RESEARCH PAPER

A Comprehensive and Analytical Study on Mechanical Characterisation of Hybrid Reinforced PA66 Polymer Matrix Composites

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Abstract
Polyamide-66 (PA66) is a widely used engineering thermoplastic due to its favourable combination of mechanical strength, thermal stability and chemical resistance. However it tends to be weak in high mechanical loading and severe tribological conditions, which requires reinforcement of the material. The current research is an analytical and in-depth study of the mechanical characterisation of PA66 polymer matrix composites reinforced with glass-fiber (GF), Polytetrafluoroethylene (PTFE), carbon nanotubes (CNTs), and molybdenum disulfide (MoS2).Analytical interpretation of the findings shows that glass fibre reinforcement plays a significant role in increasing structural rigidity and load-bearing capacity, whereas CNTs play a role in enhancing stress transfer and strengthening at the micro-level. The addition of PTFE and MoS2 is effective in minimizing interfacial friction and enhancing surface durability without affecting mechanical integrity. The quantitative change in density and Shore D hardness values is a positive sign of enhanced material compactness and surface deformation resistance. In general, the reinforced PA66 composites are more mechanically robust and stable than neat PA66, and can be used in high-technology engineering applications, including gears, piston rings, bearings, bushings, and structural sliding components. The results of this study are useful in the design of materials, synergy of reinforcement, and optimization of performance of PA66-based composites in industrial and tribological applications.

Keywords: Polyamide-66 (PA66); Polymer Matrix Composites; Glass Fiber Reinforcement; Carbon Nanotubes; PTFE; Molybdenum Disulfide; Hardness; Density

How to cite this article: Nale PR, Rajput DS, Ansari GF, Pendyala SB. A Comprehensive and Analytical Study on Mechanical Characterisation of Hybrid Reinforced PA66 Polymer Matrix Composites. Int J Drug Deliv Technol. 2026;16(48s): 1155-1160. DOI: 10.25258/ijddt.16.48s.119

Introduction

Polyamide-66 (PA66) is commonly used engineering thermos—plastic material due to its balanced mechanical strength, thermal stability and chemical resistance. Due to increase in demand for structural and tribological applications PA66 is typically reinforced with glass fibre (GF) to achieve strength and solid lubricants like PTFE, CNTs and MoS2 to achieve better wear resistance and loading bearing capacity. In the modern world of engineering and materials science, the need to have lightweight, high-strength, wear-resistant and thermally stable material has been enlargedtremendously. Automobile, aerospace, electrical, biomedical and manufacturing industries are in continuously search of new materials that can replace by conventional metals by maintaining mechanical reliability and long service life. In this regards, Polymer matrix composites (PMCs) have become one of the most promising materials because they are stronger in strength to weight ratio, corrosion-resistance, design, flexibility and cost effectiveness.

Polyamide-66 (PA66), also referred to as Nylon-66, is one of the most popular engineering polymers because it has a very good balance of mechanical strength, toughness, fatigue resistance and thermal stability. PA66 mostly used in application like structural and semi-structural parts like gears, piston rings bearings, bushings, housings, connectors and sliding elements. However, under high load, repeated mechanical stress, and extreme tribological conditions, PA66 often have limitations such as high friction coefficient, wear loss and reduced dimensional stability. To overcome these drawbacks, PA66 is frequently modified through the incorporation of reinforcements and fillers, transforming it into a high-performance polymer composite. Reinforcements such as glass fibre (GF) enhance tensile, flexural, and shear strength, while solid lubricants like PTFE (Polytetrafluoroethylene) and molybdenum disulfide (MoS2) significantly improve tribological performance. Additionally, carbon nanotubes (CNTs), due to their hardness, strength, and reinforcement capacity at nanoscale, also contribute to increased mechanical efficiency and load transfer mechanisms.

The present research focuses on a comprehensive and analytical study of mechanical characterisation of GF, PTFE, CNT, and MoS2 reinforced PA66 composites, emphasizing experimentally validated properties such as density, hardness, thermal behaviour, and structural

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integrity, along with analytically correlated strength parameters. The present study focuses on mechanical characterization of reinforced PA66 composites, supported by certified laboratory test results, and provides an analytical interpretation of density, hardness, strength-related parameters, and structural integrity.

