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Impact Loading on Polymer Nanocomposites - A Comprehensive Review

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ABSTRACT

In recent days, the application of polymer nanocomposites (NC) has grown exponentially due to its varied applications and efficacy. However, it is also associated with various challenges and need of optimal solutions to address the same. Excellent properties in the area of high strain rate applications are usually addressed during fabrication of nanocomposites using graphene, nano fillers, nano clay and carbon nano tubes. Such NC offer good properties associated with thermal stability and unique desirable properties making them excellent replacements for conventional materials used so far. Their applications are found in defense, space and automobile sectors. Though NC have numerous positive characteristics, the reason behind their failure mechanism under loading conditions with static and dynamic is unanswered or not comprehensively clear. This article enumerates the collective review of the challenges and solutions addressed by various researchers. It includes techniques used for characterizing nanocomposites with respect to failure governing mechanism for both organic and inorganic NC.

Keywords: Polymers; Impact load; Molecular dynamics; Nanocomposites; Strain rate.

1. INTRODUCTION

Impact loading on polymer nanocomposites (NC) is a major area of research that addresses the response of these advanced materials to sudden and dynamic forces. This field has received significant attention due to the increasing demand for durable materials with lighter weight in various applications ranging from automotive components to protective gear and structural elements. Understanding how polymer nanocomposites behave under impact loading conditions is vital for optimizing performance and ensuring reliability in real-world scenarios. When subjected to impact loading, polymer NCs exhibit complex deformation mechanisms influenced by factors such as nanoparticle dispersion, matrix properties, interfacial interactions, and loading conditions. These materials often demonstrate enhanced mechanical properties compared to the conventional polymers, due to the synergistic effects of nanoparticles that reinforce the polymer matrix and improve energy dissipation capabilities. Through comprehensive analysis and experimentation, the goal is to advance the understanding of how these materials withstand and dissipate energy during impact events, thereby paving the way for innovative applications in fields where lightweight, impact-resistant materials are indispensable. This review highlights both current challenges and future opportunities in this rapidly evolving field of materials science.

2. LITERATURE SURVEY

Nanocomposites are materials that are composed of a matrix material and a reinforcing material that has a particle size in the nanometer range. These materials find their place in various engineering applications because of their exceptional properties. Researchers have been working on NC that can prolong high strain rate (SR) loading. This is because traditional materials have limitations in energy absorption and dissipation under high SR loading conditions. Nanocomposites are lightweight with high strength and stiffness. They efficiently absorb and dissipate energy, making them ideal for developing blast-resistant materials for various engineering applications (Faur-Csukat, 2006). Moreover, the unique properties of NCs can be tailored by controlling their structure, composition, and processing conditions, adaptable for different engineering applications. Researchers have investigated combining natural fibers (NF) with synthetic fibers (SF) or other reinforcing materials. By integrating

NFs with SFs, the resulting composite can harness the beneficial properties of each component. For instance, Periyasamy *et al.* (2023) found that the synthetic fibers improved the properties, while the natural fibers contributed to the environmental benefits and also reduced material costs. Their study provided insights towards the current state of plant-based natural fiber–reinforced composites (NFRCs) and their industrial applications as sustainable alternatives to conventional composites. Mani *et al.* (2023) demonstrated the feasibility of high-density polyethylene (HDPE) films and natural fibers in fabricating decorative tiles with improved qualities, an alternative for more sustainable and eco-friendly materials in the construction and interior design industries. The study involved reinforcement of natural fibers in the HDPE matrix, making it suitable for various applications involving higher strength and impact resistance. The relatively unchanged hardness and density values implied that the composite tiles did not lose other important characteristics while gaining the desired mechanical enhancements.

The dynamics of materials are highly influenced by the SR during loading, and this is especially important in case of structural components subjected to severe dynamic conditions of loading such as impact and collision. Researchers are consistently working on optimizing the composition, structure, and processing of NC that possesses high energy absorption and dissipation. The strain rate during dynamic loading usually varies between 10^1 to 10^4 s^{-1}, depending on the loading conditions. One strategy involves integrating reinforcing nanoparticles, having higher specific surface area and excellent interfacial bonding, with the matrix. This integration improved the properties of the resulting NC. Furthermore, the dynamic behavior of the material is not only influenced by the composition but also by the processing conditions.

