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(54) Title: PROCESSING OF SINGLE-WALLED CARBON NANOTUBE METAL-MATRIX COMPOSITES MANUFACTURED BY AN INDUCTION HEATING METHOD

(57) Abstract: In some embodiments, the present invention is directed to a new composition of matter. Such a composition generally comprises a functionalized single-wall carbon nanotube (SWNT) which is coated with a metal that would not react with carbon at elevated temperatures. The metal-coated tube is incorporated into a metal matrix that could potentially form carbides. In some or other embodiments, the present invention is directed to methods of making such compositions.



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PROCESSING OF SINGLE-WALLED CARBON NANOTUBE METAL-MATRIX COMPOSITES MANUFACTURED BY AN INDUCTION HEATING METHOD

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority under Title 35 United States Code, §119 to U. S. provisional patent application U.S. Pat. App. Ser. No. 60/788,659 filed April 3, 2006 and provisional patent application U.S. Pat. App. Ser. No. 60/874/856 filed December 14, 2006.

FIELD OF THE INVENTION

[0002] The present invention relates generally to carbon nanotube-metal composites, and specifically to such composites with metals that are generally carbide-forming, but in which the carbon nanotubes remain intact.

BACKGROUND OF THE INVENTION

[0003] Matrix-reinforced materials science continues to be a rapidly evolving field of investigation both from the point of view of fundamental research as well as its industrial application. Metals can display a wide range of outstanding qualities. Certain metals, such as copper, display excellent thermal and electrical conductivities, but poor strength. Other metals like titanium display remarkable strength and corrosion resistance, but poorer thermal and electrical conductivities. Individual single wall carbon nanotubes (SWNTs) display superior qualities to all metals, characteristics that make them potentially perfect additives for metals and for the creation of new metal composites.

[0004] Such composites, however, have generally been limited to those which comprise non-carbide forming metals because high-temperature processing of carbon nanotubes in carbide forming metals will generally lead to the destruction of the nanotubes. Accordingly, a method of making such composites which permits the incorporation of carbon nanotubes into carbide forming metal matrices, while maintaining the structural integrity of the carbon nanotubes, would be highly beneficial.

BRIEF DESCRIPTION OF THE INVENTION

[0005] In some embodiments, the present invention is directed to a composition comprising: single-wall carbon nanotubes (SWNTs) coated with a first metal; and a second metal within which the single-wall carbon nanotubes coated with a first metal are dispersed, wherein the first metal is a non-carbide forming metal, and wherein the second metal, which serves as a matrix, is selected from the group consisting of carbide-forming metals and non-carbide forming metals. Regarding such compositions, in some embodiments, the SWNTs are generally functionalized as fluorinated SWNTs (F-SWNTs). The nanotubes in such compositions are structurally intact.

[0006] In some embodiments, the present invention is directed to a method comprising the steps of: (a) electrolessly-coating single-wall carbon nanotubes with a first metal to form metal-coated nanotubes; (b) mixing the metal-coated nanotubes with a second metal to form a mixture; and (c) heating the mixture to form a composite, wherein the first metal is a non-carbide forming metal, and wherein the second metal, which serves as a matrix, is selected from the group consisting of carbide-forming metals and non-carbide forming metals.

[0007] In some of the method embodiments, the SWNTs include without limitation functionalized SWNTs including fluorinated SWNTs (F-SWNTs). In some or other embodiments, the heating involves induction heating. Generally, such methods permit the nanotubes to survive (structurally) the processing and remain intact in the resulting composite.

[0008] The foregoing has outlined rather broadly the features of the present invention in order that the detailed description of the invention that follows may be better understood. Additional features and advantages of the invention will be described hereinafter which form the subject of the claims of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[0010] FIGURE 1 is a plot of Vickers hardness of titanium after SWNT addition;

[0011] FIGURE 2 depicts Raman spectra of Ni-coated F-SWNTs, wherein different spectra reflect the wide degrees of fluorination;

[0012] FIGURE 3 depicts Raman spectra for the Ti/SWNT Composite compared to that for pure SWNTs, wherein peak overlap strongly indicates that nanotubes survive the high temperature processing;

[0013] FIGURE 4 is a scanning electron microscopy (SEM) image of the Ni-coated F-SWNT; and

[0014] FIGURES 5(a)-5(d) are SEM results of nickel-coated F-SWNTs in SWNT-titanium metal-matrix composites after manufacturing by an induction heating method.

[0015] FIGURE 6 shows SEM images of (a) pure bundled SWNTs; (b) and (c) SWNTs in a titanium powder after the ball milling/incipient wetting process; (d) SWNTs in a copper powder after the ball milling/ incipient wetting process.

[0016] FIGURE 7 shows a comparison of Vickers Hardness values for titanium (a) and titanium 6-4 alloy (b) as a function of nanotube addition by percent weight.

DETAILED DESCRIPTION OF THE INVENTION

[0017] In some embodiments, the present invention is directed to a new composition of matter. Such a composition generally comprises a single-wall carbon nanotube (SWNT) which is coated with a metal that would not react with carbon at elevated temperatures. In alternate embodiments, the SWNTs may be functionalized, for example, by fluorination. The metal-coated nanotube is incorporated into a metal matrix that could potentially form carbides. In some or other embodiments, the present invention is directed to methods of making such compositions.

