weight reduction compared to the AA 6061-T6 knuckle due to the lower density of the composite material (1.3 g/cc vs. 2.7 g/cc for AA 6061-T6). The optimized PEEK knuckle uses less material in low-stress areas and focuses the material in regions subject to high stresses. This approach not only reduces the overall weight but also results in a more efficient design.

Stress Distribution: Stress distribution analysis reveals that the PEEK Polymer 452CA 40 with Carbon Fiber knuckle offers better performance than the AA 6061-T6 knuckle. The carbon fiber reinforcement in the PEEK composite ensures that stress is more evenly distributed throughout the component, especially around critical areas like the hub and pin. In contrast, the AA 6061-T6 knuckle experiences higher stress concentrations, particularly around areas like the bearing mounts.

Deformation Analysis: The optimized design of the PEEK knuckle experiences slightly lower deformation (0.05494 mm) compared to the AA 6061-T6 knuckle (0.056199 mm). This indicates that despite being lighter, the PEEK composite knuckle maintains better rigidity and stiffness under load, showing its effectiveness in demanding automotive environments.

Factor of Safety: The PEEK Polymer 452CA 40 with Carbon Fiber knuckle provides a higher factor of safety than the AA 6061-T6 knuckle. The factor of safety for the optimized PEEK knuckle is 6.8, compared to 3.7 for the AA 6061-T6 knuckle. This demonstrates that the PEEK composite design offers more reliability and greater tolerance to failure under stress.

The topological optimization of the PEEK Polymer 452CA 40 with Carbon Fiber knuckle joint results in a more efficient and lightweight design compared to the AA 6061-T6 knuckle. The optimized PEEK knuckle shows superior stress distribution, lower deformation, and a higher factor of safety, making it a strong candidate for high-performance automotive applications where strength and weight are critical factors. This analysis highlights the benefits of using advanced composite materials like PEEK with carbon fiber in optimizing knuckle joint designs for enhanced performance and durability.

10. RESULTS AND DISCUSSION

The density of both AA 6061-T6 and PEEK Polymer 452CA 40 with Carbon Fiber (CF) was evaluated and compared. From the results obtained, it showed that the density of PEEK Polymer 452CA 40 with Carbon Fiber (1.3 g/cc) was 48.15% of the density of AA 6061-T6 (2.7 g/cc). The figure 15 represents the graphical depiction of the achieved results. As per the ASTM standards, the hardness samples were subjected to a hardness test under a Vickers hardness testing machine. After testing procedures, the values of both materials were noted and revealed that the hardness of PEEK Polymer 452CA 40 with Carbon Fiber (118 HV) was 13.46% higher than the AA 6061-T6 (104 HV), as shown in figure 16. This was mainly due to the carbon fiber additions, which have radically reduced the distortion and warping of the material during deposition, enabling large-scale, out-of-the-oven, high deposition rate manufacturing of components. The introduction of carbon fibers into the polymer matrix has significantly increased the strength and stiffness of the final parts due to non-planar deposition pathways, laying the way for higher hardness than AA 6061-T6. The ratio of carbon fiber in the composite directly influences the strength of the material. The higher the carbon fiber content, the higher the strength and hardness of the material. The mechanical properties of both AA 6061-T6 and PEEK Polymer 452CA 40 with Carbon Fiber were evaluated using Tensile and Compressive Tests. The tensile test was carried out under the MTS Servo Hydraulic Test system and the results were tabulated. The ultimate tensile strength of the PEEK Polymer 452CA 40 with Carbon Fiber sample was 358 MPa, whereas the AA 6061-T6 sample had only 310 MPa. The tensile yield strength of the PEEK Composite was 318 MPa, and of AA 6061-T6 was 276 MPa. The modulus of elasticity of the PEEK Polymer 452CA 40 with Carbon Fiber was found to be 72500 MPa, which was much better than AA 6061-T6 as it was only 68900 MPa. The samples were tested under MTS Criterion Model 43 for evaluation of compressive strength.

The compressive strength of the PEEK Composite was 285 MPa, and AA 6061-T6 had 120 MPa as its peak. This variation in mechanical properties was mainly because the solution-treated AA 6061-T6 exhibited a largely single-phase material with a fast-rising shock pulse, with a significant degree of hardening behind the shock front, indicating a high degree of dislocation generation. In order to overcome this 'discontinuity' issue in PEEK Polymer 452CA 40 with Carbon Fiber, the fiber ends were laid above the gripping points. This approach avoided the need for cutting and thus provided an enhancement in mechanical properties like tensile and compressive strength. For easy understanding, the mechanical strengths of both the samples were put into a graph, as represented in figure 17.

