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Effects of laser cutting on the structural and mechanical properties of carbon nanotube assemblages

Seyram Gbordzoe [a], Sergey Yarmolenko [b], Sathya Kanakaraj [a], Mark R. Haase [b], Noe T. Alvarez [c], Ryan Borgemenke [c], Paa Kwasi Adusei [a], Vesselin Shanov [a,c,*]

[a] Department of Mechanical and Materials Engineering, University of Cincinnati, Cincinnati, OH 45221, United States
[b] Department of Mechanical Engineering, Engineering Research Center, North Carolina A&T State University, Greensboro, NC 27411, United States
[c] Department of Biomedical, Chemical and Environmental Engineering, University of Cincinnati, Cincinnati, OH 45221, United States

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ABSTRACT

Multiple applications of carbon nanotubes (CNTs) require their assembly into macroscopic materials: films, sheets, and ribbons. Most of these macro-materials are flexible thin structures and need to be cut to micrometer dimensions. Laser cutting has emerged as one of the best pressure-free alternative methods, providing accuracy and uniformity. We report on the effect of laser cutting on the structural and mechanical properties of CNT sheet assemblages. Laser cutting forms a significant and deleterious amount of amorphous carbon at and near the cut edge, and this was observed by Raman spectroscopy, transmission electron microscopy, and electron energy loss spectroscopy. The damage can have adverse effects on the physical properties of CNTs and applications based on them. Laser cutting at high power was found to reduce the tensile strength of CNT sheets by as much as 75%. Nevertheless, at smaller cut widths, the mechanical properties were affected irrespective of the laser power.

1. Introduction

Carbon nanotubes (CNTs) have been studied extensively since its wide introduction to the research community in 1991 [1–3]. CNTs are an allotrope of carbon and can be described as a graphene sheet rolled into a tube. Because of individual CNTs' unique structure, they have excellent physical properties, such as high mechanical strength (100–200 GPa), low electrical resistivity (3×10^{-5} Ω. cm), and high thermal conductivity (3500 W/m.K) [4–6]. Nevertheless, transferring these properties from the nanoscale into a macroscale material made of CNTs has proven challenging. To advance practical applications, more attention is being paid toward exploring and processing CNTs into bulk materials such as sheets and yarns [6–16] (generalized here as CNT assemblages). Often, applications of these assemblages require cutting and forming to particular dimensions. Some of the methods used for these tasks include mechanical cutting, liquid-phase oxidative cutting, solid-state reaction cutting, and electron-induced cutting [17,18]. Focused ion beam (FIB), although considered as an expensive approach, has also been used for fragmenting CNT assemblages [19–21]. However, such cutting methods have drawbacks, such as considerable material loss, lack of precision and reproducibility, high time consumption, and nonuniformity of the cut edge.

Laser cutting minimizes these drawbacks and therefore has become one of the most common methods for tailoring CNT assemblages for various applications [22–25]. The laser cut quality, described by the kerf and heat-affected zone (HAZ), is an important parameter that is usually studied. The kerf is defined as the width of the material that is removed during the laser cutting process, while the HAZ is the area around the cut edge whose properties are affected by the laser cutting. Determining the kerf width is necessary because for any cut sample, the amount of material removed will help identify the tolerance needed to achieve cut parts with precise dimensions. Ghavidel et al. studied the effect of CNT content on laser cutting of CNT/poly(methyl methacrylate) nanocomposites [26]. Their findings showed that an increase in CNT content led to a decrease in HAZ. This is because CNTs are more thermally conductive than the polymer and therefore reduced the thermal focus. Hix et al. also studied the effect of laser power and cutting speed on the kerf width. They found that an increase in laser power and cutting speed caused an increase in the kerf width [27]. The kerf width was also shown to depend on the alignment direction of the material. It was reported that the kerf width was smaller when the direction of cutting was parallel

* Corresponding author at: Department of Mechanical and Materials Engineering, University of Cincinnati, Cincinnati, OH 45221, United States.
E-mail address: vesselin.shanov@uc.edu (V. Shanov).

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to the fiber direction than that when the direction was perpendicular [28]. This was because the thermal conductivity is higher in the parallel direction than that in the perpendicular direction, thereby allowing heat to be propagated better. There have also been studies on how laser cutting affects the structural properties of CNTs. Tachibana examined the effects of laser-induced defects on single-wall carbon nanotubes (SWCNTs) by Raman spectroscopy and reported that the laser irradiation increased the D band intensity, and this can be attributed to the defects created in the tubes [29]. On the contrary, Cheong et al. reported that the laser trimming of CNT forests did not transform the tubes into amorphous carbon, preserving their pristine nature [30]. There is, however, very little research published on how laser cutting affects the physical properties of CNT assemblages or their composites. The publication closest to our topic describes how CO_2 laser was used to improve the electrical conductivity of CNT/poly(methyl methacrylate) composites [31].

