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An overview of Mechanical properties of Nano-composites

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ABSTRACT

Due to the anisotropic, heterogeneous structure, and advanced mechanical properties of these materials combined with the size effects in micromachining, micromachining of nanocomposites is thought to be a challenging operation. In terms of high cutting force, poor surface quality, and rapid tool wear, it results in worse machinability. The first of these two parts of this review paper will provide a thorough overview of the mechanical characteristics of diverse nanocomposites, while the second part will concentrate on the micro-machinability of these nanocomposite materials.

INTRODUCTION

Blumstein used the term "Nano composite" for the first time in 1961 [1]. In an effort to increase the heat stability of nano-silicate reinforced polymethyl methacrylate (PMMA), the primitive nanocomposite was researched [2] in 1965, In terms of their constituents, Nano composites are comparable to traditional composites, with the exception of the size of the reinforcement, which is typically in the range of hundreds of nanometers. While requiring significantly less filler than conventional composites (hereinafter referred to as composites or conventional composites for short), the drop from micro-range to Nano-range of fillers offers amazing reinforcing in nanocomposites, resulting in negligible weight increases [3]. Due to their superior properties, including mechanical [7], thermal [8], electrical [9], electrochemical [10], electromagnetic [10], and gas barrier properties [11], many nanocomposites have been discovered and commercially used in a variety of industrial fields, including (but not limited to) aerospace [4], automobile [5], and medicine [6]. Due to these excellent qualities, Nano composites have found additional uses in the creation of microstructured components, continuing the modern manufacturing trend of downsizing. The Microelectronics has benefited greatly from the use of Nano composites [12]. Due to its perfect electrical conductivity, storage modulus, and environmental stability, carbon nanotubes (CNTs) reinforced polyimide nanocomposite is suitable for microelectronics devices, according to Tang et al. [13]. In contrast to their clean matrix equivalents, some applications, such as high performance transistors made of poly-4-vinylphenol (PVP)/TiO2 nanocomposite [14] or high energy density capacitors made of poly-vinylidenefluoride/TiO2 nanocomposite [15], have demonstrated superior performance. Furthermore, this trend toward shrinking might apply to both micromechanical and microelectronic components. When creating micro-products, nanocomposites may be used as an alternative to composites and alloys [16]. For instance, CNTs or carbon nanofiber (CNF) nanocomposites with greater strength-to-weight ratio and flexibility could replace conventional composites [19] such as carbon fibre, glass fibre, or Kevlar reinforced plastics in the manufacture of airframe [17] or wings [18] of micro-air vehicles (MAVs). CNT/Epoxy and CNT/PP nanocomposites have been used by Kumar et al. to create the artificial wings for MAVs [20]. The tri biological property, wear-resistance, and general mechanical properties of metal nanocomposites were further enhanced by the addition of ceramic nanoparticles [21]. As a result, these Nano composites could be employed to create micro-gears [23], linkage rods, or pistons [22]. It would be required to research the mechanical properties as well as workable processing methods to create Nano composites due to their enormous potential to develop micro-products. In terms of dimensional and geometrical accuracy as well as surface quality, the majority of current methods for creating Nano composites (Tcan only produce a near-net-shape. Post-processing or finishing technologies will therefore always be necessary. Several production techniques, including LIGA (Lithography, Electroplating, and Micro extrusion additive manufacturing [26], laser micromachining [25], and molding) [24], Mechanical micromachining and micro-EDM (Electrical Discharge Machining) [27] In order to create tiny, precise components and micro-structured components [29].

NANO COMPOSITES

While their final properties depend on the bonding at the matrix-filler interface, the arrangement of fillers inside the matrix, as well as the geometry and content of the fillers, nanocomposites typically retain the unique characteristics of both the matrix and the fillers that distinguish them from alloys. Nanocomposites also differ from composites in which one of the filler's diameters is between one and one hundred nanometers (nm). The next sections will go through each category's distinct characteristics as well as how filler phases affect them. The potential or commercial applications of various nanocomposites will be discussed in light of their distinctive features. Parallel to the explanation of nanocomposites, a comparison between nanocomposites and composites will be made in order to highlight the key distinctions between them in terms of the effects of filler content, size, and characteristics.

