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# Comprehensive Review on Mechanical Properties and Optimization of Machining Parameters of Nanoclay-Filled Glass-Reinforced Plastic Composites

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**Abstract:** Nanoclay-filled Glass-Reinforced Plastic Composites (GFRP) have attracted the automotive and aerospace industries due to outstanding properties such as high strength and stability, lightweight, and enhanced durability. The objective of this review is to synthesize recent advances in the use of nanoclay and other fillers in polymer foams and nanocomposites, emphasizing their effects on mechanical properties, foam morphology, and processing characteristics. Studies reviewed span various types of fillers, including nanoclay, carbon nanotubes, and silica, and cover a range of polymers such as polypropylene (PP), polylactic acid (PLA), and epoxy resins. The review also explores the role of manufacturing techniques such as Vacuum Assisted Resin Transfer Molding (VARTM), Seemann Composites Resin Infusion Molding Process (SCRIMP), and Resin Transfer Molding (RTM) in achieving effective nanoclay dispersion and structural performance of GFRP. Additionally, it highlights the effect of nanoclay on machining parameters, including surface roughness, tool wear, and optimization methods. The review highlights key findings, trends, and practical implications, providing a comprehensive overview of the current state of research in this field.

## 1. Introduction

Composite materials are engineered or naturally occurring materials made from two or more constituents with significantly different physical and chemical properties. When combined, these materials create materials with properties superior to those of the individual components, often exhibiting enhanced strength, stiffness, or other desirable characteristics. Historically, early civilizations utilized composites such as bricks by incorporating mud and straw, marking the beginning of the use of composite materials [1]. Since then, significant progress has been made in composite research. Recent studies have presented new approaches that allow for an increase in composite efficiency, with a particular focus on the addition of nanoclay to the matrix. This incorporation of nanoclay has been found to improve mechanical properties such as flexural strength and tensile toughness etc. Owing to

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the increasing pressure for plastic and polymeric materials, industries are turning toward sustainability. When employed as fillers in natural and synthetic composites, nanoclays help minimize the environmental footprint of non-degradable materials. In addition, nanoclay intercalation into the composite matrix has been associated with better mechanical, electrical, and thermal characteristics, which have been a key focus of hybrid composite studies. This improvement is mainly due to the incorporation of several nanoparticles, such as nanoclays. These additives have been used across a broad spectrum of industries, particularly the automotive sector. Research has shown that the addition of nanoclay to epoxy-based composites presents difficulties because of the effects of curing, nanoparticle dispersion, and the catalyst, as they directly impact material properties [2].

Epoxy resins, a highly integrated class of materials in nanoclay-reinforced composites, are prized for their mechanical, thermal, adhesive, and electrical improvements. Nevertheless, upon mixing with natural fibers, the intrinsic brittleness of epoxy polymers is a challenge, and therefore restricts their application in critical applications. Therefore, much research has been dedicated to addressing these deficiencies and boosting the performance of epoxy-based composites. Research suggests that it is possible to significantly improve resin performance by adding nanoparticles, optimizing the direction of fibers, regulating the fiber weight percentage, and altering fiber surfaces, as environmental pressure on the use of non-renewable materials. Silicate clay minerals, especially nanoclay, are highlighted as fillers in composite matrices because they are abundant and feature-rich [3]. Organoclays in montmorillonite are commonly employed because of their high aspect ratio and tight interfacial binding among polymer matrices to disperse effectively [4]. Pioneering studies by Toyota in the 1990s demonstrated the utility of nanoclay in enhancing the crystallinity and structural properties of nylon-based composites [5]. Because of their high aspect ratio and ability to exfoliate, nanoclays has received considerable attention as a reinforcement component in polymers. At low levels, nanoclay can also improve the properties of polymer matrices, such as gas barrier, solvent resistance, mechanical and thermal stability, and flame retardancy [6]. This article explores the influence of nanoclay on the mechanical and morphological properties of composites reinforced with natural or synthetic fibers.

### 1.1. Nanoclay

Nanoclay is a layered mineral silicate at the nanoscale. The individual chemical structure and composition classify them into different classes, such as montmorillonite, bentonite, kaolinite, hectorite, and halloysite. It provides a significant opportunity when applied as matrix modifiers or gas adsorbents of composite materials. Originally found in montmorillonite deposits in France, MMT has received wide attention in research for its capacity to promote the mechanical and thermal stability of composites. Fig. 1 shows the contribution of nanoclay to composite materials. Fig. 2 shows the usage of nanoclay.

Nevertheless, because of its lack of compatibility with hydrophobic polymers, fillers in the form of thermosetting polymers, poor dispersion and agglomerates are formed. To overcome this, organo-modified montmorillonite, which is represented by modifying montmorillonite with chemicals such as alkyl ammonium and alkyl phosphonium compounds, can be rendered more compatible with hydrophobic polymers [7]. The problem associated with MMT is its hydrophilic characteristic, giving rise to a very large volume increase on water uptake. To improve the compatibility of MMT with polymer matrices and dispersion in polymer matrices, the surface properties of MMT are modified, and the properties of nanocomposites are therefore enhanced. It is known that the changing of the concentration of MMT (1–3 wt%) affects curing and the mechanical behavior of the composite [8]. The types of nanoclay and their properties as shown in Table 1.