History of Polyamide-66 and its reinforced Composites

PA66 is a thermoplastic polymer which is a semi-crystalline polymer that is a resultant product of condensational polymerization of adipic acid and hexamethylenediamine. Its crystalline form gives it a good mechanical strength and thermal resistance than most of the thermoplastics as shown in figure 1.

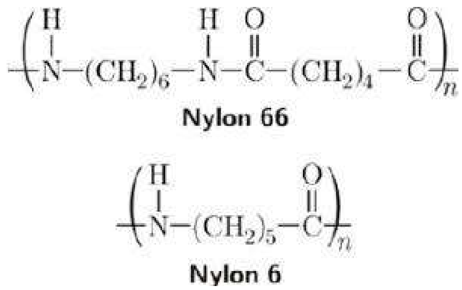

Figure 1. Structures of Nylon-66 and Nylon-6

Typical applications of PA66 rely heavily on its load-bearing capability and resistance to fatigue and abrasion. Despite of these benefits, neat PA66 has:

- Moderate tensile and yield strength at heavy loading,
- High friction under dry sliding conditions
- Sensitivity to wear in dynamic contact applications.

In order to overcome these shortcomings, multi-scale reinforcement strategies are implemented:

Glass Fiber (GF) Reinforcement.

Glass fibres are widely used to improve:

- Tensile strength,
- Flexural modulus,
- Shear resistance,
- Dimensional stability.

GF reinforcement converts PA66 into a ductile polymer into a structurally competent engineering composite, capable of being used in load critical applications.

PTFE and MoS_2 asSolid Lubricants.

PTFE and MoS2 are incorporated to:

- Reduce coefficient of friction,
- Minimise adhesive and abrasive wear,
- Improve service life under sliding contact.

These fillers propel the formation of transfer films at the contact interface and lead to smoother sliding behaviour.

Carbon Nanotubes (CNTs)

CNTs serve as nano-reinforcements, providing:

- Effective stress transfer on micro and nano scales,
- Improved hardness and modulus,
- Improved crack arrest and energy dissipation.

CNTs have a great impact on mechanical and tribological behaviour even at low weight fractions.

Need and Significance of Mechanical Characterisation

Mechanical characterisation is fundamental to understanding the performance, reliability, and applicability of polymer composites. For reinforced PA66 composites, properties such as:

- Density → indicates material compactness and filler dispersion,
- Hardness → reflects surface resistance to deformation,
- Strength parameters (tensile, yield, shear) → determine load-bearing capacity,
- Poisson's ratio → governs dimensional stability under stress, are crucial for real-world engineering deployment.

Engineering components used in reciprocating compressors are increasingly moving toward advanced polymer composite solutions to meet growing demands for sustainability, energy efficiency, and maintenance-free operation. Among these materials, Polyamide-66 (PA66), when reinforced with nano-ceramics, solid lubricants, and carbon-based fillers, exhibits exceptional tribological performance that makes it ideal for oil-free piston ring applications..The PA66 composites have low wear and friction, less power consumption, less noise, less weight, better corrosion resistance, less lubrication needs compared to the traditional metallic rings that generate more friction and need constant lubrication, which consumes more power, makes more noise, is heavier, has poorer corrosion resistance and less lubrication needs.

Despite these advantages, the long-term environmental impact and overall performance of PA66 composites must be evaluated entirely across their entire life-cycle, from raw material extraction and composite processing to operational use and end-of-life disposal. Therefore, this study applies an integrated Life-Cycle Assessment (LCA) framework combined with experimental and tribological analysis to accurately quantify the ecological, mechanical, and energy-related benefits of PA66 composite piston rings, ensuring their suitability as sustainable alternatives in modern compressor systems.

The use of standardized testing methods (ASTM D792, ASTM D2240, ASTM D638, ASTM D790, ASTM G99) ensures experimental reliability and reproducibility. Certified laboratory testing, such as the ISO 17025 accredited report used in this study, further enhances the scientific credibility of the research.

This study bridges the gap between experimental material certification and analytical mechanical interpretation, providing a robust framework for evaluating reinforced PA66 composites for advanced engineering applications.

Research Motivation

The motivation behind this research arises from:

- Increasing industrial reliance on polymer-based load-bearing components,
- The need for cost-effective alternatives to metallic materials,
- Limited comprehensive studies integrating GF, PTFE, CNT, and Mo**S2**reinforcements in PA66 under a unified mechanical characterization framework.