[0018] In some exemplary embodiments, the present invention is directed to the production of new composite materials using carbon nanotubes (CNTs) in a metal-matrix where titanium (Ti) is used as the matrix. In particular embodiments the CNTs used are single wall carbon nanotubes (SWNTs). This new composite material is considered to be advantageous over pure Ti in many aspects. Prior art methods used to create metal/CNT composites have not been shown to be successful in metal atmospheres capable of forming carbides. Methods of the present invention allow for the successful creation of new composites with metal-coated CNT reinforcements in a matrix capable of forming carbides from the CNT, wherein such carbide formation would otherwise destroy the basic nanotube structure. The creation of this new material allows for improved properties over those of pure

Ti. The production steps are part of the successful creation of the new composite material. The creation of this particular material makes it unique compared to other metal matrix composites.

[0019] The new material(s) derived from the present invention can be used as an improvement for any past, present, or future application that uses titanium and titanium alloys. To some extent, the present invention incorporates existing technology [Sathuvalli, U., and Bayazitoglu, Y., "The Lorentz Forces on an Electrically Conducting Sphere in an Alternating Magnetic Field," *IEEE Trans. Mag.*, Vol. 32, pp. 386-399, March 1996; Bayazitoglu, Y., Sathuvalli, U., Suryanarayana, P., and Mitchel, G., "Determination of Surface Tension from the Shape Oscillations of an Electromagnetically Levitated Droplet," *Phys. Fluids*, Vol. 8, pp. 370-383, February 1996; Stickel, V.G., and Bayazitoglu, Y., "The Sublimation of an Electrically Conducting Droplet through the Use of an External Alternating Magnetic Field," *Metallurgical and Materials Transactions B*, Vol. 26B, pp. 1209-1216, December 1995; Shampine, R., and Bayazitoglu, Y., "Analysis of the Longitudinal Electromagnetic Levitator," *IEEE Trans. Mag.*, Vol. 33, pp. 4427-4433, November 1997; Bayazitoglu, Y., and Shampine, R., "Longitudinal Electromagnetic Levitator," *Journal of Materials Processing & Manufacturing Science.*, Vol. 5, pp. 79-91, July 1996.] and can be expanded to include previous patents [*U.S. Patent No. 5,887,018* and *U.S. Patent Application No. 20040206470*] from the Rice University containerless manufacturing group in which the method of processing can be modified to longitudinal levitation [*U.S. Patent No.*, 5,887,018] or in which alloys can be made by infiltration [*U.S. Patent Application No. 20040206470*]. Additionally, the new material has been shown as an improvement in strength. Vickers hardness was used as an indicator of strength increase. FIG. 1 is a plot of Vickers hardness of titanium after SWNT addition.

[0020] The present invention provides a method for incorporating SWNTs in composite materials with survival of the SWNTs despite high processing temperatures. Hence, the steps and methods described herein to produce metal/SWNT composites have all been taken to ensure the best possibility of SWNT survival. Nanotubes at elevated temperatures have been known to decompose in oxygen [Hiura, H. Ebbesen, T.W. and Tanigaki, K. "Opening and Purification of Carbon Nanotubes in High Yields," *Advanced Materials*, 7 (3), pp. 275-6, 1995; Ebbesen, T.W., Ajayan, P.M., Hiura, H. and Tanigaki, K., "Purification of Carbon Nanotubes", 367, pp. 519, 1994; Bougrine, A. Dupont-Pavlovsky, N., Naji, A. Ghanbaja, J.,

Mareche, J.F., Billaud, D. "Influence of high temperature treatments on single-walled carbon nanotubes structure, morphology and surface properties," Carbon, 39, 685-95, 2001].

[0021] The process involves two main stages. The first stage is a coating stage and that is then followed by a manufacturing stage. First, the SWNTs are functionalized with fluorine, thereby creating fluorinated SWNTs (F-SWNTs) [Mickelson, E.T., Huffman, C.B., Rinzler, A.G., Smalley, R.E., Hauge, R.H. and Margrave, J.L. "Fluorination of single-wall carbon nanotubes," Chem. Phys. Lett., 296, pp.188-194, 1998.]. The F-SWNTs are then coated with nickel using the electroless plating method [Zeng, Q., Bayazitoglu, Y., Zhu, J., Wilson, K., Iman, M.A., and Barrera, E.V., "Coating of SWNTs with Nickel by Electroless Plating Method," *Materials Science Forum*, Vol. 475-479, pp. 1013-1018, 2005.]. Both processes are important to make the nickel-coated F-SWNTs. The coating acts as a thermal and chemical barrier for many environments. Specifically, this coating acts as a barrier for the prevention of carbide formation in the processing of the metal-matrix composite. Such a barrier might not be necessary when working with other metals such as a copper matrix composite due to the fact that copper carbide would be difficult to form. A barrier would most certainly be necessary when trying to manufacture metal/SWNT composites in a carbide forming atmosphere such as aluminum, titanium and tungsten.