Table 1. Milestones in testing (Field *et al.* 2004)

Year	Milestones	Remarks
1978-80	Direct impact Hopkinson bar miniature	Viscous behaviour of dislocations
1985-86	Split-Hopkinson Pressure Bar (SHPB)	Structure and concrete testing
1990-91	One pulse loading SHPBs technique	Soft recovery techniques
1991-93	Torsional SHPB	Lubricants - sliding friction and shearing properties
1992-03	Polymer SHPB	Foam testing
1997-02	Wave separation techniques	Extension - effective length
1997-98	Magnesium SHPB	Softer materials
1998-99	Radiant methods for heating	Heating metallic specimens (SHPB)
1998-02	Wave propagation	Non-uniform viscoelastic rods
1999	Pulse torsion	Safe, reaction free operation
2003-04	Extension of Hopkinson bar	Strain rates - intermediate
2003-04	Speckle metrology	Deformation in specimen

Table 2. Test results from ballistic impact (Naik and Shrirao, 2004)

Specimen: Plain weave E-glass/epoxy
Twill weave T300 carbon/epoxy composites
Size : d ¼ 5 mm, h ¼ 2 mm

Material	m_p (g)	$V_{BL,}$ (m/s)	V_{50} (m/s)	r_d (mm)	r_e (mm)	r_t (mm)
A_1	2.9	158	151	9.7	11	36
A_2	1.9	99	104	-	-	58
A_3	2.9	84	-	-	-	62

A_1 - E-glass; A_2 - Twill Carbon (T300); A_3 - Twill Epoxy (T300)
m_p - Projectile mass; V_{BL} - Predicted ballistic limit; V_{50} - Experimental ballistic limit
r_d - Predicted damage; r_e - Experimental damage; r_t - Predicted surface cone radius

Another study by Iyyadurai *et al.* (2023) emphasized the potential of epoxy hybrid composites (CQF-reinforced) with TiB_2 filler for diverse applications, including automotive, electrical, and construction sectors. These composites offer a compelling combination with higher mechanical and dielectric properties, making them versatile for replacing traditional materials with sustainable, high-performance alternatives. However, further testing and validation in real-world applications may be necessary to fully assess their suitability and performance in specific industrial sectors. For example, high-pressure shockwave compaction and dynamic compression techniques can be used to achieve high-density NC with improved mechanical properties and energy absorption capacity. Therefore, researchers need to carefully design and test

NC under different strain rates to ensure their performance under dynamic loading conditions (Field *et al.* 2004; Hopmann and Klein, 2015; Shui-Sheng *et al.* 2013).

Table 1 shows different milestone in testing. This can involve employing techniques such as Split-Hopkinson Pressure Bar (SHPB) testing for simulating dynamic loading and measure the material's dynamic response. Developing high-performance structural components capable of withstanding dynamic loading necessitates a comprehensive knowledge on the behaviour of the material and tuning its properties to meet specific requirements. The NCs offer a promising approach for developing such materials because of their exceptional properties and the ability to customize their composition and structure (Smith and Hetherington, 1994). Fiber materials (carbon, glass, Kevlar, and Spectra) were utilized in the development of high-performance NCs. Carbon fiber finds its wider applications in the aerospace and automotive industries. Glass fiber, known for high strength and low cost, is employed in the construction industry. Kevlar fiber, with its exceptional tensile strength and superior energy absorption capacity, is frequently used for ballistic protection applications (Jiang *et al.* 2018; Nandi *et al.* 2011; Wu *et al.* 2006; Yamauchi *et al*. 2008). Table 2 shows the ballistic impact data for E-glass, Twill carbon (T300) and Twill epoxy (T300).

In another study (Felix *et al.* 2023), addition of nano-silica to the cissus quadrangularis stem fiber (CQSF) reinforced epoxy NC resulted in significant improvement in mechanical properties. These enhanced mechanical properties make the composite a promising material for wider applications, like usage in structural components, automotive parts, and various engineering projects. However, further research and testing are necessary to optimize the nano-silica content for specific applications and to evaluate performance under varied environmental conditions. Researchers have used computational and experimental approaches to study characteristic properties in composites. Various failure mechanisms have been identified in these composites under dynamic loading conditions. Delamination between layers, compressive failure, matrix cracking, and tensile failure are among the primary failure of these composites under impact loading (Bresciani *et al*. 2016; Hazell *et al*. 2009; Naik and Shrirao, 2004).

