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(54) **Title:** A PROCESS OF DIRECT LOW-TEMPERATURE GROWTH OF CARBON NANOTUBES (CNT) AND FIBERS (CNF) ON A STEEL STRIP

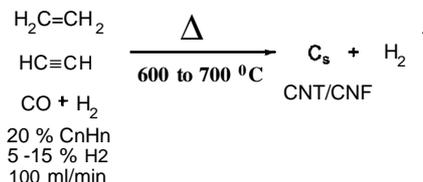


Figure 1

(57) **Abstract:** This invention relates to process of direct low-temperature growth of carbon nanotubes and carbon nanofibers on a strip substrate and a substrate provided therewith.

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A PROCESS OF DIRECT LOW-TEMPERATURE GROWTH OF CARBON NANOTUBES (CNT) AND FIBERS (CNF) ON A STEEL STRIP

Carbon nanotubes and carbon nanofibres (hereinafter abbreviated to CNT/CNF) have
5 miniature cylindrical structures with a diameter on the order of a few nanometres and an aspect
ratio of 10 to 1000. CNT/CNF have a honeycomb-like hexagon pattern in which each carbon
atom is combined with three neighbouring carbon atoms. Also, CNT/CNF can function as either
a conductor, like metals, or a semiconductor, according to their structures, and application
10 fields of these CNT/CNF are expected to be extensive. CNT/CNF have further attractive
properties such as low density, high strength, high toughness, high flexibility, high surface area
and excellent electrical conductivity. Unfortunately, production of CNT/CNF is not
straightforward.

To synthesize CNT/CNF on a large scale, electrical discharging, laser deposition, and
chemical vapour deposition using hydrocarbons have been widely used. In particular, the
15 electrical discharging technique is to grow CNT/CNF by arc discharge using a carbon
electrode. The laser deposition method is to synthesize CNT/CNF by irradiating graphite with
laser light. However, these two methods are inappropriate for controlling the diameter and
length of CNT/CNF, and the structure of carbonaceous materials. Thus it is difficult to obtain
excellent crystalline structure during the synthesis of CNT/CNF. Furthermore, a large amount of
20 amorphous carbon lumps are also produced at the same time, so that further complicate
purification is necessary after the synthesis of the CNT/CNF, thus complicating the process.
Another drawback of these methods is that it is impossible to synthesize CNT/CNF over a
relatively wide area. Thus, these methods cannot be applied to a variety of devices. A method
of synthesizing CNT/CNF by plasma CVD is unattractive because CNT/CNF can be damaged
25 from plasma impact and synthesis of CNT/CNF on a relatively large substrate is difficult.

It is an object of this invention to provide a simple process of growth of CNT/CNF on a
steel substrate.

It is an object of this invention to provide a process of producing a corrosion resistant
coating on a steel substrate.

30 It is also an object of this invention to provide a process of producing an adhering
coating of carbon nanotubes and/or nanofibres on a steel substrate.

According to a first aspect, at least one of the objects is reached by providing a process
of direct low-temperature growth of an adhering coating of carbon nanotubes and/or carbon
nanofibres (CNT/CNF) on one or both surfaces of a carbon steel or low alloy steel strip
35 substrate which comprises the following steps:

- providing a steel substrate, optionally provided with a metallic coating;
- growing CNT/CNF onto a surface of said substrate by using a carbon source gas
comprising hydrogen through a thermal chemical vapour deposition (CVD) process at a
temperature of between 500 to 750 °C, preferably of between 600 to 750 °C.;

- wherein no catalysts are added to catalyse the growing of the CNT/CNF, and wherein the growing of the CNT/CNF is catalysed by iron, nickel and/or chromium present in the substrate and/or the metallic coating.

The inventors found that a layer of CNT/CNF could be grown over the steel substrate through CVD by using a carbon-containing source gas, such as olefin gases or low molecular weight oils at low temperatures. Nano-particles of the catalyst such as iron were found at the tip and/or bottom of the CNT/CNF. The CNT/CNF had diameters ranging between 30 and 120 nm depending on the reaction conditions. The adhesion of these CNT/CNF to the steel substrate proved to be very strong. Layer thickness of between 1 to 60 μm could be achieved. The CNT/CNF show bi-directional growth as well as tip growth. The steel used as a substrate is 1. a carbon steel or 2. a low alloy steel defined as preferably containing no more than 7% non-iron elements and preferably no more than 4% non-iron elements. In the SAE system the steels of category 1. and 2. are designated by a four digit number, where the first digit indicates the main alloying element(s), the second digit indicates the secondary alloying element(s), and the last two digits indicate the amount of carbon, in hundredths of a percent by weight. For example, a 1060 steel is a plain-carbon steel containing 0.60 wt% C. The steel substrate is not a stainless steel. In the SAE designation, stainless steel grades are designated by a three digit number, optionally followed by one or more letters. The substrate preferably is provided in the form of strip, sheet, or foil. The substrate is preferably cleaned and/or oxide free before depositing the CNT/CNF coating.

