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# Laser welding of vertically aligned carbon nanotube arrays on polymer workpieces

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ABSTRACT

Here we demonstrate laser transmission welding of vertically aligned carbon nanotube (VACNT) arrays for joining polymer sheets. The unique characteristics of VACNTs make them suitable for use in laser welding. First, the excellent light absorption of the VACNTs induces selective heating at the contact plane with a polymer sheet, minimizing thermal damage to the polymer. Second, the porous and compliant structure of the VACNTs prevents the formation of air pockets inside the contact space. Successful welding is obtained when the laser irradiation power is at an optimal level, below which the adhesion is too weak and above which the excessive heat causes periodic damage along the scanning path. The optimized laser welding technique is expected to become a new method for implementing carbon nanotubes as mechanical linkers for various thermoplastic polymers.



## 1. Introduction

Laser processing has been steadily developed and widely applied in various fields of engineering owing to its unique advantages. For instance, as a non-contact process for easily deformable and sensitive structures, laser processing enables precise control of heat input and reduced thermal damage. Among its ubiquitous applications, laser light is employed in selective heating for welding a wide range of materials, including polymers, which are the key elements constituting daily commercial products [1,2]. The main process for laser welding is the absorption of the laser light to generate heat in polymers. The wavelength of the laser, the type of polymer, and the type and content of the pigment of the polymer affect the absorption and therefore should be controlled for effective laser welding. Laser welding techniques in standard use today can be divided into two main categories: laser butt welding and laser transmission welding. In laser butt welding, the joining surfaces are heated through a system of mirrors and then pressed together in the molten state. In laser transmission welding, which is adopted in this study, an absorbing material is inserted between the joining surfaces and heated by absorbing a laser beam passing through the transparent workpiece [1].

Recently, we developed a laser transmission-based welding technique to integrate vertically aligned carbon nanotube (VACNT) arrays and polymeric substrates into a functional composite [3]. VACNTs, which are also called carbon nanotube (CNT) forests, constitute a unique mesoporous material system comprising a self-assembled anisotropic network of CNTs. Individual CNTs feature an exceptionally high Young's modulus (ideally up to approximately 1 TPa) [4,5] and tensile strength (11–63 GPa) [6]. However, as a collective material system, VACNTs are mechanically compliant and exhibit foam-like behavior [7]. It has been revealed that the bundled and coiled structure of the nanotubes alleviates external loads [8]. That is, VACNTs behave like a porous cushion. By exploiting these unique characteristics, excellent contact between VACNTs and the polymer can be achieved, which is a crucial factor for successful welding.

In contrast to other heating techniques for CNT–substrate welding, such as hotplate and microwave heating [9–11], the

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programmable patterning and transfer capability of the laser method enables the direct writing of VACNT patterns on thermoplastic polymer substrates such as polycarbonate (PC), polymethylmethacrylate, and polyethylene terephthalate. The heat-affected zone induced by laser irradiation is relatively small, which minimizes thermal damage to the polymer. The heat can be selectively generated on the surface to be welded in a contact-free manner. Thus, the laser method allows the welding of complicated points and areas that are not readily accessible. Moreover, a designed weld geometry for obtaining sufficient mechanical strength can be achieved by scanning the welding laser.

While the transferred VACNTs could potentially be used as a flexible electrical element on the polymer sheets [3], we found another promising use of this technique: the mechanical joining of polymers. In this study, the technique for laser welding VACNTs onto a polymer sheet is applied twice to join two polymer sheets. The VACNTs simultaneously serve as a light absorber [12] that converts the irradiating laser light into local heat for welding and as a linker material [13] that connects the two polymer sheets. The influence of the laser power on the strength of the weld is investigated systematically. The macro/micro morphologies of the VACNT–polymer interface welded using different laser powers are examined. In addition, the welding strength is measured in a tensile test to determine the optimal laser power for welding.

## 2. Experimental

### 2.1. CVD synthesis of VACNTs

For the catalytic chemical vapor deposition (CVD) growth of VACNTs, a catalyst film consisting of iron (4 nm)/alumina (30 nm) was prepared on a silicon wafer by using electron beam evaporation and sputtering, respectively. VACNTs were produced in an atmospheric pressure CVD system. The catalyst substrate was annealed under a flow of hydrogen and argon gases to form nanoparticles, which are necessary templates for nucleation and growth of the CNTs. The growth was initiated by introducing ethylene at 740 °C. To avoid the deposition of excessive amorphous carbon, the ethylene gas (200 standard cubic centimeters per minute (SCCM)) was diluted with argon (200 SCCM) and hydrogen (50 SCCM) during the growth period. Approximately 300 μm of VACNTs were produced for 10 min. Our previous work offers a more detailed description of the CVD procedure [14].

