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Radio Frequency Welding of Multi-Walled Carbon Nanotubes for Plastic Bonding

Abstract

Current plastic welding technology often involves heating up an entire piece in order to achieve a weld. This paper discusses how time and energy may be saved due to the unique property of CNTs as thermal dissipaters. Thus, CNTs may be placed only on the plastic parts where plastic welding or targeted heating is required. This paper discusses the theories for this powerful heating property of CNTs and provides discussion of how this might work in a bench scale environment. Furthermore, this includes an explanation of how dispersion of the CNTs in appropriate solvents, as well as other material properties, can enhance the heating rate and uniformity of the weld. We designed a solution of MWCNTs to weld high density polyethylene (HDPE), along with the RF system and properties. The result of the design of these solutions as well as future work is given.

Motivation

The motivation of this project comes from current processing techniques used to bond plastics. Despite the ubiquitous number of plastics techniques; from contact to laser plastic welding, they often share the common problem: relatively low energy efficiency and high power inputs. In order to weld two thermoplastics, the plastic body must be heated close to its melting temperature, a process which requires excessive amounts of heat, time, and money.[1] Additionally, the weld or interface of the bond limits the overall mechanical properties, and is often the location of eventual failure.

An alternative approach is to utilize the energy absorption properties of carbon nanotubes to achieve a more targeted form of heating in comparison to current technologies. The absorption of radio/microwave waves can be converted to thermal energy through two main mechanisms: dielectric and joule heating. Dielectric heating involves the movement of dipoles to an AC electromagnetic field. Joule heating is caused by electron scattering and collisions from the induced current due to the AC field.

Due to the high conductivity and energy absorption of carbon nanotubes the bulk of the heating of a CNT-polymer system is localized in the CNTs. Consequently, by applying a nanotube mixture to a specific area, the heating can be localized and allow manufacturers to forgo bulk heating a plastic piece.

Materials Science and Engineering Aspects

For this project, we are attempting to design a carbon nanotube solution/dispersion that can be applied to plastic pieces to locally bond it. There are several materials parameters that we must consider for the system to be chemically compatible, and to optimize/increase efficiency.

Our main materials parameters include those of the plastic, CNTs, solvent, and RF system. The plastic and solvent type must be chemically compatible; the solvent must not corrode, degrade, or react with the plastic within our time scale. The CNTs must be able to be well dispersed within the solvent, and this mixture must exhibit a high enough dielectric loss tangent (imaginary dielectric component over the real component) and conductivity at the chosen RF frequency to optimize/maximize dielectric and joule heating.

Furthermore, using the density, specific heat, thermal conductivity, and system geometry; this heating rate must be able to demonstrate a 'sharp temperature' gradient within the solvent mixture, melting the plastic within ~micron-mm range (targeted heating). The final bond should display mechanical properties on par or better than the bulk plastic for the desired application (i.e. the part must not fail at the bond itself at significantly lower stress/strain than the bulk).

Previous Work

Kanzius radio frequency (RF) cancer therapy has demonstrated the ability of single walled carbon nanotubes (SWCNTs) to absorb and convert electromagnetic radiation in the RF range into thermal energy under an external field. The phenomenon is attributed to the SWCNTs phonon ballistic conduction, which allow for the unimpeded flow of particles carrying a specific energy across large distances.[2] The authors, C. Gannon et al., achieved localized heating through RF induction of SWCNTs, and were able to treat human cancer cells in a noninvasive and selective manner.[2] The study used SWCNTs functionalized with Kentera, and found that small concentrations of Kentera SWCNTs, significantly enhanced the RF heating of the solution. At a concentration of 50mg/L, the heating provided by the SWCNTs alone was 0.9K/s.

Design Goals

The goal of this project is to predict the heating rate of a CNT solution using a variety of theories. This heating rate should be optimized, or maximized at least within the desired frequency range (which is dependent upon environment and government regulations), based on several materials properties such as the CNT aspect ratio, CNT type, plastic and solvent type, and AC frequency/field strength.

