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Electro Spun Nanofiber Reinforced Composites

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Abstract

This paper provides a comprehensive overview on the properties of electrospun nanofibers and their application as reinforcements in composites. The paper first introduces the remarkable properties of electrospun nanofibers including high aspect ratio and molecular orientation, large specific surface area, small pore size, as well as excellent mechanical performance. Next the fabrication methods for the electrospun nanofiber reinforced composites are described. Then different kinds of electrospun nanofiber reinforced composites are discussed in terms of the classifications of electrospun nanofibers. After that, the influences of the mechanical performance of fibers, fiber diameter, fiber amount, fiber/ matrix interfacial interaction and the distribution of fibers in matrix on the reinforcement of composites are discussed. At the end, the possible future challenges, and conclusions for electrospun nanofiber reinforced composites are highlighted.

Introduction

Composites are well-known fascinating materials, which are made from two or more components with different physical, chemical and mechanical properties. When the components are combined, the composites possess better properties than those of each individual components alone [1]. Until now, composites have been broadly applied in aerospace industry, military industry, automobile industry, construction materials and other engineering applications due to their advantages, such as high specific strength and modulus, ease of fabrication, high design flexibility, good resistance to fatigue and corrosion, desirable thermal expansion characteristics, and economic efficiency. Usually, composites are comprised of one continuous phase (matrix) and one or more discontinuous phase (reinforcement), which is harder, stronger, stiffer, and more stable than the continuous matrix phase. Based on the reinforcement materials, the composites could be divided into three classifications, including particulate (particles and flakes) reinforced composites, fiber (continuous and discontinuous) reinforced composites, and hybrid material (particles, flakes and fibers) reinforced composites [2-5]. Among these composites, fiber reinforced polymer composites (FRPs) play an important role in civil infrastructure and high-tech equipment for aerospace industry, military industry, civil engineering area and so on. In the last 30 years, FRPs have gradually, partially or completely replaced the traditional engineering materials such as wood, metal, glass, and even ceramics in a few areas of applications [6,7]. FRPs are defined as a combination of polymer resins (matrix or binders) and strong and stiff fibers (reinforcements). The main functions of fibers are to bear the load and provide high strength, high modulus, high stiffness, and thermal stabilities to the FRP composites, while the polymer matrix has functions of binding the fibers, holding the position of fibers, transferring the load to the fibers by adhesion/ friction, and protecting the fibers from environment damages. However, by appropriately selecting the types of the polymer resins and the reinforcement fibers and using different processing technology, the physical properties of the FRP composites can be versatilely tailored. In many cases, the FRP composites also can be imparted other functional properties, such as optical properties, magnetic properties, electrical properties and conductivity by tailed modifying the fibers or matrix.

Traditional FRPs usually use fibers with diameter in micrometer range as reinforcement. Composites reinforced with these microfibers possess excellent structural properties such as high specific modulus and strength [8]. However, the amazing development of nanotechnology provides another choice that using nanofibers as reinforcement in making nanocomposites. Compared with traditional microfibers, nanofibers can possess even better mechanical properties including high modulus, high tensile strength and toughness due to the amazing size effect of nanofibers and hence improve the structural properties of nanocomposites.

Until now, three main kinds of nanofibers, cellulose nanofibers/ nanowhiskers (CNFs/CNWs), carbon nanofibers, and synthetic polymer nanofibers, are used as reinforcements. CNFs/CNWs usually come from the isolation of cellulose-based materials [9-11]. Carbon nanofibers can be produced by a straightforward way of charring of the natural or synthetic textile fibers in the absence of air, and by pyrolysis of a hydrocarbon feedstock (natural gas, acetylene, etc.) or carbon monoxide on a metal catalyst such as iron. Synthetic polymer nanofibers can be efficiently produced by electrospinning technology.