In this paper, we present an in-depth study of the effect of laser cutting on the structural properties of CNT sheets and how the laser exposure can affect their mechanical properties. The effect of laser power on the kerf width and HAZ was examined by scanning electron microscopy (SEM) and Raman spectroscopy. The effects of laser cutting on the structural properties of CNTs were also studied by transmission electron microscopy (TEM) and electron energy loss spectroscopy (EELS). Mechanical tests were also conducted on CNT sheets cut at different laser powers.

2. Experimental methods and techniques

2.1. CNT sheet fabrication

CNTs used in this study were grown by the chemical vapor deposition (CVD) method. Iron (Fe)-based catalyst with a thickness of approximately 1.2 nm was sputtered on a 4-inch silicon (Si) wafer, which was previously coated with a 5-nm alumina (Al_2O_3) buffer layer. The coated Si wafer was loaded into a modified commercial CVD reactor ET3000 from CVD Equipment Corporation for CNT growth. Details about the growth conditions can be found elsewhere [32]. The CNTs grown by this method are vertically aligned and predominantly multiwalled with approximately 3–5 walls. The vertically aligned CNT arrays were used for preparing CNT sheets. A ribbon was drawn from one end of the array and wound onto a roller covered with Teflon film. The sheet assembling process is illustrated in Fig. 1, where each revolution of the roller produces a layer of CNT sheet. The sheets were densified by spraying acetone every 10 layers until a total of 100 layers were accumulated. Nanotubes in the sheet produced were aligned parallel to the drawing direction as shown in the inset of Fig. 1(b). The thickness of the CNT sheets was measured using a micrometer and confirmed by SEM to be 6 μm.

2.2. Laser cutting

A laser micromachining system by Oxford Lasers with an X-Y stage was used to cut CNT sheets. The device characteristics are as follows: solid-state laser with a wavelength of 532 nm, maximum pulse energy of 2 mJ, maximum average power of 4 W, frequency of 1000 Hz, resolution of 1 μm, and pulse duration of 10–500 ns. Laser cutting was performed in ambient air and pressure. The samples were cut under different powers (0.5%, 5%, and 50% of the maximum average power of 4 W) for each width at a speed of 2 mm/s and three cutting passes. The cutting speed and number of passes reported are the optimized parameters to ensure complete cutting of CNT sheets.

2.3. Characterization methods

Surface and cross-sectional morphology of CNT sheets were analyzed using an FEI XL30 SEM. The effect of laser cutting on the structural properties of CNTs was studied using an FEI image-corrected Titan3 G2 30–300 TEM. Raman spectroscopy (Horiba LabRam Aramis μ-Raman system, wavelength 532 nm, laser power: ~10 mW, grating: 600 lines/mm, and spectral resolution: ~2.8 cm^{-1}/point) was used to conduct spectral analysis of CNT sheets.

Mechanical testing of the CNT sheet samples was conducted using a uniaxial tensile testing machine (Instron 5948, maximum air pressure applied to the pneumatic grips equal to 5 Bar and maximum load equal to 100 N). The strain rate of testing was kept constant at 0.5 mm/s for all experiments

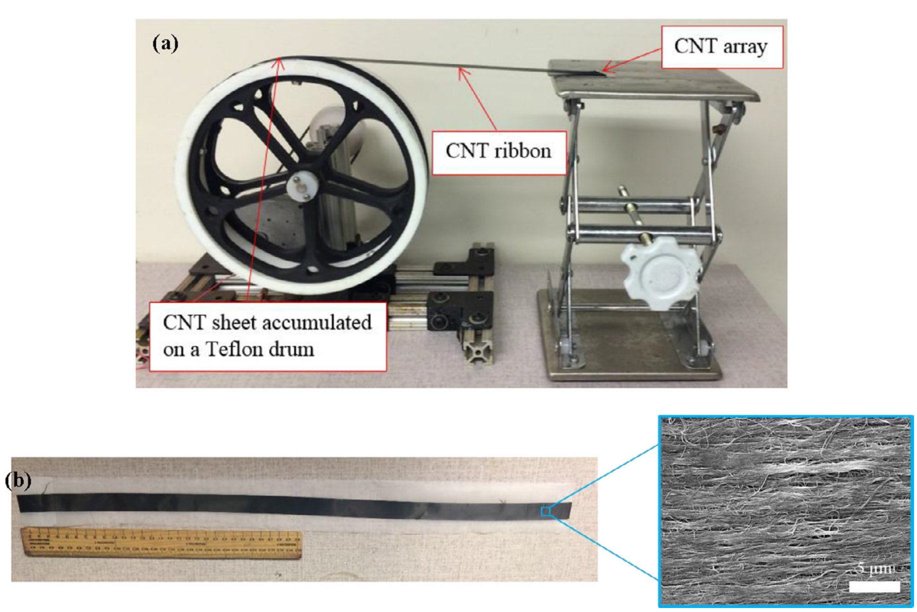

Fig. 1. (a) CNT ribbon being drawn from a CNT array and accumulated on a Teflon-covered drum to form a sheet and (b) CNT sheet after accumulation and densification, displayed along a 30-cm ruler. SEM image in the inset shows CNT alignment direction.