Understanding the failure mechanisms is essential for developing strategies to improve the performance of NCs under dynamic loading conditions. Researchers employed diverse strategies, such as, modifying the fiber-matrix interface, optimizing the architecture, and incorporating nanofillers to improve their mechanical performance under high SR loading conditions. The defects in composites typically occur in the scale of micrometers, while nanofillers have dimensions in the nanometer range, allowing them to fill in the gaps between the fibers in the composite and reinforce the material at a smaller length scale (Hasanzadeh *et al*. 2019; Hassanzadeh-Aghdam and Ansari, 2019; Hucker *et al*. 2003). Furthermore, computational modeling and simulation techniques have also been helpful in predicting the dynamic behavior of the composites and designing new materials with customized properties to meet specific application requirements (Bandaru *et al*. 2015; Mata-Diaz *et al.* 2017; Pernas-Sánchez *et al.* 2016; Reddy *et al.* 2017; Reis *et al.* 2018; Suresh *et al.* 2022). Fig. 1 shows the absorbed energy and specific energy density plots for different composites.

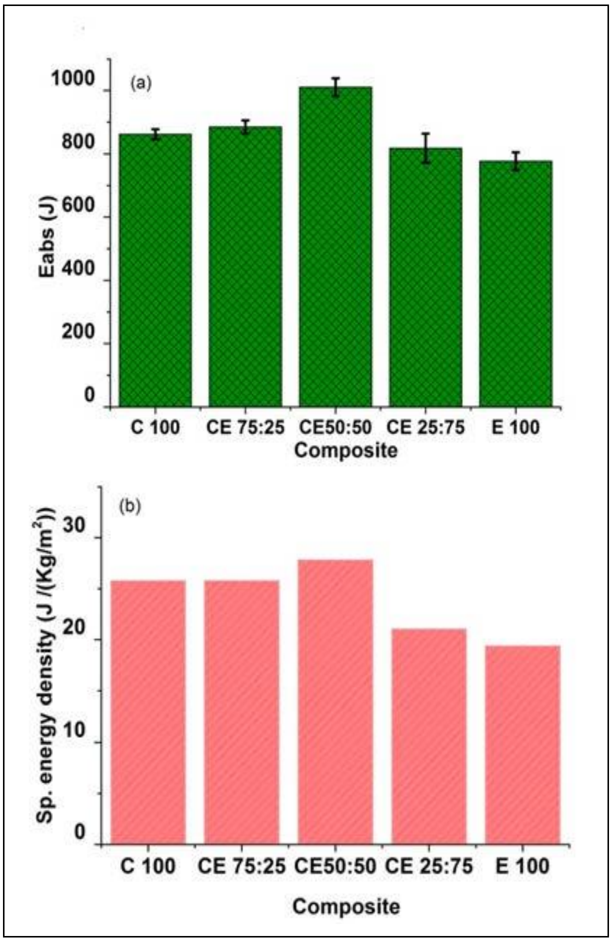

Fig. 1: (a) Composites - Absorbed energy, (b) Composites - Specific energy density (Reddy *et al.* 2017)

Nanocomposites and hybrid NCs exhibit excellent blast-resistant properties. The addition of NCs significantly enhances the properties (de-Borbón and Ambrosini, 2013). Researchers have demonstrated improved energy absorption in glass/polymer composites by carbon nanotubes (CNTs) as nano-reinforcements. The inclusion of CNTs into the matrix enhanced the properties (Boddu *et al*. 2016; Ma *et al.* 2014; Kumar *et al*. 2021b). However, the higher cost of NCs remains a limiting factor for their widespread application.

Currently, the production cost of NCs is higher than that of conventional composites due to the added expenses associated with producing and incorporating nanomaterials. As a result, their application is primarily limited to high-end industries such as aerospace, defense, and automotive (Gómez-del *et al.* 2014; Miao *et al.* 2016; Pandya *et al.* 2015). Table 3 shows the strain rate and strain rate sensitivity values for different materials.

Table 3. Strain rate and SR sensitivity of different materials (Gómez-del *et al.* 2014)

Material	SR, (s^{-1})	Classification	SRS, β (MPa)
A	0.001 - 0.1	Q_s	2.6
	1569 - 3203	D	35
B	0.001 - 0.1	Q_s	2.7
	1569 - 3203	D	38
C	0.001 - 0.1	Q_s	1.1
	1569 - 3503	D	54
D	0.001 - 0.1	Q_s	2.7
	1569 - 3403	D	46

A - Neat epoxy; B - Epoxy + SBM; C - Epoxy + CNTs; D - Epoxy + SBM + CNTs; Q_s - Quasi-static; D - Dynamic; SR - Strain rate; SRS - Strain rate sensitivity;