Electrospinning is the most effective state-of-the-art method for the generation of continuous polymer nanofibers and nanofiber nonwovens. The nanofibers/nanofiber materials fabricated using this technology have a large surface area, large porosity, high aspect ratio of length to diameter and high molecular orientation along fiber axis, making them very useful in many applications in diverse fields such as energy storage, healthcare, biotechnology, environmental engineering, defence and security [12]. The quite high-speed developments in electrospinning technology in the last few years, on the one hand, make the modifications on the morphology of the nanofibers possible by varying the processing parameters; on the other hand, have enhanced the production from few grams to kilos of nanofibers/nanofiber nonwovens in short time. Such developments also promote many new application areas of nanofibers/nanofiber nonwovens and there is no doubt that the electrospun nanofiber reinforced composites have risen as a shining star in the horizon on the path of the FRP.

In the past decade, significant progresses have been made according to our fundamental understanding of the preparation and properties electrospun nanofibers and their applications in composites as reinforcement. Herein, a comprehensive review of the state-of-the-art research activities regarding to the electrospun nanofiber reinforced composites is provided. A general introduction of electrospinning technology including the background of electrospinning technology and the advanced electrospun nanofibers has been made. The properties of electrospun nanofibers have been discussed. The size effect, the molecular orientation, optical and mechanical properties are discussed in this part [13-16]. The fabrication method of electrospun nanofiber reinforced polymer composites in the previous studies have been dealt with. A comprehensive discussion on electrospun nanofiber reinforced composites reinforced by different types of high-performance polymer nanofibers has been discussed. The factors affecting the properties of electrospun nanofiber reinforced composites have been highlighted. Conclusions have been drawn regarding the activities of the research area and showing the challenges and prospects of the electrospun nanofiber reinforced composites.

Electrospun nanofibers

Electrospinning technology experienced a dramatic development due to the convenience of producing nanofibers and huge potential of these fibers for varied applications. Until now, the sources of electrospun fibers are not only restricted to single component polymers, but also come from the polymer blends, and hybrid materials like polymers with metals, metal oxides, ceramics, carbon nanotubes, even bacteria, virus, and enzymes [17]. These diversities make 1D fibrous structures more unique with additional functionalities like optical, electronic, sensoric, magnetic, and catalytic properties and make them broadly apply in tissue engineering and drug delivery, filters and textiles, sensors, fuel cells and batteries, catalysis, nanocomposites, etc [18,19].

Preparation of electrospun nanofiber reinforced polymer composites

During the preparation of fiber reinforced polymer composites, the fibers should be embedded into the polymer matrix. Depending on the formation of fibers, including continuous fibers (nonwovens, knitted fabrics, and aligned fiber mats) and short fibers (CNTs, short microfibers and short nanofibers), different fabrication methods (dip-coating, film-stacking, solution casing, in-situ polymerization, melt blending and electrospinning) would be applied for the preparation of fiber reinforced polymer composites [20].

Due to the entanglement of the fibers, the continuous fibers can't be dispersed into the polymer solutions or melts homogeneously. Thus, dip-coating and film-stacking (layer-by-layer hot-pressing and layer-by-layer deposition) methods were suitable for the continuous fiber reinforced composites. Dip-coating is a good way to impregnate the electrospun fiber membranes into the polymer matrix solutions or melts. Labronici and Ishida had a review on toughening composites via fiber coating [21]. The wetting behaviour has been studied and compared the mechanical properties of nylon-6 nanofiber reinforced melamine formaldehyde (MF) with dip-coating method and the method by passing the MF solution through the nylon-6 fiber mat. The reinforcing effect is significantly affected by the thickness of the electrospun fiber membranes and the amount of fibers in the matrix. Too thick fiber membranes or too much fibers would hinder the homogeneous coating process. One efficient way to avoid inhomogeneous coating is applying small vacuum while coating. Film-stacking is another common way to prepare fiber reinforced polymer laminates [22].

Neppalli et al. made PCL composite by sandwiching the electrospun nylon-6 nanofibers between PCL films. Akangah et al. using nylon-66 nanofiber as interleaving layer to toughen the sixteen-ply quasi-isotropic epoxy/carbon fiber composite laminates [23]. In 2012, our group developed a novel film stacking procedure combined solution casting and electrospinning to produce transparent electrospun nylon-6 nanofiber reinforced TPU composites with reinforced tensile strength and toughness.