[0022] The fluorination process is not considered to be destructive in that the structural symmetry of the carbon atoms is not compromised in the process [Mickelson, E.T., Huffman, C.B., Rinzler, A.G., Smalley, R.E., Hauge, R.H. and Margrave, J.L. "Fluorination of single-wall carbon nanotubes," Chem. Phys. Lett., 296, pp.188-194, 1998.]. The process occurs when fluorine, diluted with helium, is passed through a temperature-controlled Monel flow reactor which contains the SWNT sample. The flowing fluorine passes over the SWNTs creating a chemical bond with the carbon atoms of the SWNTs, thereby forming F-SWNTs. Time and temperature are variables in the process that may be controlled based on the desired amount of fluorination. For larger amounts of fluorination longer times and higher temperatures in the process. Heavier fluorination will most certainly allow for a better coating to be created, but at the cost of the great electrical and thermal conductivities of the SWNTs. It can be seen in FIG. 2 that the degree of fluorination can vary greatly and can cause a great difference in the Raman spectroscopic results.

[0023] The F-SWNTs are then ready to be coated in nickel. Since the structure is nano-micro in size, an electroplating method cannot be used. An electroless plating method is used instead [Zeng, Q., Bayazitoglu, Y., Zhu, J., Wilson, K., Iman, M.A., and Barrera, E.V.,

“Coating of SWNTs with Nickel by Electroless Plating Method,” *Materials Science Forum*, Vol. 475-479, pp. 1013-1018, 2005; Ang, L.M., Hor, T.S.A., Xu, G.Q., Tung, C.H., Zhao, S.P. and Wang, J.L.S. “Decoration of activated carbon nanotubes with copper and nickel,” *Carbon*, 38, pp. 363-72, 2000; Ebbesen, T.W., Hiura, H. Bisher, M., Treacy, M., Shreeve-Keyer, J.L. and Haushalter, R.C. “Decoration of Carbon Nanotubes,” *Advanced Materials*, 8 (2), pp.155-7, 1998]. The fluorination has been shown to entrap catalytic nucleation sites along the F-SWNT wall. The procedure of electroless plating is divided into the steps of sensitization, activation and plating. The F-SWNTs were first ultrasonicated for improved dispersion. They were then dispersed into a sensitizing solution (0.1 MSnCl₂/0.1 MHCl) and mixed for 30 minutes. They were then further mixed in an activating solution (0.0014 MPdCl₂/ 0.25 MHCl) for another 30 minutes. Finally, the F-SWNTs are mixed in the nickel electroless plating bath. The bath contains: (concentration g/l) NiCl₂6H₂O (40), NiSO₄6H₂O (10), NaH₂PO₂2H₂O (100), Na₂HC₆H₅O₇ 1.5H₂O (15), NH₄Cl (100), and Pb(NO₃)₂ (2.5).

[0024] The final product after the first stage can be seen in FIG. 4. The nickel-coated F-SWNTs are viewed by a scanning electron microscopy (SEM) method. The SWNTs, generally ~1 nm in diameter, are ~20 nm in diameter after fluorination and nickel coating. This is of course a function of the amount of electroless plating that takes place. The diameter of these coated nanotubes can be as large as ~100 nm.

[0025] The method described above can create Ni-coated SWNTs which can then be used to manufacture a metal/SWNT composite material. The coating can prevent the destruction of carbide formation from the SWNT structure. Currently, it is an essential step in the successful creation of composite materials comprising carbon nanotubes and carbide forming metals.

[0026] The second stage requires the final manufacturing of the composite material. The nickel-coated SWNTs were mixed next with titanium powder using a ball-milling method [Kuzumaki, T., Miyazawa, K., Ichinose, H. and Ito, K. “Processing of carbon nanotube reinforced aluminum composite,” *Journal of Materials*, 13 (9) pp. 2445-9; Wilson, K., Zeng, Q., Barrera, E.V., and Bayazitoglu, Y., “Electromagnetic Containerless Processing of Single-Walled-Carbon-Nanotube Reinforced Metal-Matrix Composites,” in *Proc. NanoTech 2005*, Anaheim, California, 2005.] to improve the dispersion of the SWNTs in the titanium. Then the well-mixed titanium powder was pressed (~40 MPa) into a cylindrical preform (0.25 inches in diameter by ~0.25 inches in length) using a die as in basic powder metallurgy. Finally, the samples were melted by induction heating. FIG. 3 depicts Raman spectra for the

Ti/SWNT Composite compared to that for pure SWNTs, wherein peak overlap strongly indicates that nanotubes survive the high temperature processing. The result can be seen in FIGS. 5(a)-5(d) (see also Example below). The composite was fractured in order to see the SWNTs, the image is of the fractured surface.

[0027] As mentioned above, a method of manufacturing currently used (but not limited to) in this process is induction heating. Induction heating is a process by which an electrically conduction material is placed inside an electromagnetic field generating eddy currents in the material which then generate heat. Induction heating is not an extremely popular method in industry for manufacturing, and this fact leads one to inquire why it is selected as a method for manufacturing metal/SWNT composites. Conventional heating ovens can often take hours to heat to the melting temperature of common metals such as copper, nickel, and titanium. The advantage of induction heating is that it is capable of melting the same metals in only a few seconds due to the highly concentrated induced eddy currents. The current system used by the inventors is a radio frequency 40 kilowatt Radyne power generator.