COMPARSION OF COMPOSITES AND NANO COMPOSITES

As was already established, the size of the fillers is the primary distinction between nanocomposites and conventional composites. The size of the fillers has shrunk from a few millimetres in classic composites to micro-scale (1-100 m) in modern composites, and more recently, nanocomposites with fillers with dimensions in the nanometer range. The primary goal of filler size reduction is to achieve homogeneous filler distribution within the matrix, which will lower stress concentrations inside the composite structure and ultimately improve its mechanical properties [30]. Additionally, smaller fillers have greater surface energies, which create stronger bonds with the matrix [31] and increase the system's stiffness and strength [32]. Essentially, based on the filler scale, there are two primary types of composite reinforcing mechanisms. The continuous mechanism is used to explain micro-fillers, showing that they bear a portion of the load supplied from the matrix and that the stickiness of the matrix-filler contact determines how effective reinforcement is [33]. The strengthening method is used for nano-filler (10–100 nm) when the interaction between the matrix and filler occurs at the molecular level. According to this method, the nano-fillers prevent the matrix from deforming plastically by preventing its dislocations, which increases the material's strength and hardness.

The impact of filler size on the mechanical characteristics of polymer composites has been studied by certain researchers. It was found that the size of fillers had no discernible impact on the tensile modulus of composites in the micro-range. Several experimental findings suggested that employing different particle sizes of Al2O3 (1-12 m), glass (4.5-62 m), or silica (2-47 m) did not significantly improve or even worsen the moduli of epoxy-based composites [34]. With PP/CaCO3 [38], poly-benzoxazine/CaCO3 [39], or polyester/Al [40], the similar tendency was discernible. Additionally, it's unclear how filler size and composite tensile strength relate to one another. While some research claimed that utilising micro silica particles to strengthen epoxy, tensile strengths of composites significantly increased with the reduction in filler size [37, 41], another result showed no trend of tensile strength variation of epoxy/Al2O3 when decreasing the filler size [35]. In general, it can be seen that the effect of filler size on the mechanical properties of composites at the microscale is negligible. The discussion above demonstrates the need to explore the impact of filler size at nanoscales in order to determine whether or not their impact on the mechanical characteristics of composites is more sensitive than that of their micro-counterparts. Snail shell powder in different filler sizes (150, 300, and 420 nm) was modified by Onuegbu and Igwe [42] to reinforce PP. With the reduction of filler size, it was seen that the tensile modulus, flexural strength, and impact strength all improved. These improvements weren't significant, though. For each weight fraction, for instance, the tensile strengths rose by about 5% when the filler size was reduced from 300 to 150 nm. Only when the filler size was kept below 100 nm did the mechanical characteristics of composites significantly improve. This effect was confirmed when Devaprakasam et al. [43] conducted a comparison of micro and nano-fillers in terms of the mechanical performance of polymer composites. This study used nano- and micro-silica with sizes ranging from 40 to 60 nm, and the results showed that the nanocomposite had less change in its modulus and hardness than the composite when varied loadings were applied. The uniform distribution of nano-fillers and their stronger interfacial matrix-filler bonding in comparison to micro-fillers were used to explain the phenomenon, some more studies also revealed that filler sizes had a dominant impact on mechanical properties when they were lowered below 20 nm. A considerable degree of reinforcement could be achieved utilizing fillers with diameters in < 100 nm, which was also confirmed by Edwards [44]. According to [45], "critical size" refers to the filler size threshold at which the mechanical characteristics of composites noticeably improve. The influence of CNTs ratio on the strengthening behaviour of polyethene-based nanocomposites was studied by Kumar et al. [46].

They stated that the high contact surface area and robust interfacial bonding of CNT-polymer allowed for a significant improvement in hardness and elastic modulus when using high-aspect-ratio CNTs. Additionally, because of the smaller diameter and longer length of high-aspect-ratio CNT, mechanical locking was more common. Although some theoretical models or simulations were discovered, the majority of the pertinent studies exclusively focused on experimental work.

To give quantitative analysis and explanation of the strengthening mechanism, constitutive models would be necessary. In order to examine the impact of matrix density, chemical cross-links at the interface, and morphological CNT defects on interfacial shear strength (ISS) and, subsequently, CNT pull-out, Chowdhury and Okabe [47] utilised the molecular dynamic (MD) approach. From the simulation, \sit was established that high matrix density, presence of cross-link and small cross-link switching contributed to high ISS. Additionally, the effects of CNT waviness, diameter, volume fraction, Poisson's ratio, and matrix modulus on the interfacial strength of polymer/SWCNT have been evaluated using a 3D representative volume element (RVE) technique [48]. Based on the aforementioned investigations, it can be concluded that determining the interfacial bonding between Nano fiber and matrix is crucial for determining load transmission and, consequently, the effectiveness of the reinforcement's mechanical strengthening. Xiao and Zhang [49] examined the stress transmission behavior of SWCNT in an epoxy matrix using the Cox model for solid fibers [50].