Upon application of the CNT solution and irradiation, the polymers should ideally melt or bond together within a smaller range than resulting from conventional techniques. This bond will need to exhibit better mechanical performance for the current system or compared technique, which may mean that the bond exhibits a higher tensile or yield strength than the bulk, but it depends upon the application. Additionally, the time it takes to sufficiently bond the plastics should be minimized. This can be achieved by cutting off the RF source at an appropriate time. Thermally activated adhesives represent a bonding method similar to ours, so our design could be compared to it as an additional metric.

Technical Approach

The technical approach of the project revolves around two key goals: (1) determining if there is an optimizable heating rate and determining that heating rate (2) targeted heating. Furthermore, the components of our system must be physically and chemically compatible, abide by federal and laboratory regulations regarding microwave/RF radiation, follow the project's budget, and the plastic weld should display appropriate mechanical strength.

The heating rate and efficiency will be designed utilizing; dielectric physics; percolation theory; General Effective Media theories. The goal is to optimize heating rate and efficiency by maximizing microwave energy absorption and heat generation through conduction and dielectric losses. Dielectric mixing theories will help us estimate the overall dielectric properties of the system based on the combination and interaction of/between the individual components. By modeling CNTs as antennas we can determine their ideal length, and from percolation theory we know we want the lowest possible diameter. Using the calculated properties from these theories, the heating rate can be predicted. Material parameters of importance include dielectric constant, dielectric loss, loss tangent, percolation parameters, CNT geometry, and CNT dispersion.

Design

First, we will determine the ideal heating of a carbon nanotube mixture using theories and equations, provided below. For the ideal case we are assuming that all nanotubes are evenly dispersed (no agglomeration), perfectly straight (no bending or curling), orient themselves perfectly parallel with RF radiation, the electric field strength remains constant due to the high penetration depth of RF/microwaves and our small volume, and all are single-walled carbon nanotubes (SWNT). In addition, estimating the ideal heating rate will help set up a system that could be used to predict heating of less ideal systems.

Microwave frequencies are often used in telecommunications, since these frequencies are highly regulated to ensure there is no interference, it is important to choose a compliant frequency band. Many countries use 2.450 (+/- 0.050) GHz for research, medical, and industrial uses.[4,5] There are

lower compliant frequencies, but at higher frequencies there is a tendency for the induced current due to dipole movement to become more out of phase and produce more heating.

To determine our nanotube length we will assume that the CNTs do not agglomerate, and do not curl, bend, or deform in any way. In this context, we will assume that the nanotubes act as an antenna and will resonate at particular frequencies based on their length. Additionally, placing an antenna in a dielectric decreases the resonant frequency and also decreases the necessary length for resonance.[6] For reasons stated later, we will use DMF, which has a dielectric constant, or relative permittivity, of 36.7.[7] The equation for reduced wavelength, or antennae length is as follows,

$$(1) \ \lambda = \frac{c_o}{f\sqrt{(\varepsilon_r)}}$$

From this we can obtain a wavelength, or nanotube length of 2.02 mm. Many people use lambda/4 antenna, because it saves money even though the efficiency is reduced due to it being below the true resonant length. However, we are not considering money in the ideal case.

The next parameter to consider is CNT diameter. The smallest diameter SWCNT that can be theoretically obtained is the metallic (4,4) 'armchair' nanotube at 0.542 nm, which results in an aspect ratio of $3.72*10^6$.[8]

We chose the lowest possible diameter because we want a high aspect ratio to decrease the critical volume fraction (and amount of material and money needed) at the percolation threshold. The percolation threshold in our case is the volume or concentration of a conductive filler in a dielectric material at which the conductivity drastically increases (often orders of magnitude) and signifies a transition of overall properties from dielectric to conducting. This relationship generally holds for a small concentration or volume range, after which the conductivity saturates, or rises more slowly. The reason for this sharp conductivity increase is due to the formation of a random long range carbon nanotube network that creates pathways for electrons to flow through the material.