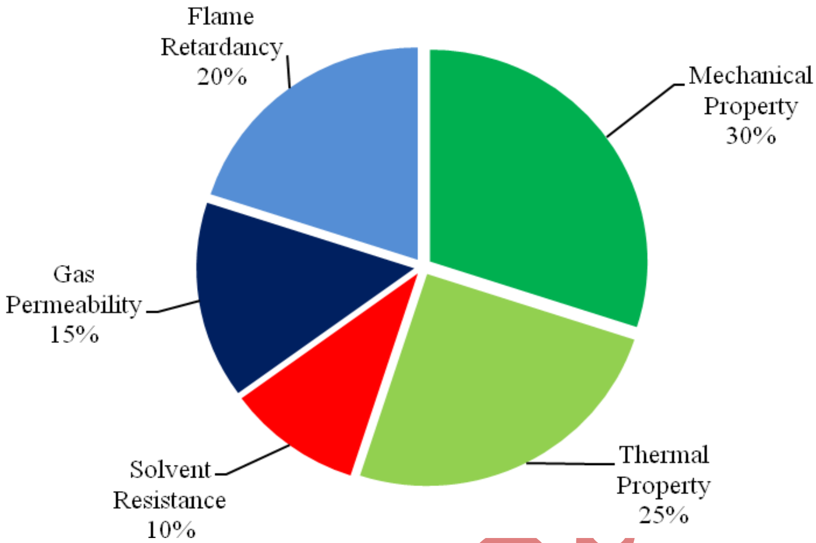


**Fig. 1: Contribution of nanoclay to composite materials** [6].

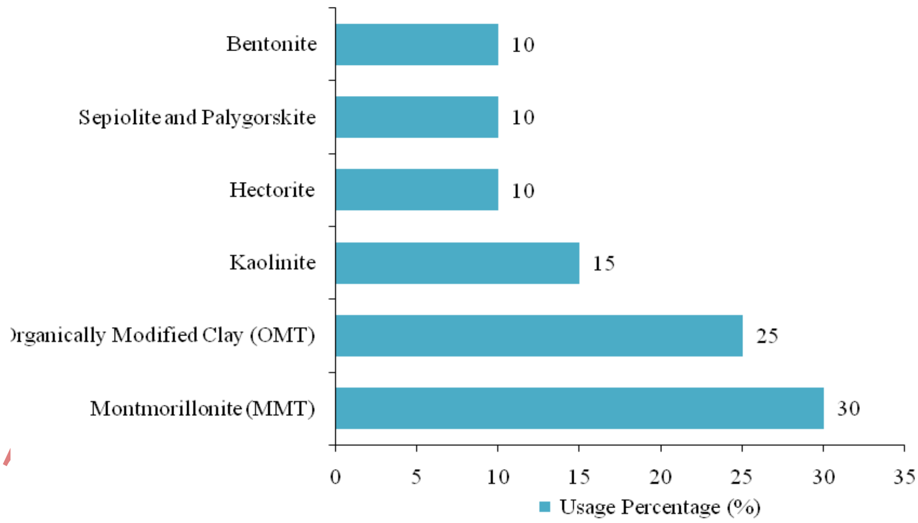


**Fig. 2: Usage of nanoclay** [1-8].

### 1.2. Nanoclay-Infused glass fiber reinforced composites

Glass fibers have traditionally been used in reinforcement for composites and have now been further improved by the addition of nanoclay. According to research, the use of up to 5 wt% nanoclay brings the desired physical and mechanical improvements to the composite materials, such as flexural, tensile, and impact strength [9-10]. This progress is assumed to be a result of the better fiber–matrix adhesion and of the stronger bonding between the fiber, matrix, and filler. A big challenge of using composite materials in high-rise construction is their fire resistance, with fiber-reinforced polymers being one of the materials that can be easily set on fire due to their thermoset resins and glass fiber reinforcement, which can worsen the flammability issue [11-12]. The use of nanoclay to modify the composites has resulted in better thermal and flame-retardant properties; hence, a potential alternative to the commercial approaches that are not fire-resistant [13-14]. The various characteristics of these compounds, which are used in automotive and aerospace industries, were shown to drastically change when three weight percent organo-modified clay was added [15-16].