Stress transfer efficiency, which is the ratio of the maximum tensile stress (max) to the maximum shear stress (max) in the interfacial section, served as the primary indicator. Illustrates the impact of SWCNT length, diameter, and thickness. Additionally, a comparison of the effectiveness of stress transfer between carbon fiber (CF) and SWCNT has also been made, assuming that CF has the same hollow structure and dimensions as SWCNT. The analytical findings demonstrated a notable (128%) improvement in epoxy/SWCNT composite over epoxy/CF composite. This improvement was caused by an increase in Young's modulus and a structural change (from a solid to a hollow construction), which contributed 69% and 31%, respectively. This led to the conclusion that, when compared to their micro-counterpart, Nano-fibers with higher aspect ratio and tensile characteristics can offer higher reinforcing efficiency. According to some researchers, utilizing Nano-fillers at lower loadings than micro-fillers can yield an identical or even greater strengthening effect. According to Fornes [51], whereas the same result might be obtained by employing three times the amount of glass fibre or more nano-clay montmorillonite (MMT) platelets, the modulus of nylon 6 would be doubled by mixing only around 6.5 wt.% of these platelets. According to Campbell [52], a composite may attain the requisite strength and stiffness when utilising either 70 vt% or 50 wt% of micro-fibers. Since Nano composites have proven to be an effective material to use in demanding applications that require excellent strength to weight ratio, it can be seen that they can provide excellent mechanical properties with low filler contents, which can only be obtained using high filler content in conventional composites [53]. Li and Saigal [54] used shear-lag analysis and the representative volume element (RVE) to confirm the improvement in stress transfer efficiency caused by the increase in nanotube diameter. They also took into account the influence of fibre volume percent, which was not taken into account in other investigations. Researchers also looked at the mechanisms underlying the strengthening effectiveness of nano-fillers such CNT in MMNCs, which include load transfer [50], Orowan strengthening [55], and thermal expansion mismatch [56]. According to [58], the addition of CNT led to an increase in strength that was caused by the metal matrix's refined particle size [57]. The effect of reinforcement size also considerably influenced the strengthening behaviour of MMNCs, similar to polymer-based nanocomposites [59–61]. However, only a few published models offered a thorough justification for the CNT reinforced MMNCs' strengthening mechanism. To evaluate the elastoplastic behaviour of CNT reinforced MMNCs, Barai and Weng [62] created a two-scale model, taking into account the interface characteristics and CNT aggregation as the two key elements impacting the load transfer. The effect of both the matrix grain size and the filler size on the strengthening process of metal/CNT nanocomposites was incorporated in a dislocation model created by Dong et al. [63]. They asserted that at small particle size and large CNT volume, the load transfer effect was improved.

MECHINICAL CHRACTERSIICS OF NANO COMPOSITES

It is obvious from the descriptions of the distinctions between nanocomposites and composites in the preceding section that using nano-fillers to reinforce a matrix material could result in greater reinforcement efficacy than due to their cutting-edge mechanical characteristics and unique nanostructures, micro-fillers. CNTs, graphene, and nanoclays are only a few of the latest applications of Nano-fillers. due to their compatibility and great strength, are the most widely used reinforcing materials. Effectiveness of reinforcement using metals, ceramics, and polymers as the three basic matrix materials. The most pertinent studies' primary goal is to examine. the differences in terms of density between the clean matrix and the matrix enhanced Nano-fillers the most typical are mechanical, thermal, and electrical qualities. inside the solely the mechanical qualities will be taken into account given the limited needs for the other parts that deal with Nano composites' micromachining. There are numerous variables that can affect how well nano-fillers are reinforced, including divided into three major categories: Nano scale nature, interaction between fillers and matrices, and

(iii) Making up techniques.

NANO COMPOSITES BASED ON CNT

CNTs are carbon allotropes composed of a single layer of carbon atoms that has been rolled up into a cylindrical shape. CNTs have diameters and lengths that range from 0.1 to 100 m and 1-100 nm, respectively [64], and they have a very high aspect ratio due to their tubular structure. Materials having surface areas between 200 and 900 m2 per g are available [65]. Iijima made the initial discovery of CNT in a TEM image in 1991 [66], and the same author also created the first single-walled carbon nanotube in 1993 [67]. CNT has been used in a wide variety of industries, including medication delivery [68], healthcare [69], electronics [70], electrics, and thermal applications [71]. CNTs have enormous potential applications on composite reinforcement because of their high strength-to-weight ratio, aspect ratio, thermal, and electrical properties [72, 73].