The relationship between conductivity and concentration above this threshold can be modeled as a power law equation,

$$(2) \ \sigma = \sigma_o(V - V_c)^t$$

The exponent, t, is mainly dependent upon the geometry of the system, so it can be estimated from previous research that uses similar systems. 3D systems consisting of two components, a dielectric and a conductor, usually have an exponent around t=2.[9]

Additionally, it has been shown experimentally that the loss tangent is locally maximized in a small range above the percolation threshold, which may be in part due to the large increase in conductivity, and henceforth, joule heating or conduction losses.[27] The volume fraction at which

percolation threshold occurs can be calculated from excluded volume theory, which considers the fact that carbon nanotubes cannot exist in the same location at the same time and factors in rotation/orientation in a medium.[10] It is important to note that this equation has been shown to overestimate the volume fraction because it does not consider the tunneling between CNTs. This equation can be written as,

$$(3)\ V_c = 1 - \exp\left(\frac{-<V_{ex}>V}{<V_e>}\right)$$

where,

$$(4)\ <V_e> = \frac{4}{3}\pi W^3 + 2\pi W^2 L + 2WL^2 <\sin(\gamma)>_\mu$$

$$(5)\ V = \frac{\pi}{4}W^2 L + \frac{\pi}{6}W^3$$

Where Vc is critical volume fraction, and sin(y) for randomly oriented nanotubes converges to lambda/4, and 0 for strictly parallel nanotubes.[10] The strictly parallel case causes the volume threshold to become invariant with respect to nanotube dimensions; it only depends upon the average excluded volume, <Vex>. The average excluded volume is a constant based on particle geometry. This constant can be approximated as 1.4 for' infinitely' long nanotubes and 2.8 for spheres.[10] For real systems of high aspect ratio, 1.4 is accurate.[10] From our nanotube length and diameter, one obtains a critical volume fraction of $1.88*10^{-7}$ for the onset of percolation, which is small due to the large nanotube aspect ratio. For the strictly parallel case the critical volume fraction is 0.161 for an excluded volume of 1.4.

For the ideal system we will consider the parallel case because dielectric properties and conductivity are greatly increased in the longitudinal direction. The longitudinal dielectric response of an isolated carbon nanotube is determined by the following equation,

$$(6)\qquad \varepsilon_{||} = 1 + \frac{4\pi}{\Omega}\alpha_{||} \approx \varepsilon_r$$

,where a|| is the polarizability per unit length, and is Omega the area of the unit cell. The unit cell of a (4,4) nanotube was calculated from equations provided by the Maruyama-Chiashi Laboratory at The University of Tokyo,[11] and determined to be 43.1 Å². The polarizability was calculated using an empirical relationship determined using density-functional perturbation theory (DFPT), and is shown as,[12]

$$(7)\ \alpha_{||} \approx 8.2R_o^2 + 20.5$$

Where R_o is in Angstroms and the polarizability is approximately 80.72, resulting in an e‖ of 24.54. Since our ideal system consists of completely parallel carbon nanotubes, we will assume they are oriented in the direction of the incident microwave radiation, and e‖ approximates e'r.

Now with the volume fraction, we can use dielectric mixing theories to estimate the real permittivity of a mixture based on its individual components. There are several mixing theories, all of which require the critical volume fractions of the materials, and their relative permittivities, many of which also include the critical volume fraction and exponent from percolation theories. We will be looking at a mixing theory known as General Effective Medium (GEM) theory, which combines percolation and other approaches into one equation,[12]

$$(8)\ \frac{V_l(\varepsilon_l^{\frac{1}{s}}-\varepsilon_m^{\frac{1}{s}})}{\varepsilon_l^{\frac{1}{s}}+A\varepsilon_m^{\frac{1}{s}}} + \frac{V_h(\varepsilon_h^{\frac{1}{t}}-\varepsilon_m^{\frac{1}{t}})}{\varepsilon_h^{\frac{1}{t}}+A\varepsilon_m^{\frac{1}{t}}} = 0$$

Where el and eh are the lower and higher dielectric constants, V_l and V_h are the lower and higher volume fractions, and A is given as,

$$(9)\ A = \frac{1-V_c}{V_c}$$

From the above equation we get A=5.211. Plugging in our other parameters we obtain an effective relative permittivity of 34.52 for the nanotube-DMF mixture.