[0028] Any titanium or titanium alloy powder product that is currently made by induction heating should also be able to be made into the new composite material as described by the methods given here. Since the process is a powder metallurgy process the final product will not be fully dense, which is generally undesired. Most if not all powder metallurgy products are not fully dense. This problem in the industry has not been overcome yet.

[0029] It should be noted that fluorination of the SWNTS seems to sacrifice some of its properties. Currently the steps to minimize this are to fluorinate the nanotubes as little as possible. Variations on this may involve SWNTs functionalized with species other than fluorine.

[0030] The present invention relates to all common methods of manufacturing titanium and titanium alloy specifically dealing with powder metallurgy. Some of these are forging, sintering, induction heating, electromagnetic levitation, and electric welding methods—all of which could be used in methods of the present invention.

[0031] The present invention may be expanded to include any other electrical conductor as the matrix. Many variations of manufacturing could be attempted with different equipment or methods. Most obviously, a convection oven could be used as the method of heating. Regarding induction heating, any generator with any power-rating could be used.

The amount of power only causes a variation in the heat input to the conductor. Theoretically this method may work at any frequency.

[0032] The present invention is not limited to single-walled carbon nanotubes (SWNTs). It can include multi-walled carbon nanotubes (MWNTs) and carbon nanotubes (CNTs), in general. It may also include all carbon fibers. Other nanotubes could also be included such as silicon, titania and any other structure containing titanium. The coating of the nanotube is to prevent chemical reactions between the tube and the matrix. The present invention may include, as the matrix, any metal that easily forms carbides such as titanium, tungsten, and aluminum.

Example:

[0033] The following experimental example is included to demonstrate particular aspects of the present invention. It should be appreciated by those of skill in the art that the methods disclosed in the examples that follows merely represent exemplary embodiments of the present invention. However, those of skill in the art should, in light of the present disclosure, appreciate that many changes can be made in the specific embodiments described and still obtain a like or similar result without departing from the spirit and scope of the present invention.

[0034] The present inventors conducted metallurgy research in an electromagnetic levitation (EML) facility where a conventional conical levitation coil was used.

[0035] Induction heating has been chosen as the present method since it provides rapid heat and cooling conditions and short transient times. Heating and melting the metal as fast as possible minimizes the possibility of the SWNTs changing morphology or chemically reacting with the metal to form carbon compounds. Induction heaters melt metals in only seconds.

[0036] The present inventors successfully created SWNT-Titanium and SWNT-Titanium alloy metal matrix composites using electromagnetic melting in the levitator. Purified SWNTs were functionalized with fluorine to provide for higher order dispersion. The fluorinated SWNTs were then coated with nickel via the electroless plating method to insulate them thermally and protect them chemically from carbide formation. The nickel-coated SWNTs were mixed next with titanium powder or with titanium alloy powder using ball-milling to improve the dispersion of the SWNTs. The well-mixed powder was then pressed (40 MPa) into a cylindrical preform (0.635 cm in diameter by ~0.635 cm in length)

using a standard dye assembly. Sintering followed at 800 °C for 15 hours to improve the electrical resistance. The samples were held in position within the hot zone by a tungsten wire (considered inert in the processing) of the Electromagnetic Levitator. The sample size varied from 1 gram to around 25 grams. SEM micrographs of the resulting samples are shown in Figure 5, where nanotubes are seen following fracture of the as-processed samples.

[0037] Evidence of SWNT survival can be seen from the Raman analysis of Figure 3. In our study the metal matrix was separated from the reinforcing nanotubes by submerging the composite in a corrosive solution. The SWNTs were then filtered out of the solution, and Raman spectroscopy was performed to evaluate SWNT survival. Hydrofluoric acid was used to corrode the Ti/SWNT composite. The major concern here is that the chemical which corrodes titanium might also damage the SWNTs, yet when pure nanotubes were added to the acid system they were not altered. One milligram of pure SWNTs was placed in hydrofluoric acid and then analyzed by Raman spectroscopy. The hydrofluoric acid did not have any effect on the SWNTs as determined by subsequent Raman analysis.

[0038] Figure 3 shows the Raman spectra of pure SWNTs and the material recovered from the Ti/SWNT powder that was melted by induction heating. The overlapping peaks corresponding to the peaks of purified SWNTs are strong indicators that the nanotubes did survive this process. The peaks occur at ~ 1300 and ~ 1590 (cm^{-1}) which corresponds to the Raman spectrum of the nickel coated SWNTs. As can be seen in the figure, the existence of an overlapping peak below 250 (cm^{-1}) indicates the existence of a radial breathing mode, which further indicates the structure of the nanotube was not compromised. The Ni-coated functionalized SWNT (F-SWNT) is shown as the condition of the nanotube at the intermediate step just before processing in Ti.

[0039] The facility is capable of levitating and melting aluminum, copper, and nickel in the conical configuration. This is due to the fact that these metals have the best electrical conductivities which yield a stronger Lorentz force on samples of equal size. Metals with poor electrical conductivities such as titanium do not levitate in this facility. Currently, the facility uses a Radyne EI-40 radio frequency generator. The output power of this equipment is 40 kW, with an output current of ~ 400 -600 A.