Nanomaterials and nanoclays are extensively utilized in the development of armor and blast-resistant materials (Miao *et al.* 2016). These materials are chosen for their exceptional mechanical properties, including thermal and electrical conductivity (Falvo *et al.* 1997). Graphene holds great promise for the development of blast-resistant materials. Its 2D structure offers high surface area, exceptional tensile strength, and excellent electrical conductivity. Graphene-based NCs have proven track record in enhancing mechanical properties and exhibiting excellent energy absorption capacity (Lim *et al.* 2011; Ma *et al.* 2010). Graphene nanosheets, like graphene or CNTs, are utilized for reinforcing polymer-based NCs. They share a two-dimensional structure with graphene but are more cost-effective and easier to produce in large quantities. When incorporated, graphene nanosheets enhance the mechanical properties. Moreover, graphene nanosheets are particularly suitable for applications in electronic and thermal management due to their exceptional thermal and electrical conductivity (Han and Fina, 2011; Kumar *et al.* 2019). Graphene oxide (GO), enhances the interfacial properties of polymer matrices by promoting better dispersion and bonding. It acts as a precursor for producing reduced graphene oxide (rGO), which involves partial or full reduction to remove oxygen functional groups. The rGO shares similar properties with graphene and is employed as reinforcement material in various applications (Bortz *et al.* 2012; Kumar *et al.* 2020).

Rajaram *et al.* (2023) have extensively discussed the emergence of metal-organic frameworks (MOFs) in a comprehensive review work. They provided an overview for better insight on MOF synthesis, their unique structure, properties, and significance. The exceptional properties of MOFs that include high surface area and pore structures (customizable) render them highly attractive for diverse applications.

Nanoclay, an inorganic nanofiller is used for the development of pyrolytic boron nitride (PBN). It is composed of layered silicates that have a plate-like morphology, which provide an excellent reinforcing effect in polymer matrices. When nanoclay is added to a matrix, it improves stiffness, strength, and toughness of the matrix. It can also improve thermal stability and flame retardancy of the matrix. These improved properties make nanoclay-reinforced polymer-based NC a potential candidate for blast-resistant armor grade materials. Nanoclay is comparatively more affordable than other nanofillers (carbon nanotubes and graphene), making it a more appealing choice for large-scale industrial applications (Brownson *et al.* 2011).

Table 4. Effect of CNT dispersion (Ma *et al.* 2010)

Technique	FM, (GPa)	FS, (MPa)
N_e	3.44 ± 0.01 (+0.00%)	141.0 ± 2.3 (+0.00%)
W_s	3.40 ± 0.04 (0.57%)	143.1 ± 1.8 (+2.94%)
S_m	3.37 ± 0.09 (2.07%)	141.4 ± 2.4 (+0.28%)
P_s	3.46 ± 0.06 (+1.15%)	143.7 ± 1.7 (+1.94%)
C_g	3.66 ± 0.02 (+6.42%)	144.2 ± 0.82 (+3.72%)

N_e - Neat epoxy; W_s - Sonication in water bath; S_m - Shear mixing; P_s - Probe sonication; C_g - Calendering; FM - Flexural modulus; FS - Flexural strength

Montmorillonite, a type of clay mineral, is frequently employed as a nanofiller in polymer-based NC. This clay mineral has a layered structure, and its individual layers disperse in a polymer matrix forming NC material. The resulting NC displays enhanced mechanical properties and barrier properties such as resistance to gas and moisture permeation (Ma *et al.* 2010; Uddin *et al.* 2018). The incorporation of nanoclay into the matrix provides additional benefits of increased fire resistance, UV protection, and dimensional stability. Nanoclay serves as a diffusional barrier, effectively reducing the permeability of gases and liquids. The high heat deflection temperature of nanoclay significantly contributes to the thermal stability of the composite (Kumar and Parashar, 2016). Hexagonal boron nitride (h-BN) is an inorganic nanofiller with a layered structure similar to graphite. It can be synthesized in the form of nanotubes or nanosheets. The h-BN finds its applications in electronics, energy storage, and high-temperature materials. When incorporated as a nanofiller in polymer-based nanocomposites, h-BN enhances their mechanical properties (Ray and Okamoto, 2003).

Achieving a uniform dispersion of nanofillers is a critical challenge in developing high-performance NCs.