In an embodiment of the invention the iron from the steel substrate catalyses the growing of the CNT/CNF. Surprisingly, the process for providing a layer of CNT/CNF on the steel substrates also provided a layer of CNT/CNF without the addition of iron as a catalyst. However, also in this case electron microscopy revealed iron nanoparticles at the tip and/or bottom of the CNT/CNF, leading to the conclusion that the catalysing effect is provided by iron particles originating from the steel substrate.

In an embodiment of the invention the carbon-containing source gas comprises one or more of acetylene, ethylene, methane, carbon-monoxide, carbon dioxide or low molecular weight fatty oil. It was found that the use of these carbon-containing sources provided a good layer of CNT/CNF on the substrate. In a preferable embodiment the carbon source gas consists of hydrogen, carbon monoxide and carbon dioxide, preferably in a ratio of volumes of about 30:60:10. Experiments showed that mixtures from 44 to 65 vol.% CO : 26 to 5 vol.% CO₂ : 30 vol.% H₂ provided excellent results and growth rates. A variation of the hydrogen content of between 25 to 35% in this mixture while keeping the ratio of CO to CO₂ roughly in a ratio of between 2 to 1 and 8 to 1 also provided good results. The addition of carbon dioxide to the CO:H₂ mixture therefore provided surprising results.

In an embodiment of the invention the CNT/CNF are grown onto the surface of the substrate at a temperature of between 600 to 750 °C. Because of the catalysing effect of the iron the process temperature can be kept low. A range of 600 to 750 °C appeared to be a good temperature window and generated good layers of CNT/CNF reliably and economically. A more

preferable temperature window is from 600 to 700 °C. A more preferred maximum temperature is 695 °C.

In an embodiment of the invention the steel substrate is a high strength steel (HSS), advanced HSS, boron-containing steels, Ultra HSS or complex phases steel, preferably
5 comprising 0.01-1%C, 0.15-2%Mn, 0.005-2%Si, 0.01-1.5%Al, 10 to 200 ppm N, at most 0.015% P, at most 0.15%S, optionally one or more of 0.01-0.1%Nb, 0.002-0.15%Ti, 0.02-0.2%V, 10-60 ppm B, and balance iron and inevitable impurities.

In a preferred embodiment of the invention the steel substrate is provided with a nickel,
10 nickel-chromium or chromium plating layer or a zinc alloy layer prior to growing CNT/CNF onto one or both surfaces of said substrate.

In a preferred embodiment of the invention a process of producing a corrosion resistant coating on a steel strip substrate by in-situ providing a layer of CNT/CNF on the substrate according to the invention is provided, wherein the layer of CNT/CNF is coated with a polymer coating. In a preferable embodiment the polymer coating is a poly-imide (PI) based coating.
15 The thickness of the CNT/CNF along with the polymer layer can be varied from 1 µm to 60 µm and it provides a thermal resistance from 300 to 550 °C at 0.2-0.5 % weight loss.

