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Comparative Analysis of Solid and Hollow Shafts Using Mild Steel and Aluminum 6061 for Lightweight and Cost-Effective Applications

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***Abstract* - Shafts serve as vital mechanical components that facilitate the transfer of torque and rotational motion in automobiles, turbines, pumps, industrial drives, aerospace, and marine applications. Conventional solid shafts made from Mild Steel are known for their high strength, stiffness, and durability; however, their higher density increases rotational inertia, energy consumption, and overall system weight. Consequently, there is an increasing demand for lightweight and energy-efficient mechanical systems, leading to the development of hollow shaft configurations and lightweight materials such as Aluminum 6061 alloy. This paper presents a comparative analysis of solid and hollow shafts fabricated using Mild Steel and Aluminum 6061 for lightweight and cost-effective engineering applications. The study evaluates the influence of shaft geometry and material selection on torsional strength, stress distribution, angle of twist, rotational inertia, fatigue behavior, weight reduction, and overall mechanical performance. Hollow shaft designs can reduce shaft weight by approximately 25-40% while retaining nearly 90–95% of the torsional strength of equivalent solid shafts. Similarly, Aluminum 6061 shafts provide significant weight reduction because of their lower density and favorable strength-to-weight ratio. Mild Steel remains suitable for high load and high-rigidity applications, whereas Aluminum 6061 demonstrates superior performance in lightweight and high-speed systems because of its excellent corrosion resistance and lower rotational inertia. Overall, hollow Aluminum 6061 shafts provide superior performance for lightweight engineering applications, while hollow Mild Steel shafts offer a balanced combination of strength, durability, and cost-effectiveness for industrial power transmission systems.**

***Keywords:* Aluminum 6061, Hollow shaft, Power transmission, Shaft design, Solid shaft, Mild Steel, Torsional strength, Weight reduction**

I. INTRODUCTION

Shafts are a basic mechanical part in power transmission systems that are used to transmit the torque, rotation, and mechanical energy between two connected parts of machinery. Shafts can be found in many applications ranging from automobiles to turbines to compressors to pumps to industrial machines to aerospace or marine equipment, and they have an important effect on the performance, reliability, and longevity of those applications based on the strength, stiffness, fatigue resistance, and weight characteristics of the shafts. Historically, most solid shafts that have been used to transmit mechanical power have been produced from mild steel due to its good strength characteristics and ease of manufacture, as well as low costs to produce and long-lasting service life under large loads (Patel and Shi, 2025). However, because of the desire to build lighter weight, better fuel economy, and more energy efficient mechanical systems, an increasing number of researchers and businesses are investigating new designs and advanced engineering materials to develop better shaft designs. An increase in shaft weight results in higher rotational inertia, loss of energy from power losses, higher bearing loads, increased vibrational effects, and, ultimately, more total energy consumed by an application, particularly in high-speed rotating shaft applications. The basic types of shafts are classified into two types that are solid and hollow shafts as shown in Fig. 1. With the parameters of shafts (Gebrehiwet et al., 2023). The development of hollow shaft designs has provided a viable alternative to standard shaft designs with significant weight savings. Under torsional loads, the maximum shear stress is generated at the outer surface of a solid shaft, while the material found near the center of the shaft contributes a small percentage of the total torque. Removing the inside material of the shaft makes it much lighter while still having enough torsional strength and stiffness. As illustrated in Fig. 1, hollow shafts remove the low-stress central material while maintaining effective torque transmission.

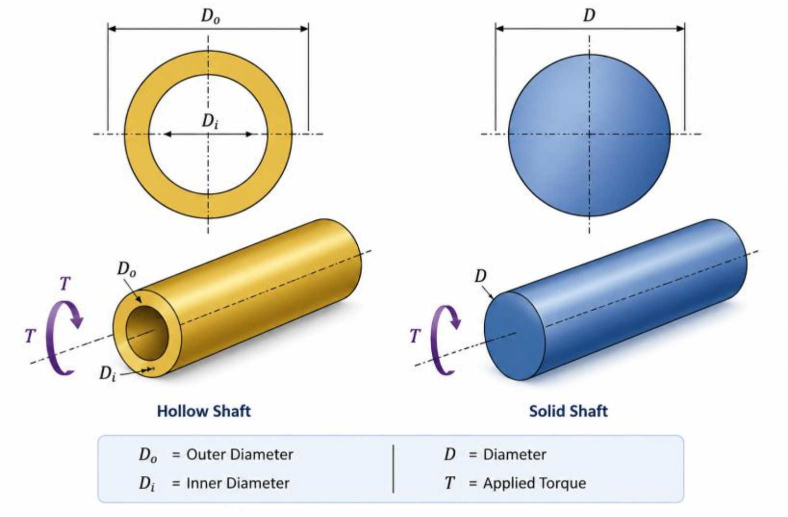

Fig.1. illustration of hollow and solid shaft with schematic diagrams

Hollow shafts are commonly being used in automobile drive shafts, aircraft transmissions, marine propulsion systems and high-speed industrial machines due to these benefits. Lightweight

Table 1. Comparative Material Properties of Mild Steel and Aluminum 6061 (Usca-Gomez et al., 2025)

