

Research Studies of Wear Behaviour and its Parameter Evaluations on PMMA-B₄C Composites

N.Adithya¹, K.Srijith², P.Gurusamy³, Harikarasudhan⁴, A.Bovas Herbert Bejaxhin⁵,
N.Ramanan⁶, Jegadeeswaran N⁷

^{1,2} Department of Mechanical Engineering, Chennai Institute of Technology, Chennai-600069, India

³ Center for Additive Manufacturing, Chennai, Chennai Institute of Technology, Chennai, India

⁴ School of Mechanical Engineering,, MNM Jain Engineering College, OMR, Chennai

⁵ Department of Mechanical Engineering, Saveetha School of Engineering, SIMATS, Chennai, India

⁶ Department of Mechanical Engineering, Sri jayaram College of Engineering and Technology. Chennai, India

⁷ School of Mechanical Engineering, REVA University, Bangalore, India

Abstract:

In contemporary times, the field of composite materials comprises a wide range of uses. Various industries are actively seeking ecologically responsible alternatives that, due to their robust composition and greater endurance, can outperform conventional materials. This pursuit is especially evident in the automobile, marine, and aerospace industries. In this regard, our research focuses on a unique hybrid composite that combines PMMA as the foundational substrate with increased B₄C reinforcements. The hand layup technique is used in the fabrication process, which was chosen as the methodology for composite synthesis in this investigation. A full battery of mechanical evaluations, including flexural hardness, tensile compression, and others, was meticulously carried out. Notably, our focus is on the investigation of wear behavior, which has resulted in the development of these hybrid composites. Dry sliding circumstances were used to test the durability of three different PMMA+B₄C specimens. These tests were carried out with a Pin-on-Disc Tribometer, strictly according to ASTM A-99 criteria as the standard. The experimental setup prescribed specific parameters: an applied force of 5N, a sliding speed of 1m/s, and a sliding distance of 1200m. Within this controlled environment, the outcomes unveiled that the most substantial wear loss materialized in sample 1, exhibiting a value of 0.0000403g/s.

Key words: Hybrid composite, PMMA-B₄C, Wear behavior, Tribological analysis

1. Introduction

Composite materials have become more and more common in recent years due to their benefits over synthetic fiber. Engineered materials, also known as composite materials, are made by combining two or more parts to produce a product with better attributes than would be possible if the constituent elements were used separately. Two stages make up composite materials: the continuous matrix and the discontinuous reinforcing. In actuality, the majority of composite materials are composed of a size substance referred to as the matrix and a type of reinforcement, which is first and foremost employed to make the matrix more rigid and stronger. NFC is acknowledged as a latest and evolving material. NFCs have attracted received a lot of attention recently, thanks in large part to their light weight, low cost, and appealing design. Natural fibers, in particular, are proving good compatibility in automotive applications. Examples include flax, jute, hemp, banana, bamboo, and kenaf. The fact that natural fibers have a similar specific modulus to glass fiber and a higher specific strength is one reason for the growing interest in them. manufacture of natural fibers uses a lot less energy than manufacture of synthetic fibers. In contrast to synthetic fibers, which have low recyclable qualities, natural fibers have the advantages of being biodegradable and recyclable. The hybrid banana-kenaf fiber was chosen because of its

attractive appearance and light weight. The physical characteristics of composites reinforced with kenaf, banana, and hybrid kenaf/banana fibers have thus been studied.