By coating the adhering coating of CNT/CNF with a polymer coating the properties of the CNT/CNF layer are retained. The polymer coating provides the CNT/CNF coated substrate with additional corrosion protection. Poly-imide based coatings are known for their thermal
20 stability, good chemical resistance, excellent mechanical properties and insulating properties. However, the adhesion of these polymers to a steel substrate is problematic. By first providing a layer of CNT/CNF onto a steel substrate as described above, followed by coating said layer of CNT/CNF by a poly-imide based coating, the adhesion of the poly-imide based coating to the steel substrate is much improved, because the adhesion of the PI to the CNT/CNF layer is
25 excellent as well as the adhesion of the layer of CNT/CNF to the steel substrate. The CNT/CNF on the surface of the steel create a large interfacial surface area for the poly-imide based coating or any other polymer coating to adhere to. The chemical similarity between CNT/CNF and the polymer increases its wettability and compatibility, and so it prohibits microcrack formation and its propagation. Tests have shown excellent formability of the CNT/CNF-PI
30 coated steel substrate and of the CNT/CNF-Polymer coated steel substrate. This product is a good replacement for the composites where CNT/CNF are dispersed in the polymer such as the poly-imide based coatings. The dispersion of CNT/CNF in polymers is notoriously difficult, and suffers from coagulation of the CNT/CNF leading to an imperfect dispersion. The addition of a polymer layer such as a poly-imide based coating on top of the CNT/CNF also has the
35 advantage that the CNT/CNF can no longer get dislodged from the layer. Thereby any potential health issues associated with free CNT/CNF can be prevented. It should be noted that the poly-imide coating is a preferred embodiment of the invention. However, it should also be noted that other polymers which are able to withstand the conditions of production and service may be used, e.g. polyolefins like polyethylene.

In an embodiment of the invention the poly-imide based coating is produced onto the layer of CNT/CNF by applying a polyamic acid (PAA) layer preferably by roll coating and/or spraying followed by imidization.

5 In an embodiment of the invention the poly-imide based coating is produced onto the layer of CNT/CNF by adding Mn, Ag, Si, Ti, Al and/or Mg while synthesizing PAA followed by imidization

10 In an embodiment of the invention the poly-imide based coating is produced from poly-ether imides the poly-imide based coating is produced onto the layer of CNT/CNF by applying a liquid polyether amic (PEA) solution followed by imidization. In an embodiment of the invention a process of producing the coating is provided wherein the CNT/CNF are subsequently treated with a suitable compound such as MgO or CaO to produce a catalytic support for storing CO₂ in the form of carbonaceous compounds, or with a photocatalyst such as titania or organic photo initiators to produce a catalytic converter to convert carbon dioxide into carboxylic acid such as formic acid (HCOOH) and/or alcohols such as ethanol (C₂H₅OH).
15 By treating a steel surface provided with the thus treated CNT/CNF and, for instance, converting them in tubular form, or by depositing the CNT/CNF onto the surface of a carbon steel or low alloy steel tube and treating them with a suitable compound or a photocatalyst as described hereinabove a very effective and economical catalyst for reducing the carbon footprint of any process producing carbon dioxide.

20 In an embodiment of the invention a process as described hereinabove comprises the steps of providing a coil of cold-rolled steel strip, subjecting the coil to continuous annealing, optionally recrystallising the cold-rolled coil, reducing, deoxidising and/or cleaning the surface of the steel, providing a layer of CNT/CNF onto the steel at temperatures of between 600 to 750 °C and cooling the steel, optionally followed by providing the coated steel with a poly-imide based coating. By means of this process the economy of scale of a continuous process can be exploited. The coils of cold-rolled strip provide a relatively cheap substrate and these can be coated with an adhering coating of CNT/CNF in a continuous manner. This will greatly reduce the costs of such a coated substrate. By reducing the surface it is meant that the steel surface is made oxide free in a reducing atmosphere.

30 In an embodiment the process of producing CNT/CNF further comprises removing the CNT/CNF from the surface of the steel substrate, e.g. by mechanical scraping, and collecting the CNT/CNF. The simple and cheap method to produce CNT/CNF provides an ample and cheap supply of CNT/CNF which can be used in electrical and mechanical applications.

35 In an embodiment the process a steel substrate provided with a layer of CNT/CNF as described is provided for use in corroding environments, solar cell applications, in fuel cell applications, in hydrogen storage, as catalytic supports, for radar capturing coatings or as an interfacial conductive layer or for use as anti-bacterial product.

40 In a preferred embodiment of the invention a steel substrate provided with a layer of CNT/CNF as described is provided coated with a polymer coating, such as a poly-imide based coating, for use in corroding environments, in solar cell applications, in fuel cell applications, in

hydrogen storage, as catalytic supports, for radar capturing coatings or as an interfacial conductive layer or for use as anti-bacterial product. It will be clear that in order for the coating to act as radar capturing coating that the optional polymer coating must be transparent to the radar radiation in question.