Property	Mild Steel	Aluminum 6061	Influence on Shaft Design
Density (kg/m³)	~7850	~2700	Aluminum provides major weight reduction
Yield Strength (MPa)	250–370	240–310	Steel preferred for heavy loading
Ultimate Tensile Strength (MPa)	400–550	290–350	Steel possesses higher load capacity
Modulus of Elasticity (GPa)	~200	~69	Steel offers better rigidity
Modulus of Rigidity (GPa)	~80	~26	Aluminium shows higher angle of twist
Corrosion Resistance	Moderate	Excellent	Aluminium suitable for marine/outdoor use
Machinability	Good	Very Good	Aluminium easier to machine
Thermal Conductivity	Moderate	High	Aluminium dissipates heat better
Fatigue Strength	Higher	Moderate	Steel better for cyclic loading
Weldability	Good	Good	Both suitable for fabrication
Cost	Lower	Higher	Steel economical initially
Recyclability	Moderate	Excellent	Aluminium more sustainable
Weight Reduction Capability	Limited	Excellent	Key advantage of aluminium
Surface Finish Quality	Moderate	Better	Aluminium provides smoother finish

Application Areas	Heavy-duty machinery	Aerospace, automotive	Depends on design objectives

materials such as Aluminum 6061 alloys have also been used extensively in modern engineering because of their low weight, excellent corrosion resistance, good machinability and favorable strength-to-weight ratios. Compared to conventional steel shafts, Aluminum 6061 shafts reduce system mass and rotational inertia significantly, improving fuel efficiency, response and performance (Zhou et al., 2022). However, Mild Steel is still the preferred choice for heavy-duty uses that require increased stiffness and load capabilities. The comparative mechanical and physical properties of Mild Steel and Aluminum 6061 used in shaft applications are presented in Table 1. This paper will present a full data analysis of solid and hollow Mild Steel and Aluminum 6061 shafts and provide a comprehensive description of how shaft geometry and material selection will affect torsional strength, stress distribution, amount of twist, lightweightness, fatigue characteristics, endurance, cost-effectiveness, and more. The paper will also concern itself with the new developments in light-weight shaft design; finite element analyses; and optimization methods to provide research reference points in advanced shaft design engineering systems (Chaturvedi et al., 2023).

II. NEED FOR LIGHTWEIGHT SHAFT DESIGN

The industry is in constant need of mechanical systems that are light-weight, energy-efficient, cost-effective and able to perform at a high level with no degradation due to variability in operational conditions. To do this, we must look at other parts of the entire system to decrease weight. An important aspect of this process is the use of hollow shaft configurations for mechanical assemblies such as rotating machinery or power transmission systems (Du et al., 2025). More specifically, a significant portion of the overall weight of these systems comes from their respective shafts and their excessive weight creates additional rotational inertia (also known as energy consumed), which is static in nature, at a greater bearing load due to added dynamic force generated during operation, and increased vibration levels due to the inability to bracing the shaft securely via bearings to the housing; thus reducing both the overall efficiency and service life expectancy of a machine (Thagunna et al., 2023). Table 2 presents the comparative engineering analysis between conventional heavy shaft systems and lightweight hollow shaft systems.

Table 2. Comparative Engineering Analysis of Conventional and Lightweight Shaft Systems

Parameter	Conventional Heavy Shaft System	Lightweight Hollow/Aluminum Shaft System	Typical Improvement Achieved
Shaft Material	Mild Steel	Aluminum 6061 / Hollow Steel	40–70% weight reduction
Shaft Geometry	Solid	Hollow	Lower material usage
Density (kg/m³)	~7850	~2700 (Al 6061)	Nearly 65% lower density
Rotational Inertia	High	Low	Faster acceleration response
Torque Transmission Efficiency	Moderate	High	Improved power transfer
Energy Consumption	Higher	Lower	Reduced operating power
Bearing Load	Higher	Lower	Improved bearing life
Vibration Characteristics	Higher vibration tendency	Improved dynamic stability	Better operational smoothness
Centrifugal Force Effects	Significant at high speed	Reduced considerably	Safer high-speed operation
Fuel Efficiency (Automotive)	Lower	Improved	Reduced fuel consumption
Corrosion Resistance	Moderate	Excellent (Aluminum)	Longer service life

Fatigue Performance	Good	Good with optimized design	Improved fatigue efficiency
Manufacturing Material Usage	More	Less	Sustainable design
Maintenance Requirement	Moderate to High	Lower	Reduced maintenance cost
Dynamic Response	Slower	Faster	Better machine performance
Industrial Suitability	Heavy-duty machinery	EVs, aerospace, robotics	Advanced lightweight systems
Cost Effectiveness	Lower initial cost	Better long-term efficiency	Operational savings
Environmental Impact	Higher material consumption	Reduced material and energy usage	Sustainable engineering