**Table 1: Types of nanoclay and their properties**

| Type | Description | Properties | Applications |
|---|---|---|---|
| Montmorillonite (MMT) | A smectite clay with a high aspect ratio and surface area. | High cation exchange capacity improves mechanical, thermal, and barrier properties. | Packaging, aerospace, automotive, and construction. |
| Organically modified clay | Montmorillonite modified with organic surfactants to improve compatibility with polymers. | Enhanced dispersion in organic matrices, improved flame resistance and mechanical properties. | Flame-retardant composites, structural components. |
| Kaolinite | A non-swelling, layered aluminosilicate clay | Low cation exchange capacity, used for improving barrier and mechanical properties. | Coatings, rubber, and plastics. |
| Hectorite | A rare clay with high thermal stability | Excellent rheological properties, used in high-temperature applications. | Cosmetics, electronics, and high-performance composites. |
| Sepiolite and Palygorskite | Fibrous clays with unique morphology and surface area | High water adsorption, excellent mechanical and thermal properties. | Adsorbents, paints, and composites. |
| Bentonite | A type of MMT with sodium or calcium ions, widely available. | Improves water resistance, barrier, and mechanical properties. | Drilling fluids, construction, and nanocomposites. |

## 2. Manufacturing and processing of nanoclay-infused composites

The best mechanical and other performance characteristics of composite materials can be derived from the manufacturing process. Various production techniques such as Seeman Composite Injection Moulding Process (SCRIMP), Resin Transfer Moulding (RTM), and Vacuum Assisted Resin Transfer Moulding (VARTM) have been widely adopted practices for producing nanoclay-infused composites. Natural fibers have to be cleaned with detergent for the removal of impurities, and then they undergo an alkaline treatment, usually with NaOH, which helps to improve the mechanical properties. Nanoclay particles are added to the resin phase for better dispersion and distribution. This nanoscale dispersion is significant in avoiding fracture propagation of composites by enhancing flexural strength. In general, a mixture of resin and nanoclay is mixed with the help of mechanical stirring or ultrasonication. This results in a slurry, which is then further mixed with the reinforcing fibers through different fabrication techniques. The final curing process is complete once the composite material is produced. In this context, the VARTM technique has been popular for the production of high-quality composites by offering even resin flow and improved mechanical properties [17-18]. The two alternative methods are SCRIMP and RTM. They provide several advantages, including decreased volatile organic compound emissions and enhanced material properties. The techniques have been successfully utilized to prepare nanoclay filled composites with improved mechanical performance and sustainability [19-20]. Table 2 summarizes various manufacturing processes for composite materials.

**Table 2: Summary of composite manufacturing process**

| Ref. | Manufacturing Process | Description | Advantages | Applications |
|---|---|---|---|---|
| [23-24] | VARTM | Vacuum-assisted process ensures uniform resin distribution and improved mechanical properties. | High-quality composites, uniform resin distribution, and improved mechanical strength. | Automotive, aerospace, and structural components. |
| [25-26] | SCRIMP | Advanced infusion technique reduces emissions and enhances properties. | Reduced VOC emissions, improved sustainability, and good mechanical performance. | Large-scale structures, sustainable composites. |
| [27] | RTM | Resin injection into a mold with fibers achieves nanoscale dispersion. | Enhanced mechanical properties, precise control over fiber–matrix interactions. | Industrial, automotive, and aerospace sectors. |
| [28-29] | Natural Fiber Treatment | Cleaning with detergent and NaOH alkaline treatment for enhanced bonding and properties. | Enhanced mechanical properties, improved bonding of natural fibers. | Eco-friendly composites, lightweight structures. |
| [30] | Dispersion techniques | Mechanical stirring or ultrasonication ensures uniform nanoscale dispersion in the resin. | Prevents fracture propagation, improves flexural strength. | All applications requiring high-performance composites. |

## 3. Study of mechanical properties

The tensile strength of the composite is the property that influences its applicability to a given process. The addition of nanoclay significantly impacts tensile strength and shows variability in dependence on concentration, type of material, and conditions of processing. Fig. 3 shows the tensile properties of epoxy specimen for different levels of clay loading [31]. It is reported that the addition of very low concentrations of nanoclay, generally about 1-2 wt%, enhances tensile properties by employing better dispersion and strong interfacial bonding between the matrix and the filler. However, high concentrations result in agglomeration, leading to stress concentrators and decreased matrix flexibility, which have adverse effects on tensile strength. Shi [31] found an increase in tensile strength at 1 wt%

nanoclay, but it was observed to decrease with increased concentration due to particle aggregation. Material-specific studies report that in epoxy-based composites, tensile strength increases with nanoclay addition up to 5 wt%, as reported by Kanny [32] and Karippal [33], but the mechanical properties degrade beyond this concentration. In the case of polymer composites such as PLA, the addition of nanoclay has been found to have mixed results.