5 In a preferred embodiment of the invention the steel substrate provided with a CNT/CNF layer according to the invention is used for the production of the electrode part of a battery such as Li-based batteries and/or alkali batteries or for the production of a photovoltaic substrate for a flexible back contact electrode. The thickness of the CNT/CNF along with the polymer layer can be varied from 0.5 μm to 60 μm and it provides thermal resistance from 300
10 to 550 $^{\circ}\text{C}$ at 0.2-0.5 % weight loss. By means of example it is noted that because of the low diffusion rate of Li through electrode materials a Li-battery consists of thin layers of electrode material, electrolyte and current collectors. To get sufficient material these layers are rolled up. In conventional Li-batteries these layers comprise a copper layer coated on each side by a carbon layer. By using a plated steel substrate, such as a Ni-Cr steel plated substrate, coated
15 with a CNT/CNF coating layer on both sides, optionally provided with a top coat of a polymer layer, such as a PI-layer, this expensive copper substrate can be replaced by a cheaper substrate provided with a CNT/CNF coating. The excellent adhesion of the coating to the plated layer, e.g. the Ni-Cr layer, and the corrosion protection of the layer, optionally complemented with the polymer layer, make this substrate excellently suitable to replace the expensive copper
20 layer. Since this electrode does not need any binder it also decreases the weight of the battery.

In a preferred embodiment of the invention the CNT/CNF powder removed from the substrate e.g. by scraping are used in the production of aqueous dispersed nano-coolant or fluid for heat exchangers or in the production of nano-composite coatings. Using these powders for the formulation of the aqueous dispersed nano-coolant fluid for heat exchangers which cool
25 more efficiently than water.

The invention will now be further explained by the following, non-limitative examples and figures.

Figure 1 shows a general reaction scheme for CNT/CNF formation.

Figure 2 shows a SEM image revealing the formation of CNF on the steel surface in the presence of ethylene gas in accordance with the reaction scheme of Figure 1.
30

Figure 3 shows a TEM image revealing the formation of CNF in the presence of ethylene gas in accordance with the reaction scheme of Figure 1.

Figure 4 shows a schematic presentation of the formation of PI coating.

Figure 5 shows the result of potentiodynamic studies of different samples, bare steel metal, CNT/CNF coated steel, and CNT/CNF coated steel coated with a PI-based coating.
35

Figure 6 shows a battery and its composing layers.

Figure 7 shows a TEM photograph of the formation of CNT on a steel surface.

Figure 8 shows a schematic presentation of a combination of CNT/CNF (3) and a polymer layer (2) on a steel substrate (1) for fuel cell applications.

Examples: Steel substrates were provided with chemical compositions within the following ranges (min - max):

C	Mn	Si	Al	N(ppm)	P	S	Nb	Ti	V	B
0.01-0.2	0.2-1.5	0.005-2	0.03-1.5	0.02-0.2	0.01-0.015	0.002-0.15	0.01-0.02	0.002-0.007	0.05-0.132	0.001-0.006

CNT/CNF were synthesized on cold rolled steel by chemical vapour deposition using ethylene as the carbon-containing source as follows. High purity gases, H₂ (99.999%, INDUGAS) N₂ (99.999%, INDUGAS) and ethylene (99.95%, PRAXAIR) were used. A cold rolled sample (3cm x 3cm) was placed on a quartz plate in the glass tube which has inlet and out let for the gas mixture. The glass tube was heated to the required temperature in the oven. The sample was first reduced with H₂/N₂ with a total flow rate of 100 ml/min. Then CNT/CNF were synthesized using a gas mixture containing C₂H₄/N₂ with the same flow rate of 100

Sample	Pre-treatment	Reaction conditions	carbon weight increase (mg)	Mechanical test weight loss (%)	Comments
Steel	H ₂ pretreatment (400 °C to 700 °C)	C ₂ H ₄ and H ₂ (600 °C to 750 °C)	22.9 - 85	0-30	uniform layer

ml/min. The sample was cooled down in N₂ to room temperature. The amount of carbon formed on the steel substrate was determined by measuring the increase in weight caused by the formation of CNT/CNF. Carbon nanotube coated steel samples were flushed with pressurized air and mechanical loss was calculated. Morphological features were studied by scanning electron microscopy (SEM) LEO 1550 FEG-SEM equipped with inlens detector.

The reaction schedule in Figure 1 shows that instead of ethylene, also acetylene (C₂H₂) or carbon-monoxide optionally carbon dioxide with hydrogen can be used. A SEM image of a CNF coated sample is presented in Figure 2. It clearly shows the uniform distribution and growth of CNF. It also shows the tip growth of CNF with iron nanoparticles on the tip.