The use of conventional solid shafts manufactured with Mild Steel provides excellent strength and rigidity; yet when you consider that traditional solid shaft material is comprised of very dense metals (Mild Steel), creating a weight advantage would be difficult to achieve without an overall reduction in the number of materials required to create mechanical assemblies used for various applications such as automotive, aerospace, marine, industrial, etc. (Abankar et al., 2024). As a result of the advancement of those technologies, there are increasing opportunities to reduce structural weights without sacrificing the mechanical strength and torsional performance characteristics. One of the most successful means of accomplishing the goal of reducing the weight of mechanical systems is by the adoption of hollow-shaft configurations (Cai et al., 2019). With respect to torsional loading, the maximum shear stress occurs at the outer surface of the shaft, while the material located near its center is significantly less effective at transmitting a torque; therefore, removing the core material from that inner area (in a hollow configuration) can substantially reduce the overall weight of the shaft while still providing the necessary torsional strength and rigidity characteristics. Lightweight materials are improving the performance of shafts, in addition to geometric optimization methods. Aluminum 6061 alloy is an example of lightweight materials used in modern lightweight applications (Themisana et al., 2023). Aluminum 6061 has a low density, excellent corrosion resistance, good machinability and a favorable strength-to-weight ratio. The use of lightweight materials and a hollow shape improve fuel efficiency, reduces energy losses, reduces the effects of vibration, and enhance the dynamic response of rotating systems. Lightweight shaft systems are being used more frequently in electric vehicles, aircraft transmissions, robotic systems, wind turbine applications, marine propulsion systems, and high-speed industrial equipment. These systems experienced reduced centrifugal forces, improved acceleration performance, reduced maintenance requirements, and improved operating efficiency. The design of lightweight shafts has become one of the most important research areas in current mechanical engineering, as they strive to design and develop materials that provide an optimal combination of strength, rigidity, durability, lightweight, and cost (M. Singh et al., 2025).

III.SHAFT MATERIALS USED IN MECHANICAL APPLICATIONS

Mild Steel and Aluminum 6061 alloys are common materials for manufacturing shafts due to their variety of mechanical characteristics and economics. The basic engineering characteristics of these materials used to make shafts are represented in Table 3. Traditionally, Mild Steel is selected for use in heavy-duty applications due to its high strength, toughness, low cost, and superior load-carrying ability; however, due to the comparatively high density of Mild Steel, it will contribute significantly to the overall weight and rotational inertia of a mechanical system (Nturanabo et al., 2019). In contrast, the aluminum 6061 alloy is a better option for light-weight applications due to its low density, excellent corrosion resistance, and good strength-to-weight ratio. The performance, durability, efficiency, and reliability of a shaft depend on the materials that are selected for that shaft. When selecting shaft materials in mechanical power transmission systems, the shaft materials must exhibit high strength, adequate rigidity, good fatigue resistance, good machinability, and good corrosion resistance to withstand torsional and bending loading during operation (Khademian and Peimaei, 2020). The need for lightweight and energy-saving systems has increased the importance of material selection in current shaft design. When considering all available engineering materials, by utilizing aluminum as a material instead of steel for shafts will provide improved fuel economy as well as improved dynamic response and operational efficiency in the automotive, aerospace, marine and robotics industries. Factors that determine whether mild steel or Aluminum 6061 should be used include load conditions, rotational speed, structural rigidity, operating environment, cost-effectiveness and ease of manufacturing (Ashraf and Thakur, 2023). Heavy duty systems usually require shafts made from steel due to their greater rigidity and fatigue resistance; while lightweight applications are being increasingly designed to use Aluminum 6061 due to its lower unit weights and greater energy efficiency. Therefore, it is important to understand the mechanical properties of these materials, their benefits and disadvantages, and the different types of industrial applications to improve shaft function and achieve an efficient mechanical system design (Simões, 2025).

Table 3. Comparative Properties of Mild Steel and Aluminum 6061 Used in Shaft Applications

Parameter	Mild Steel	Aluminum 6061	Engineering Significance
Density (kg/m³)	~7850	~2700	Aluminum provides major weight reduction
Tensile Strength (MPa)	400-550	290-350	Steel suitable for heavy loads
Yield Strength (MPa)	250-370	240-310	Steel provides better load resistance
Modulus of Elasticity (GPa)	~200	~69	Steel offers higher rigidity
Modulus of Rigidity (GPa)	~80	~26	Aluminum shows higher angle of twist
Weight	Heavy	Lightweight	Aluminum improves efficiency
Corrosion Resistance	Moderate	Excellent	Aluminum suitable for marine/outdoor use
Machinability	Good	Very Good	Aluminum easier to machine
Fatigue Strength	Higher	Moderate	Steel better under cyclic loading
Thermal Conductivity	Moderate	High	Aluminum dissipates heat efficiently
Rotational Inertia	Higher	Lower	Aluminum improves dynamic response
Manufacturing Cost	Lower	Higher	Steel economical for industry
Strength-to-Weight Ratio	Moderate	Excellent	Aluminum preferred for lightweight systems
Weldability	Good	Good	Both suitable for fabrication
Common Applications	Industrial machinery	Aerospace, automotive, robotics	Application-dependent selection

3.1 Mild Steel

Mild Steel is one of the most widely used materials for shaft manufacturing because of its high strength, toughness, good machinability, and economical cost. It provides excellent torsional rigidity and fatigue resistance, making it highly suitable for heavy-duty applications such as industrial drives, conveyors, turbines, pumps, machine tools, and agricultural machinery. Due to its good weldability and fabrication characteristics, Mild Steel shafts are easy to manufacture, assemble, and maintain in industrial systems. The shaft material most used is mild steel because of its strength, toughness, machinability and cost-effective nature (Allison et al., 2014). Mild Steel exhibits high stiffness to torsion and high fatigue resistance for use in demanding industrial applications (drives, conveyors, turbines, pumps, machine tools, agricultural machines, etc.) Thus, Mild Steel Shafts will meet all requirements for the manufacture, assembly and maintenance of shafting for the industrial systems (Hassan and Saeed, 2024).