As reinforcements, short fibers could be incorporated into the polymer matrix by solution casting, in-situ polymerization, melt blending, electrospinning, etc. Many kinds of short fibers like CNTs, glass, carbon, nature plant, nylon, cellulose whisker and aramid, have been applied to fabricate short fiber reinforced polymer composites by the above processing technique. For examples, CNTs were added into the polymer matrix by solution casting,

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electrospinning, melt mixing, shear mixing, melt fiber spinning and in-situ polymerization. However, until now, there are very few reports regarding the preparation of short electrospun nanofiber reinforced composites. Recently, we attempted to disperse short electrospun nanofibers into polymer solution and made composites by film-casting. Due to the similar characteristics, we believe that short electrospun nanofiber reinforced composites could be prepared using the same methods as for fabricating CNT/short fiber reinforced composites.

Composites reinforced by different kinds of electrospun nanofibers

Until now, hundreds of polymers could be electrospun into nanofibers. However, not all of them are suitable as reinforcements to make fiber reinforced composites. Electrospun nanofibers with excellent tensile strength, modulus and toughness would be good candidates as reinforcements [24]. In this part, a comprehensive review regarding the high performance electrospun nanofibers and the corresponding fiber reinforced composites will be introduced in the following sections.

Electrospun nylon nanofiber reinforced composites

Electrospun nylon nanofibers exhibit excellent mechanical properties. Molnar et al. found that the single nylon-6 nanofibers have 48% higher tensile strength than the bulk nylon-6 material by modeling tensile behavior of the nanofibrous mat [25]. Bazbouz et al. developed a set-up for tensile testing of a single nanofiber and their results indicated that the aligned single electrospun nylon-6 nanofiber with diameter of 800 nm had a Young's modulus of 902 MPa, a tensile strength of 304 MPa and a strain at break of 40%. Hwang et al. obtained the tensile strength of single electrospun nylon-6 fiber by a "hooking method". The fibers with diameters of 60, 100 and 170 nm showed tensile strength of 364, 125 and 94 MPa, respectively. Li et al. and Ding et al.243 studied the mechanical performance of electrospun single nylon-6 and single nylon-6 composite fiber by AFM.

Their results indicated that the Young's modulus of nylon-6 electrospun single nanofibers was much higher than that of the conventional nylon-6 fiber and could be significantly improved by incorporating organically modified montmorillonite and SiO2 particles. Another report by Zussman et al. indicated that single electrospun nylon-6,6 nanofiber with take-up velocity of 5 and 20 m/s had mechanical strength of 110 and 150 MPa and Young's modulus of 453 and 950 MPa, respectively. Therefore, a lot of researchers devoted their efforts to fabricate electrospun nylon nanofiber reinforced composites (Figure 1).