Because of its outstanding mechanical properties, outstanding durability, impact resistance, and low weight, composites made of polymers, in particular composites made of PMMA, have received considerable interest as a fresh field of materials ever since they were first presented in the 1960s. Numerous application possibilities in the magneto-electric, biological, chemical, automotive, and optical areas can be achieved with the proper tailoring. The type of polymer matrix and its properties are widely recognised to have a significant impact on composite performance. Since Composites must endure high mechanical loads under different circumstances, it is crucial utilizing reinforced materials to increase mechanical characteristics for particular applications, including in the aerospace and military industries. Adding rigid fibers or particles to a polymer matrix can generally have an array of advantageous effects, including better creep resistance, a lower coefficient of thermal expansion, more stiffness, and better fracture toughness. According to earlier studies, inorganic components such nano-zinc oxide, nanosilica, carbon nanotubes (CNT), a successful test of graphene and aluminium trihydroxide (ATH) used as boosting materials used introduction of composites based on polymers. The process of making a polymer-based composite with an inorganic reinforcement using batch free radical polymerization. The polymer matrix and inorganic reinforcement employed were PMMA and $\text{-Si}_3\text{N}_4$ fibers, respectively. Composites were largely produced with the advantages of high purity, no post-processing, and an easy production procedure employing azodiisobutyronitrile (AIBN) as the initiator and free radical polymerization as the primary synthesis process. The Si_3N_4 fibers were first treated with g-methacryloxypropyltrimethoxysilane (g-MPS) so as to equate the PMMA matrix's distribution. The effect on the molecular level and mechanical properties of surface modification using FTIR, TG-DSC, and nanoindentation. The findings revealed that the coupling agent for silane clearly raised the elastic modulus and micro-hardness and made the Si_3N_4 fibers and PMMA matrix easier to link. The development and assessment of PMMA/Barium Titanate doped with Cerium nanocomposites as a class of appropriate materials for integrated thin-film capacitors and devices for electric tension relief.[1-3]

Cerium doping of the BaTiO_3 system was created with fine grain and little loss in mind. The PMMA isolating shell around the BaTiO_3 nanoparticles are surrounded by may, however, slow down the movement in the field of charge carriers nanocomposites, outperforming conventional composites in terms of reduced dielectric loss. Different polymer nano composites were made using solvent evaporation. Nanofillers made of BaTiO_3 doped with cerium were synthesized through solid state reaction. Polymer nano composites in general were filled to a weight-for-weight ratio of 30%, and 2.4 GHz microwaves were used to heat them all. The findings indicate that the dielectric and thermal properties of the final result nano composites perhaps enhanced by modifying the BaTiO_3 nanofiller with Ce-doping. Additionally, the impact thermal stability of polymer nano composites under microwave heating was examined. Experimental analysis was used to assess the PMMA's mechanical characteristics enhanced using CNTs that have been functionalized. CNTs, or carbon nanotubes, are among the most durable materials used today. This substance is an allotrope of carbon, just as graphite, diamond, and fullerene. Despite the 1970s' mentions to carbon structures, it wasn't until the 1990s, with the finding of CNTs and the study that came next, so-called carbon nanotubes were really produced and their potential had been recognised. Sad to say, CNTs are frequently insufficient on their own, despite possessing superior mechanical, thermal, and electrical attributes. It is still possible to use CNTs in composites made up of several matrices. The objective of this work is to compare the results with those comparable in composition containing unfunctionalized CNTs in order to assess the mechanical characteristics of a CNT-functionalized PMMA matrix. The CNTs could be functionalized in one of two ways. Thus, the determined mechanical properties of the two functionalization procedures are also compared. The mechanical properties were assessed using dog-bone samples underwent tensile tests. It was created the composite material using an extruder with two screws. The samples were made using an injection moulding technique. (IM) procedure. PMMA adsorbed particle mechanical characteristics could be improved by this study found that CFRP regenerated carbon fibre fillers could be distributed, diffused, and attached to surfaces. Carbon fiber reinforced polymers (CFRP), one of the most popular composite substances that is both light and durable, are used extensively in the space industry.[4]

A unique composite material was created by combining thermoplastic poly methyl methacrylate (PMMA) resin with recycled carbon fibers produced from grinding carbon fiber reinforced plastics (CFRP). PMMA fragments