3.2 Aluminum 6061 Alloy

Aluminum 6061 is one of the most widely used alloy materials on the market today. It is extremely light weight and high level of corrosion resistance has made it a popular material for use in a wide variety of lightweight engineering applications. This high level of corrosion resistance combined with a good strength-to-weight ratio makes 6061 aluminum a very suitable material for modern shaft systems were reducing materials weight and increasing energy efficiency will be important factors in the design process (Thakur, 2024). By using 6061 aluminum shafts versus using heavier materials, the overall mass of the shafts significantly reduces the amount of rotational inertia and improves the responsiveness of acceleration while providing increased efficiency for automotive vehicles, aerospace vehicles, marine vessels, and robotics (Kumar et al., 2025). In addition, the high degree of machinability and excellent thermal conductivity associated with 6061 aluminum shafts contribute to the ease with which they are manufactured as well as to the effective dissipation of heat generated during normal operation. Although many of the advantages associated with the use of 6061 aluminum as a shaft material may be found with the use of mild steel, the rigidity and fatigue strength provided by mild steel are much greater than what is provided by 6061 aluminums (Singh and Thakur, 2024). Therefore, under torsional loading, aluminum shafts tend to deform significantly more than those made from mild steel and would therefore be more suited for applications involving light to moderate loads rather than for heavy-duty applications. All in all, however, the lightweight characteristics, corrosion resistant properties, and improved dynamic performance of 6061 aluminum shafts make them one of the best choices of materials for advanced lightweight shaft applications (Vereshchaka et al., 2016).

IV. SOLID AND HOLLOW SHAFT CONFIGURATIONS

Many considerations affect the selection of hollow and solid shaft types. These include the type of load, the speed at which the shaft will be rotating, the fatigue strength of the material selected, the blasting costs involved in manufacturing the shaft, and finally the environment in which the shaft will be used(Shalbafan, 2013). Heavy-duty machines normally use solid shafts due to such things as better stiffness and durability. Conversely, in automotive, aerospace, marine, and robotic applications there has been an increase in hollow shaft usage resulting from improvements in strength to weight ratios, as well as better dynamic performance of the hollow shaft type. The geometry of the shaft has a significant impact on how efficiently the shaft will function mechanically, as well as its ability to provide adequate load-bearing support. Mechanical power transmission shafts are generally categorized into two different families: (1) solid shafts and (2) hollow shafts; both families of shafts are found in various types of industrial applications, depending upon the operational requirements such as: maximum torque, operating speed, rigidity, weight, and manufacturing cost. Traditionally, solid shafts have been commonly used in product manufacturing because of their comparatively simplistic construction, high level of torsional resistance, and very good load bearing capabilities; however, due to recent increases in demand for lighter weight systems with improved energy efficiencies, hollow shaft configurations are becoming more common in current engineering applications. The removal of unnecessary material from the center cross section of a shaft where torsional stress impacts a shaft less proportionately decreases the overall weight of the shaft, which therefore increases the overall efficiency of the shaft's functionality (Noaman et al., 2019).

4.1 Solid Shafts

A solid shaft is typically made of a uniform circular cross-section along its entire length. Solid shafts are used in many conventional mechanical systems that require high torsional strength, rigidity, and an ability to resist shocks (B. Singh et al., 2025a). They also contain uniform geometry, which allows them to be resistant to over-deformation in all cases and be manufactured and machined more easily. Most solid shafts will be manufactured from either Mild or Alloy steel and be used in applications that include industrial drive systems, turbines, conveyors, machine tools, pumps, and agricultural machinery. Solid shafts can twist far less than hollow shafts when subjected to torsional loads due to their greater amount of rigidity and material volume (Singh et al., 2024). However, both disadvantages of having a much more significant weight and consume a lot more material than hollow shafts; thus, increasing their inertia, bearing loads, energy consumption, and overall cost of operation. Such disadvantages become even more pronounced when you are developing lightweight and high-speed applications where dynamic efficiency is a key component of the design process (Singh and Kaur, 2025).

4.2 Hollow Shafts

Material is eliminated in the middle part of hollow shafts and kept in the outer part because this part has the greatest amount of twisting force. According to torsion theory, the part close to the center of a shaft has very little contribution to twisting force, so hollow shafts enable considerable weight reductions but only small decreases in twisting forces (Singh et al., 2023)(B. Singh et al., 2025b). Hollow shafts are being used increasingly for automotive drive shafts, aircraft transmissions, marine propulsion, wind turbines, robots and high-speed rotating machinery because of their high strength-to-weight ratio. Additional benefits from using hollow shafts are the lower amount of inertia, lower number of centrifugal forces, improved fuel economy and better dynamic response compared to solid shafts. However, hollow shafts typically require a higher level of precision during manufacturing and may have less torsional stiffness than an equivalent solid shaft. Therefore, careful design optimization should be performed to have the best combination of strength, stiffness and weight reduction (Rajeev Rathi, 2023). A comparative analysis between solid and hollow shaft configurations is presented in Table 4.