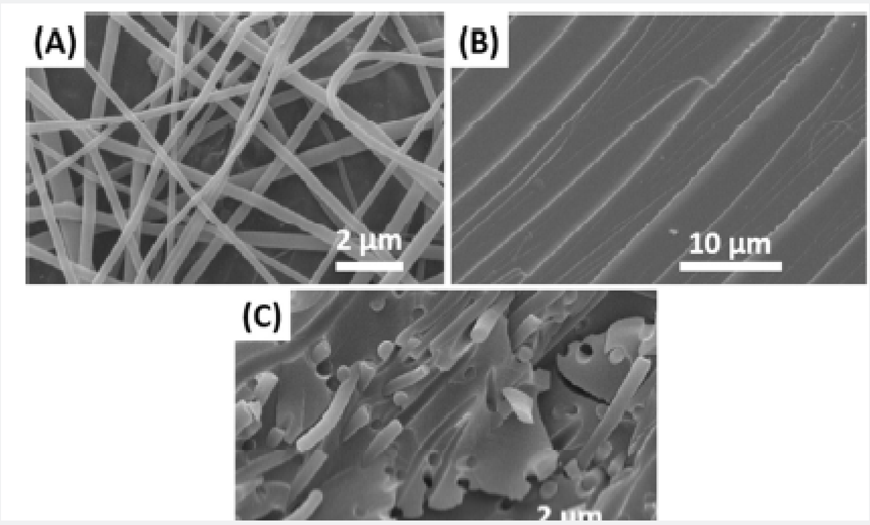

Figure 1: Respondents

One of the first papers concerning the preparation and the structure-property of such composites was published by Bergshoef and Vancso. They prepared electrospun nylon-4,6 nanofibers with diameter (30-200 nm) smaller than the wavelength of visible light to prepare transparent composites with an epoxy matrix. The tensile tests showed that a low fiber content of 3.9 wt% led to a significant improvement in both stiffness and tensile strength [26]. Li et al. fabricated transparent PMMA composites reinforced by electrospun graphene-incorporated nylon-6 nanofibers. Chen et al. combined coaxial electrospinning technique and hot-pressing to prepare nylon-6 nanofiber reinforced transparent composites. They found that the nylon-6/PMMA composites could achieve significant improvement on mechanical properties with a minor loss of the transparency.

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Recently, Li et al. prepared nylon-6 reinforced PMMA transparent composites by a self-blending co-electrospinning followed by hot-press molding. The obtained composites showed anisotropy optical and mechanical properties. In another report by Stachewicz et al, they prepared transparent nylon-6/PVA composites and investigated the effect of the nanofiber amount on the voids between the matrix and fibers. They found that the composites by impregnating nanofibers in an optimum 16 wt% PVA solution exhibited the highest failure stress, which could be due to the void-free structures of the composites.

Fong and co-workers made efforts to use electrospun nylon-6 nanofibers to reinforce BIS-GMA/TEGDMA dental materials. They prepared defect-free electrospun nylon-6 nanofibers with fiber diameter of 100-600 nm and embedded them in the neat BIS-GMA/TEGDMA resin. The obtained composites with 5 wt% amount of nylon-6 fibers showed an enhanced elastic modulus, the flexural strength and the fracture work of the composite by 26, 36 and 42%, respectively, which could be attributed to the strong interface interactions between fibers and matrix. Later they found that hybrid reinforcement of electrospun nylon-6 nanofibers and salinized fibrillar silicates could greatly improve the fracture work of the composite by 98%. Bottino's group made random and aligned MWCNT/ntylon-6 composite fibers by electrospinning and studied their reinforcing effect on the flexural strength of a dental resin. They found that the dental composites could be significantly reinforced by the aligned nylon-6 nanofibers with 0.5 wt% MWCNTs. Romo-Uribe et al. demonstrated that the electrospun nylon-6 nanofiber mat (250 nm of fiber diameter) effectively improved the mechanical properties and thermal stability to polyaniline (PANI) thin films. In addition, recently, An et al. presented a semi-transparent electrospun nylon-6,6 nanofiber reinforced cyclic butylene terephthalate composites by electrospinning process followed by hot press method. Compared with the pristine nylon-6,6 nanofibers, the composites with enhanced mechanical properties could be because of the formation of hydrogen bonds between cyclic butylene terephthalate and nylon-6,6 molecules [27].