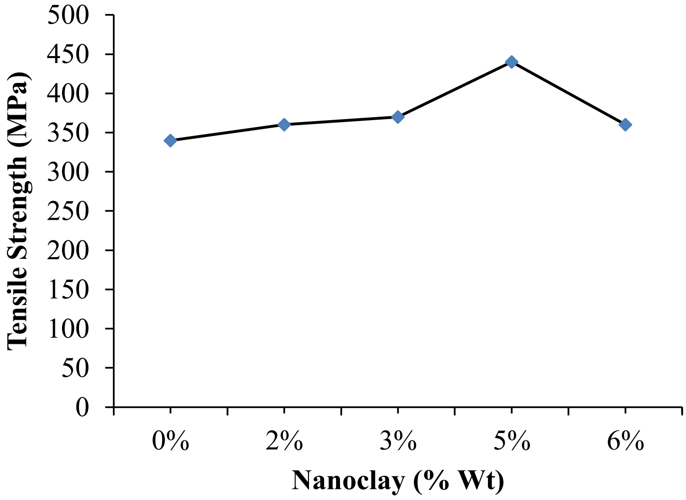


**Fig. 3: Effect of varying nanoclay on tensile strength** [31].

Hwang [34] and Xin-Chao Hwang [35] observed decreased tensile strength with higher nanoclay content, attributing this to reduced matrix flexibility and increased cell size. In hybrid composites, combining nanoclay with fibers, such as glass or carbon fibers, generally enhances tensile strength [36]. Chan [37], Hussin [38], and Mahesh [39] noted significant improvements with 5 wt% nanoclay due to enhanced interlocking and bridging effects. Furthermore, Li [40] demonstrated a 134% increase in impact strength when nanoclay and rubber were simultaneously incorporated into PLA composites, showcasing the potential for synergistic effects in specific hybrid formulations. Fig. 4 depicts tensile strength for TPU, TPUCN5 and TPUCN5. Mechanical properties of PLA, PLA-20A-05, and PLA-30B-05 composites are tabulated in Table 3.

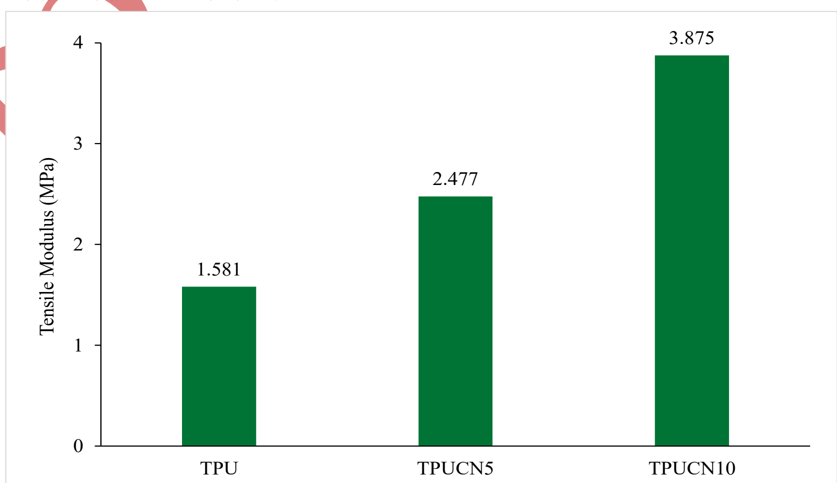


**Fig. 4. : Tensile modulus for TPU, TPUCN5, and TPUCN10 samples** [34-40].

**Table 3: Mechanical properties of PLA, PLA-20A-05, and PLA-30B-05 composites**

| Samples | Impact strength | Tensile | Tensile | Strain at break |
|---|---|---|---|---|

| | ($KJ/m^2$) | modulus (MPa) | strength (MPa) | (%) |
|---|---|---|---|---|
| PLA | 2.20 + - 0.14 | 1805 + -30 | 61.00 + -1.00 | 6.59 + -0.54 |
| PLA-20A-05 | 2.24 + - 0.24 | 2068 + -42 | 55.94 + -1.13 | 3.92 + -0.19 |
| PLA-30B-05 | 2.10 + - 0.06 | 2183 + -30 | 56.60 + -1.10 | 4.46 + -0.14 |

**3.1 Impact strength**

Impact strength is a very important property that determines the durability and continuity of polymer accoutrements, especially in operations that require resistance to unforeseen forces. The impact strength of polymer nanocomposites is greatly impacted by the concentration of nanoparticles like silica, carbon nanotubes (CNTs), and nanoclay. Among these, nanoclay, similar to MMT, is a commonly used underpinning agent. A study by Singh suggests that the impact strength of nanoclay-associated polymers relies on the type and amount of nanoclay. For example, an investigation by a researcher discovered a reduction in impact strength at advanced nanoclay ladings attributed to poor dissipation and the conformation of agglomerates acting as stress concentrators [41]. Again, moderate amounts of nanoclay can improve impact resistance, as reported by Singh, who showed that nanoclay enhances the polymer matrix and improves durability when well-dispersed and effectively interacting with the matrix. CNTs, particularly multi-walled carbon nanotubes (MWCNTs), have had mixed results on impact strength. Li [43] noted that MWCNTs improved cell morphology and strength in microcellular PEI foams by improving the transport of the cargo. Table 4 represents details of microcellular PEI/MWCNT foams. Nevertheless, Pilla [44] reported specific strength and strain-at-break reduction in PLA blends owing to the aggregation of CNT. Silica nanoparticles also show biphasic products in impact strength. Hwang [45] established that silica enhanced tensile strength and cell conformation, thus leading to improved impact resistance, whereas excessive silica content resulted in fineness because of stress focus. Other factors, such as natural fiber mounts and processing conditions, further influence the impact of parcels. Research work of Ding [46] revealed that the natural fibers improved the strength and durability, but it depends on concentration and dissipation. Fig. 5 shows the effect of the nanoparticle on impact strength.