Table 4. Comparative Analysis of Solid and Hollow Shafts

Engineering Parameter	Solid Shaft	Hollow Shaft
Cross-Section	Completely solid	Hollow inner cavity
Weight	Higher	Lower
Material Consumption	More	Less
Torque Carrying Capacity	High	Nearly equivalent
Strength-to-Weight Ratio	Moderate	High
Rotational Inertia	Higher	Lower
Torsional Rigidity	Higher	Slightly lower
Angle of Twist	Lower	Slightly higher
Dynamic Performance	Moderate	Better
Energy Efficiency	Moderate	Improved
High-Speed Suitability	Moderate	Excellent
Vibration Characteristics	Moderate	Better stability
Manufacturing Complexity	Simple	Moderate
Fuel Efficiency	Lower	Improved
Common Applications	Heavy industrial machinery	Automotive and aerospace systems
Overall Mechanical Efficiency	Moderate	High

V. THEORETICAL BACKGROUND OF TORSIONAL ANALYSIS

The analysis and design of shafts mainly rely upon the theory of torsion which is used to evaluate the behavior of circular shafts being twisted by twisting moments or torque. The shafts used in mechanical power transmission systems experience torsional load while rotating mechanical power and rotational motion through machine components. The performance of a shaft in terms of torsion is influenced by four variables: material properties, shaft geometry, diameter and loading condition (Singh et al., 2021). When a torque is applied to a circular shaft, shear stress develops over its cross section. Shear stresses are lowest at the shaft's center and gradually increase towards the outside of the shaft until they reach their maximum value at the shaft's outer surface. Given this relationship, more of the total torque will be provided by the material near the outer surface than by the material near the center of the shaft. This principle is used when developing hollow shaft configurations for lightweight engineering applications. The torsion equations for circular shafts are a mathematical relationship between the torque applied to the shaft, the shear stress experienced by the shaft, the angle of twist experienced by the shaft and the shaft's dimensions (Pandey et al., 2023). These equations indicate that the torsional resistance of a shaft is heavily influenced by the outside diameter of the shaft. Therefore, it follows that removing material from the center of the shaft has a lesser effect on the shaft's ability to carry torque when compared to the reduction in weight of the shaft. This principle explains why hollow shafts are preferred in modern lightweight engineering systems. The theoretical analysis of torsion is essential for determining shaft dimensions, predicting stress distribution, evaluating angle of twist, and ensuring safe and efficient power transmission under operating conditions. The torsional stress distribution and hollow shaft geometry used for torsional analysis are illustrated in Fig. 2. The design and analysis of shafts are primarily based on torsion theory.

The torsion equation for circular shafts is:

$$\frac{T}{J} = \frac{\tau}{R} = \frac{G\theta}{L} \quad [1]$$

Where:

- T = Applied torque
- J = Polar moment of inertia
- τ = Shear stress
- R = Outer radius
- G = Modulus of rigidity
- θ = Angle of twist
- L = Length of shaft

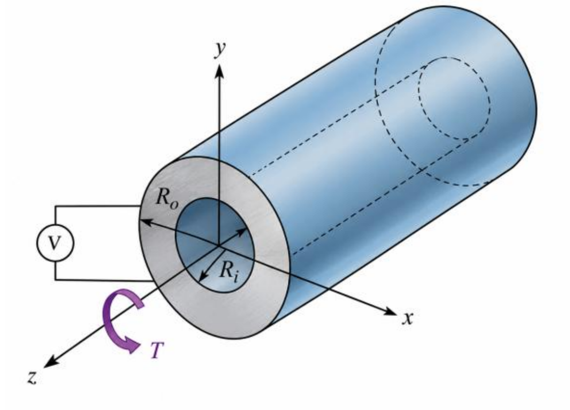

Fig. 2. Torsional loading and stress distribution in hollow circular shaft

For solid shafts:

$$\tau = \frac{16T}{\pi d^3} \quad [2]$$

For hollow shafts:

$$J = \frac{\pi(D^4 - d^4)}{32}$$

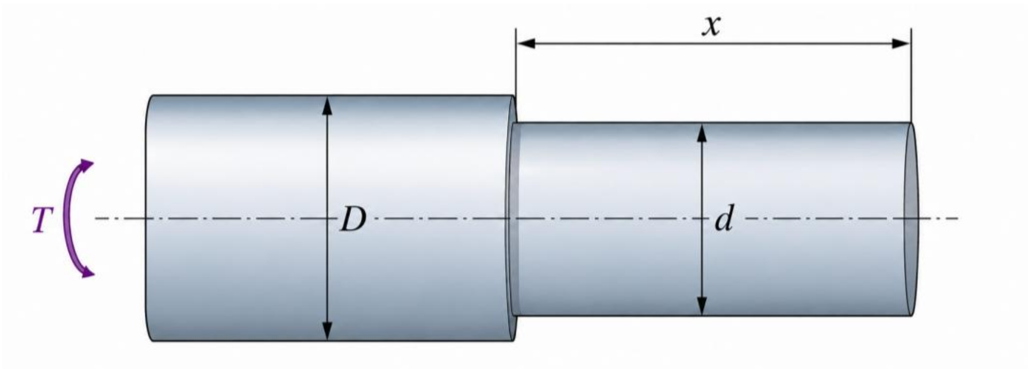

Fig. 3. Stepped shaft geometry used in torsional analysis

These equations indicate that torsional resistance is highly dependent on shaft diameter, particularly the outer diameter A stepped shaft configuration subjected to torsional loading is shown in Fig. 3. Even a small increase in outer diameter can significantly improve torque carrying capacity and rigidity. For example, increasing shaft diameter by 20% can improve torsional strength by nearly 70%, because torsional resistance varies with the fourth power of

Table 5. Engineering Data for Torsional Analysis of Shaft Systems

Parameter	Solid Shaft	Hollow Shaft	Engineering Observation
Weight Reduction	Baseline	25-40% lower	Significant mass saving
Torque Carrying Capacity	100%	90-95% of solid shaft	Minor strength reduction
Material Utilization Efficiency	Moderate	High	Better stress utilization