Electrospun nylon nanofibers were used as interleaved layer to make composites. Akangah et al. fabricated quasi-isotropic composites using electrospun nylon-6,6 nanofibers as interleaved layer. The nanofiber interleaving significantly increased the threshold impact force by 60% and reduced the rate of impact damage growth rate to one-half with impact height. Similar study with electrospun nylon-6,6 nanofibers as interleaved layer to toughen the carbon/epoxy was conducted by Beckermann et al. and it was found that a 4.5 g/m nylon-66 veil led to an enhancement by 156% and 69% for Mode I and Mode II interlaminar fracture toughness. De Schoenmaker et al. investigated the effect of electrospun nylon-6 nanofibers as interlayered structure on the mechanical properties of a glass/epoxy composites and they demonstrated that some mechanical improvement was achieved by the addition of electrospun nylon-6 nanofibers. Saghafi et al. also systematically studied the effect of electrospun nylon-6,6, PCL and their combination as interleaved layer on mode I and mode II fracture response of composite laminates. Goodarz et al. applied electrospun graphene nanoplatelets/nylon 66 mats as hybrid multi-scaled interlayer to fabricate expoxy composites. It was found that, at 0.5 wt% GNPs, toughness went up by 25% while it pronouncedly increased by 68% at 1 wt% loading. In another recent report, Habibi Zarabadi et al. presented a protein based composites containing an interlayer of electrospun nylon-6 nanofibers with greatly improved oxygen and water vapor permeability, glass transition temperature and mechanical properties, which could be attributed to the good adhesion between matrix and filler.

Electrospun nylon-6 nanofiber sheets were reported to reinforce biodegradable and biocompatible PCL and polylactide (PLA) by Neppalli et al. The nylon-6/PCL composites could be easily prepared by compression moulding and very small amount of nanofibers (3 wt%) could led to improved stiffness with a simultaneous increase in uctility. In another report, PLA composites reinforced by electrospun nylon-6 nanofibers were fabricated and good interfacial adhesion between PLA and fibers were observed. Compared to the neat PLA, the nylon-6/PLA composites showed a modulus increase up to 3 fold. Although, an increase in mechanical properties were seen, but the use of non-degradable reinforcing fibers for reinforcing the biodegradable matrix could be a matter of debate [28].

Electrospun nylon-6 nanofiber mats were also used to reinforce melamine-formaldehyde (MF) resin and TPU to prepare nanofiber reinforced transparent composites.103, 104 Depending on the fabrication methods, drastic effect of the wetting process of the fiber mat by the MF precursor on both morphology and mechanical properties were found and in comparison to the MF resin, the composite showed transparency and enhanced mechanical strength and toughness.103 In another report, transparent nylon-6 nanofiber reinforced TPU composites were fabricated by a lay-by-layer assembling by film casting and electrospinning. With this method, very small amounts of nanofibers (0.4-1.7 wt%; fiber diameter: 150-300 nm) could significantly improve the mechanical properties like tensile strength, modulus and toughness without scarifying the optical transparency.

Similarly, Lu et al. prepared polyolefin-based composites with very small amount of electrospun nylon-6,6 nanofibers and the composites showed improved tensile strength, modulus and toughness.

Electrospun polyacrylonitrile (PAN) nanofiber reinforced composites

Electrospun PAN nanofibers possessed excellent tensile strength, modulus and toughness. Gu et al. studied the effect of

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the applied electrospinning voltage on the Young's modulus of a single electrospun PAN nanofiber by AFM bending test. The result indicated that the single PAN fiber electrospun from 22 kV showed much higher Young's modulus (14.07 GPa) than that from 18 kV (6.88 GPa). Recently, Dzenis's group systematically investigated the size effect on the mechanical properties and the structures of single electrospun PAN nanofibers.189 When the fiber diameter reduced from 2.8 μm to around 100 nm, simultaneous the elastic modulus, true strength and toughness significantly increased from 0.36 to 48 GPa, 15 to 1750 MPa and 0.25 to 605 MPa, respectively, which could be attribute to the increase of crystallinity [29].