[0040] Due to the strong inter-tube Van der Waals attraction of SWNTs, they are likely to aggregate into tangled ropes with typically 10 to 50 congregated tubes. Ball milling and

incipient wetting may be used to achieve high dispersion. It can be seen from Figure 6 that this method yields some improvement in nanotube dispersion.

[0041] Titanium alloys are significantly stronger than pure titanium itself. The use of pure Ti may serve as a model system. The present inventors have also used alloy powders. The alloy is expected to improve strength at least over that of pure titanium samples. Results from Vickers Hardness testing are presented in Figure 7, and it is very encouraging and promising. The addition of 3% SWNT gives a 175% increase the Vickers hardness value of the titanium alloy (b) itself. Similarly, one can see that the addition of 3% SWNTs would yield about a 195% increase in the hardness value of pure titanium (a). Such increases serve to enhance further the strength capabilities of titanium and titanium alloys which are already known to have incredibly high strength to weight ratios.

[0042] Using the existing EML facility, the present inventors were capable of processing 25 gram samples by this method. Using a longitudinal EML setup, it is possible to fabricate and manufacture samples an order of magnitude larger than conical EML. While some experiments may use the conical EML, the present inventors contemplate performing experiments using longitudinal EML in order to achieve the largest possible sample.

[0043] The current stage to improve sample size combines multiple samples to create a larger sample. This is achieved through the use of a hot isostatic press (HIP). The HIP is a very common piece of industrial equipment used in the manufacturing industry for titanium. The current sample sizes are about 25 grams. These samples are then placed in a larger titanium container referred to as a can. The can in this case is a square container. The container measures 4"x4"x0.5". Based on the theoretical density of titanium and common packing density, the can is capable of holding about 400 grams of titanium. This is achieved by placing the can, now full of smaller (inductively heated) samples of titanium, in a large pressure vessel and maintaining the internal inert environment of the vessel at common conditions of 900 °C and 15,000psi. The samples are typically held at these conditions for two hours. The final product is a flat plate measuring almost identically the dimensions of the can.

[0044] The manufacturing of this larger plate opens up a number of new opportunities for more research. The present inventors contemplate that this material could replace bullet proof vests, be used in any area for improved impact testing, or used in any aerospace application where titanium is currently used because of its weight.

[0045] Currently, a standard conical heating coil is used as the principle method of heating the samples. The largest samples possible are made with this configuration. There is evidence that other configurations provide electromagnetic interactions up to 10 times better than the conical configuration based on experiments in EML. These will need to be applied to the current manufacturing system and exploited for an even greater increase in production capabilities.

[0046] The present generator is a 40kW max power system in operation with vacuum tube parts. Solid-state generators may alternatively be used and the power output on standard generators now is about 200kW. This is a fairly generic number and larger supplies do exist (300kW in the RF range, and 3000kW at lower frequencies). Considering only an increase in production due to coil configuration (conservative estimates at 5 times increase) and power supply (5 times increase), it is estimated that sample production size can rapidly increase from 25 g to 625 g and should the full capabilities of the coil configuration be exploited it would be possible to produce about 1.25 kg of product/run. The present inventors contemplate 100 samples/day as a production rate. With this increased production/sample one can expect to see potentially 62 kg/day.

[0047] All patents and publications referenced herein are hereby incorporated by reference. It will be understood that certain of the above-described structures, functions, and operations of the above-described embodiments are not necessary to practice the present invention and are included in the description simply for completeness of an exemplary embodiment or embodiments. In addition, it will be understood that specific structures, functions, and operations set forth in the above-described referenced patents and publications can be practiced in conjunction with the present invention, but they are not essential to its practice. It is therefore to be understood that the invention may be practiced otherwise than as specifically described without actually departing from the spirit and scope of the present invention as defined by the appended claims.

WHAT IS CLAIMED IS:

1. A composition comprising:
single-wall carbon nanotubes coated with a first metal; and
a second metal within which the single-wall carbon nanotubes coated with a first metal are dispersed,
wherein the first metal is a non-carbide forming metal, and wherein the second metal, which serves as a matrix, is selected from the group consisting of carbide-forming metals and non-carbide forming metals.
2. The composition of Claim 1, wherein the single-wall carbon nanotubes are functionalized.
3. The composition of Claim 2, wherein the functionalized single-wall carbon nanotubes are fluorinated.
4. The composition of Claim 1, wherein the first metal comprises nickel.
5. The composition of Claim 1, wherein the second metal comprises titanium.
6. The composition of Claim 1, wherein the second metal comprises titanium alloy.

7. A method of forming a composite comprising:

- a) electrolessly-coating single-wall carbon nanotubes with a first metal to form metal-coated carbon nanotubes;
- b) mixing the metal-coated carbon nanotubes with a second metal to form a mixture; and
- c) heating the mixture to form a composite,

wherein the first metal is a non-carbide forming metal, and wherein the second metal, which serves as a matrix, is selected from the group consisting of carbide-forming metals and non-carbide forming metals.

8. The method of Claim 7, wherein the single wall carbon nanotubes are functionalized prior to electroless coating with the first metal.

9. The method of Claim 8, wherein the single-wall carbon nanotubes are fluorinated.

10. The method of Claim 7, wherein the mixing involves ball milling.

11. The method of Claim 7, wherein the step of heating comprises at least one selected from the group consisting of forging, sintering, induction heating, electromagnetic levitation, and electric welding.