Rotational Inertia	Higher	20–35% lower	Improved dynamic response
Torsional Rigidity	Higher	Slightly lower	Depending on diameter ratio
Angle of Twist	Lower	Slightly higher	Acceptable in lightweight systems
Shear Stress Distribution	Across full section	Concentrated near outer surface	Core contributes less
Power Transmission Efficiency	Moderate	Improved	Lower rotational losses
Fuel/Energy Efficiency	Moderate	Better	Important in automotive systems
High-Speed Stability	Moderate	Improved	Reduced centrifugal effects
Typical Applications	Heavy machinery	Automotive, aerospace, robotics	Lightweight systems preferred

diameter. Similarly, hollow shafts can reduce shaft weight by approximately 25-40% while maintaining nearly 90-95% of the torsional strength of an equivalent solid shaft. Due to this superior strength-to-weight ratio, hollow shafts are increasingly preferred in automotive drive shafts, aircraft transmission systems, turbines, and high-speed rotating machinery. The angle of twist is another important parameter in torsional analysis. Materials with higher modulus of rigidity, such as Mild Steel ($G \approx 80$ GPa), experience lower angular deformation compared to Aluminium 6061 ($G \approx 26$ GPa). Consequently, steel shafts provide better rigidity, whereas aluminium shafts offer lower weight and improved dynamic performance. The engineering data associated with torsional analysis of shaft systems are summarized in Table 5.

VI. SHAFT DESIGN AND POWER TRANSMISSION SYSTEMS

Shaft design is one of the most crucial facets of mechanical power transmission systems. The primary function of a shaft is transmitting torque, rotational motion and mechanical power from different machine components (e.g., gear, pulley, sprocket, coupling and rotor) to each other. The design of a shaft will have a large impact on the mechanical systems efficiency, reliability, vibration characteristics, fatigue life and overall performance. As a result, good shaft design is a critical factor in the safe operation under torsional, bending and dynamics loads that occur during operation. Although in modern engineering applications shaft design is primarily based on strength criteria, there are many other considerations involved in the proper design of a shaft including: weight optimization, dynamic stability, power transmission efficiency and fatigue resistance, along with manufacturability. There is a progressive trend in industrial sectors (automotive, aerospace, marine, wind energy, robotics and heavy machinery) for designing lightweight and high-performance shaft systems that can perform at high speeds and under dynamic loading conditions. The design of a shaft is determined by numerous parameters such as power transmitted, rotational speed, torque applied, allowable shear stress, angle of twist, material selection and geometrical configuration of the shaft. Excessive shaft weight results in increased rotational inertia and higher bearing loads, centrifugal forces, vibration levels and energy losses associated with the operation of a rotating system. Therefore, in today's modern engineering applications, there is increased emphasis on designing lightweight hollow shaft configurations. The power transmitted by a rotating shaft is determined using the following relation:

$$P = \frac{2\pi NT}{60} \quad [3]$$

Where:

- P= Power transmitted (W)
- N= Rotational speed (RPM)
- T= Torque (N·m)

This equation indicates that power transmission capability increases with both torque and rotational speed. Therefore, shaft dimensions and material selection must be carefully optimized to safely transmit the required power without excessive stress or deformation. Table 6 compares the engineering performance of conventional and lightweight shaft systems using different material and geometric configurations.

Table 6 Comparative Engineering Performance of Conventional and Lightweight Shaft Systems

Engineering Parameter	Conventional Solid Mild Steel Shaft	Hollow Mild Steel Shaft	Solid Aluminum 6061 Shaft	Hollow Aluminum 6061 Shaft
Density (kg/m³)	~7850	~7850	~2700	~2700
Approximate Weight Reduction	Baseline	20-30% lower	60-65% lower	70-75% lower
Torque Carrying Capacity	100%	90-95% of solid steel shaft	65–75% of steel shaft	60-70% of steel shaft
Strength-to-Weight Ratio	Moderate	High	Very High	Excellent
Modulus of Rigidity (GPa)	~80	~80	~26	~26
Angle of Twist	Lowest	Slightly higher	Higher	Highest
Rotational Inertia	Very High	Moderate	Low	Very Low
Dynamic Stability	Good	Better	Very Good	Excellent
High-Speed Performance	Moderate	Good	Very Good	Excellent
Vibration Characteristics	Higher vibration tendency	Reduced vibration	Better damping response	Best vibration performance
Fuel/Energy Efficiency	Moderate	Improved	High	Excellent
Corrosion Resistance	Moderate	Moderate	Excellent	Excellent
Fatigue Resistance	Excellent	Very Good	Moderate	Moderate
Manufacturing Complexity	Simple machining	Moderate fabrication	Easy machining	Precision fabrication required
Initial Manufacturing Cost	Low	Moderate	Moderate	Higher
Maintenance Requirement	Moderate	Moderate	Lower	Lowest
Bearing Load	Higher	Lower	Significantly lower	Minimum
Typical Service Life	Long	Long	Moderate to long	Moderate
Preferred Applications	Heavy industrial machinery	Automotive shafts, turbines	Robotics, lightweight machinery	Aerospace, EVs, aircraft systems

Lightweight and modern shaft systems have several engineering advantages such as decreasing rotational inertia; increasing acceleration response, fuel efficiency, and reducing energy usage; improving dynamic stability; etc. For example, because of their hollow design, they can result in up to a 25%-40% reduction in the weight of the shaft compared to solid equivalent models while retaining approximately 90%-95% of the torque strength of a solid shaft.