The polyimide coating was produced as follows: The PAA acid was prepared according to the scheme of Figure 4 and then applied on the CNT/CNF coated steel substrates and put in the oven at different temperatures from 250 to 350 °C for 5 mm and then this sample was allowed to cool to room temperature and subsequently characterized by different methods.

A number of the steel substrates provided with a carbon nanotube layer was coated with a poly-imide based coating. These samples were exposed to simulated saline environment as per ASTM B117 to evaluate wet adhesion and corrosion behaviour. Potentiodynamic measurements were performed in simulated saline environments. The results show that the CNT/CNF coated with a poly-imide based coating showed performed much better (1000 hrs in SST) than the uncoated CNT/CNF layer.

Table 3 presents an overview of various process conditions for growing CNT/CNF onto a low carbon steel substrate. The growth rate is expressed in a ratio and is based on the mass of CNT/CNF formed per unit of time and surface.

5 Table-3: Summary of CNT/CNF growth using CO, CO₂ and H₂

Substrate	Carbon Source Gas	Temperature	Growth rate
Cold rolled deep drawing steel (low carbon steel)	CO+H ₂ = 50:50	550	0.16
		600	0.31
		650	0.26
		700	0.06
		750	0.05
	50:50	650	0.23
	70:30		0.22
	90:10		0.14
	95:5		0.09
	CO+H ₂ = 70:30	450	0.01
		550	0.16
		600	0.46
		650	0.27
	CO+CO ₂ +H ₂ = 30:40:30	600	0.01
	CO+CO ₂ +H ₂ = 30:40:30		0.23
CO+CO ₂ +H ₂ = 40:30:30	0.29		
CO+CO ₂ +H ₂ = 44:26:30	0.59		
CO+CO ₂ +H ₂ = 60:10:30	1.00		
CO+CO ₂ +H ₂ = 70:0:30	0.40		

The potentiodynamic measurements were conducted at the scan rate of 1.67 mV/s in the potential range of -0.5 mV to 1.5 mV in 3.5% NaCl solution (see Figure 5). A significant depression in current density from 2-3 x 10⁻² A/cm² in case of bare steel to 1-2 x 10⁻⁷ A/cm² in case of the polymer coated CNT was measured. A large passivation band (-0.225 V to +1.032 V) and a clear evidence that the electrochemical reaction at the coating surface was cathodically controlled. When there was no polymer layer over the CNT/CNF coating, Figure 5 shows that the current density of the CNT/CNF coated substrate is already an order of magnitude smaller compared to bare steel sheets. It was found that the carbon nanotube-PI coated sample shows significant passivity and reduced current density, which is the measure of low corrosion rate. Bare steel on the other hand performs an order of magnitude worse than CNT/CNF coated steel. It should also be noted that a CNT/CNF layer wherein the CNT/CNF have been treated or filled with corrosion inhibitors provide a self-healing behaviour to the layer.

Additional experiments with a carbon source gas comprising 60% CO, 10% CO₂ and 30% H₂ at 600°C showed a growth rate of 1.00 mg/min

A Ni-Cr plated steel substrate coated with a CNT/CNF coating layer on both sides was applied in a Li-battery according to figure 6. The capacity was found to be as high as 1500 mAh/g using a 0.1C charge rate. Both in the small potential range 1V - 5mV and the large potential range 3 V - 5 mV, this electrode retains nearly similar capacity in a cycling test. When comparing these results to commercial carbonaceous anodes these capacities are very good. In figure 6, L represents the liquid electrolyte, C the can wall, S a separator, A is a metal layer (e.g. aluminium) covered on both sides with Li_{1+x}Mn₂O₄. F is the carbon or low alloy steel

substrate coated on both sides with a CNT/CNF layer and optionally a polymer layer such as a PI-based coating.

The corrosion resistance of the steel provided with CNT/CNF and a PI-based coating was compared to that of the same steel without the CNT/CNF interlayer. The PI coating delaminates after 5 days in an accelerated corrosion test. On the other hand, the coating lasted more than 30 days with the CNT/CNF interlayer.