Now the time average heating of a dielectric material can be described as,

$$(10)\ <Q> = \pi f \varepsilon_m \varepsilon_o E^2 \tan(\delta)$$

Where f is the frequency of microwaves, e0 is the permittivity of vacuum, E is the electric field strength, tan(delta)is the loss tangent, and Q is the power density (W/m^3). The loss tangent represents the energy loss in a material, which is dissipated as heat. The loss tangent can be expressed as a sum of the energy losses due to dielectric dipoles tan(delta)$_d$, and joule heating due to electrons tan(delta)$_e$,[12]

$$(11)\ \tan(\delta) = \tan(\delta)_d + \tan(\delta)_e = \frac{\varepsilon_r''}{\varepsilon_r'} + \frac{\sigma}{\omega\varepsilon_r\varepsilon_o} = \frac{\varepsilon_r''}{\varepsilon_m} + \frac{\sigma}{\omega\varepsilon_m\varepsilon_o}$$

The conductivity of a 1D object can be determined by the Landauer formula, where it is assumed that G=2G$_0$, because single-walled carbon nanotube have four electron channels due to spin and sub-lattice degeneracy,[13]

$$(12)\ = \left(\frac{4e^2}{h}\right)T = \sigma\frac{A}{L}$$

,where e is the electron charge, h is Planck's constant, and T is the transmission coefficient. For the ideal case for now, we will assume there is minimal electron scattering, resulting in ballistic conduction (T=1). This gives G= 155 S, or =$1.36*10^{12}$ S/m. This number is very high, because it assumes a perfectly straight, high aspect ratio, defect free nanotube with ballistic transport. This is not the reality, but it will serve our purposes for now, and can easily be changed later.

For dielectric loss (e"), we could not find for isolated carbon nanotubes or carbon nanotube-DMF mixture. However, due to the symmetry of carbon nanotubes, there is minimal or no dipole moment, and the dielectric loss component of the heating from CNTs can be ignored. This suggests that any dielectric heating of the CNT-DMF system is mainly due to DMF. The dielectric loss of DMF at 2.45 GHz and room temperature is 5.9.[15] The electric field strength is chosen to be 1.2 kV/m to represent a standard commercial microwave oven.[16]

Plugging all of these numbers into equation (10) yields a very large dissipated power density of $1.96*10^{18}$ W/m^3, or $6.32*10^{11}$ W for a 25.4 mm x 25.4 mm x 0.5 mm film of nanotube-DMF mixture. This result also confirms that for high electrical conductivity, the dielectric component can be ignored, even if the contribution of dielectric loss was considered. The contribution of dielectric loss of DMF for total power dissipation in this case is $5.9*10^{-13}$ %.

In order to determine the heating profile/rate over time, SolidWorks heat transfer simulation was used. The ideal case was not used as the total heating would be so high that it would most likely melt or vaporize the entire system 'instantaneously'. Instead to represent a more accurate system, we modeled the CNT solution as a CNT film with 50W of internal heat generation. At a RF power of 600W this would indicate an 8.3% efficiency. The 50W is used to get initial simulation results and provide a framework for further calculations, once a more accurate prediction of heating is reached.