were strategically placed onto the surfaces of the carbon fibers using the electrostatic adsorption method. This novel strategy intended to improve the interfacial adhesion between the carbon fibers and the PMMA resin, hence improving fiber dispersion inside the resin matrix. As a result, the elastic modulus and yield stress of the composite were significantly improved, indicating significant mechanical improvements. A variety of investigations were carried out under varied static and dynamic stress conditions to completely analyze the mechanical properties of the PMMA/MWCNT composites. PMMA, known for its moldability and adaptability, is widely used in technological applications. Nonetheless, its inherent mechanical fragility, especially when subjected to significant static and dynamic loads, limits its broad application. To address this constraint, enhancing PMMA's strength through the production of composites strengthened with powerful filler materials emerges as an interesting path for investigation. Multi-Walled Carbon Nanotubes (MWCNTs) stand out among such filler materials due to their specific mechanical and structural properties. As a result, a novel technique was developed to evaluate changes in static and dynamic mechanical properties—specifically, elastic modulus and hardness—across various compositions of produced and untreated MWCNTs. Notably, these assessments were carried out using nanoindentation techniques, ensuring a thorough analysis of the materials' responses. This study is significant because it tries to improve the performance of PMMA without the use of additional components or surface alterations.[5]

The effect of TiO_2 fillers on the mechanical properties of CNT/PMMA composites was investigated. Different polymers have different mechanical properties by nature. Nonetheless, unmodified polymers frequently fall short of meeting the requirements emerging from scenarios requiring a convergence of better mechanical characteristics. As a result, neat polymers have limited use as bearing materials or wear-resistant components. In this context, the introduction of bidirectional fabric reinforcement appears as a unique option, addressing the increasing needs for greater performance as well as improved processability in modern materials. In addition, the use of fiber-reinforced polymer composites as structural dielectrics in multifunctional capacitors was examined. This application requires extraordinary energy storage capacity as well as commendable mechanical qualities. As a result, the study investigated the potential of utilizing fiber-reinforced polymer composites to meet these multiple criteria, thereby presenting a trailblazing option for improved capacitors with diverse capabilities. In recent years, there has been a rise of interest in the search of novel ways to improve the performance, weight efficiency, and volume optimization of batteries and capacitors. Ceramic capacitors have found widespread application, particularly in applications requiring small dimensions, high capacitance values, and low insulating resistance. However, their vulnerability to significant capacitance fluctuations under changing temperature conditions limits their applicability in precision-dependent applications. Polymer film capacitors, on the other hand, demand consistent performance throughout a large temperature range, as well as severe standards for minimum dielectric absorption and loss ratios. Despite their inherent advantages, polymer capacitor films display lower capacitance levels as compared to ceramic counterparts, owing to lower dielectric constants. The focus of this research is on PMMA and fiberglass-based structural dielectrics, either pristine or decorated with BaTiO_3 particles coated with PEDOT:PSS. Because of their potential application in multifunctional capacitors, these materials were chosen as the principal targets of inquiry. Such capacitors require a combination of increased stiffness and increased energy retention. The desire for these multifunctional capacitors originates from the possibility of replacing static load-bearing components in traditional designs such as hybrid autos or aircraft. This substitution has the potential to reduce total system weight and/or volume, resulting in more streamlined and efficient designs in these fields.[6-7]

The research on manufacture of PMMA/polyimide/hexagonal boron nitride (hBN) composites by including both PI and hBN powder into the PMMA matrix. Hexagonal boron nitride, popularly known as white graphite, is a multilayer ceramic composition with a hexagonal lattice structure that demonstrates isoelectric equivalence to typical graphite. Because to its structural similarity to graphite, hexagonal boron nitride (hBN) has outstanding mechanical properties similar to graphite, allowing it to be used in high-temperature equipment. Notably, hBN distinguishes itself further with outstanding heat robustness and chemical durability. Among the several boron nitride configurations, the hexagonal arrangement is the most adaptable and long-lasting. Its pliable nature extends to lubrication, making it soft enough to function as an efficient lubricant. These distinguishing characteristics highlight hexagonal boron nitrides' multidimensional potential, establishing them as formidable