**Table 4: Cell morphology of Microcellular PEI/MWCNT foams**

| MWCNT content (wt% %) | Mass density ($g/cm^3$) | | Cell density ($cell/cm^3$) | Cell size (µm) |
|---|---|---|---|---|
| | Solid | Foam | | |
| 0 | 1.24 | 1.18 | $2.9 \times 10^9$ | 16.7 |
| 0.2 | 1.25 | 1.18 | $3.0 \times 10^9$ | 23.3 |
| 0.5 | 1.25 | 1.18 | $5.3 \times 10^9$ | 22.1 |
| 1 | 1.26 | 1.2 | $9.7 \times 10^9$ | 18.3 |
| 2 | 1.26 | 1.17 | $2.8 \times 10^9$ | 21.3 |
| 3 | 1.27 | 1.17 | $1.9 \times 10^9$ | 23.8 |

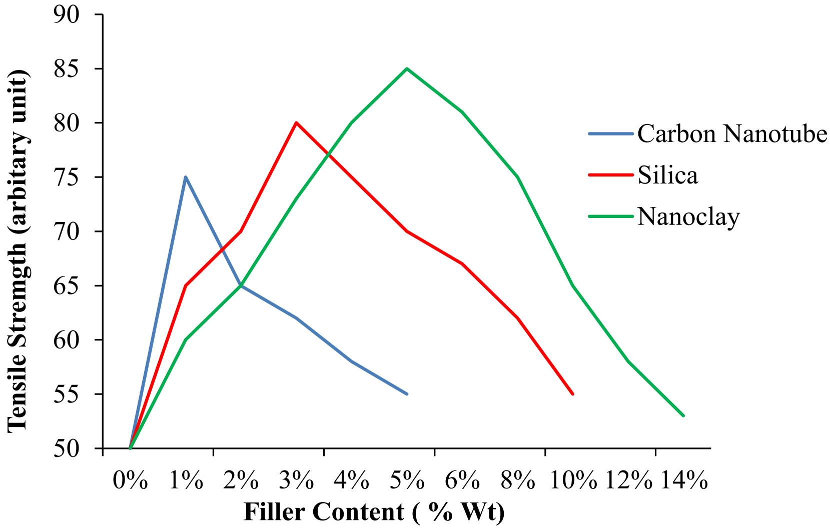


**Fig. 5: Effect of nanoparticle on impact strength.**

### 3.2 Thermal properties

According to various studies, the thermal properties of polymer composites, such as thermal stability, thermal conductivity, and glass transition temperature (Tg), are greatly affected by the inclusion of nanoclay. Thermal stability, generally evaluated through TGA, increases considerably with nanoclay addition. Mylsamy [47] also reported enhanced interfacial adhesion for nanoclay composites, which in turn enhances the interaction rate between polymer and nanoclay and their thermal behavior. Though Bian [48] focused their attention on the aspect of supercritical fluid and nanoclay reinforcement on physical dimensions such as shrinkage and warpage, the results obtained also exhibit potential thermal stability benefits. For thermal conductivity, the results are not that uniform but promising. Gao [49] found that glass fibers coated with nanotubes improve their mechanical strength, which is believed to result in better thermal performance. Similarly, Li [50] noted that the matrix structure enhanced due to nanoclay addition was responsible for enhanced thermal conductivity. Glass transition temperature, Tg, is another critical thermal property influenced by nanoclay content [51-52].

Studies report slight increases in Tg at 2-5 wt% nanoclay because of increased matrix rigidity, but observed decreases at higher loadings because of possible aggregation [53-54] and poor dispersion [55]. Moreover, filler type and content greatly affect thermal properties [56-60]. Shelly [61] reported that unreinforced nanoclay possessed better reinforcement and thermal stability in comparison to the organically modified nanoclay, whereas some researchers reported DA-GO having better performance concerning storage modulus as well as the resistance of the material towards thermal aging [62-65]. Fig. 6 shows the effect of temperature with varying fillers. Surface treatments and fine modifications of the nanoclay and glass fibers also improve mechanical and thermal properties, as discussed by Prabhakar [66] reported that optimal nanoclay content enhances thermal conductivity and stability, with an emphasis on the importance of precise processing parameters. Overall, nanoclay's ability to enhance thermal properties depends on dispersion, interaction with the matrix, filler type, and processing conditions. The effect of nanoclay content on thermal properties are shown in Fig. 7.

