A Review on: Enhancement of Mechanical Properties of Al_2O_3-TiO_2/Epoxy Nano Composites

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Abstract: Epoxy resins (EP) are high-performance thermosetting polymers that are often used in construction applications because they are very stable in size, strong, resistant to chemicals, and attach well to other materials. But because they are naturally brittle, they can't be used in situations where there is a lot of impact. Recently, scientists have been working on making epoxy resins that are less likely to break. One of the most studied methods in polymer science is the addition of inorganic nanoparticles to the polymer matrix, such as alumina (Al_2O_3), titanium dioxide (TiO_2), silica (SiO_2), and other different types, which can be added either alone or in hybrid combinations (two or more types) with other modifiers to enhance overall mechanical performance. These nanomaterials have a high surface area to volume ratio, high surface energy, and light weight, which makes their properties unique. Also, metallic materials can be substituted with these nanocomposites in various fields, such as optoelectronics, semiconductors, automotive, and aerospace. Through reviewing many previous studies, it was shown that adding (TiO_2) to any type of thermoset polymer significantly improved the toughness, while adding (Al_2O_3) increased the hardness, stiffness, and tensile strength. This overview of many studies focuses on the use of nanoparticles as reinforcements, their different shapes and interfaces, and the structure of the resin that is reinforced with nanomaterials. Also, the dispersion strategies, interfacial modifications, and the ensuing mechanical enhancements are summarized in this review to highlight toughening mechanisms and the synergistic effects of hybrid systems.

Keywords: Hybrid Systems, Epoxy Resin, Alumina, Titanium Dioxide, Mechanical Properties.

1. Introduction

Epoxy resins are utilized in high-performance sectors due to their chemical flexibility and processing capabilities. They are particularly used in fiber-reinforced composites in aviation and renewable energy, serving in the production of wind turbine and airplane components. Additionally, their strong adhesion and processability make them suitable for traditional applications like engineering adhesives, coatings, paints, and electronic device manufacturing. Since their discovery, epoxy resins have become essential in composite research and development [1]. Thermoset polymers like epoxy

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dissolve instead of melting when heated. The viscosity of uncured thermosets is low because of their short molecular chains. A curing technique is used on these chains to produce a 3-dimensional crosslinked network. This structure has four different kinds of bonds: network, crosslinked, branching, and linear [2], as shown in figure 1 below.

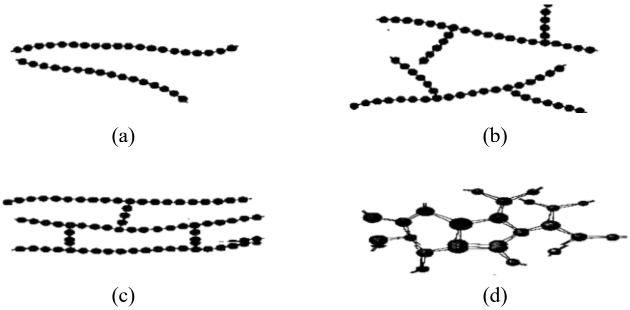

Fig. 1. Schematic illustrations of (a) linear, (b) branched, (c) crosslinked, and (d) network 3D molecular structures [3].

Pure epoxy resins have several problems that make them less useful, such as being brittle, having low tensile strength, and not being very resilient when they break. To solve these problems, epoxy nanocomposites have been made using reinforcing nanofillers or hybrid nanoparticles like Al_2O_3 and TiO_2 [3]. This integration improves the mechanical and functional performance of epoxy resins, making high-efficiency nanocomposites with better mechanical, thermal, and durability qualities.

1.1 Nanomaterial as Reinforcement

Nanomaterials are becoming increasingly significant in nanotechnology, and they may be used in everything from toys to planes. These materials, which range in size from 1 to 100 nm, are typically too small for the human eye and ordinary optical microscopes to see. To analyze them, we need complicated approaches. The scanning electron microscope (SEM) is a common instrument for looking at the surface structure of nanoparticles. It uses an electron beam to provide detailed pictures that aid with this [4]. Materials at the nanoscale display characteristics that differ from those at greater sizes, mostly affected by relative surface area and the quantum limitation effect. As particles get smaller, more atoms gather toward the surface; this makes nanoparticles have more surface area and energy per unit mass. The ratio of surface area to volume increases as the size of the particles gets smaller, especially for particles less than 100 nm [5]. See Figure 2.

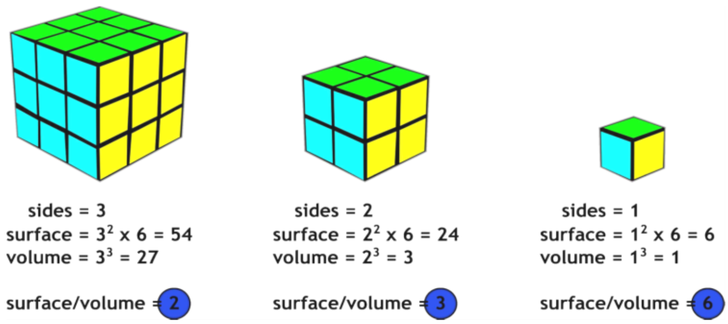

Fig. 2. The surface area per unit volume [3].