12. The method of Claim 11, wherein the step of heating the mixture comprises induction heating.

13. The method of Claim 7, wherein the step of heating the mixture to form a composite minimizes structural damage to the single wall carbon nanotube structure.
14. The method of Claim 7, wherein the first metal comprises nickel.
15. The method of Claim 7, wherein the second metal comprises titanium.
16. The method of Claim 7, wherein the second metal comprises titanium alloy.

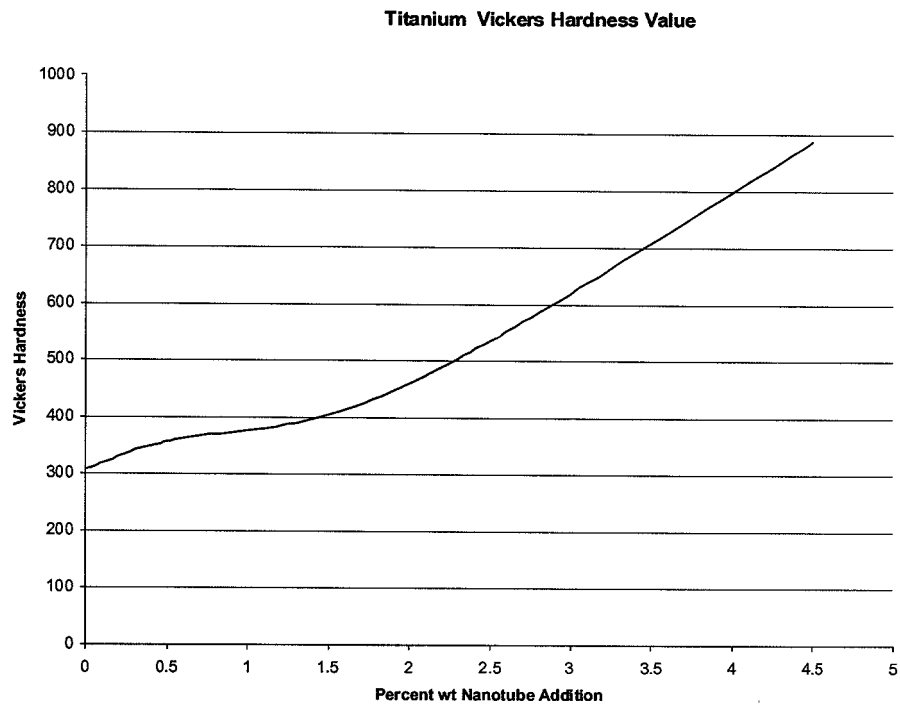


Fig. 1

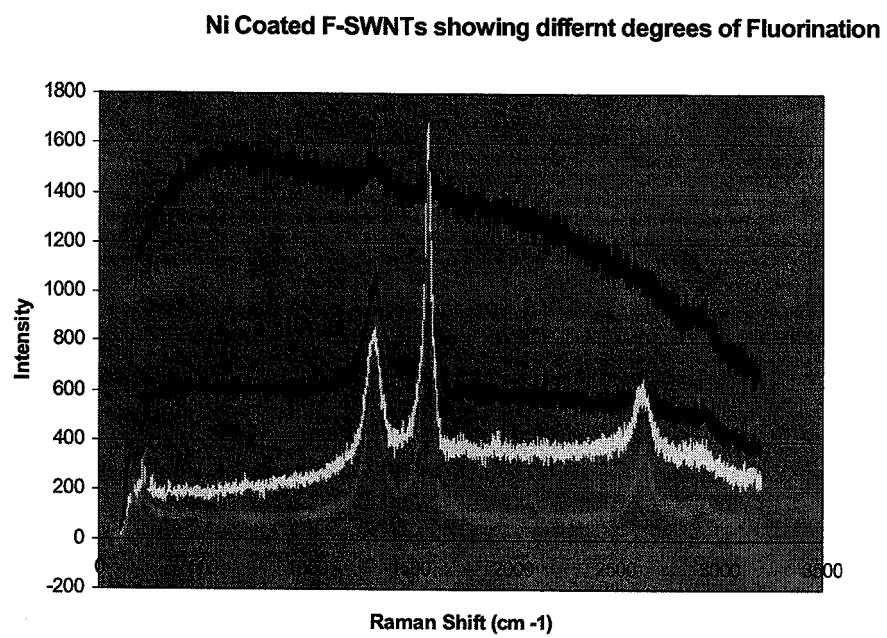