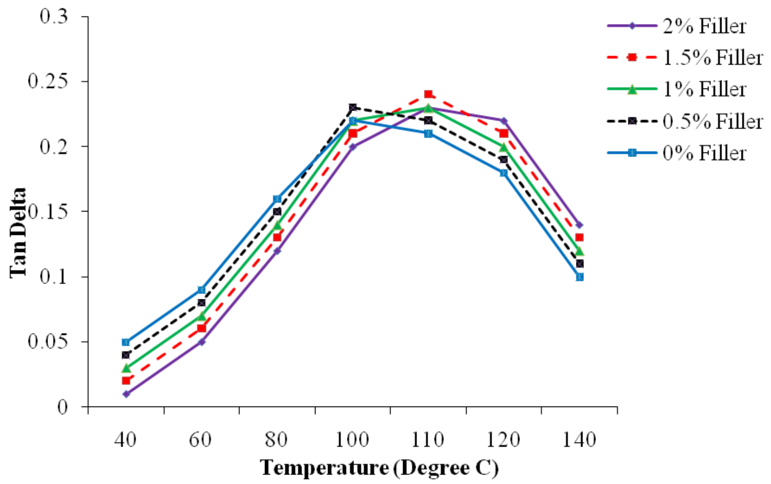


**Fig. 6: Variation of loss modulus and variation of tanδ at frequency 10 Hz** [50-60].

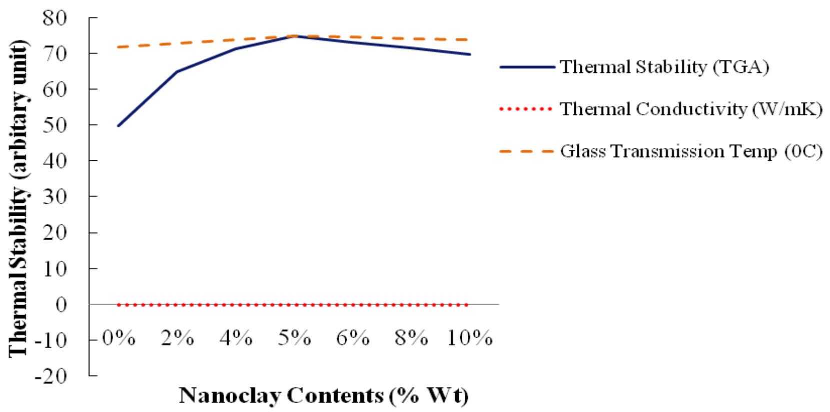


**Fig. 7: Impact of nanoclay on thermal properties of polymer composite** [62-66].

### 3.3 Fatigue life

The addition of nanoclay to polymer composites generally improves the mechanical properties, tensile strength, flexural strength, and impact resistance; all of these increase fatigue performance. According to previous comprehensive studies, nanoclay increases tensile strength and modulus, which improves the material's overall structural integrity and, in turn, prolongs its fatigue life [67-68]. Improved interfacial bonding between the polymer matrix and nanoclay further enhances fatigue resistance, as reported in several studies [69-70]. Careful regulation of the nanoclay content is necessary to obtain optimal performance since excessive levels can cause poor dispersion and aggregation, which impair fatigue performance [71-72]. It also affects fatigue crack propagation by changing crack growth rates and mechanisms, which can extend the material's fatigue life [73-76]. Such improvements are particularly useful for high-performance composites, which require long durability in cyclic loading; nanoclay-reinforced composites show excellent high-cycle fatigue properties because of the improvement in the matrix-reinforcement interaction [77]. Comparison studies suggest that while nanoclay is an excellent filler, in some applications, CNTs and graphene derivatives may be better than nanoclay [78], showing better mechanical and fatigue properties in some cases. The processing conditions, like quality of dispersion, interactions between the filler-matrix, pressure while molding, and temperature, also need to be considered. It controls the fatigue life of nanoclay composites [79]. Its proper optimization is important for better benefits from nanoclay in the fatigue-resistant material. Fig. 8 represents the mechanical and fatigue performance for various fillers.