The model consisted of a 50.8mm x 50.8mm x 0.25mm CNT film sandwiched between two 50.8 x 50.8mm x 20mm high-density polyethylene samples (HDPE). Convective heat transfer with 20C ambient air with a transfer coefficient of 10.45 W/m^K was placed at all outer boundaries. The initial temperature was set to 20C everywhere. A 50W total heating was set for the entire CNT-film volume, and a 'thermostat' cutoff was used to change the heating power to 0W after the outer vertices of the film reached 120C. The purposed of this was to ensure that full contact was made between the plastic pieces, but the sample wasn't heated so long as unnecessarily melt excess HDPE and contribute to bulk heating.
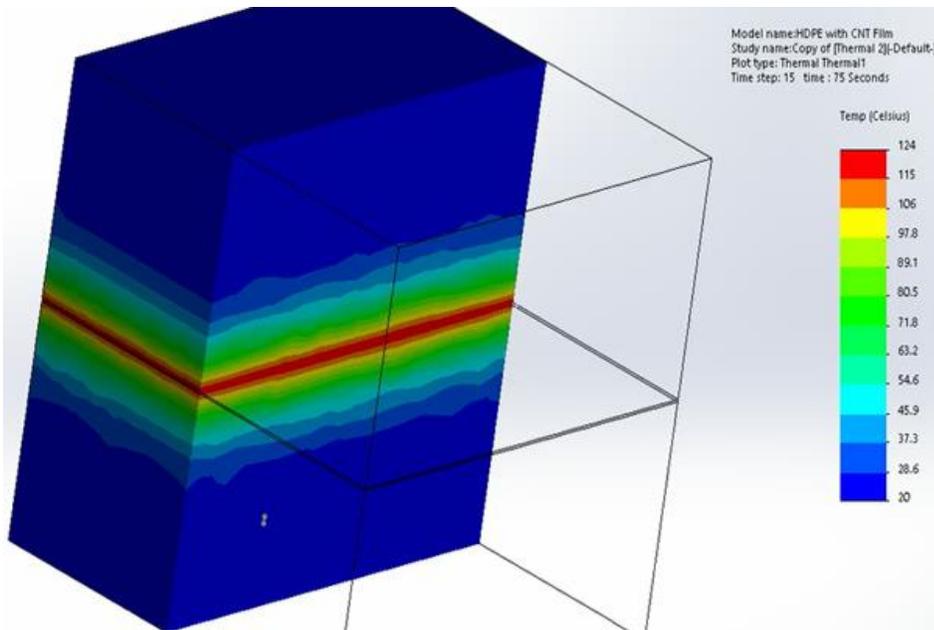
Figure 1: Results of transient heat transfer simulation in Solidworks. Maximum temperature of 124C at 75 seconds.
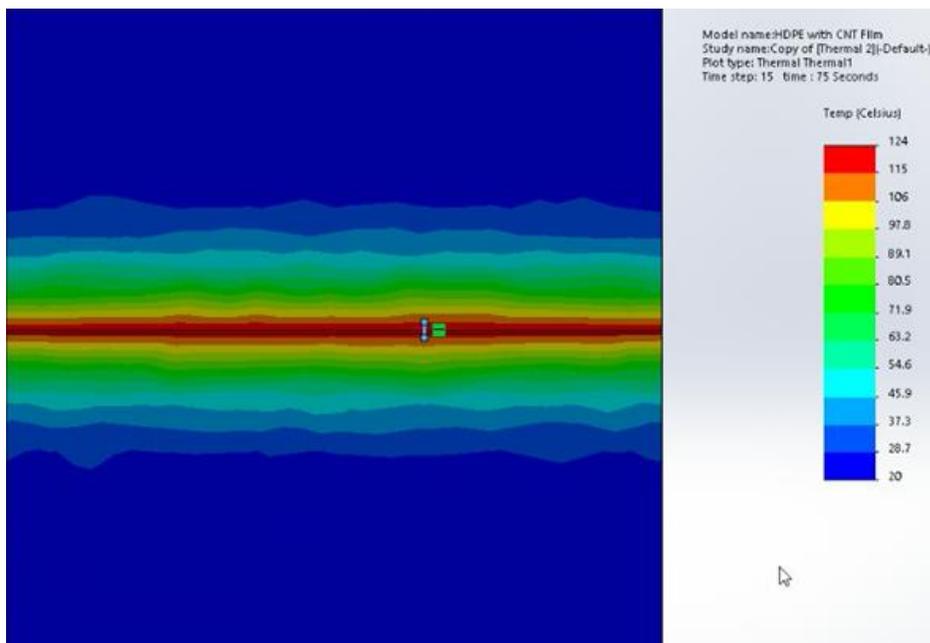

Figure 2: Line covers an approximate range for the melting of HDPE. The line length was ~1.2mm, and the thickness of the film was 0.25mm.

From the results of the simulation it can be seen that the maximum temperature was 124C at 75 seconds, which is a reasonable timeframe if 50W internal heating can be achieved. The total 'width' of the heating was around ~1mm after subtracting the film thickness.