Figure 8 shows a schematic presentation of a combination of CNT/CNF (3) and polymer layer (2) on a steel substrate (1) for fuel cell applications. The main components of a PEM fuel cell structure are bipolar plates and the membrane electrode assembly (MEA). The MEA comprises the proton exchange membrane, gas diffusion layer (GDL) and a catalyst layer. The main requirements for bipolar plates include low cost, easy fabrication, and good electrical and mechanical properties. Bipolar plates play vital functions in the so-called stack in a fuel cell such as to carry electric current away from each cell, to distribute fuel and oxidant homogeneously within individual cells, to separate individual cells and to facilitate the water management within the cell. According to the method of this invention bipolar plates can be produced by growing CNT/CNF on a steel substrate. CNTs were grown on cold rolled and a thin polymer film, in this case of polyether-imide, was applied using a roll coater and cured at 250°C for 2 min. The coating thickness was 8 µm. This substrate was then tested for contact resistance and potentiodynamic test. The further application of a polyetherimide layer provides the corrosion resistance and the CNT/CNFs provide good conductivity and the properties of the CNT/CNF-PEI combination satisfy the criteria of the United States Department of Energy (DOE).

CLAIMS

1. A process of direct low-temperature growth of an adhering coating of carbon nanotubes and/or carbon nanofibres (CNT/CNF) on one or both surfaces of a carbon steel or low alloy steel strip substrate which comprises the following steps:
- 5
- providing a steel substrate, optionally provided with a metallic coating;
 - growing CNT/CNF onto a surface of said substrate by using a carbon source gas comprising hydrogen through a thermal chemical vapour deposition (CVD) process at a temperature of between 500 to 750 °C, preferably of between 600 to 750 °C,

10

 - wherein no catalysts are added to catalyse the growing of the CNT/CNF, and wherein the growing of the CNT/CNF is catalysed by iron, nickel and/or chromium present in the substrate and/or the metallic coating.
2. A process according to one of the preceding claims wherein the carbon source gas
- 15
- comprises one or more of acetylene, ethylene, methane, carbon-monoxide, carbon dioxide or low molecular weight fatty oil.
3. A process according to one of the preceding claims wherein the carbon source gas consists of hydrogen, carbon monoxide and carbon dioxide, preferably in a ratio of about
- 20
- 30:60:10.
4. A process according to one of the preceding claims wherein the steel substrate is high strength steel (HSS), advanced HSS, Ultra HSS or complex phases steel, preferably comprising 0.01 -1%C, 0.15-2%Mn, 0.005-2%S, 0.01-1.5%Al, 10 to 200 ppm N, at most
- 25
- 0.015% P, at most 0.15%S, optionally one or more of 0.01 -0.1 %Nb, 0.002-0.15%Ti, 0.02-0.2%V, 10-60 ppm B, and balance iron and inevitable impurities
5. A process according to one of the preceding claims wherein the steel substrate is provided with a nickel, nickel-chromium or chromium plating layer or a zinc alloy layer
- 30
- prior to growing CNT/CNF onto one or both surfaces of said substrate.
6. A process of producing a coating on a steel substrate by in-situ providing a layer of CNT/CNF on the substrate according to any one of the preceding claims, and wherein the layer of CNT/CNF is coated with a polymer coating, such as a poly-imide based coating.
- 35
7. A process of producing the poly-imide based coating according to claim 6 wherein the poly-imide based coating is produced onto the layer of CNT/CNF by:
- applying a polyamic acid (PAA) layer followed by imidization and/or by
 - adding Mn, Ag, Si, Ti, Al and/or Mg while synthesizing PAA followed by imidization