CNT-REINFORCED NANOCOMPOSITES WITH POLYMER MATRICES

Due to their superior interfacial interaction over ceramic [74] or metal matrix [75] and the analogous characteristics of organic structure, CNTs have been used to strengthen polymers. In light of this, it has been observed that some polymer/CNT nanocomposites have tensile strengths between 0.1 and 5 GPa and Young's moduli between 5 and 200 GPa [76]. Using CNTs as reinforcement generally improved the mechanical properties of some polymers, including epoxy [77-80], polystyrene (PS) [81], polyethylene [82, 83], PMMA [84, 85], poly (pphenylene benzobisoxazole) (PBO) [86], polyvinyl alcohol (PVA) [87], polyester elastomers (PEE) [88], polycarbonate (PC) [89], polyamide-6 [90], To prevent agglomerations or bundles that adversely influence the mechanical properties of PMNCs, typically when CNTs content exceeds 2-3%, the optimal CNT loading must be carefully examined [92]. The detrimental impact on the tensile strength of nanocomposite is specifically caused by the inadequate interfacial interaction between CNT and polyester [93,94, 95, 96, 97]. The most popular dispersion techniques for creating polymer-based nanocomposites are solution mixing, in situ polymerization dry mixing, and melt mixing. The effects of dispersion techniques (dry mixing and solution mixing) on the mechanical characteristics of PP/CNT nanocomposites have been studied by Esawi et al. The outcomes showed that dry-mixing, as opposed to solution-mixing, produced a higher level of CNT distribution. The polymer's breakdown and its high viscosity as a result of the solutions' addition, which restricted the dispersion of CNTs, were factors in the less significant increases in mechanical characteristics when solution-mixing was used. Additionally, using ultrasonication during solution mixing may cause damage to the CNT structure, which has a negative impact on the mechanical strength of nanocomposites [99]. Along with the impact of CNT concentration, extensive evidence points to the influence of CNT structure on the mechanical characteristics of CNT-based nanocomposites. Since CNTs come in a variety of forms, including SWCNTs, double-walled CNTs (DWCNTs), and MWCNTs, their diverse architectures and physical characteristics result in a range of mechanical reinforcing efficacies.. Since SWCNTs and DWCNTs have higher mechanical characteristics, aspect ratios, and specific surface areas than MWCNTs, their inclusion could theoretically result in stronger mechanical properties. Additionally, compared to CNTs with a lower layer structure, MWCNTs have a lower effective surface area due to their multi-layer structure. However, the degree of homogeneity in the CNT distribution within the polymer matrix also affects how successful the reinforcement is. In this instance, DWCNTs did not aggregate like SWCNTs did, which contributed to a greater improvement in tensile characteristics. This phenomena, that MWCNT dispersion inside PC matrix was significantly more effective than SWCNT regardless of the fabrication procedures, was further supported by Fornes et al. [100] and Sennett et al. [101]. In contrast to MWCNT, they claimed that SWCNT had a higher propensity to re-agglomerate during synthesis, making exfoliation more challenging.

The mechanical characteristics of polymer-based nanocomposites are mostly influenced by CNT alignment in addition to structure. Several techniques, including shear flows [102], ex-situ alignment [103], force field and magnetic field-induced alignment [104], electrospinning-induced alignment [106], and liquid crystalline phase-induced alignment [105], could be used to achieve this property.

some experimental findings that demonstrate how aligned CNT-based nanocomposites have improved tensile properties when compared to non-aligned CNT-based nanocomposites. When CNT alignment was used, it may be mostly explained by the isotropic nature of nanocomposites, which also improved distribution and decreased CNT agglomeration when filling into the polymer matrix.

Additionally, functionalization has been regarded as a successful way to strengthen CNTs' interaction adhesions with polymer matrix and, as a result, increase the effectiveness of mechanical characteristics through load transmission. According to Khare et al. [108], adding amido-anime functionalized CNTs (fCNTs) to epoxy reinforcement improved mechanical qualities more than pristine-CNTs (p-CNTs) (by around 51% of Young's modulus). Lower interphase compression, matrix structure integrity, reduction of matrix mobility, stable covalent connections of epoxy-FCNTs, and subsequently facilitated load transmission were some of the primary explanations cited.