Nanofiller agglomeration, driven by van der Waals forces, creates weak points and degrades the mechanical characteristics. Addressing this issue is essential in terms of performance and reliability of NCs. Hence, researchers use various techniques such as sonication, mechanical mixing, and chemical functionalization to improve the dispersion of nanofillers. Additionally, surface modifications such as functionalization with organic groups or inorganic coatings are also employed to enhance the compatibility between filler and matrix. In situ polymerization is effective in producing NC with excellent interfacial adhesion and uniform dispersion of the nanofiller, which are crucial for enhancing the overall properties. The impact of incorporating custard apple (CSA) seed powder on the mechanical, thermal, and biodegradability properties of SGF/epoxy composites was performed in a study by(Kumar *et al*. 2022). The findings highlighted the potential of CSA as a reinforcing filler in composite materials. Enhanced mechanical properties, thermal resistance, and biodegradability are desired attributes of NCs for their application in different areas. Further research and optimization are necessary to determine the optimal content of CSA seed powder for specific applications and to evaluate the long-term performance in diverse environmental conditions. Suyambulingam *et al.* (2023) explored improving the wear behavior of hybrid composites by incorporating custard apple seed powder as a filler. The study analyzed the mechanical properties, wear resistance, and durability of natural fiber-reinforced composites with varying fiber volumes, aiming to reveal potential applications across various industries.

Solution-based methods involve dispersing the nanofiller in a solvent, adding the polymer matrix, and then removing the solvent to produce nanocomposites with high filler content and uniform dispersion. Melt mixing, on the other hand, entails blending the nanofiller and polymer matrix at elevated temperatures. This method generally achieves good dispersion of the nanofiller but may result in some agglomeration. It is widely preferred for large-scale production of NC due to its simplicity and cost-effectiveness. Also, techniques for developing nanocomposites suited for high strain rate and blast-resistant applications are discussed (Maksimkin *et al.* 2012; Sharma and Parashar, 2020). Table 4 shows the effect of CNT dispersion.

2.1 Computational Approach

It is true that experimental techniques are essential for characterizing the properties and behavior of NC. Also, the failure morphology is influenced by the atomic level interactions between the matrix and the reinforcing materials. The capabilities of experimental techniques tend to limit the characterization of NCs. For example, it may be challenging to observe the atomic-level interactions that govern the mechanical properties and failure mechanisms of NCs using traditional experimental techniques. Therefore, researchers have turned to computational techniques to complement and extend experimental observations. With advanced computational tools, researchers can develop sophisticated behavioral models to study the mechanical response of NCs under higher strain rates. These models encompass pure atomistic models (AM), multi-scale models (MM), and continuum-based models (CBM), each capable of simulating NC behavior across different length and time scales. In a multi-scale approach, researchers can accurately capture the complex interactions between the matrix and reinforcing material at the atomic level, while also modeling behavior of the material at larger scales. This method provides a realistic representation of NC properties under high strain-rate loading conditions.

Conversely, in structural mechanics-based approaches, the geometric structure of nanofiller is often represented as a space frame, while the matrix is treated as a continuum. This allows for modeling NC behavior using continuum mechanics principles, assuming the material is homogeneous and continuous. This approach is valuable for understanding macroscopic behaviors and interactions within NC structures.

Li and Chou simulated carbon-based nanofillers using the structural mechanics approach of atomistic model (Kumar *et al*. 2015). The study used a molecular mechanics approach to model the CNTs as a space frame structure, which was then integrated with the continuum mechanics for simulation. In their model, the CNTs were modeled as one-dimensional space frame structures, where each atom was treated as a point mass connected by elastic springs. The properties of CNTs, including their stiffness and strength, were determined through molecular mechanic simulations. In these simulations, the matrix was typically represented as a continuum using the finite element method (FEM). This computational approach enables researchers to solve equations of motion and predict the deformation and failure mechanisms of the nanocomposite at different scales, providing valuable insights into its structural behavior under various loading conditions. (Li and Chou, 2003) and Tserpes and Papanikos (2005) extended this model by using FEM to discretize NC into smaller finite elements, allowing the simulation at a larger length scale. The space frame structure representing the CNTs was integrated into the finite element mesh using appropriate boundary conditions to simulate the interactions between the matrix and reinforcing materials. This approach allowed for a more accurate and realistic simulation of the mechanical behavior of NC, taking into account the complex interactions between the matrix and reinforcing materials at both the atomic and macroscopic levels. To capture the failure morphology of NC, more appropriate and discrete atomistic models are required. These models explicitly simulate the behavior of each atom in the nanocomposite, taking into account the interatomic interactions, the bond formation and breaking that occur during deformation and failure.