Sun et al. used a multi-syringe electrospinning technique to prepare electrospun PAN nanofiber –PS composite fibers by simultaneous spinning of the two polymers using moving syringes. They demonstrated that at a syringe number ratio of 3/1 PS/PAN, the composites has a three times increase of tensile strength compared to the pure PS mats. Wu et al. prepared transparent PMMA composite films reinforced by randomly organized and uniaxially aligned PAN nanofibers (diameter: around 550 nm). Depending on the fiber orientation, the composites with aligned fibers showed 40% tensile strength and 30% Young's modulus more than that with randomly organized PAN nanofibers. Similarly, recently Zainab et al. prepared a PAN/PU based composites by multi-needle electrospinning. The composites exhibited good mechanical and thermal properties, and were used for lithium ion battery separators. In order to improve the interfacial adhesion between the fibers and matrix, PAN-core PMMA-shell nanofibers were prepared by coaxial electrospinning to reinforce dental materials. Lin et al. found that the PMMA part could guarantee the good interfacial adhesion between the matrix and the coaxial fiber, while the PAN core could provide the high mechanical properties as reinforcement. In a following report, Sun et al. improved the tensile properties by post-drawing aligned PAN-core PMMA-shell nanofiber membranes and found that the BIS-GMA/TEGDMA reinforced by these membranes showed increased flexural strength, flexural modulus and work of fracture by 51.6%, 64.3% and 152.0%, respectively, in comparison to the pure resin. Cheng et al. prepared sodium fluoride (NaF)-loaded PAN core PMMA shell nanofibers by coaxial electrospinning and determined the reinforcing effect of these fibers on Bis-GMA/TEGDMA dental composites (Figure 2).

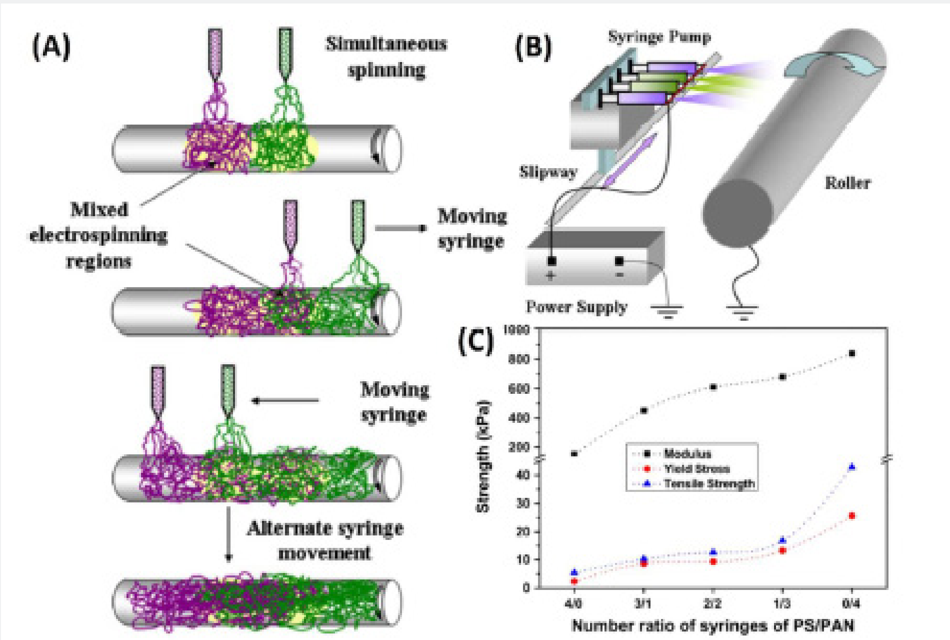

Figure 2:

The results indicated these fibers not only improved the flexural strength and flexural modulus of the composites, but also exhibited sustained fluoride release, which was helpful in preventing secondary caries. The electrospun PAN nanofibers could also be used as interlaminar layers for the improvement of the impact properties. Molnar et al. deposited PAN nanofibers directly on the surface of carbon fabrics by a needless electrospinning technique and applied these composite to reinforce epoxy. Compared to the neat composite without PAN nanofibers, the hybrid PAN/carbon/epoxy composites showed an increase absorbed energy

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to maximum force by 64%. Recently, Herwan et al. inrerleaved electrospun PAN nanofibers to fabricate a carbon fiber reinforced polymer pin joined composite laminates. The composites showed improved load bearing strength by 18.9%, flexural modulus by 20.9% and flexural strength by 55.91%, respectively.