### 2.2. TEM characterization of VACNTs

Portions of the CNT arrays were scratched from the substrates and deposited onto copper grids for inspection by transmission electron microscopy (TEM) using a 200 MC Zeiss Libra transmission electron microscope operated at 200 kV. Surveys of the CNT diameters and the number of carbon layers making up the multi-walled nanotubes were performed by acquiring high-resolution TEM images of 40 CNTs and analyzing them using DigitalMicrograph™ software. Scanning electron microscopy (SEM) of CNTs was conducted using a FEI Nova NanoSEM 650 scanning electron microscope.

### 2.3. Laser welding setup

A galvanometer mirror system (SCANLAB hurrySCAN II-14) was coupled to a continuous-wave argon ion laser (wavelength: 514 nm; Lexel 3000) to direct the laser beam onto the VACNT–PC interface. This setup enabled dynamic scanning with minimal change of the scanning speed. The beam spot size was estimated to be 50 μm. The scanning speed was fixed at 1 mm/s. For areal patterning, contour scanning was conducted with a 20-μm scan spacing to ensure complete welding of the CNTs over the entire pattern area.

### 2.4. Tensile test

The tensile strength of the weld was measured using a home-built measurement system consisting of a motorized linear stage and a force sensor (Dillon GL025). An epoxy adhesive (Loctite®) was coated on the opposite side of the laser-welded VACNT–PC sample by using a doctor-blade method. As soon as the VACNTs came into contact with the epoxy layer (detected by the force sensor), the contact region was illuminated with bright halogen light through a small hole for complete and fast curing. The intensity of the illumination was adjusted to avoid excessive heating of the PC–VACNT–epoxy weld, and the temperature was monitored using a non-contact thermometer (Micro-Epsilon CT-SF22).

## 3. Results and discussion

### 3.1. Laser transmission welding of VACNTs and polycarbonate

Fig. 1 shows a schematic of the laser transmission welding process used. The basic welding method is consistent with our previously reported technique [3]. CNTs are thermally stable at the melting temperatures of most polymers. Thus, the entire welding process was conducted under ambient conditions. The as-grown VACNT sample was covered with the polymer substrate and a glass slide. The glass slide was pressed down using mechanical clamps with spacers to enhance the VACNT–polymer contact. Then, the first welding step was performed by irradiating the top of the VACNTs with an $Ar^+$ CW laser beam (wavelength: 514 nm) through the glass–polymer stack. In laser transmission welding, the purpose of the laser irradiation is to heat the weld interface selectively, and direct absorption of the incident light by the polymer should be avoided. Thus, transparent PC sheets were used as the polymer substrate. Instead, the VACNTs, which are known as an extremely dark material [12], absorbed most of the laser light, increasing the temperature of the contact surface of the PC sheet above its glass transition temperature. After the completion of the laser scanning and the separation of the welded PC sheet from the as-grown VACNTs, the first VACNT–polymer weld was obtained. To fabricate a welding joint of two polymer sheets, the first weld was used as a VACNT support. The same welding process was repeated with the second polymer sheet.

Different kinds of polymers can be used as the second sheet, provided that they are compatible with the laser welding technique. For instance, a PC–VACNT–acrylic plate assembly was fabricated using an acrylic plate as the second sheet (Fig. 1b). As shown in Fig. 1c, the welded area was bonded so tightly that no immediate leakage of green fluorescent liquid (polymer microspheres, 1% solid; Duke Scientific) was observed. The empty inner pocket of the welding pattern was filled with the colloid via a syringe needle. It should be noted that VACNTs constitute a mesoporous material system with a spacing of 10–100 nm between the nanotubes. Therefore, despite the tight adhesion, a liquid can eventually infiltrate the welded VACNTs. A welded assembly (1 $cm^2$ in area) was able to withstand an external load (approximately 3.79 L (one gallon) of water) for longer than 10 min, as shown in Fig. 1d. The welded PC sheets and the binder clip were fixed using an epoxy adhesive.

Similar to the conventional laser transmission welding of plastics, the laser welding of VACNTs and thermoplastic polymer materials involves (1) heating by the absorption of the laser light, (2) intermixing of the CNT extremities and the contacting polymer at a