Discrete atomistic models, such as Molecular Dynamics (MD) and Monte Carlo simulations, are capable of providing detailed information on the deformation and failure mechanisms of NC, including the formation and propagation of cracks, dislocations, and other defects. These models are also instrumental in studying the interactive effects of parameters such as temperature, strain rate, and size and shape of reinforcing materials on the mechanical behavior of NCs. Molecular dynamics simulations offer an effective alternative to continuum models for analyzing the mechanical behavior of NC. These simulations excel at capturing detailed factors related to failure morphology, making them particularly suited for investigating NC behavior at the atomic scale. By leveraging MD simulations, researchers can gain insights into how these factors influence the structural integrity and performance of nanocomposites under varying conditions. Molecular dynamics simulations employ classical mechanics to describe the motion and interactions of atoms and molecules within a system. They numerically solve the equations of motion, allowing the behavior of the system to be simulated over time with high detail and accuracy. Here, Newton's second law of motion governs the dynamics of each particle, determining how its motion is influenced by the forces acting upon it. The forces acting on each atom or molecule in the system are typically computed using a force field, which accounts for interatomic interactions and potential energies. By numerically solving these equations of motion, MD simulations can effectively model various deformation and failure mechanisms in NCs, including the formation and propagation of defects such as cracks and dislocations. Overall, MD simulations provide a powerful tool for investigating the structural behavior of NC at the atomic scale, offering insights into their mechanical properties and responses under different environmental and loading conditions. Despite their computational intensity, MD simulations have become an increasingly popular tool for investigating the mechanical behavior of NC. With the continued improvement of computational resources and algorithms, MD simulations are becoming more efficient and accurate, allowing for even more detailed and realistic simulations of nanocomposite behavior.

3. PERFORMANCE OF DIFFERENT NANOCOMPOSITES

3.1 Nanoclay-based NC

Nanoclay is widely utilized as a nanofiller in polymer-based nanocomposites, and research indicates that it significantly enhances the material properties. Nanoclay particles disperse uniformly throughout the polymer matrix due to strong interfacial interactions, improving load transfer and preventing crack propagation. Compared to conventional composites, nanoclay-based NC exhibit enhanced tensile strength, modulus, and impact resistance. In nanoclay/polymer-based NC, nanometer-sized clay particles are dispersed within the matrix. The properties of these NC depend on factors such as the type of polymer matrix, nanoclay loading, and the morphology of nanoclay particles in the matrix. Understanding the behavior of nanoclay-reinforced polymer NC under high strain rates is crucial, especially for applications involving high-speed impact or deformation. Researchers have conducted various studies to investigate the dynamic behavior of these materials to enhance our understanding of how nanoclay influences the mechanical response of polymer NC under dynamic loading scenarios, offering insights into optimizing their performance for applications in industries.

Wang *et al.* (2012) investigated the dynamic behavior of two distinct nanoclay-reinforced polymer nanocomposites. One type featured an organic clay-based polypropylene matrix, while the other utilized a modified montmorillonite-based matrix. The study was focused on the dynamic compressive yield response and proposed a micromechanical model for behaviour prediction under dynamic loading conditions. The work involved SHPB to apply dynamic compression loading at strain rates ranging from 10^2 to 10^4 s^{-1}, followed by quasi-static compression tests to obtain the static yield properties of the composites. The results indicated that the dynamic compressive yield strength increased with SR and surpassed the static yield strength. Researchers also noted that the dynamic compressive yield strength of the composites rose with higher volume fractions of reinforcement. They proposed a micromechanical model to predict dynamic behavior. This model considered the composite's microstructure and the properties of its individual components, providing insights into how these factors influence the material's response under dynamic loading conditions.

Peter and Woldesenbet (2008) investigated on syntactic foam composites reinforced with nanoclay to study their high SR behavior. These composites consisted of an epoxy matrix, microballoons, and nanoclay reinforcement. The study varied the nanoclay volume fraction from 1% to 5% and the microballoon volume fraction from 10% to 60%. The composite was subjected to high strain loading using SHPB. The inclusion of nanoclay in the syntactic foam composites enhanced their dynamic mechanical properties. This improvement was evidenced by higher compressive strength and modulus, along with increased energy absorption capacity. The researchers also noted that the optimal volume fraction of nanoclay in the composites depended on the volume fraction of microballoons. For example, with a microballoon volume fraction of 10%, the optimal nanoclay volume fraction was 3%. However, as the microballoon volume fraction increased to 40%, the optimal nanoclay volume fraction decreased to 2%. This finding underscores the complex interplay between nanoclay and microballoons in determining the optimal composite formulation for achieving enhanced mechanical properties under high strain conditions.