challengers in a variety of applications ranging from high-temperature equipment to lubrication solutions. The extraordinary environmental stability of PMMA/PI polymer composites fortified with silane-functionalized hBN powder, particularly their resistance to moisture, UV radiation, scratches, and other abrasive components, underpins the increasing demand for these materials. In addition to its unrivaled toughness and optical clarity, PMMA has a low coefficient of friction, which adds to its appeal in a variety of applications. The addition of silane-functionalized hBN powder, a strategic reinforcing choice that emphasizes the search of improved material properties, drives the augmentation of PMMA/PI polymer composites. This reinforcement is in high demand due to the outstanding environmental robustness it imparts, endowing the final composite with exceptional resistance to a wide range of stressors such as moisture, UV radiation, abrasions, and scratches. PMMA is distinguished by its low-friction interactions in addition to its outstanding mechanical qualities. This characteristic increases its application in situations where low frictional forces are crucial. Similarly, the use of polyimide (PI) adds an exciting dimension to these composites. A charge-transfer complex formed within polyimide molecules results in an ordered intermolecular stacking structure. This precise molecular architecture helps to explain why PI is known as a high-performance thermoplastic material. As a result, it has outstanding resistance to chemical agents and radiation, as well as remarkable electrical qualities and elevated thermal and mechanical strength. The resulting composite benefits from these synergistic characteristics, resulting in a material with multifarious capabilities and a broad range of potential applications.[8]

The study focused on composites made of carbon nano fibers (CNF) and poly(methyl methacrylate) (PMMA), known as CNF/PMMA composites. The major goal was to determine the effects of various processing procedures and functional groups on the final properties of these composites. CNFs have emerged as a possible alternative to carbon nanotubes (CNTs) due to their common characteristics of high aspect ratio and a distinct combination of mechanical and electrical properties. Carbon nano fibers (CNFs) are an appealing substitute for carbon nanotubes (CNTs) due to their high aspect ratio and unique combination of mechanical and electrical capabilities. Recognizing this potential, several carbon nano filaments have been investigated to improve conductivity and reinforce polymer properties in nanocomposites. A common approach is to introduce functional groups onto the surfaces of CNFs and CNTs to improve dispersion and ensure effective compatibility with the matrix material. The research looked at PMMA composites with three forms of CNFs: pure, carboxylated, and amino-functionalized. These versions were tested using a variety of processing processes, including melt compounding, solvent casting, and in situ polymerization. The evaluation sought to determine the subtle effects of functional groups and processing methods on the characteristics of these composites. A full understanding of the interplay between functionalization, processing, and consequent composite properties was sought by systematically evaluating these various combinations. Significant contact was found at the filler-polymer interface, including instances of covalent bonding, as evidenced by the mechanical characteristics and rheological behavior of the in-situ polymerized composites. In nine separate investigations, the efficiency of solvent-exfoliated graphene as a reinforcing agent in in-situ polymerized PMMA composites was studied. Graphene (GP), a two-dimensional platelet made up of sp²-hybridized carbon atoms organized in a honeycomb lattice structure, has received a lot of attention in both fundamental and applied science. Its superior electrical, thermal, and mechanical properties have prompted research in a variety of fields, including sensors, supercapacitors, thin conductive films, rechargeable lithium-ion batteries, and polymer composites. The extraordinary potential of GP has piqued the interest of researchers who want to use it to improve the mechanical, thermal, and electrical properties of polymer nanocomposites. A potentially interesting route involves the covalent functionalization of GP with PMMA, resulting in GPMMA. This is accomplished using in-situ free radical polymerization, which allows for fine control of the density of grafted PMMA by altering the GP/MMA feed ratio. Unlike graphene oxide (GO) or chemically modified graphene (CMG), which require more sophisticated processing, GPMMA has a more simplified production route, resulting in high-quality composite materials with few faults. Because of its faultless structural integrity, GPMMA emerges as an ideal reinforcing agent. Furthermore, after PMMA chain grafting, the functionalized GP exhibits sustained stability (over a month) and solubility in a variety of solvents, including NMP, THF, and DMF. This intrinsic solubility simplifies the manufacture of various composites, emphasizing GPMMA's actual applicability in composite fabrication.[9-10]