Upon analysis of theoretical calculations for the ideal case, one can deduce that the ideal system we portrayed is unrealistic due to the large amount of assumptions made. The combination of all of the errors from these theories and approximations is no doubt large, however, for a more realistic scenario these assumptions could be easily removed or tweaked. These equations provide a framework to help calculate different properties and eventually predict the heating rate. By empirically determining materials properties, or through other means, the number of equations and assumptions could be reduced to arrive at a more accurate prediction of heating rate. However, these models would still need to be compared to actual data from experiments to determine their effectiveness and accuracy.

Empirical Studies/Derivation of Parameters

The dielectric properties of CNTs and the CNT-DMF dispersion can be found using impedance (dielectric) spectroscopy data. Impedance spectroscopy measures the dielectric properties of a material as a function of frequency. The data would be output in the form of a Nyquist or Bode plot, where the impedance of the system is plotted against frequency. The dielectric constant can then be found by fitting the Nyquist plot with an equivalent circuit equation using impedance analyzing software such as Zview.[20] An equivalent circuit is needed in order to isolate the responses from different parts of the system. Then the fitted capacitance values of different parts of the system can be found, which can then be used to find the dielectric constant of the material. Unfortunately, this equipment and software was out of our budget, but this process could still be used to obtain more a more accurate prediction of heating.

Another important parameter, both for determining heating and percolation threshold, is the electrical conductivity. The electrical conductivity can be determined by measuring the resistivity of the carbon nanotube solutions, and the solvents themselves. This can be accomplished by using a standard two probe conductivity meter and a standard solvent/solution for calibration, or a four probe method. The probes must be set up so that their distance apart is precisely known; there are types of probes that are already designed with this in mind. The conductivity of the carbon nanotubes can be determined by measuring the nanotube powder directly (which may be difficult or inaccurate), or through the use of a mixing theory similar to GEM knowing at least two out of three values. It is important to measure both the AC and DC conductivity, since our system will use relatively high frequency radiation.

In order to determine the percolation threshold, DC conductivity measurements can be taken at various concentrations. The measured concentrations will be determined through estimations of the percolation threshold using volume exclusion theory, mentioned above. If necessary the concentrations will be adjusted until a power law-type relationship is observed or a large spike/transition occurs, which will be approximately at the critical volume fraction. Equation (2)

will be fitted to the graph for different V_c, and then regression analysis can be used to maximize R^2 and obtain the parameters t, and o.

Prototype

From the recommendation of Zyvex Technologies (Kentera CNT distributor), two CNT dispersions were made with DMF and silicone oil at a concentration of 10mg/5mL and sonicated for 30 minutes. Two 1 inch copper wires were cut and attached to the leads of an ohmmeter. The wires were placed at opposite ends of the vial (2.25 cm apart, a depth of 15 mm) and the resistance was measured. The resistance of DMF dispersion was measured at 250±50kOhms. The resistance of the silicone oil was too high and thus not measureable. After 24 hours the silicone oil had almost completely separated, and the DMF had slightly separated.

A second set of dispersions were made using the same concentration and solvents, but sonicated for 60 minutes instead of 30 minutes. The resistance of the DMF dispersion decreased to 150±50kOhms. The resistance of the silicone oil was still too high to be measured. After 48 hrs the silicone oil dispersion had separated, but the DMF dispersion showed no visible signs of separation.

In order to see the effect of CNT concentration on the dispersion and resistance, two other solutions were made at a lower concentration of 5mg/5mL and sonicated for 30 minutes. When the resistance was measured there was too much fluctuation to reliably record a value.

Ethics and Environmental Impact

The ethical stipulations of this project include following: CNT/materials disposal, harmful/toxic materials, RF range and its effect on humans and on manufacturing processes. It is widely known that CNTs are an environmental hazard and potentially toxic. Therefore, the CNT solution needs to be disposed of properly (into specific laboratory containers for the project).

Silicone oil is not considered a particularly toxic substance, but it is flammable and should be stored and disposed of appropriately. Any simple lab gloves will do for handling it, along with standard laboratory attire such as close-toed shoes, lab-coat, and goggles.