3.2 CNT-based NC

Carbon nanotubes have indeed been extensively investigated as reinforcing agents in NC designed for high SR loading conditions. Their exceptional tensile strength and stiffness render them highly desirable for enhancing the mechanical properties of composites intended for high-performance applications. The critical factors that significantly influence the properties of NC are achieving uniform dispersion, alignment, and strong interfacial bonding between CNTs and the polymer matrix. The challenge lies in preventing agglomeration of CNTs within the matrix, which can hinder their effectiveness in reinforcing the composite material. To address the challenges of achieving uniform dispersion and strong interfacial bonding between CNTs and the polymer matrix, various methods are employed. These include functionalization of CNTs with surfactants or polymers, sonication to disperse CNTs, and melt processing techniques. Additionally, coupling agents or surface treatments can be applied to enhance the interfacial bonding between CNTs and the matrix. Numerous studies have investigated the reinforcement of CNTs and their impact on the high strain rate behavior of polymer NC. These studies consistently demonstrate that the presence of CNTs improves the dynamic mechanical properties of the composite materials (Sabet *et al*. 2015; Zhu *et al*. 2003). Table 5 shows new techniques that are employed for the fabrication of CNT/polymer nanocomposite.

Table 5. New techniques for CNT/polymer nanocomposite (Ma *et al.* 2010)

Technique	CNT	Process	Advantages
Densification process	Used as CNT forest	a) The CNT is embedded into a bath of uncured epoxy resin. b) Impregnated into the CNT and subsequently cured.	1. Varying densification 2. Aligned CNTs
Spinning of coagulant technique	Surfactant solution	a) Structured into a mesh through wet spinning b) Transformed into a solid fiber through gradual drawing	1. Fabrication of fiber
Layer-by-layer deposition method	Pre-dispersion	a) Immersing solid substrates into solutions containing CNTs b) Followed by proper curing	1. Structural defects minimized 2. Higher loading
Pulverization technique	Used as received	a) Polymers and CNTs are blended together b) Followed by pulverization	1. Grafting of polymers 2. Scale-up 3. No solvent

Sun *et al*. (2009) have conducted a comprehensive review on the parameters that influence CNT based NCs and their properties. The review covers various aspects, including the shape, size, geometry, particle stiffness, aspect ratio, surface morphology, pretreatment of the nanofiller, and interfacial adhesion. They emphasized the critical role of optimizing these parameters to achieve maximal enhancement of CNT-based NC, particularly for high SR loading applications. Longer and thinner CNTs with higher aspect ratios were shown to impart superior mechanical properties to the NC compared to shorter and thicker tubes. The surface morphology of CNTs, including defects, functional groups, and amorphous carbon content, plays a crucial role in determining the interfacial bonding between the filler and matrix. Surface treatments, such as functionalization with surfactants or polymers, are effective methods to address these surface characteristics and enhance their bonding.

Energy dissipation mechanisms in single and multiwall CNT reinforced polymer matrices under high SR loading conditions was studied by (Suhr and Koratkar, 2008). The research explored various aspects of energy dissipation, focusing on how CNT properties such as aspect ratio, diameter, chirality, and number of walls affect the capacity of NC to dissipate energy. The study highlighted that energy dissipation primarily occurs through the deformation and fracture of the matrix, sliding, buckling, and breakage of CNTs. This optimization increases the number of CNT-polymer interfaces and improves interfacial shear transfer between CNTs and the matrix, thereby enhancing overall composite performance under dynamic loading conditions. In some cases, a reduction in strength occurs recorded after reaching a certain level of SR. This reduction in strength indicates the onset of dynamic failure mechanisms, such as localized deformation, damage accumulation, and crack initiation and propagation, which can result in premature failure of the NC. Moreover, the strength reduction can vary depending on factors such as the type of nanofiller, polymer matrix, and processing conditions employed during NC fabrication.

3.3 Graphene Nanofiller–based NC

The high SR performance of graphene-based NC, using a compressive SHPB at rates ranging from 1500 to 5000 s^{-1}, was investigated by Sun *et al.* (2009). The study examined the influence of graphene loading and interfacial bonding on the dynamic mechanical response of the NC. Results demonstrated that incorporating graphene into the matrix enhanced both the strength and stiffness of the NC under high SR conditions. Efficient load transfer was achieved through the addition of graphene. Shadlou *et al.* (2014) investigated dynamic loading using graphene nanoplatelets (GNP) in epoxy NCs, evaluating their impact under high SR conditions. The aspect ratio and dispersion of GNPs played pivotal roles in shaping the mechanical response under dynamic loading conditions. Thus, incorporating GNPs significantly improved the dynamic mechanical properties, specifically, the aspect ratio influenced load transfer efficiency and the dispersion affected overall mechanical properties in optimizing NC performance. Moeini *et al.* (2020) conducted a study on graphene/epoxy NC under high SR loading conditions ranging from 10^7 to 10^9 s^{-1}. The research evaluated the impact of graphene loading and orientation on the dynamic mechanical properties of the NC. Results indicated enhanced strength, stiffness, and energy absorption capacity of the NC, due to efficient load transfer between graphene and the matrix.