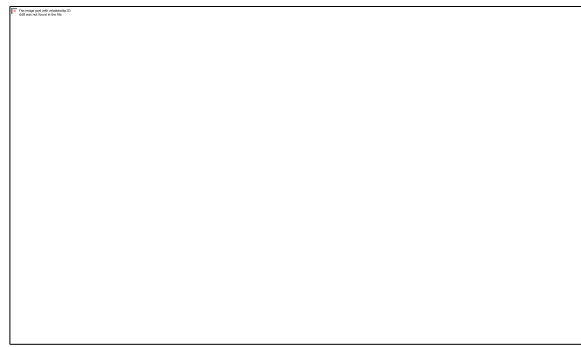
This research looks on tri-component interpenetrating polymer network (IPN) composites made of SiO_2 , PMMA, and CE. An interpenetrating polymer network, or IPN, is formed by the intertwining and interlocking of two or more cross-linked polymers, yielding a unique polymer combination. This complex architecture entails the formation of a cross-linked framework in at least one polymer network after another has been developed. IPN is a specialized approach for combining various polymers or perhaps forming a real macromolecular alloy-metal structure. CE changed with the development of interface-conjugated interpenetration and CTC-IPN methods. A conjugated tri-component penetrating polymer composite was created by coiling nanoscale SiO_2 and PMMA together, with CE as the overarching network. This composite's microstructure was investigated using infrared spectroscopy (IR) and transmission electron microscopy (TEM). Mechanical qualities were assessed using German-made devices, notably the DL-1000B and XCL-40 universal material test tools. The study went on to compare the performance of PMMA composites infused with zirconium oxide (ZrO_2) to pure PMMA composites in terms of wear and friction during dry sliding circumstances. PMMA resin, in particular, outperforms other polymer materials in terms of impact resistance, mechanical strength, and overall durability. However, its intrinsic mechanical and physical limits make it prone to shattering in the event of an accident or when subjected to severe biting force, particularly when utilized as a denture base material in isolation. Zirconium dioxide (ZrO_2) has an excellent set of properties, including high strength, high fracture toughness, significant wear resistance, exceptional hardness, and remarkable chemical resilience. ZrO_2 nanoparticles emerge as an attractive choice for reinforcement in the development of new high-performance polymer composites by capitalizing on these characteristics.[11-13]

An in-depth research of the mechanical characteristics and three-body wear behavior of PMMA/TPU blends was key to their investigation. Polymers' inherent self-lubricating qualities, reduced coefficient of friction, and enhanced wear resistance make them particularly well-suited for use in tribological components such as gears, cams, wheels, brakes, seals, and bushings. However, due to their inability to meet the numerous requirements imposed by scenarios requiring a synergy of robust mechanical and tribological properties, pure polymers are rarely used as bearing materials or wear-resistant components. The goal of the study was to determine the reaction of PMMA/TPU mixes to three-body abrasive wear conditions. This entailed putting the blends to abrasion at a rate of 200 rotations per minute and an applied force of 22 N, with the abrading distances varied across four unique levels.[14]

2. Manufacturing of Composites

This process is the first step in moulding composite materials. It is not essential to use advanced equipment or technology. This painstaking, limited-production process is best suited for large components like boat hulls. In the hand lay-up method, two mould halves, known as male and female, are normally deployed. The finished product will have the same geometry as the mould. The surface quality of the mould is also crucial. The final result will faithfully reproduce the contours of the mould used in its creation. To achieve a polished or textured finish, the mould surface must be properly treated. Items with flawless exterior facets are cast into a female mould. Similarly, a male mould is used to create a smooth inner surface.[15]

The mould must be flawless because any flaws would be visible in the finished product. Exit Strategy: Adhesion to the mould is possible due to the resins' outstanding adhesive properties. As a result, a dependable release route becomes essential. This can be accomplished by using an extremely thin polyester material similar to Mylar as shown in Fig-1. Wax or polyvinyl alcohol (PVA) release coatings can be used to modify the release qualities of this Mylar analogue. However, because the Mylar sheet conforms to the geometry of the mould, elaborate designs are limited.