DMF is very hazardous and has flammable vapors. Extreme care should be taken when handling to avoid inhaling and contact with skin, or eyes. Lab goggles and butyl rubber gloves should be used, and DMF should never be handled outside of a fume hood. Lab procedure should be created to minimize exposure time. Similar to silicone oil and other lab chemicals, it should be disposed of properly. Both silicone oil and DMF should pose no environmental or health hazard inherently if handled appropriately. While we use DMF to test lab-scale dispersion of CNTs. It is not

recommended to scale up for industrial processes unless proper care is taken and stricter regulations are put in place.

The RF system must also be set-up to ensure safety. The FCC's maximum permissible exposure from §1.1310 is 85.2mW/cm^2 for 10.56 MHz. Reaching this limit is highly unlikely, even for higher powered radio towers, but we will use RF shielding to protect humans and laboratory equipment.

Finally, our single most important issue involves any potential advertising of the product when bringing it to market. Any experimental product, which may be commercialized must be incorporated into a manufacturing process and go through the testing needed to certify its functionality. Fraud is a serious issue, we do not want to inadvertently mislead the public or manufacturers.

Furthermore, life cycle analysis and ethical studies of our project will help protect the consumer, and reduce total cost through the increase of efficiency from minimizing disposed materials.

Intellectual Merit

The purpose of the project was to find a more cost and energy effective method of bonding/welding plastics. We can show this by exhibiting targeted heating of SWCNTs via RF irradiation. This can be demonstrated by observing the time-dependent temperature profile of the physical plastic and CNT system. If the plastic melts or bonds occurs over an appropriately small range for a specific application then it can be said that heating occurs locally.

Additionally, we hope to learn more about the heating mechanisms of CNTs by comparing results to estimations from theoretical equations. The time-dependent temperature profile can be modeled from system initial and boundary conditions, and experimentally determined materials properties using simulation software. Which, can then be compared to the results obtained from theoretical predictions.

Broader Impact

A phenomenon as rudimentary as plastic welding has the ability to revolutionize many industries related to the manufacturing of plastics. CNTs thermal properties under a RF wave allows for targeted heating of large plastic pieces for welding purposes in the aerospace, automotive, and even 3D printing industry. Most importantly the rapid prototyping, assembly and manufacturing of industrial parts for consumer and producer goods would be possible. Finally, it could be used to shorten the production process and reduce the equipment used to create manufactured plastic parts. If successful, this new form of plastic bonding will provide a novel method for the selective heating of plastics, and/or other materials, and provide a more sustainable, environmentally friendly, and cost effective alternative for plastics manufacturers and their subsidiaries.

Results & Discussion

We have selected DMF to disperse our MWNTs. DMF is recommended to disperse CNTs by several sources, because it has low evaporation volatility, allows coupled CNT movement in an electric field generated by the RF transmitter, and creates a uniform suspension.[24,25] Low evaporation volatility gives manufacturers a larger time window for processing, because evaporation would increase the relative MWNT concentration, and consequently, the overall properties. According to W., Jiaxin, et al. (2012), MWNTs reorient themselves and lineup end-end along electric field lines.[24] In fact, this was the proposed mechanism by Gannon, C., J., et al. (2007), for their larger than predicted heating rate from the addition of SWNTs to cancer hyperthermia agents.[2] The formation of CNT 'antennae' of larger effective length increases RF absorption.[2] Similarly, a uniform suspension is important, because agglomeration of CNTs lowers thermal conductivity by preventing reorientation in an electric field, and increasing phonon scattering.[26] Unfortunately, DMF reacts with many types of plastics and can cause swelling. Our choices of plastics are mainly limited to the use of polyethylene (PE), polypropylene (PP), Nylon, as well as some others. However, polyethylene and polypropylene are easily obtainable, and can be used to show proof of concept and obtain initial results.