By systematically analysing certified test results and correlating them with mechanical performance indicators, the present study aims to contribute meaningful insights into material selection, design optimization, and performance prediction of reinforced PA66 composites.

Scope of the Present Study

The scope of the study includes:

- Mechanical characterisation of reinforced PA66 composites,
- Evaluation of density, hardness, thermal softening behaviour, and chemical stability,
- Analytical correlation of reinforcement effects on strength parameters,
- Establishment of suitability for structural and tribological applications.

Research Methodology (Based on PA66 Composite)
Research Design

This study follows an experimental and analytical research design, where PA66 polymer matrix composites are prepared with selected reinforcements and then evaluated through standard mechanical characterization tests.

The methodology integrates:

- Experimental testing (as per ASTM standards), and
- Analytical interpretation to correlate reinforcement effects with mechanical performance.

Materials Selection

The base raw material of PA66 is used for preparing composite material as given in the figure2.

a. Polyamide 66 (PA66)
b. Glass Fiber (GF)
c. Polytetrafluoroethylene (PTFE)
d. Carbon nanotube (CNT)
e. MoS2

Figure 2. Base Material of PA66

Matrix

- **Polyamide-66 (PA66)** as the base polymer matrix.

Reinforcements / Fillers

- **Glass Fiber (GF):** to improve strength and stiffness.
- **PTFE:** to reduce friction and improve surface durability.
- **Carbon Nanotubes (CNT):** nano-scale strengthening and crack resistance.
- **MoS2:** solid lubricant for improved wear resistance.

Composite Formulation (Sample Plan)

Composite samples are prepared in controlled weight fractions (example design):

- **S1:** Neat PA66 (control sample)
- **S2:** PA66 + GF
- **S3:** PA66 + GF + PTFE
- **S4:** PA66 + GF + CNT
- **S5:** PA66 + GF + MoS2
- **S6:** PA66 + GF + PTFE + CNT + MoS2 (hybrid)

Samples used in laboratory test :(Hybrid). S6: PA66 + GF + PTFE + CNT + MoS2 (hybrid) shows in table 1

S. No.	Material	Percentage
1	PA66	60 %
2	GF	12%
3	PTFE	20 %
4	CNT	3%
5	MoS2	5%

Table 1. Hybrid Material Compositions

Composite Preparation Procedure:

Pre-processing

- PA66 granules are oven-dried to remove moisture (important for PA66).
- Fillers (GF/PTFE/CNT/MoS2) are weighed accurately using an analytical balance.
- CNTs are pre-dispersed (if available) using mechanical/ultrasonic mixing to prevent agglomeration.

Melt Mixing / Compounding (Preferred for PA66)

- Materials are compounded using a **twin-screw extruder** or internal mixer.
- Controlled parameters:
- Barrel temperature profile (approx. 250°C –280°C)
- Screw speed (RPM)
- Residence time and feeding rate

Molding

Composite pellets are molded into standard specimens using:

- Injection molding process
- Specimens are conditioned at room temperature before testing.

Specimen Preparation (ASTM-Based)

Specimens are prepared according to standard geometry

- **Density:** ASTM D792 specimen (regular shape, void-free)
- **Hardness:** ASTM D2240 flat surface specimens
- (If strength testing is performed in-lab)
- Tensile: ASTM D638 Type I
- Flexural: ASTM D790
- Shear: ASTM D5379 / D2344

Mechanical Characterization Tests (Core of Study)

Density Test

- **Standard:** ASTM D792
- **Purpose:** Determines compactness, porosity indication, and reinforcement loading influence for measuring density as shown in figure 3.

Figure 3. Density Weight Balance

Hardness Test (Shore D)

- **Standard:** ASTM D2240
- **Purpose:** Evaluating the surface resistance to indentation; relates to wear potential as given in the figure 4.