1.2 Influence of Adding Al_2O_3 Nanoparticles on Epoxy

Nano-Al_2O_3 is one of the most common metal oxides used to make polymer nanocomposites that have better mechanical and thermal characteristics. Another good thing about alumina nanoparticles is that they are cheaper to make than carbon-based nanofillers and nanotitania [6]. Several studies examined the mechanical properties of alumina nanocomposites, highlighting both their potential and their limitations.

Initially, **Verma et al**. explored how the weight percentage, size, and shape of Al_2O_3 nanofiller change the tensile characteristics and fracture toughness of epoxy composites. They tried out spherical nanoparticles and nanorods at 0.5, 1.0, and 1.5 wt.%. The research indicated that 1.0 wt.% of spherical nanoparticles enhanced tensile strength and failure strain by 10% and 29%, respectively. On the other hand, 1.5 wt.% of big nanorods made fracture toughness 52% better but made tensile strength and failure strain worse than tiny nanorods [7].

Continuity in this direction, **D. Bazrgari et al.** examined Al_2O_3 nanoparticles in epoxy resin using ultrasonic mixing and mechanical stirring, finding that up to 1% vol. improves the nanocomposite's mechanical properties by increasing flexural strength, stiffness, and impact strength, while lowering wear rate and friction coefficient. But above 3% vol., these benefits decrease because the nanoparticles bond together [8].

To further evaluate this path, **Khalil et al.** improved the thermal and mechanical properties of epoxy adhesive by using 0.5–1 wt.% alumina nanoparticles. At 1 wt.%, tensile strength improved by 54% compared to pure epoxy, but when the load was increased, the strength dropped because the particles bonded together. At 30°C and 0.5 wt.%, the storage and loss modulus rose by 17.3% and 68.3%, respectively. The study shows that the highest performance comes from a reinforcement ratio of 0.5 to 1 wt.% [9].

Fouly A, Alkalla M, more recent investigations show that adding alumina nanoparticles (0.1–0.4 wt.%) greatly improves the mechanical characteristics of epoxy resin. With 0.4 wt.% Al_2O_3, toughness improved by 47.3%, ductility by 12%, hardness by 14%, Young's modulus by 22%, and compressive yield strength by 25.3%. Also, the friction coefficient declined by 32%, which made it more resistant to wear. FEM and SEM measurements verify these results, indicating a 43% increase in surface roughness and a 31.5% decrease in shear stresses. This shows that the performance of the epoxy may be improved without losing its light weight [10].

1.3 Influence of Adding TiO_2 Nanoparticles on Epoxy

Titanium dioxide (TiO_2) is a safe element that is useful in nanomaterials for health and environmental purposes since it is biocompatible, strong, and stable. Scientists are very interested in titanium dioxide nanoparticles (TiO_2 NPs) since they are used in many different ways and made in many different ways. Also, TiO_2 is a nanofiller in composite systems and is easy to find in shops.

According to **Kumar et al.**, research was conducted that involved incorporating TiO_2 nanoparticles (30-40 nm) into an epoxy matrix at concentrations of 5, 10, and 15 wt.% by the UDM method to enhance dispersion and minimize agglomeration. The findings demonstrated that a 10% TiO_2 incorporation maximized tensile strength and toughness, improving them by around 22% and 69%, respectively. On the other hand, raising the TiO_2 level to 15% caused big agglomerates to develop, which made the mechanical characteristics deteriorate [11].

In other research, according to **Spinella et al.,** a reactive suspension approach was used to make epoxy/TiO_2 nanocomposites in other studies. This process generated hydrogen bonds at the particle/polymer interface, which improved the mechanical characteristics compared to regular mechanical mixing. The reactive suspension approach produced superior elastic modulus, glass transition degree, and uniform particle distribution, while inhibiting agglomeration, in contrast to the traditional method, which resulted in significant aggregates and poor performance [12].

Also, many studies deal with using TiO_2 as a reinforcement, such as **Sagar et al.** evaluated epoxy composites reinforced with TiO_2 nanoparticles at concentrations ranging from 0.5 to 2.5 wt.%. The highest mechanical performance, with a 51% increase in tensile strength and a 10% increase in compressive strength, was seen at 0.5 wt.%, which was due to strong bonding at the interface. More TiO_2 made the elastic modulus and hardness better, whereas less TiO_2 made the thermal stability much better [13].

In another advanced research study, **Al-Hawezi et al.** mixed flowable dental resin with TiO_2 nanoparticles (50 nm) at concentrations of 1.25% and 2.5%. We tested the composite resins to see how hard, flexible, and strong they were. The results showed that 1.25% TiO_2 NPs made materials harder by more than 2.5%. With 1.25% TiO_2, the flexural strength reached its highest point at 134.5 MPa. With 2.5%, it dropped to 85.5 MPa. Lastly, when the concentration of TiO_2 was enhanced from 1.25% to 2.5%, fracture toughness became better [14].