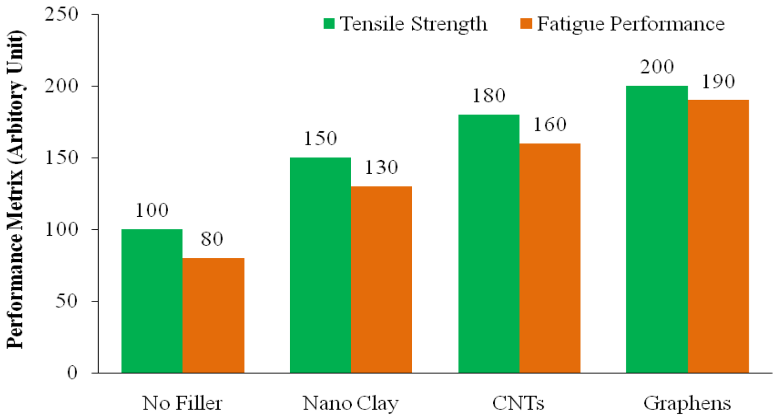


**Fig. 8: Comparison of mechanical and fatigue performance across filler** [71-80].

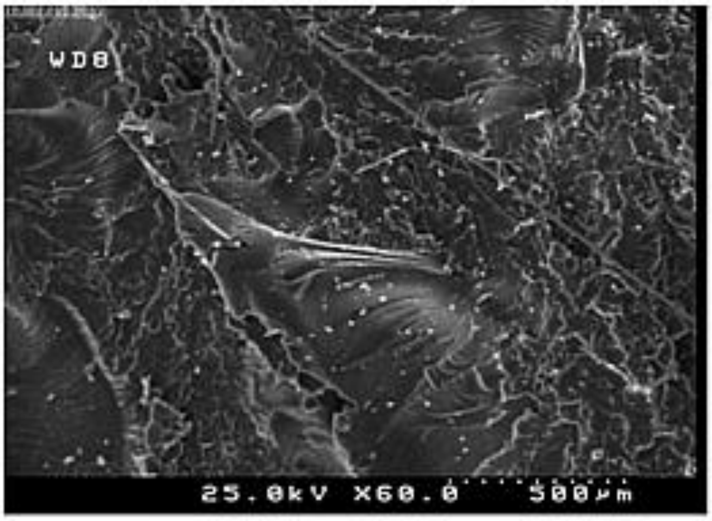


**Fig. 9: Fracture surface of the matrix of the IGSC panel containing 5 wt. % of silane functionalized nanoparticle** [85].

### 3.4 Processing and morphological effects

Dispersion of nanoclay in the polymer matrix is the most crucial factor for getting maximum mechanical properties in nanoclay-reinforced composites. Poor dispersion often leads to agglomeration, thereby decreasing the benefit of addition and decreasing the material's overall performance [80-81]. The interaction of nanoclay and polymer matrix is equally important because strong interfacial bonding increases the tensile strength and modulus [83-83]. Processing conditions, such as injection molding parameters, also play a significant role in the determination of the final properties of composites. Injection speed, pressure, and temperature affect the nanoclay dispersion and directly affect the mechanical performance of the composite material [84]. Nanoclay affects the cell morphology and structure in microcellular composites. Studies by Zhao [85] show that nanoclay reduces cell size and increases cell density due to its nucleation effect, which promotes uniform cell distribution [86-87]. Interaction of nanoclay particles with polymer matrix further promotes cell nucleation and distribution because it provides more nucleation sites for finer and more uniform cell structures [88-92]. A high content of nanoclay can cause agglomeration of particles; this will influence the uniformity of cell distribution and reduce all the benefits offered by nanoclay reinforcement [93-99].

## 4. Effect of machining parameters

Machining parameters are critical factors influencing the performance and quality of composite materials. This review synthesizes findings from various studies on the impact of machining parameters, particularly focusing on nanoclay-reinforced composites.

### 4.1 Effect of nanoclay nontent on machining parameters

Several studies have analyzed the effect of nanoclay content on machining operations, mainly with respect to tool wear and surface roughness. Prabhu [101] observed that the addition of nanoclay to Carbon Glass Reinforced Polymer (CGRP) increases tool wear due to the abrasive nature of the nanoclay particles, a result in line with other studies which emphasized the correlation between higher nanoclay content and increased tool wear. In addition, surface roughness has been influenced by nanoclay content. Ragunath [102] reported a decrease in surface roughness with an increase in nanoclay content until 6%. However, it started to increase from that point and beyond due to agglomeration. Surface finish was, therefore, found to improve through better dispersion of the nanoclay particles into smaller sizes and reached an optimal level. Optimization of machining parameters like feed rate and spindle speed is critical. According to Prabhu, a lower feed rate at 0.1 mm/rev and spindle speed at 852 rpm minimizes delamination and enhances surface quality. The choice of tool material is also a determining factor since the carbide tools offer greater performance and much higher durability compared to High-Speed Steel (HSS) in handling the abrasiveness of the nanoclay-reinforced composites.

### 4.2 Impact of nanoclay on composite machinability

Nanoclay has an impact on machinability, especially in relation to tool wear, cutting forces, and surface finish. Increased hardness of the nanoclay particles increases the cutting forces and tool wear and calls for adjustment of machining parameters for optimal tool life and surface quality [102]. Although the inclusion of nanoclay can provide a better surface finish by reducing the void size and particle distribution. The excessive content of nanoclay leads to agglomeration, which aggravates the surface roughness. Other factors, such as depth of cut and tool geometry, also need to be considered during the optimization process of machining due to their interaction with nanoclay content, balancing tool wear, surface finish, and machining efficiency. Both experimental and modeling studies, such as finite element analysis, offer valuable insights into how varying nanoclay contents and machining parameters affect tool wear and surface roughness, providing a comprehensive understanding of the machining process. Table 5 summarizes the impact of nanoclay on machinability.

**Table 5: Impact of nanoclay on composite machinability**

| Aspect | Influence of nanoclay | Observations | Optimization considerations |
|---|---|---|---|
| Tool Wear | Increases due to the abrasiveness of nanoclay particles. | Higher nanoclay content accelerates tool wear. | Optimize machining parameters to reduce wear. |
| Cutting Forces | Increases with nanoclay addition due to particle harness. | Excessive cutting forces reduce tool life and machining efficiency. | Adjust feed rate and spindle speed for balance. |
| Surface Finish | Improves at moderate nanoclay content due to reduced void size and better particle dispersion. | Excess nanoclay leads to agglomeration, increasing surface roughness. | Optimize nanoclay content to achieve balance. |
| Nanoclay Content | Moderate content enhances machinability. Excessive content causes agglomeration, increasing roughness and tool wear. | Optimal content varies by composite type and machining process. | Identify optimal nanoclay percentage for specific applications. |
| Depth of Cut | Interacts with nanoclay content, affecting cutting forces and tool wear. | Larger depths of cut may amplify wear and roughness issues. | Match the depth of cut to nanoclay characteristics and tool material. |
| Tool Geometry | Influences chip formation and heat dissipation during machining. | Improper geometry can exacerbate tool wear with abrasive nanoclay particles. | Design tool geometry for better wear resistance and heat management. |
| Modeling Studies | FEA provides insights into the effects of nanoclay on machining parameters. | FEA helps predict optimal parameter combinations. | Use simulation tools to complement experimental findings. |