Similar adhesive joint reinforced by electrospun PAN nanofibers was reported by Razavi et al. In their report, the PAN nanofibers with 362 nm average diameter resulted in a maximum improvement of 127% in the mode I fracture energy of adhesive by incorporating 2 g/m2 of PAN nanofibers into the adhesive layer. Neisiany et al. prepared electrospun functionalized PAN grafted glycidyl methacrylate (PAN-g-GMA) nanofibers and incorporated them between the plies to improve the interfacial adhesion. The grafting strategy led to the stronger interactions between nanofibers and the epoxy matrix, which gave rise to the better mechanical properties of the composites

Electrospun PLA nanofiber reinforced composites

Tan and Lim studied the elastic modulus of single electrospun PLA nanofiber by three-point bend test and nanoindentation performed on an AFM. Both methods showed that the elastic modulus of single PLA nanofiber with diameter less than 350 nm was about 1.0 GPa and decreased with increasing the fiber diameter more than 350 nm. Another two studies by Ryuji et al. and Li et al. revealed that the higher take-up velocity led to more packed internal structure and enhanced the tensile properties of the PLA single nanofibers. Single PLA nanofiber with take-up velocity of 630 m/min possessed tensile modulus of 2.9 GPa and tensile strength of 183 MPa, which were 0.9 GPa and 94 MPa higher than the fiber with 63 m/min take-up velocity, respectively. Recently research indicated that the increasing of take-up velocity led to obvious decrease of fiber diameters and the increase of tensile modulus from 1.82 GPa (630 m/min) to 5.04 GPa (1890 m/min) and tensile strength from 48.39 MPa (630 m/min) to 195.2 MPa (1890 m/min). However, to the best of our knowledge from the available literature, only a few reports regarding the elelctrospun PLA nanofiber reinforced composites are available. Dong et al. investigated the potential use of electrospun PLA nanofibers to reinforce epoxy. The pilot study showed an increase by 50.8 and 24.0% on flexural moduli of the composites with 5 and 10 wt% PLA nanofibers respectively. In another report, Chen et al. proposed a novel strategy to prepare PLA/PCL composites [30].

They compared the reinforcing effect of the composites reinforced by pure PLA fiber mats and PLA/PCL blend fibers and found that the latter blend fibers had a better reinforcing effect to PCL due to the improvement of affinity of the minor PCL component in the electrospun blend fibers.

Electrospun carbon nanofiber reinforced composites

Carbon nanofibers could be easily prepared from electrospun PAN and its copolymer nanofibers followed with thermal treatments, carbonization and graphitization. The electrospun carbon nanofibers had excellent mechanical strength and tensile modulus. Hou's group devoted many efforts on the mechanical properties of electrospun carbon nanofiber bundles (ECNFB). The aligned ECNFB from pure PAN nanofiber precursor showed tensile strength of 550 MPa and Young's modulus of 58 GPa. By using phosphoric acid as stabilization promoter, the tensile strength of the aligned ECNFB increased to 969 MPa.291 Recently, they prepared ECNFB from poly(acrylonitrile-co-monobutylitaconate-co-n-butylacrylate) (co-PAN) with different amounts of monobutyl itaconate (MBI). The incorporation of MBI significantly improved the stabilization of co-PAN nanofibers and promoted the formation of ordered graphite crystals in aligned ECNFB [31]. The fibers obtained from co-PAN with 5 wt% MBI showed a tensile strength and Young's modulus of 1.8 and 97 GPa, respectively. Due to the very brittle nature of electrospun carbon nanofibers, it is a challenge to get the mechanical properties of single carbon nanofibers directly by tensile test.

Zussman et al. firstly demonstrated the tensile strength (0.32-0.9 GPa) and average Young's modulus (63 GPa) of PAN-derived single electrospun carbon nanofibers by AFM. Later, Arshad et al. adopted a microelectromechanical (MEMS)-based nanoscale tesing platform equipped with a high resolution optics for measuring the mechanical properties of single electrospun carbon nanofibers. Their results indicated that the PAN-based single ECNF had tensile strength of 3.5 GPa and elastic modulus of 172 GPa through optimizing the electrospinning parameters, stabilization and carbonization process. Therefore, ECNFs with superior tensile strength and modulus would be good potential for the preparation of ECNF reinforced composites. However, there were few reports regarding the fabrication of ECNF reinforced composites [32].