Table 7. Engineering Data and Industrial Applications for Shaft Power Transmission Systems

Industry/Application	Common Shaft Type	Typical Speed Range (RPM)	Primary Material Used	Major Design Requirement	Typical Performance Advantage
Automotive Drive Shafts	Hollow Shaft	3000–7000	Aluminum 6061 / Alloy Steel	Lightweight and fuel efficiency	Reduced rotational inertia and improved mileage
Aerospace	Hollow	5000–	Aluminum	Minimum weight	Improved aircraft

Industry/Application	Common Shaft Type	Typical Speed Range (RPM)	Primary Material Used	Major Design Requirement	Typical Performance Advantage
Transmission Systems	Lightweight Shaft	15000	alloys / Composites	with high strength	efficiency
Wind Turbine Systems	Hollow Steel Shaft	10–30	High-strength Steel	High torque and fatigue resistance	Better dynamic stability
Marine Propulsion Systems	Hollow Corrosion Resistant Shaft	100–1500	Stainless Steel / Aluminum	Corrosion resistance	Longer service life in marine conditions
Industrial Conveyor Systems	Solid Shaft	100–1000	Mild Steel	Heavy load carrying capacity	Reliable continuous operation
Machine Tools	Solid Precision Shaft	500–5000	Alloy Steel	High rigidity and accuracy	Reduced deformation during machining
Robotic Systems	Hollow Aluminum Shaft	1000–8000	Aluminum 6061	Fast dynamic response	Lower weight and higher movement efficiency
Electric Vehicle (EV) Systems	Hollow Lightweight Shaft	4000–12000	Aluminum Alloy / Composite	Energy efficiency	Reduced power loss and higher range
Turbine Rotor Systems	Hollow High-Speed Shaft	3000–20000	Alloy Steel / Titanium	High-speed rotational stability	Lower vibration and centrifugal effects
Agricultural Machinery	Solid Mild Steel Shaft	300–1500	Mild Steel	Durability and low cost	Better resistance to fluctuating loads
Heavy Industrial Drives	Solid Steel Shaft	200–3000	Mild Steel / Alloy Steel	Maximum torsional strength	High load transmission capability
High-Speed Compressors	Hollow Shaft	5000–25000	Alloy Steel / Aluminum	Reduced vibration and inertia	Improved operational efficiency

The weight of the components can also be reduced by approximately 60%-65% compared to conventional Mild Steel shafts with Aluminum 6061 as the material used to manufacture shafts. Another very important design consideration is fatigue failure associated with rotating shafts which experience repeated cycles of loading. Research shows that over 70%-80% of shaft failures are due primarily to fatigue, stress concentration, misalignment, and improper design. Therefore, the incorporation of modern shaft systems includes the application of optimized and enhanced fillet geometry; surface finish enhancements; utilizing finite element analysis (FEA) for shaft design; and dynamic balance techniques for improving operational reliability and service life. More recent advancements in shaft design include utilizing composites; hybrid combinations of metals and composites; using artificial intelligence-based optimization techniques to improve the lightweight design and structural efficiency of the component parts; and utilizing additive manufacturing methods for increased component performance. Table 7. shows the industrial applications and operational characteristics of various shaft power transmission systems. These new advancements in shaft engineering are becoming even more common in many industries such as electric cars, aviation, turbines, high-performance industrial machines, etc.

VII. COMPARATIVE ANALYSIS OF MILD STEEL AND ALUMINIUM 6061 SHAFTS

The selection of shaft material significantly affects the mechanical performance, weight, durability, energy efficiency, and operational reliability of power transmission systems. Among the commonly used engineering materials, Mild Steel and Aluminum 6061 are extensively utilized because of their favorable mechanical and manufacturing characteristics. Table 8 presents the comparative engineering analysis of Mild Steel and Aluminum 6061 shafts for different operating conditions. Choice of shaft material can greatly affect mechanical performance (torque & speed), weight, durability, energy efficiency, and reliable operation of any system relying on power transmitted via a shaft. Of the commonly utilized engineering materials, Mild Steel and Aluminum 6061 are by far the most prevalent due to their desirable mechanical properties and fabrication techniques (Table 8 shows a comparative engineering analysis of the use of Mild Steel vs. Aluminum 6061 shaft materials based on different conditions). Historically, Mild Steel was almost exclusively used for heavy-duty applications due to its increased strength and rigidity, whereas Aluminum 6061 is increasingly used for applications where reduced weight is a priority, due to its low density and greater strength-to-weight ratio. Mild Steel shafts offer exceptional torque (torsional rigidity) and fatigue life (fatigue resistance) and carry load (load capacity) making them ideally suited to industrial machinery and conveyor belts, turbine generators, pumps, and high-capacity power transmission systems. However, the high density of Mild Steel increases the weight and rotational inertia (rotating inertia) of the system and causes increased energy consumption by significant amounts, particularly in high-speed, rotating applications. In contrast, Aluminum 6061 shaft