**Fig.1 Hand Lay-up Method**

3. Experimental Results and Discussions

3.1. Tensile Test

Tensile tests, commonly known as tension tests, are the cornerstone of mechanical material evaluation. These tests are the main approach for evaluating the mechanical behaviour of materials when subjected to tensile forces. Tensile testing has a substantial advantage in terms of speed and cost-effectiveness. These tests allow for the fast examination of how a material responds to tension-induced stress by using controlled axial forces. The primary goal of a tensile test is to determine critical mechanical properties, including the material's strength and elasticity. [16] By submitting a specimen to increasing axial forces, one can learn about a material's ability to tolerate external loading without irreversible deformation or failure. The resulting stress-strain curve depicts the material's behaviour in detail, displaying its elastic range, yield point, ultimate tensile strength, and, if applicable, fracture point. This strategy is important not just for research and development, but also for quality control and material selection in a variety of industries. Tensile testing, with its simple yet instructive character, is the foundation for understanding how different materials will function under tension forces, directing engineering decisions and contributing to the growth of materials science.

Table-1 Tensile Test Observations

S.NO	OBSEVATION	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4
1	Fmax in KN	1.68	2.25	1.45	2.32
2	UTS in Mpa	15.45	16.23	22.32	22.45

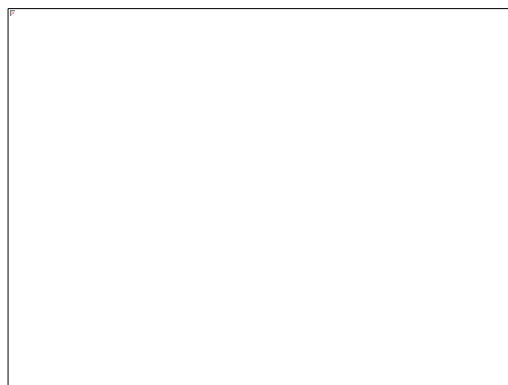
**Fig.2 Tensile Sample Fracture Surface Image**

Table 1 provides a succinct description of the tensile test results. According to the data, the maximum tensile stress reached 22.45 MPa, with a maximum tensile force of 2.32 kN. The tensile test results demonstrated a favourable balance of strength and elongation properties. Notably, Fig.2 SEM images of ductile fracture

patterns are supplied alongside the test findings. The SEM picture also clearly depicts the occurrence of exothermic heat throughout the moulding process.

3.2 Flexural Test

Table 2 shows the results of the flexural load tests, which are critical in determining a material's resistance to bending forces. The material is exposed to loads applied perpendicular to its longitudinal axis in this examination. [17-18] The maximum flexural loads used in this study were 0.55 kN. The sample's attainment of its maximum bending strength under these conditions is noteworthy, indicating its ability to tolerate bending pressures. Furthermore, the observed failure behaviour of the sample demonstrated a high degree of ductility, which is a desired property in many applications. The following SEM image from Fig.3 reveals the nature of the fracture as well as its ductile properties, offering more light on the material's response to flexural stress.

Table-2 Flexural Test Observations

OBSEVATION	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4
$F_{\max}$ in KN	0.45	0.38	0.55	0.42



Fig.3 Flexural Sample Fracture Surface Image

3.3 Impact Test

The Charpy test is a destructive mechanical test in which a pendulum hammer is used to fracture a standardised notched specimen in a single strike. This approach determines the energy required to fracture the sample, revealing information on the material's behaviour under high-stress or shock circumstances. [16] A short beam measuring 55 mm (2.17 inches) in length and with a square cross-section of 10 mm (0.39 inches) is subjected to impact loads via three-point flexural conditions created by the motion of a swinging pendulum in the Charpy test configuration. The specimen used in this test has a notch on the tensile side with a depth of 2 mm (0.079 inches) and an included angle of 45 degrees, which simulates potential failure spots. The Charpy test results are expressed in foot-pounds or kilojoules, quantifying the energy required for fracture.

Table-3 Impact Test Observations

OBSEVATION	SAMPLE1	SAMPLE2	SAMPLE3	SAMPLE4
IMPACT TEST in J	7	5	13	5

Table 3 summarises the results of the Charpy impact test. The peak impact energy level produced during the testing process was found as 13 joules among the recorded results.