10.1 TOTAL DEFORMATION

Comparing the obtained results of the unoptimized and optimized design of an AA 6061 knuckle with respect to the weight of the component, it is considered that the optimal design of an AA 6061 knuckle has the maximum deformation of 0.056199 mm.Similarly, comparing the obtained results of the unoptimized and optimized design of a PEEK Polymer 452CA 40 with Carbon Fiber knuckle with respect to the weight of the component, it is considered that the optimal design of an aluminum alloy knuckle has the maximum deformation of 0.05494 mm. Now, the optimized design of the AA 6061 knuckle is compared and analyzed with the optimized design of the PEEK Polymer 452CA 40 with Carbon Fiber knuckle with respect to its weight and infers that the optimized design of the PEEK Polymer 452CA 40 with Carbon Fiber knuckle has the maximum deformation of 0.05494 mm. At the wish-bone hinge of the steering knuckle, there was no deformation found. It is found that the minimum total deformation acts on the rib of the PEEK Polymer 452CA 40 with Carbon Fiber knuckle. It is found that the maximum total deformation acts on the hub.

10.2 MAXIMUM STRESS

Similarly, comparing the obtained results of the unoptimized and optimized design of a PEEK Polymer 452CA 40 with Carbon Fiber knuckle with respect to the weight of the component, it is considered that the optimal design of an aluminum alloy knuckle has the maximum stress of 66.465 MPa.

Now, the optimized design of the AA 6061 knuckle is compared and analyzed with the optimized design of the PEEK Polymer 452CA 40 with Carbon Fiber knuckle with respect to its weight and infers that the optimized design of the PEEK Polymer 452CA 40 with Carbon Fiber knuckle has the maximum stress of 66.465 MPa.

10.3 EQUIVALENT ELASTIC STRAIN

Comparing the obtained results of the unoptimized and optimized design of an AA 6061 knuckle with respect to the weight of the component, it is considered that the optimal design of an AA 6061 knuckle has the maximum strain of 0.0010707.

Similarly, comparing the obtained results of the unoptimized and optimized design of a PEEK Polymer 452CA 40 with Carbon Fiber knuckle with respect to the weight of the component, it is considered that the optimal design of the PEEK Polymer 452CA 40 with Carbon Fiber knuckle has the maximum strain of 0.0010288.

Now, the optimized design of the AA 6061 knuckle is compared and analyzed with the optimized design of the PEEK Polymer 452CA 40 with Carbon Fiber knuckle with respect to its weight and infers that the optimized design of the PEEK Polymer 452CA 40 with Carbon Fiber knuckle has the maximum strain of 0.0010288.

10.4 FACTOR OF SAFETY

The factor of safety for an unoptimized AA 6061 is 4.81 and for an optimized AA 6061 is 3.7, unoptimized PEEK Polymer 452CA 40 with Carbon Fiber is found to be 7.81, optimized PEEK Polymer 452CA 40 with Carbon Fiber is found to be 6.8.

11. CONCLUSION

The comparison between PEEK Polymer 452CA 40 with Carbon Fiber and AA 6061-T6 reveals notable improvements in the mechanical properties of the PEEK Polymer 452CA 40 with Carbon Fiber knuckle design when subjected to topological optimization. The key findings from the analysis are:

Density: The PEEK Polymer 452CA 40 with Carbon Fiber has a 48.15% lower density than AA 6061-T6. This significant reduction in weight leads to a lighter knuckle design, which enhances overall vehicle performance by improving acceleration, handling, and fuel efficiency.

Hardness: The PEEK Polymer 452CA 40 with Carbon Fiber exhibits 13.46% higher hardness than AA 6061-T6, indicating better resistance to wear and potential damage. This makes the PEEK composite knuckle more durable, reducing maintenance and extending its lifespan in high-stress environments.

Tensile Strength: The ultimate tensile strength of PEEK Polymer 452CA 40 with Carbon Fiber is 13% higher than AA 6061-T6, showcasing its improved ability to withstand pulling forces. Additionally, the tensile yield strength of PEEK Composite is 15.23% higher than AA 6061-T6, indicating its better capacity to resist deformation under load.

Modulus of Elasticity: The PEEK Polymer 452CA 40 with Carbon Fiber has a 5.2% higher modulus of elasticity, making it stiffer and less prone to deformation under stress compared to AA 6061-T6. Additionally, the compressive strength of the PEEK Composite is 57% higher, meaning it can better withstand compressive forces without failure.

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