3.4 Inorganic Nanofillers

Guo and Li (2007) conducted a study on the uniaxial compressive behavior of nanosilica/epoxy NC under high SR ranging from 10^4 to 10^4 s^{-1} using a SHPB. The research demonstrated a substantial enhancement in compressive strength and energy absorption capacity with the addition of nanosilica at high strain rates. This indicates that nanosilica effectively improved the mechanical performance under dynamic loading conditions. The improvement in the compressive strength and energy absorption capacity of nanosilica/epoxy NC under high SR was attributed to enhanced load transfer and energy dissipation capabilities. This enhancement results from the strong interfacial bonding between nanosilica particles and the epoxy matrix. The study suggests that nanosilica/epoxy NC hold significant promise for high-performance applications subjected to dynamic loading conditions. Additionally, the research indicated that increasing the nanosilica content led to a 3% increase in yield stress and a 7% increase in flow stress of the nanosilica/epoxy NC. This demonstrates the effectiveness of nanosilica in reinforcing the epoxy matrix and improving its mechanical properties. At quasi-static strain rates, nanosilica/epoxy NC typically exhibits initial strain hardening behavior, where the material becomes harder and stronger as it deforms. However, under high strain rates, this strain hardening behavior may diminish or disappear due to the rapid deformation and dynamic loading conditions.

Naik *et al.* (2014) and Kumar *et al.* (2023) conducted a study using SHPB for analyzing the SR behavior of alumina/epoxy NC. Their research demonstrated that the addition of alumina nanoparticles significantly enhanced both compressive strength and energy absorption. Specifically, at a strain rate of 1000 s^{-1}, the compressive strength of NCs containing 2% and 5% alumina nanoparticles increased by 147% and 142%, respectively. This improvement in strength was attributed to effective stress transfer mechanisms from the epoxy matrix to the alumina NC. It was further supported by an increase in the interfacial bonding strength between the epoxy matrix and the alumina nanoparticles. These findings underscore the potential of alumina/epoxy nanocomposites for applications requiring superior mechanical performance under dynamic loading conditions.

4. CONCLUSION AND FUTURE ASPECTS

Nanofillers have been extensively studied owing to their remarkable mechanical properties and their potential towards improving the high strain rate behavior. Additionally, other nanofillers such as nanosilica and alumina have also shown promising contributions for enhancing the high strain rate properties of nanocomposites. Overall, the development and characterization of NCs for high strain rate loading is an active area of research with many promising findings. Split-Hopkinson Pressure Bar technique is widely used to improve the response of materials to high strain-rate impacts. This is done by measuring their dynamic stress-strain response. Other techniques such as the Kolsky bar and the Taylor impact test are also used, but to a lesser extent.

However, it should be noted that some studies have reported a reduction in strength of SR. Also, the specific type of nanofiller and level of dispersion, alignment, and interfacial bonding with the matrix are critical parameters affecting NC properties. When NC is under high SR loading, they experience sudden and intense deformation that generates stress and thermal shock waves. These waves can induce damage and initiate failure mechanisms. Such failures include debonding, fibre breakage, matrix cracking, delamination. The failure morphology of NC under high SR loading is therefore strongly influenced by the propagation and interaction of these waves with the NC structure. Inorganic nanofillers, such as metal oxides, clay, and ceramics can have exceptional thermal properties in addition to their mechanical properties. For example, some metal oxides, such as aluminum oxide have high thermal conductivity, while certain clays, such as halloysite nanotubes, have high thermal stability. Inorganic nanofillers such as, alumina, silica, and graphene have exceptional mechanical properties improving the high SR performance of NCs and thus used in the development of armor grade materials. Polymer and h-BN-based NC have the potential to be used in space and nuclear structures as replacements for conventional material. High neutron cross-section property makes them effective in shielding against harmful radiation in space and nuclear environments. Additionally, their lightweight and durable nature make them attractive materials for space applications.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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