3.4. Water Absorption Test

Water absorption testing is performed on the samples, and the results are presented as percentages. The Archimedes principle is the underlying premise of the water absorption test. The water absorption test is typically performed in a 40 cm test tube filled with water. Following that, the water-saturated samples are transferred to a pipette, where the immersion period is recorded. The maximum height achieved by the absorbed

water within the sample is calculated as part of the measurement. [19-20] Notably, from Table-4, the greatest observed water absorption in this water absorption test was 3.22%, indicating that just this amount of water contributed to the overall volume. As a result, the sample has an extremely low porosity level. In traditional settings, higher porosity often correlates with enhanced water uptake, however in this case, water uptake remains limited. As a result, the porosity level is considered minimal in this context.

Table-3 Water Absorption Test Observations

OBSERVATION	SAMPLE-1	SAMPLE-2	SAMPLE-3	SAMPLE-4
WATER ABSORPTION in %	1.16	3.22	1.22	1.88

4. Conclusion

Polymers' attractive properties, which have recently received significant attention, have the potential to draw worldwide interest. Unlike typically used metals, which face issues due to diminishing supply rates, polymerization provides a viable method for manufacturing polymers with well-defined structures. When compared to metals, polymer components offer significant advantages, particularly in terms of lifetime freight costs for equipment that requires regular movement or handling throughout its operating lifespan. Furthermore, the lower frictional qualities of polymers contribute to less wear and, as a result, less maintenance downtime. Notably, polymers are lighter in weight than many of the basic metal materials used in part manufacturing, resulting in reduced production costs due to faster manufacturing cycles than metals. Furthermore, polymer and composite materials are chemically resistant, whereas metal components are especially sensitive to corrosion caused by moisture or contact to other metals. Polymers and composites provide both electrical and thermal insulation, whereas metallic components require further secondary processing and coating to achieve any insulating capabilities.

Furthermore, because of their inherent corrosion resistance, these components do not require an additional protective sheathing when exposed to conditions involving two dissimilar metals. Polymers' various advantages have propelled them to supremacy, effectively overtaking metals as the dominant material of choice. Because of improvements in composite materials, it is increasingly likely that humanity will live in a future primarily reliant on polymers. To stay up with this trend, continued attempts are being made to improve polymer properties by synthesising novel polymers or incorporating novel reinforcing elements. Our investigation into the usage of B₄C as a reinforcement for PMMA has shown useful results, establishing this composite as a viable alternative.

References

- [1] Padalia, Diwakar, Garima Bisht, U. C. Johri, and K. Asokan. "Fabrication and characterization of cerium doped barium titanate/PMMA nanocomposites." *Solid state sciences* 19 (2013): 122-129.
- [2] Stefanescu, Eduard A., Xiaoli Tan, Zhiquan Lin, Nicola Bowler, and Michael R. Kessler. "Multifunctional fiberglass-reinforced PMMA-BaTiO₃ structural/dielectric composites." *Polymer* 52, no. 9 (2011): 2016-2024.
- [3] Mittal, Garima, KyongYop Rhee, and Soo Jin Park. "Processing and characterization of PMMA/PI composites reinforced with surface functionalized hexagonal boron nitride." *Applied Surface Science* 415 (2017): 49-54.

