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Carbon Nanotubes in Carbon Fiber

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For a long period of time the materials we used were available in their applicable form naturally, for example sticks and stones. However, we soon discovered that we could use and create different metals that were stronger and sometimes lighter than what was previously available. Fast-forward to the modern era and one can see that instead of using materials that are found naturally, materials are now being designed specifically for the task that they are to perform. An example of one such material is carbon fiber. According to Behabtu and colleagues (2008) carbon fiber has been extremely useful in industries where both strength and weight of materials are extremely important. Industries such as aerospace, and sporting equipment have already replaced other materials with carbon fiber as a stronger and lighter alternative (Behabtu *et al.*, 2008), yet there continue to be improvements.

One idea for the improvement of carbon fibers is the use of carbon nanotubes (CNTs) within the carbon fibers. Carbon can be found in nature in three different forms: diamond, graphite, and Buckminster fullerene (Moberg, 2008). However carbon can be constructed to produce another stable form, CNTs. CNTs are made from one molecule thick sheets of graphite, known as graphene, which are cut and wrapped into a tube. There are two categories that nanotubes fall under: single walled carbon nanotubes (SWCNTs), and multi-walled carbon nanotubes (MWCNTs). As one would expect a SWCNT is comprised of a single sheet of graphene. On the other hand a MWCNT is comprised of multiple sheets of graphene, which are used to produce nanotubes of different diameters so that there are nanotubes surrounding smaller ones. What is of particular interest are the properties that these CNTs exhibit.

While looking at the possible integration of CNTs into carbon fiber their mechanical properties are extremely important. As stated by Byrne and Gun'ko (2010), when comparing a CNT to the strongest steel, it is much lighter and 10-100 times stronger. Determining the strength of CNTs has proven to be difficult as their sizes are extremely small; in the region of 10nm or less (Demczyk *et al.*, 2002). Demczyk and his team (2002) were able to design a test for the tensile strength of nanotubes. The testing done by Demczyk and colleagues (2002) found the tensile strength of CNTs to be 0.15 TPa, and the elastic modulus to be 0.9 TPa. These values are very large when compared to steel, one of the strongest materials known, which has a maximum value of 0.0017 TPa as reported by Pavlina and Van Tyre (2008). To analyze the CNTs during testing Demczyk and his partners (2002) used both transmission electron microscopes and atomic force microscopy. During the testing of tensile strength the CNTs were placed under tension until they broke (Demczyk *et al.*, 2002). They also performed testing of the flexibility to determine the value of the elastic modulus, a measure of the force that can be applied to an object divided by how much it stretches before deforming or failing. It was found that they were able to bend the CNT over itself without the CNT breaking (Demczyk *et al.*, 2002). CNTs do not only separate themselves from other materials because of their strength but also because of

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their flexibility. Although the strength and flexibility of single CNTs are very high, these figures do not hold when looking at them in a micro or macro scale.

CNTs can be spun together to form a carbon nanotube fiber (CNTF). CNTF is constructed by spinning individual CNTs together. According to Lu and colleagues (2012) there are four main ways in which nanotube fibers are made. They are spinning from a CNT solution, spinning from an array of vertically aligned CNTs (that were previously grown on a substrate), spinning from a CNT aerogel (created in a chemical vapor deposition reactor), and twisting/rolling from a CNT film (Lu *et al.*, 2012). The different methods of production are a very important to look at because the properties of CNTFs are dependent on the method by which they are made. Spinning from a CNT aerogel was the method that produced the strongest CNTF. According to Lu and his colleagues (2012) they were able to produce CNTFs with a tensile strength of 8.8 GPa and an elastic modulus of up to 397 GPa. Unexpectedly these values for the tensile strength and elastic modulus of CNTFs were significantly smaller that those of a single CNT. In fact these values are only 5.87% and 44.11% respectively of the highest measured values in one CNT. This is an intriguing and unexpected result, that when you have a very strong material and you combine it with more, it becomes weaker. The mechanical properties of CNTs appear to be very dependent on the scale in which they are being observed (Lu *et al.* 2012).

Currently nanotubes are seen in three different scales; the nano-scale, the micro-scale, and the macro-scale (Lu *et al.*, 2012). When viewed in the nano-scale CNTs are each looked at individually. At this scale the mechanical properties of the nanotubes are dependent on factors like the diameter, length of the tube and the thickness of its wall (Lu *et al.*, 2012). However when scaled up to the micro-scale, for example a cluster of CNTs, the mechanical properties are dependent on other factors. At this scale the properties are linked to factors like the arrangement and entanglement of the nanotubes, and the inter-tube load transfer, the balancing of a force over multiple CNTs (Lu *et al.*, 2012). Finally, the macro-scale properties are dependent on the twist angle and diameter of the fiber, as well as the manner in which the fiber is presented, for example, braided string compared to a woven fabric (Lu *et al.*, 2012). All of the properties listed above are very closely linked to the processes by which the individual CNTs were made as well as how the CNTF was spun, and add to the variability of the strength and flexibility of CNTFs.

Lu and colleagues (2012) found that CNTF had strength varying from 0.23 GPa to 9.0 GPa, and elastic moduli ranging from 70 GPa to 350 GPa. Some interesting conclusions that his group came to were that the length and diameter of each individual CNT, and the diameter of the CNTF are very important when looking at the CNTFs mechanical properties (Lu *et al.*, 2012). First of all as the length of the CNTs increase so does the strength of the CNTF (Lu *et al.*, 2012). This is due to the CNTs having more surface area in contact with others in the CNTF, as well as giving them the ability to intertwine more with each other (Lu *et al.*, 2012). These occurrences lead to a better dispersion of a force therefore increasing the load that it can take (Lu *et al.*, 2012). Also with longer CNTs fewer of them are needed to produce the same length of CNTF. Less CNTs in the CNTF means that there are less ends or breaks in the strands of the fiber reducing the number of defects (Lu *et al.*, 2012). The diameter of the CNT can easily affect the CNTF since when the diameter increases so does the possibility of the CNT deforming (Lu *et al.*, 2012). When the diameter is large the CNTs are prone to flattening out. At this point they tend to resemble sheets of graphene, which are very

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weak between sheets (Lu *et al.*, 2012). This leads to fraying or unraveling of the CNTF producing a much weaker point that is susceptible to breakage. The diameter of the CNTF also decreases the tension that it can handle (Lu *et al.*, 2012). It is a trend that as the scale of the CNTs increase, the tensile strength and elastic modulus are lost.

Although CNTs appear to be incredibly strong objects they do contain a weakness. Individual CNTs are very susceptible to compression, as they will buckle in upon themselves. However, compression is less destructive on a CNTF as the fiber bends, without fracturing, before enough CNTs encounter enough pressure to buckle in upon themselves (Lu *et al.*, 2012).

Conclusion

The future of CNTF is very promising as it continues to develop. Before CNTF can be used commercially, improvements need to be made on the quality of CNTs as well as the production of CNTFs. These improvements will allow for stronger materials as well as more efficient yields of CNTs and CNTF (Behabtu *et al.*, 2008). One of the next stages could be to weave the CNTF in the same manner that is currently used to make carbon fiber. Once this is accomplished these sheets of CNTF could be used to replace current carbon fibers as a stronger and lighter alternative. These sheets could be applied to the bodies of space/aircraft or even to more common items such as sports equipment (Byrne and Gun'ko, 2010). Overall, CNTFs have proven to be extremely resilient (Demczyk *et al.*, 2002), and only with more research into CNTFs will their use commercially become more common.

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