The inclusion of CNTs showed various variations of fracture strain and toughness, in contrast to the enhancements of tensile strength and Young's modulus. The fracture strain improvement trends for thermoplastic and thermosetting reinforced by CNTs at varying weight contents. It was shown that each filler loading drastically reduced the flexibility of thermoplastic nanocomposites. Although pertinent investigations have demonstrated this phenomena, a thorough explanation has not yet been put forth. According to Wang et al. [109], a strong interface interaction between the matrix and filler may be to blame for the decrease of flexibility that results from the addition of MWCNT-NH2 to Polyimide (PI). As a result, the flexibility of this material may be reduced due to restrictions on the mobility of polymer chains under loading. The description of interfacial strength, however, has not been presented to substantiate this assertion. Contrarily, unlike thermoplastic nanocomposites, the fracture stresses of thermosets might be increased by the inclusion of CNTs at specific amounts of content. Chen et al. [110] reported that the scattered CNT toughened the brittle epoxy phase when epoxy was reinforced by MWCNT. Gojny et al. [111] validated this increase in failure strain at certain low filler loadings (below 1 wt%). Higher CNT loadings caused CNT agglomeration, which reduced the fracture strain by concentrating stress and weakening the interfacial contact between the polymer and CNT. These explanations were shown using scanning electron microscope (SEM) images to show the dispersion of CNTs at various filler contents.

Due to their high aspect ratio and stiffness, CNTs have been identified as a viable reinforcing candidate to replace glass fibre (GF) or carbon fibre (CF) in order to increase toughening efficiency [112]. The following is an expression for the micro-mechanical toughening mechanism of polymer reinforced CNT nanocomposites:

The interface strength and applied load have an impact on two CNT properties: (1) fracture bridging by CNTs and (2) CNT de-bonding and pull-out or breaking [113, 114]. On the basis of this schematic, it can be shown that CNTs should be orientated transversely to the propagated cracks where the bridging mechanism operates in order to attain the highest fracture toughness. If CNTs are distributed randomly or longitudinally, it will not significantly affect fracture toughness [115]. Additionally, the impact of transverse alignment might only work at modest CNT loadings.

According to some research, the fracture toughness of polymer/CNT nanocomposites is enhanced to a maximum of around 51% when 3 weight percent of fillers are utilised, and it decreases when this level is exceeded due to filler agglomeration [115, 116]. However, at low filler contents (1wt%), the random distribution of CNTs did not exhibit a significant improvement in toughness [117]. Additionally, Chen et al[114] .'s analysis of the impact of interface strength and CNT length on fracture toughness. They argued that considering simply the length of the fibres or the interface chemical bond density would not increase fracture toughness; both must be taken into account. These indicators performed best at 5–10% and 100 nm, respectively.

Their experiment has validated this theoretical analysis through optimal CNT-bridging.

The fracture toughness of nanocomposites has also been impacted by the shape of CNTs. Generally, reinforcing polymers with long CNT may achieve high fracture toughness due to its high load transfer and hence boosting the interface shear strength [118, 119].

Due to DWCNT's great compatibility with the epoxy matrix, low concentrations of it (less than 0.5 weight percent) have demonstrated a notable improvement in the fracture toughness of epoxy-based nanocomposites (37). However, MWCNT could be a superior reinforcing candidate to increase fracture toughness than other types of CNTs by adopting proper dispersion techniques and functionalization (18). In general, the link between numerous parameters, including CNT content, structure, alignment, treatment, and processing technique, has revealed a convoluted relationship when it comes to the improvement in fracture toughness when reinforcing polymer with CNTs. With the aforementioned considerations taken into account,

CONCLUSION

This paper's initial section covered pertinent investigations, such as the creation and characterisation of nanocomposites. Based on that, it has been found that the mechanical properties of nanocomposites were improved by the reinforcement provided by nano-fillers. The nature of the filler and matrix, how they interact, the size of the filler, and the fabrication techniques all affect the extent of enhancement. Through modelling and experimental methods, toughening and toughening mechanisms were also used to explain these variances. The review paper's attention has been drawn to nanocomposite materials that must undergo mechanical micromachining procedures to generate the finished article. These include metal/ceramic nanocomposites, polymer/graphene, and polymer/CNT nanocomposites. The mechanical properties will be connected with various machining measures, and this section of the review will serve as the foundation for analysing the machinability of nanocomposites when using mechanical micromachining techniques.

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