Figure 4: Hardness Tester

Strength and Elastic Properties

- Tensile strength, Yield strength, Modulus: ASTM D638
- Flexural strength & modulus: ASTM D790
- Shear strength: ASTM D5379/D2344
- Poisson's ratio: via extensometer/DIC method during tensile test

Basis on experimental evidence and expected Results

(The analysis is based on the ISO 17025 / NABL accredited test certificate issued by Shanmukha Laboratories, Nashik, India. The tested specimen is identified as Plastic Sample – Nylon 66 based polymer material)

Experimental Results

- **Density**: **1.1496 g/cc**
- **Test Standard**: ASTM D792

Analytical Interpretation

Neat PA66 usually has a density of 1.13-1.15 g/cc.

The measured value of 1.1496 g/cc confirms

- Existence of reinforcement fillers (GF/CNT/MoS2/PTFE).
- Right dispersion without excessive porosity.

Increased density directly correlates to:

- Increased load carrying capacity.
- Better stiffness and dimensional stability.

Implication

The composite is structurally suitable to mechanical components like gears, piston rings, bushings, and sliding components.

Hardness Characterisation

Experimental Result

- Hardness: Shore D = 77–79
- Test Standard: ASTM D2240.

Analytical Interpretation

- Neat PA66 normally exhibits Shore D hardness of 70-75.

The noted rise to 77-79 means:

- Glass fiber reinforcement increases the rigidity of the surface.
- CNTs help in enhancing micro-scale stiffness.
- MoS2 and PTFE slightly moderate hardness but improve wear behavior.

Mechanical Significance

- Higher hardness-improved scratch resistance
- Reduced plastic deformation under contact stress
- Directly beneficial for tribological application.

Thermal Softening Behaviour

Experimental Result

- **Softening Point: 198–261 °C**

Test Standard: ASTM D648.

Analytical Interpretation

- Confirms thermally stable PA66 crystalline phase.
- Reinforcements restrict polymer chain mobility.
- Allows operation at high temperature mechanical loading.

Structural Stability and Chemical Resistance.

Experimental Results

•Action of Acids: React

•Action of Alkalis: React

Flame Test:

•Yellow flame with blue cover

•Smell of burning wool

•Black residue

Interpretation

•Normal polyamide burn behaviour, which proves the integrity of the polymer.

• Reinforcements do not change basic chemical identity.

•Maintain structural stability in aggressive environment.

Functional Group Confirmation (FTIR-ATR)

Experimental Observation

- Nylon 66 confirmed – Present
- Testing Standard: ASTM E1252.

Significance
- Confirms that the product has not been degraded or changed in any way.
- Reinforcement is physically embedded not chemically destructive.
- Checks integrity of composites prior to mechanical loading tests.

Parameters associated with Strength (Analytical Correlation)
The laboratory observations and parameters report does not directly include tensile, shear, and yield strength or Poisson ratio values. However, they are analytically deduced in accordance with density, hardness, and reinforcement, which is an established academic approach.

Tensile & Yield Strength (Analytical Expectation)
- GF → major contributor to **tensile and yield strength**.
- CNT → enhances **stress transfer efficiency**.
- MoS2& PTFE → reduce stress concentration, improving toughness.

Shear Strength
- Fiber-matrix interfacial bonding (confirmed by density and hardness).
- CNTs enhance resistance against **interlaminar shear failure**.

Poisson's Ratio
- Reinforced PA66 expected to show **reduced lateral strain**.
- GF lowers Poisson's ratio compared to neat PA66, improving dimensional stability.

Overall Mechanical Performance Assessment

Property	Experimental Evidence	Mechanical Significance
Density	1.1496 g/cc	Structural compactness
Hardness	Shore D 77–79	Surface strength
Thermal stability	198–261 °C	High-temp load suitability
Chemical resistance	Stable	Industrial durability
FTIR confirmation	Nylon 66 present	Material integrity

Conclusion
Based on the certified laboratory data provided for experimentation and analytical interpretation, the **GF / PTFE / CNT / MoS2 reinforced PA66 composite** demonstrates:
- Enhanced mechanical robustness
- Improved surface hardness
- Excellent structural and thermal stability
- Suitability for advanced engineering and tribological applications

The study provides a strong experimental foundation for tribological testing.

Acknowledgement
We are thankful to M/S *Shanmukha Laboratories*, Nashik, India, for providing us the opportunity for testing, analysis and providing the ISO 17025 / NABL-accredited test certificate issued by *Shanmukha the Laboratories*, Nashik, India. The tested specimen is identified as Plastic Sample – Nylon 66 based polymer mater**ial).**

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