Silicone Oil is used as a standard heating fluid for different applications. The microwave absorbance of silicone oil is enhanced by 500 times with the addition of as little as 0.04 wt% carbon nanotubes.[28] Quantitatively, silicone oil has a conductivity of $\sim 10^{-14}$ S/cm. Their nanotubes were dispersed in the silicone oil through shear mixing, which indicates the importance of processing and preparatory techniques like centrifugation and ultrasonication. Consequently, this makes silicone oil a viable candidate for targeted heating of MWNT in situ.[28]

Deionized water will be used as our standard independent variable and is expected to have the lowest heating rate based on its ineffectiveness in dispersing carbon nanotubes. The polar nature and relatively low steric hindrance of water simply causes the MWNT to agglomerate. However, this makes it well suited for determining the relative effective heating rates of DMF versus silicone oil for the experimental design.

High density polyethylene was chosen due to its higher melting (~120C-130C) point and density/weight. This will allow us to determine the relative effectiveness of DMF and silicone oil on heating and adhesion of the polyethylene. In comparison, to low density polyethylene, can be melted at (105C-115C), which may be too quickly to compare effectiveness of solvents.

Kentera (poly(aryleneethynylene)s (PPE)) coatings allow for the non-covalent functionalization of CNTs; advantageously, the CNTs can then be functionalized without altering their intrinsic properties. Furthermore, the Kentera backbone selectively interacts with the CNTs via pi-stacking.

This is a non-wrapping molecular approach to creating CNT surfaces that increase their solubility. Further, it enables the introduction of various neutral/ionic functional groups onto CNT surfaces. These interaction can then be further enhanced using thermal carrier fluids such as silicon oil to allow for a greater dispersion of CNTs and a faster heating rate.[10]

Discussion of Prototype Results

It was expected that DMF would produce better dispersion than Silicone Oil (SO) because of previous research, but we did not expect SO to be completely unreadable. This could be due to having too high of a concentration of CNTs, which could cause higher amounts of agglomeration and contact resistance between CNTs. This is also supported by the visible clumping of material on the sides of the vials (for both DMF and SO), which also seems to qualitatively indicate that the CNT concentration should be reduced, albeit SO much more.

Doubling the sonication time did help for DMF, but still not for SO. It's probable that no amount of sonication or centrifugation can make up for the fact that there may be too high of a concentration of CNTs.

Doubling the sonication time to 60 minutes resulted in SO staying longer in solution, and DMF not visibly separating after ~48 hours. Halving the concentration at 30 minutes sonication resulted in highly variable conductivity measurements, which may have been due to the contact resistance of the leads, or because there were not enough CNTs to adequately form a conductive network. However, it is more likely that all solutions need to be filtered of residual graphite, or carbonaceous particles, and solutions need to be more carefully dispersed.

Conclusions

During the course of our project, we aimed to create an RF system as well as a CNT solution with the goal of locally heating plastics. We had the chance to test a couple CNT solutions of DMF and SO. Although our data is limited, from initial glance it seemed that DMF was much better at dispersing CNTs, and as a result, stayed much longer in solution and had readable resistance values (although quite variable at times). Doubling the sonication time seemed to improve both solutions, although SO still could not be measured. It is likely that filtering the solutions of residual graphite, or carbonaceous particles, and more carefully dispersing them would have better results.

From our theoretical equations we have established a framework that can be used to predict heating of carbon nanotube systems based on dielectric and joule heating. Although the heating was calculated for a very ideal scenario, these equations can easily be modified based on the assumptions used. Furthermore, if more materials properties are known, many of the equations can be removed to simplify the calculations and improve the accuracy. The simulation allows us to

examine the temperature, time, and bond thickness that could be achieved given the materials properties of the system and the calculated heating rate.

Future Work

We intend to assemble the RF system based on a short wave diathermy machine which models the Kanzius's machines design. The design should be based on the original model using the standard 13.56MHz signal applied across two metal electrodes at 600W. The following areas of research accompany our previous work regarding the CNTs: (1) to determine how to keep CNTs in solution with flocculants/additives over long period of time and (2) to vary sonication time and reduce centrifugation time to increase dispersion and rate of retention in suspension, and (3) to create a deionized water standard solution to compare the difference thermal power dissipated due to the CNTs. Given, these two part of the project, we could then move onto other forms of testing regarding the heating rate as well as the tensile properties of the weld; this could be accomplished with IR camera thermal imaging and mechanical tensile testing, respectively.

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