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Commentaries

Carbon Nanotubes After 30 Years of Research, Development and Commercialisation

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ABSTRACT

The commentary discusses the last three decades of research, development and successful commercialisation of Carbon Nanotubes (CNTs) and their related composites. Whilst the number of publications are on the decline and despite of major technical challenges, CNTs continue to emerge as significant materials due to their superlative combination of properties.

COMMENTARIES

The discipline of nanotechnology incorporating novel advanced materials continues to emerge as the scientific beacon of the future, where carbon nanotubes (CNTs) are considered as no exception. CNTs are formed by rolling graphene (one-atom-thick sheet of carbon) giving them long and narrow structure. They are considered as nearly the thinnest tubes that can be synthesised using carbon atoms. This relatively long and high aspect ratio structures of CNTs make them one of the strongest engineered fibres known to mankind.

The global CNT market is estimated to be USD 876 million (2021) and projected to reach USD 1714 million by 2026. Since their accidental discovery in 1991 by Sumio Iijima, a steep rise is number of publications was witnessed since 2000, which seems to be plateauing or declining now (figure 1) as more of their commercial applications are emerging. Nevertheless, creation of a perfectly crystalline CNT remains challenging which is 100 times stronger than steel at one-sixth the weight. The famous July-August 1997 magazine cover of American Scientist created a vision (via an artistic conception) of a space elevator cable. Such space elevator cable is still not in existence due to inability of manufacturers to produce infinite long single walled CNTs with perfect chicken wire structure. Various studies have reported CNTs' abilities to conduct heat and electricity far better than copper and aluminium.

At the beginning of this century, the most significant obstacle for the commercial success of CNT was crystallinity and the cost of production, where the latter has certainly decreased significantly. CNT production capacity has increased 10 folds, thanks to major suppliers significantly reducing the production costs, around 100 folds since 1990s. If highly crystalline and equally cheap CNTs are harnessed properly, the materialisation of applications of CNTs will revolutionise the science, engineering and technology sector, which is not the case at the moment. CNTs still remain toxic and are not considered eco-friendly by various regulatory authorities in Europe and North

America. To date, adhering to many of these stringent regulations (e.g. the European Union (EU), Control of Substances Hazardous to Health (COSHH), the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), the Globally Harmonized System (GHS), the Environmental Protection Agency (EPA) etc.) remains a significant global challenge for manufacturers.

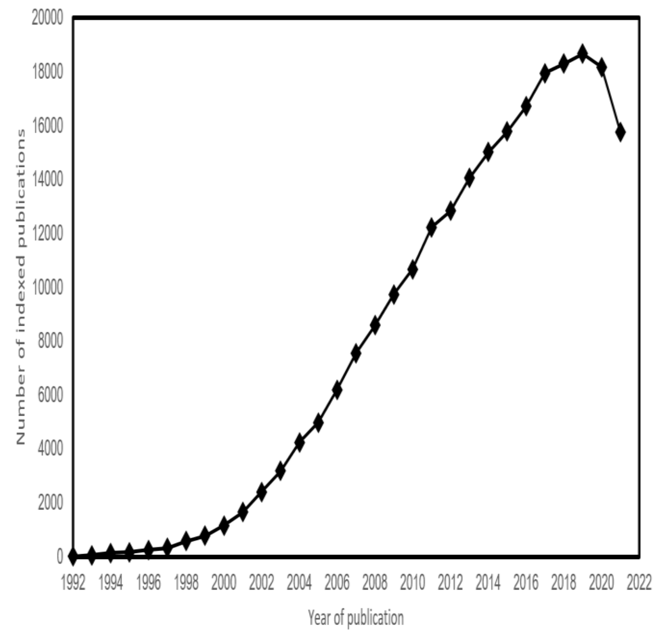

Figure 1. Number of publications (from 1992 to 2021) on CNTs indexed by Web of Science (Clarivate).

However, despite of these technical and regulatory challenges, CNT based produced are already being utilised in commercial ventures like nanodevices, electromechanical non-volatile memory, organic light-emitting diodes (OLEDs), transdermal drug delivery, proteomics, cancer treatment, conductive nano inks, conductive transparent electrodes, conductive heating devices, wearable technologies, thermal interface material, hydrogen storage, filtration membranes, biological and chemical sensors, displays, hulls for maritime boats, structural coatings and paints (including antifouling paints and flame retardant coatings), thin films, electrochemical supercapacitors energy storages, high capacity batteries including lithium-ion batteries and high-energy density solutions, anti-static packaging, EMI shielding, synthetic fibres/ yarns, solar power cells, wind turbine blades and sporting goods like bicycle frames, ice hockey sticks, baseball bats, golf shaft, archery arrows, tennis and badminton rackets. CNTs' tuneable mechanical, thermal, electrical and electronic properties allow significant customisation to the products, they become are part of. As these large quantities of CNT based products materials are already in the consumer market, it remains ever so critical to establish disposal and/or reuse procedures, which itself possess a great technical challenge. However, among these many applications, electronics, energy storage and medical applications are likely to see the rise of applications of CNTs, specially in developing regions like Asia-Pacific in the post-COVID world. With the advancement and advanced understanding of superlative properties of CNTs, CNTs still have significant potential to be mass substituted into computer chips, but again, the technical challenges exist to create significant large quantity of perfectly crystally vacancy-free CNTs.

To cut short, CNTs still possess significant competitive advantages over conventional materials. The major obstacles for mass industrial substitution and expansion of commercial CNTs are the cost of production, toxicity and eco-friendliness. It is still expected that these barriers will be overcome by CNT and emerging graphene technologies which will contribute to the frontier of nanotechnology and related commercial products for many years to come for sure!