Table 8. Comparative Engineering Analysis of Mild Steel and Aluminum 6061 Shafts

Engineering Parameter	Mild Steel Shaft	Aluminum 6061 Shaft	Engineering Observation
Density (kg/m³)	~7850	~2700	Aluminum is nearly 65% lighter
Tensile Strength (MPa)	400–550	290-350	Steel provides higher load capacity
Yield Strength (MPa)	250–370	240-310	Steel offers better resistance to yielding
Modulus of Elasticity (GPa)	~200	~69	Steel possesses greater rigidity
Modulus of Rigidity (GPa)	~80	~26	Aluminum experiences higher twist
Weight	Higher	Significantly lower	Aluminum improves efficiency
Rotational Inertia	High	Low	Better dynamic response in aluminum
Strength-to-Weight Ratio	Moderate	Excellent	Aluminum preferred for lightweight systems
Corrosion Resistance	Moderate	Excellent	Aluminum suitable for marine/outdoor use
Fatigue Resistance	Higher	Moderate	Steel better under cyclic loading
Machinability	Good	Very Good	Aluminum easier to machine
Thermal Conductivity	Moderate	High	Aluminum dissipates heat effectively
Fuel/Energy Efficiency	Moderate	Improved	Lightweight systems reduce power loss
Vibration Characteristics	Higher vibration tendency	Better damping response	Aluminum improves dynamic stability
Manufacturing Cost	Lower	Higher	Steel economical for industry
Maintenance Requirement	Moderate	Lower	Aluminum resists corrosion
Service Life	Long	Moderate to long	Depends on operating conditions
Typical Applications	Heavy machinery, turbines	Aerospace, EVs, robotics	Application-dependent selection

materials provide significantly decreased weight, less rotational inertia, and increased fuel economy. These properties allow for excellent performance of Aluminum shaft materials in applications such as automotive drive shafts, aerospace applications, robotic mechanisms, electric automobiles, as well as other lightweight industrial uses. In addition, Aluminum 6061 shaft materials have excellent corrosion resistance and abilities to be machine fabricated (machinability) providing additional value by increasing the service life of the system as well as enhancing product manufacturing flexibility. The comparative performance of solid and hollow shaft configurations using different materials is summarized in Table 9.

Table 9. Comparative Performance of Solid and Hollow Configurations by Different Materials

Shaft Configuration	Approximate Weight	Torque Capacity	Rigidity	Corrosion Resistance	High-Speed Suitability	Typical Application
Solid Mild Steel Shaft	Highest	Excellent	Excellent	Moderate	Moderate	Heavy industrial systems
Hollow Mild Steel Shaft	20–30% lower	Very Good	Very Good	Moderate	Good	Automotive and turbines
Solid Aluminum 6061 Shaft	60–65% lower	Moderate	Moderate	Excellent	Very Good	Lightweight machinery
Hollow Aluminum 6061 Shaft	70–75% lower	Good	Lower	Excellent	Excellent	Aerospace and EV systems

Despite these advantages, Aluminum 6061 exhibits comparatively lower modules of rigidity and fatigue strength than Mild Steel. Consequently, aluminum shafts generally experience higher angular deformation under torsional loading and may not be suitable for extremely heavy-duty applications where maximum rigidity is required. The comparative performance of these materials depends upon application requirements such as load conditions, rotational speed, environmental exposure, weight constraints, and economic considerations. Therefore, the selection between Mild Steel and Aluminum 6061 must be optimized according to the desired balance between strength, rigidity, weight reduction, and operational efficiency.

VIII. CONCLUSION

This literature review provides a full comparative analysis of solid & hollow shafts made from mild steel and Aluminum 6061 alloy for use in modern power transmission. The impacts of both shaft geometry and material choice on torsional strength, stiffness, stress distribution, rotational inertia, fatigue resistance, weight reduction and overall mechanical efficiency were critically evaluated within the context of this study. The results show that shaft geometry is an important factor impacting mechanical performance and energy efficiency. Conventional solid shafts are ideal for heavy duty application due to their very high torsional stiffness (resistance to twisting) and superior load-carrying capability; therefore, they demonstrate the highest ability to resist deformation. However, because of the greater amount of material used in producing solid shafts (more weight) and because they have greater rotational inertia than hollow shafts (more energy wasted) the operational dynamic efficiency of solid shafts will be less than that of equivalent hollow shafts. The hollow shaft configuration, on the other hand, has a significant weight advantage over solid shafts while having almost identical capacity to transmit torque since it is the material located closest to the outer surface of the hollow shaft that provides most of the torque-transmitting capability. The hollow shaft configuration therefore has much better strength-to-weight ratios, lower centrifugal force generated, lower vibration produced during operation and improved dynamic performance under high-speed conditions compared to their corresponding solid shaft counterparts. The benefits made it clear that they are perfect for light weight car parts like automobile drive shafts, aerospace transmission systems, robotic parts, wind turbines, and electric vehicles. The earlier comparative review of the materials confirmed that Mild Steel has a higher tensile strength, fatigue resistance, rigidity and durability making it ideal for heavy load high torque applications. In contrast, Aluminum 6061 provides major benefits such as low density and very good corrosion resistance, enhanced machinability and a much higher strength to weight ratio. Utilizing aluminum shafts results in less rotational inertia which enhances fuel efficiency, increases acceleration response and improves the entire system's performance. Of all the examined shaft configurations, the hollow Aluminum 6061 shafts have the most advantages for light weight fast moving engineering systems due to their high dynamic performance and significant reduction in weight. On the other hand, hollow mild steel shafts provide a suitable mix of strength, rigidity, durability, and affordability for industrial applications requiring limited weight savings while maintaining structural integrity. The findings from this research suggest that today's shaft designs will continue to be driven by the requirements for light-weight optimizations (e.g., advanced engineering materials) and efficient geometric configurations. The next wave of developments in terms of using finite element analysis, composite shaft systems, AI-based optimization techniques, surface engineering and additive manufacturing will create further advances in the performance, durability and sustainability of cutting-edge power train technologies.

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