The first report came from Dzenis and Wen in 2001. They prepared PAN-based continuous and uniform ECNFs with a diameter in the range from 100 to 500 nm and applied these ECNFs to reinforce epoxy resin. Later, a series of works have been done to reinforce epoxy resin by ECNFs. In 2009, Sancaktar et al. prepared epoxy composites reinforced by ECNF mat and short ECNF, respectively. The results indicated that the composites loading with ECNF mat had better mechanical properties than those with short ECNFs due to the better homogeneity of mat in the resin. Fong's group paid attention to the development of hybrid multi-scale epoxy composites reinforced by hybrid reinforcements with conventional carbon fiber fabrics and ECNF mats. When the epoxy composites reinforced by conventional carbon fiber fabrics (CFFs) with interlaminar regions comprising ECNF mats, the composites showed 86% higher interlaminar shear strength than those of comparison composite without ECNF mat. In another report, they applied vacuum assisted resin transfer molding technique to prepare epoxy composites reinforced by CFFs surface-attached with ECNF mats. Compared to the tranditional CFF/epoxy composites, the hybrid CFF/ECNF/epoxy

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composites showed better out-of-plane mechanical properties. Recently in 2014, they compared the mechanical properties of epoxy composites reinforced by ECNFs, hybrid multi-scale ECNFs/CFFs, vapor growth carbon nanofibers (VGCNFs) and graphite carbon nanofibers (VCNFs). ECNFs presented similar reinforceing effect with VGCNFs, but higher than that of GCNFs [33,34]. A small amount of ECNFs (0.1 wt% and 0.3 wt%) led to the improvemetns on impact absorption energy, inter-laminar shear strength and flexural properties for both ECNF/epoxy and CFF/ECNF/epoxy composites. In 2016, Alarifi et al. studied the mechanical and thermal properties of carbon fiber reinforced composites using electrospun nanofibers as interlayers by unidirectional pre-preg carbon fibers stacking [35]. The thermal mechanical analysis exhibited an obvious reinforcement due to the enhanced interfacial bonding between the nanofibers and the matrix.

Conclusion

Electrospinning is a facile technique to prepare fibers with diameter from tens of nanometers to several micrometers from a variety of polymers and blends with different morphologies. The electrospun nanofibers possess high aspect ratio and high specific surface area. The polymer molecules are highly oriented along the fiber axis, which leads to the excellent mechanical properties. Electrospun nanofibers have size effect on mechanical properties. In addition, the electrospun nanofiber mats/membranes also possess porous structures and high porosity. All these characteristics make electrospun nanofibers an attractive choice as reinforcements for composites. Previous reports indicate that high performance electrospun nanofibers, including nylon, PAN, PI, carbon, cellulose, ceramic, PLA, PCL, gelatin, and other materials have been successfully applied as reinforcements to produce composites. The properties of these electrospun nanofiber reinforced composites can be affected by several factors, such as the mechanical properties of nanofibers, the fiber diameters, the fiber amount, the fiber/matrix interfacial interaction, the fiber alignment, the fiber aspect ratio, and so on. Although the field of electrospun nanofiber reinforced composites have been developing for many years, there are still many challenges to conquer and many issues to solve, including (1) how to fabricate electrospun nanofibers with much higher mechanical properties; (2) how to enhance and understand the fiber/matrix interfacial interactions; (3) disclose the effect of the fiber aspect ratio and the fiber diameter on the reinforcement; (4) how to fabricate electrospun nanofiber reinforced composites in large scale and apply them in practical uses; (5) how to reduce the cost of composites fabrications; and (6) understanding the mechanism and developing theories of the effect of electrospun nanofibers on composites.

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