## 5. Optimization of the machining parameters

Optimizing machining parameters is the only method for enhancing drilling efficiency and quality when dealing with composite materials. The involvement of nanoclay reinforcement makes the process even more complicated. Such major parameters as feed rate, spindle speed, and material tool are responsible for optimum machining. Studies by Prabhu [101] and Ragunath [102] indicate that feed rate has a great influence on delimitation and surface roughness. Optimal feed rates minimize delimitation but feed rates too high can lead to tool wear and poor surface finish. Spindle speed affects cutting temperature and tool wear, where higher speeds reduce cutting forces but may increase wear; hence, a balance needs to be found to optimize tool life and machining efficiency. Tool material selection is also crucial, with carbide tools offering superior performance compared to HSS tools, especially when machining nanoclay-reinforced composites. The presence of nanoclay increases tool wear due to its abrasiveness, making carbide tools a preferred choice for these materials. Moreover, nanoclay may have a maximum optimum content to improve surface roughness, but excessive nanoclay will make the surface more abrasive with higher clogging potential. Optimization for these parameters would be possible with the use of DOE and RSM methods, wherein systematic analysis regarding the effect of parameters and the interaction of different parameters could be done. Regression models might also be used to predict performance in machining operations based on several factors, one of which includes nanoclay content. Table 6 shows the various optimization methods.

**Table 6: Optimization of machining parameters of composites**

| Parameter | Effects | Observations | Optimization Method |
|---|---|---|---|
| Feed Rate | Affects delamination and surface roughness. | Optimal feed rates minimize delamination and improve surface finish. | DOE, RSM, Regression models |
| | Excessive rates increase tool wear and reduce surface quality. | High feed rates lead to poor machining outcomes and wear | |
| Spindle Speed | Influences include cutting temperature, cutting forces, and tool wear. | Higher spindle speeds reduce cutting forces but increase tool wear. | DOE, RSM |
| | | Requires balancing speed for tool life and efficiency. | |
| Tool Material | Determines wear resistance and performance during machining. | Carbide tools outperform HSS tools, especially for abrasive nanoclay-reinforced composites. | Tool material selection analysis |
| | | HSS tools experience faster wear in such conditions. | |
| Nanoclay Content | Affects abrasiveness and surface roughness. | Optimal nanoclay levels reduce roughness, but excessive amounts cause higher roughness and potential clogging | Regression models, DOE |

## 6. **Future Scope:**

Nanoclay reinforced composites should focus on advanced optimization techniques, using artificial intelligence (AI) and machine learning (ML) to predict and fine-tune feed rate, spindle speed, and tool geometry with higher accuracy. Investigating the synergistic effect of hybrid fillers, like combining nanoclay with carbon nanotubes or graphene, on machinability and tool wear can further expand the material performance. The use of nanoclay in machining applications and the sustainability of such practices will be explored, covering the topics of eco-friendly cutting fluids and coatings in machining. Establishing robust models for predicting the effects of nanoclay content and processing conditions on tool wear and surface finish for composite systems will bridge the gap between laboratory experiments and industrial applications. Better efficiency and quality in composite manufacturing will be achieved through the understanding of nanoclay dispersion and its effect on machining outcome, along with real-time monitoring and adaptive control of the machining process.

## 7. Conclusions

Nanoclay in polymer composites improves mechanical, thermal, and fatigue properties but requires careful management to get the best out of it. Nanoclay generally improves tensile and impact strength within a specific concentration range; low to moderate concentration improves mechanical properties due to better dispersion and interfacial bonding. But excessive nanoclay can cause agglomeration and reduce strength and toughness. Its effect on thermal properties is complex, often improving thermal stability and glass transition temperature, but its effect on thermal conductivity is variable depending on composite structure and processing conditions. In terms of fatigue resistance, nanoclay can improve crack propagation mechanisms, but excessive amounts can negatively affect performance. Machining of nanoclay reinforced composites requires attention to feed rate, spindle speed, and tool material, as nanoclay is abrasive and tool wear is high, so we need to use durable tools like carbide. While nanoclay improves polymer composites, optimizing concentration, processing conditions, and machining parameters is necessary to get the best out of it and to get improvements in mechanical, thermal, and fatigue properties. Future research should focus on refining processing techniques and exploring the interactions between nanoclay and various matrices to further develop composite materials.

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