Fig. 2

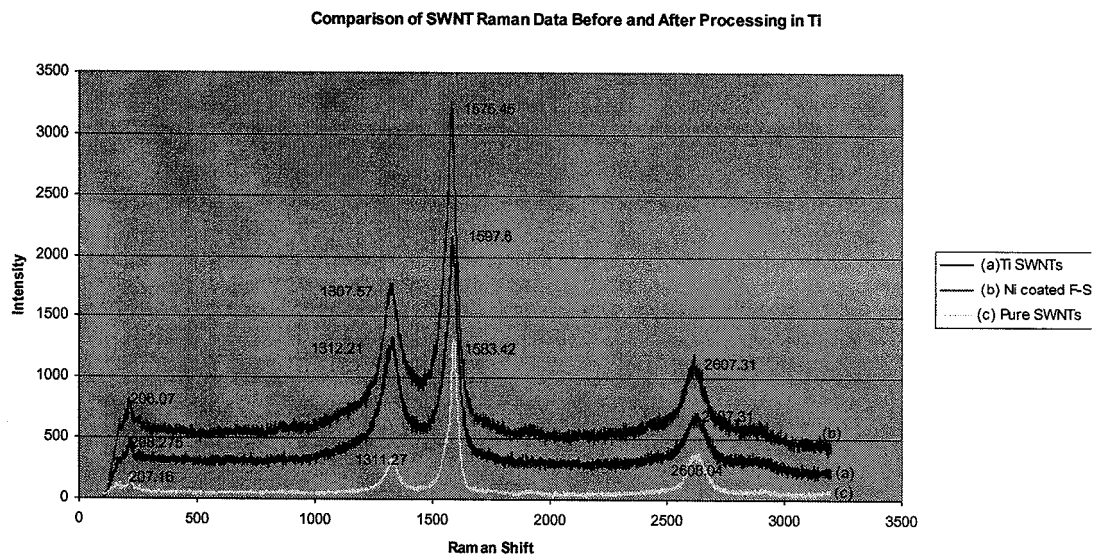
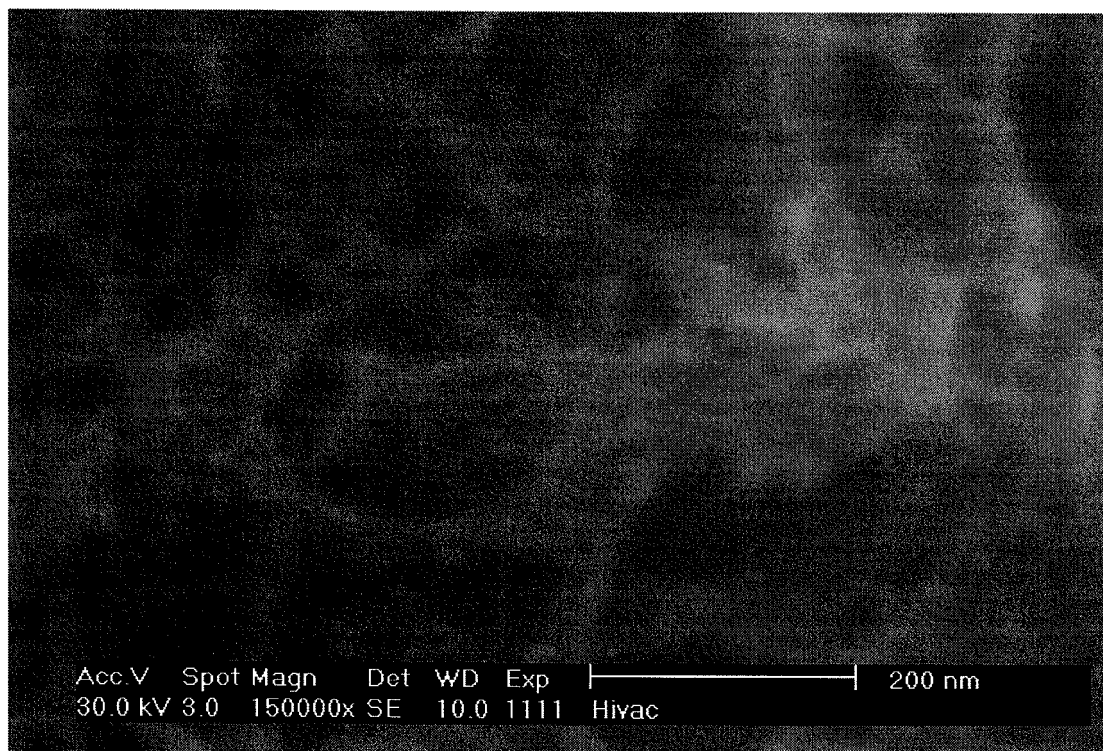
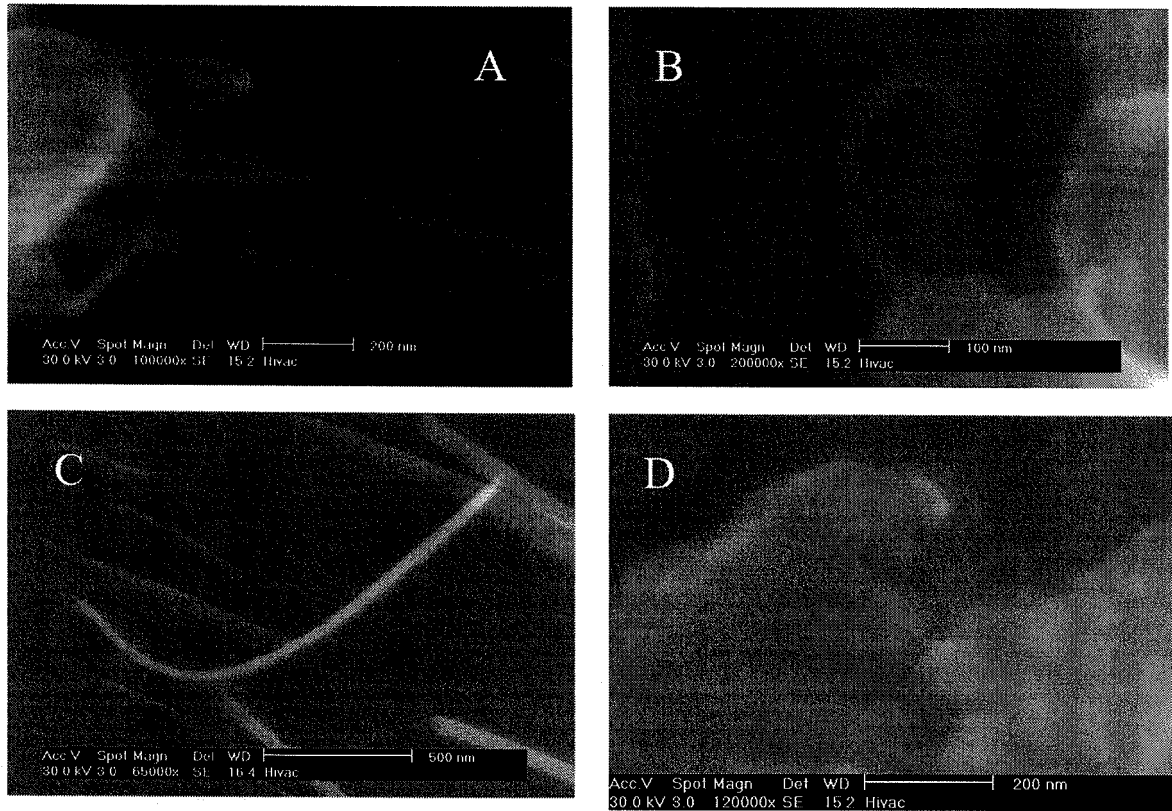
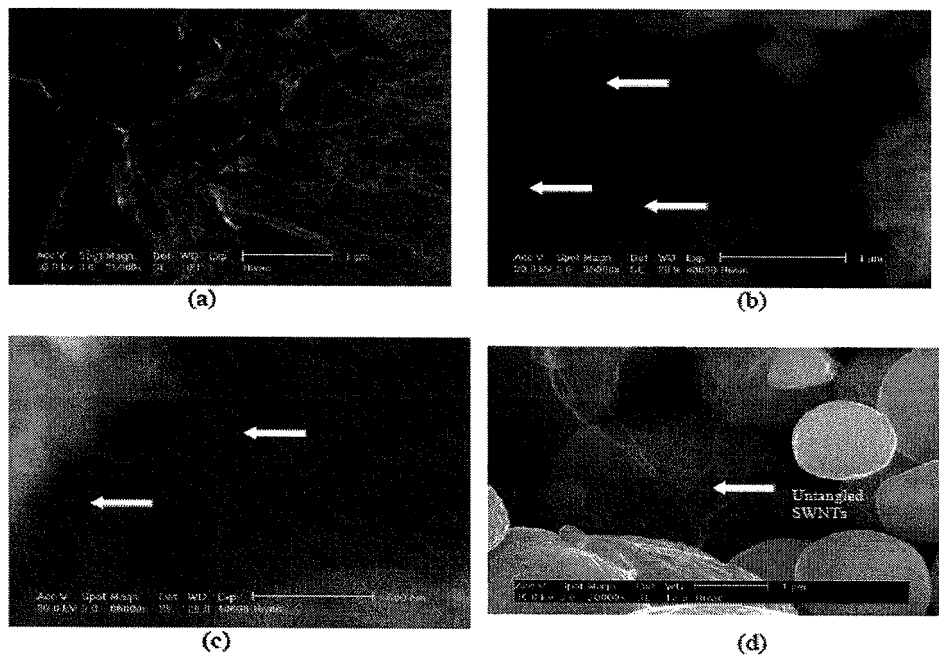
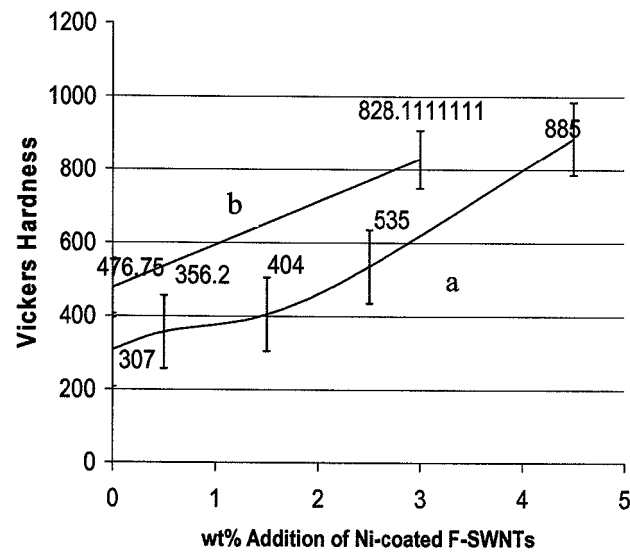


Fig. 3

*Fig. 4*

*Fig. 5*

*Fig. 6*

*Fig. 7*