1.4 Influence of Adding Hybrid (Al_2O_3/TiO_2) Nanoparticles on Epoxy

Hybrid nanoparticles, made by mixing two or more types of nanofillers in a polymeric matrix, increase mechanical properties in a way that is better than single-filler systems.

At first, **Dhabale & Jatti**, work looks at how to make biocomposites from LDPE reinforced with Al_2O_3 and TiO_2 utilizing injection molding. The best mix was 70% LDPE, 10% TiO_2, and 20% Al_2O_3. It was hardness (55 Shore D) and had better tensile (12.65 MPa) and flexural (15.09 MPa) strengths than pure LDPE. Alternatively, a mix of 85% LDPE, 10% TiO_2, and 5% Al_2O_3 was better at resisting impacts, and wearing was reduced when the amount of alumina was increased. These composites might be useful in medicine, such as for orthopedic implants and replacement parts [15].

Further studies deal with hybrid nanocomposites, like **Ugla et al.** employed a commercial coating with Al_2O_3 and TiO_2 nanoparticles (25, 50, and 75 wt.%) to improve AISI 410 steam turbine blades. The coatings were made by spraying air and mixing it with ultrasonic waves, and then they were tested mechanically. The results revealed that adding more Al_2O_3 makes the material stronger and harder, with the best results at 75% Al_2O_3 + 25% TiO_2. Coated samples showed a far lower rate of wear than natural specimens. This shows that nanocoatings increase mechanical performance and make turbines last longer [16].

Also, many studies conducted in this field, like **Njim et al.** investigated the mechanical behavior of functionally graded viscoelastic materials that have been reinforced with hybrid nanoparticles of Al_2O_3 and TiO_2. The study discovered that combining PLA with different nanoparticle fractions (1–5%) and placing the models through different mechanical examinations resulted in an ideal ratio of 1.5% Al_2O_3 and 3% TiO_2, which improved mechanical properties: the maximum flexural load increased by 17%, the tear strength by 27.5%, and the impact strength by 7.5%. The conclusion makes it obvious that nanohybrid reinforcement works better than single reinforcement [17].

Kabakçı et al. conducted a recent study in which they generated epoxy composites reinforced with (Al_2O_3/TiO_2) nanoparticles, showing enhancement in mechanical characteristics, especially at a 1.25% Al_2O_3 reinforcement level. The hardness rose by 7%, while the yield tensile strength and ultimate stress increased by 140.32% and 195.8%, respectively, as compared to pure epoxy. The nanoparticles and the epoxy matrix connect well at the interface, which is what makes these improvements possible [18].

2. Discussion

Research shows that the best combination of composite parts improves properties. Ultrasonication and mechanical mixing give better outcomes. Hybrid epoxy composites made with these methods have better thermal and mechanical properties because the nanoparticles are evenly distributed through the epoxy matrix and the interactions between the two materials are solid.

i. **Agglomeration Factor:** Several studies, such as this by D. Bazrgari et al., demonstrate that heightened surface energy of nanoparticles results in substantial agglomeration when concentrations surpass 0.25 wt.% to 1.0 wt.%. These agglomerates form holes or flaws in the polymer matrix, which greatly lowers the mechanical characteristics, even when more nanofiller is used. This pattern indicates that the quality of the dispersion has a bigger effect than just the amount of additive.

ii. **The impact of shape and size:** The dimensions and morphology of particles strongly influence reinforcement mechanisms. Verma et al. found that bigger Al_2O_3 nanorods made fracture toughness 52% better, whereas spherical particles made tensile strength and fracture stress better. This indicates that the kind of nanostructure affects toughness processes, with rods perhaps being better at connecting fractures or deflecting cracks than spheres.

iii. **Mixing Method:** Preparation techniques are crucial for achieving superior mechanical properties in materials. Kumar et al. showed that ultrasonic dual mixing (UDM) works well for making materials distribute evenly. Spinella et al. also observed that reactive suspension makes hydrogen bonds, which makes cross-linking stronger and the elastic modulus and glass transition rate better. This illustrates how nanofillers make components stronger by controlling how chemicals and physical forces interact with each other.

iv. **The best mixing ratio:** The best TiO_2 concentration depends on the size of the particles and the qualities you want. Sagar et al. discovered that a concentration of 0.5% wt. optimized tensile strength (51%), whilst elevated concentrations (up to 2.5%) enhanced stiffness and thermal stability. Conversely, Kumar et al. said that 10% wt. made toughness (69%) and tensile strength (22%) better. This shows that there is a balance between stiffness, which is helped by higher particle density, and tensile strength, which needs perfect distribution at smaller amounts.

3. Conclusion

Researchers are enhancing the mechanical characteristics of epoxy by using nanoparticles, focusing on ideal application methods and dimensions to prevent negative effects. Nanoparticles having a lot of surface area make it easier for epoxy resin to interact with them, but aggregation could damage the mechanical features. Some of the biggest problems include making sure that nanoparticles are spread out evenly, keeping performance parameters, and making production cost-effective. In the future, researchers will probably look at hybrid nanofillers, bio-based epoxy systems, and multifunctional composites that not only strengthen the structure but also have properties like self-healing and energy storage. There are also suggestions for choosing nanoparticles that will improve the mechanical properties of composite materials.

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