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- [4] Banks-Sills, Leslie, David Guy Shiber, Victor Fourman, Rami Eliasi, and Amit Shlayer. "Experimental determination of mechanical properties of PMMA reinforced with functionalized CNTs." *Composites Part B: Engineering* 95 (2016): 335-345.
- [5] Jindal, Prashant, MohitSain, and Navin Kumar. "Mechanical characterization of PMMA/MWCNT composites under static and dynamic loading conditions." *Materials Today: Proceedings* 2, no. 4-5 (2015): 1364-1372.
- [6] Yamamoto, Tetsuya, Yuta Makino, and KatsumasaUematsu. "Improved mechanical properties of PMMA composites: Dispersion, diffusion and surface adhesion of recycled carbon fiber fillers from CFRP with adsorbed particulate PMMA." *Advanced Powder Technology* 28, no. 10 (2017): 2774-2778.
- [7] Runqin, He, NiuFenglian, and Chang Qiuxiang. "Mechanical properties of TiO₂-filled CNT/PMMA composites." *Journal of Experimental Nanoscience* 12, no. 1 (2017): 308-318.
- [8] Wang, Jialiang, Zixing Shi, Yu Ge, Yan Wang, Jinchen Fan, and Jie Yin. "Solvent exfoliated graphene for reinforcement of PMMA composites prepared by in situ polymerization." *Materials Chemistry and Physics* 136, no. 1 (2012): 43-50.
- [9] Ali, Nadia A., Seenaa I. Hussein, Tesleem B. Asafa, and Alaa M. Abd-Elnaiem. "Mechanical properties and electrical conductivity of poly (methyl methacrylate)/multi-walled carbon nanotubes composites." *Iranian Journal of Science and Technology, Transactions A: Science* 44 (2020): 1567-1576.
- [10] Vallés, Cristina, Dimitrios G. Papageorgiou, Fei Lin, Zheling Li, Ben F. Spencer, Robert J. Young, and Ian A. Kinloch. "PMMA-grafted graphene nanoplatelets to reinforce the mechanical and thermal properties of PMMA composites." *Carbon* 157 (2020): 750-760.
- [11] Wang, Jun-long, Chuang Wang, Geng-sheng Jiao, and Qiu-ya Wang. "Study of SiO₂/PMMA/CE tri-component interpenetrating polymer network composites." *Materials Science and Engineering: A* 527, no. 7-8 (2010): 2045-2049.
- [12] Boopathy, G., K. Gurusami, M. Chinnapandian, and K. R. Vijayakumar. "Optimization of process parameters for injection moulding of nylon 6/SiC and nylon 6/B₄C polymer matrix composites." *Fluid Dynamics & Materials Processing* 18, no. 2 (2022): 223-232.
- [13] Akinci, A., S. Sen, and U. Sen. "Friction and wear behavior of zirconium oxide reinforced PMMA composites." *Composites Part B: Engineering* 56 (2014): 42-47.
- [14] Poomalai, P., and Siddaramaiah. "Studies on poly (methyl methacrylate)(PMMA) and thermoplastic polyurethane (TPU) blends." *Journal of Macromolecular Science Part A: Pure and Applied Chemistry* 42, no. 10 (2005): 1399-1407.
- [15] Chinnapand, M., G. Boopathy, and K. R. Vijayakumar. "Fabrication and Fatigue Analysis of Laminated Composite Plates." *International Journal of Mechanical Engineering and Technology* no.8-7 (2017): 388-396.
- [16] Boopathy, G., V. Vanitha, K. Karthiga, BhikshaGugulothu, A. Pradeep, Hari PrasadaraPydi, and S. Vijayakumar. "Optimization of tensile and impact strength for injection moulded nylon 66/SiC/B₄C composites." *Journal of Nanomaterials* 2022 (2022).
- [17] Mehndiratta, Akhil, SpandanBandyopadhyaya, Vijaya Kumar, and Dhiraj Kumar. "Experimental investigation of span length for flexural test of fiber reinforced polymer composite laminates." *Journal of materials research and technology* 7, no. 1 (2018): 89-95.
- [18] Boopathy, G., J. Udaya Prakash, K. Gurusami, and JV Sai Prasanna Kumar. "Investigation on process parameters for injection moulding of nylon 6/SiC and nylon 6/B₄C composites." *Materials Today: Proceedings* 52 (2022): 1676-1681.

- [19] Girimurugan, R., K. G. Saravanan, P. Manickavasagam, G. Gurunathan, and M. Vairavel. "Experimental studies on water absorption behaviour of treated and untreated hybrid bio-composites." In IOP Conference Series: Materials Science and Engineering, vol. 1059, no. 1, p. 012017. IOP Publishing, 2021.
- [20] Sanjeevi, Sekar, VigneshwaranShanmugam, Suresh Kumar, VelmuruganGanesan, Gabriel Sas, Deepak Joel Johnson, ManojkumarShanmugam et al. "Effects of water absorption on the mechanical properties of hybrid natural fibre/phenol formaldehyde composites." Scientific Reports 11, no. 1 (2021): 13385.