40

 - and/or

- by applying a liquid polyether imide (PEI) solution, preferably by roll coating and/or spraying and/or
 - wherein the poly-imide is produced from poly-ether imides
- 5 8. A process of producing the coating according to any one of claims 1 to 5 wherein the CNT/CNF are subsequently treated with a suitable compound such as MgO or CaO to produce a catalytic support for storing CO₂ in the form of carboneous compounds, or with a photocatalyst such as titania or organic photo initiators to produce a catalytic converter to convert carbon dioxide into carboxylic acid such as formic acid (HCOOH) and/or
- 10 alcohols such as ethanol (C₂H₅OH).
9. A process according to any one of the preceding claims in a continuous process comprising the steps of providing a coil of cold-rolled steel, subjecting the coil to continuous annealing, optionally for recrystallisation of the cold-rolled coil, reducing the
- 15 surface of the steel, providing a layer of CNT/CNF onto the steel at temperatures of between 600 to 750°C and cooling the steel, optionally followed by providing the coated steel with a poly-imide based coating.
10. A process of producing CNT/CNF powder by producing a coating according to any one of
- 20 claims 1 to 5 further comprising removing the CNT/CNF from the surface of the steel substrate by mechanical means, e.g. by scraping, and collecting the CNT/CNF.
11. A steel substrate provided with a layer of CNT/CNF according to any one of claims 1 to 8,
- 25 for use in solar cell applications, fuel cell applications, in hydrogen storage, as catalytic supports, for radar capturing coatings or as an interfacial conductive layer or for use as anti-bacterial product.
12. A steel substrate provided with a layer of CNT/CNF according to any one of claims 1 to 8
- 30 coated with a polymer coating, for use in corroding environments, in solar cell applications, fuel cell applications, in hydrogen storage, as catalytic supports, for radar capturing coatings or as an interfacial conductive layer or for use as anti-bacterial product.
13. Use of the steel substrate according to claim 5 for the production of the electrode part of a
- 35 battery such as Li-based batteries and/or alkali batteries.
14. Use of a steel substrate/ foil according to claim 5 for the production of photovoltaic's
- 40 substrate for flexible back contact electrode.
15. Use of the powders according to claim 10 in the production of aqueous dispersed nano-coolant or fluid for heat exchangers or in the production of nano-composite coatings.

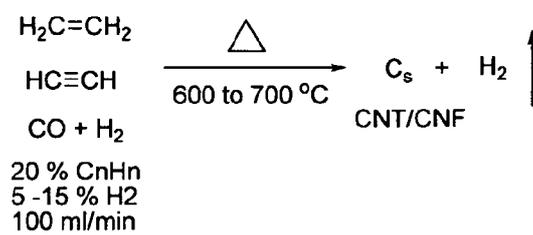


Figure 1

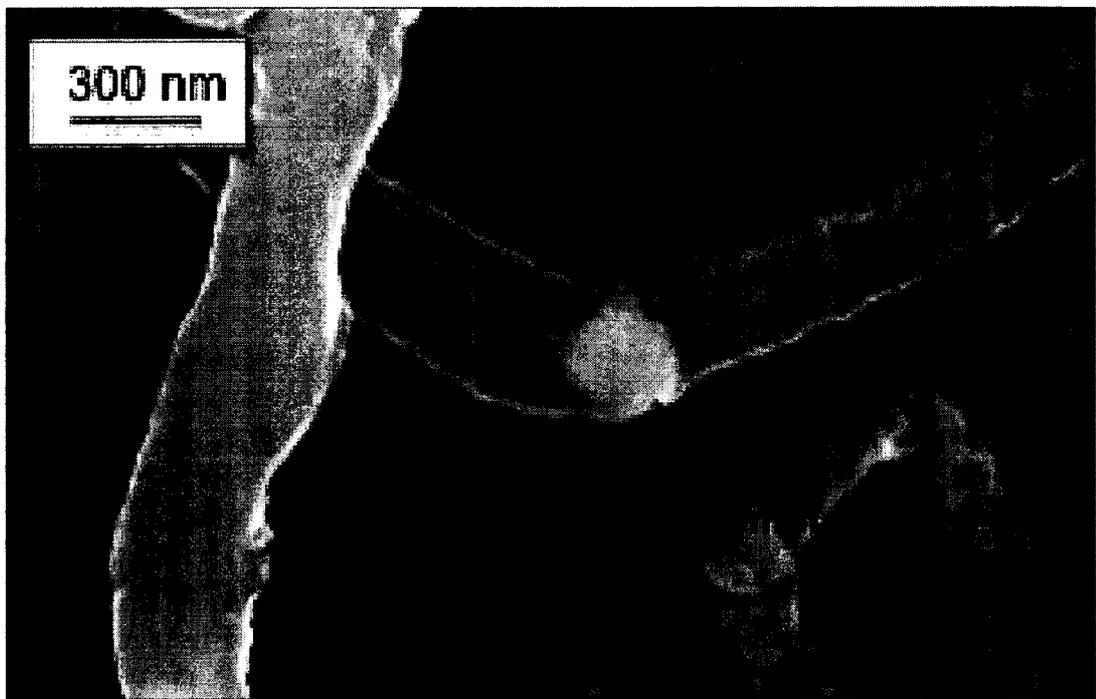
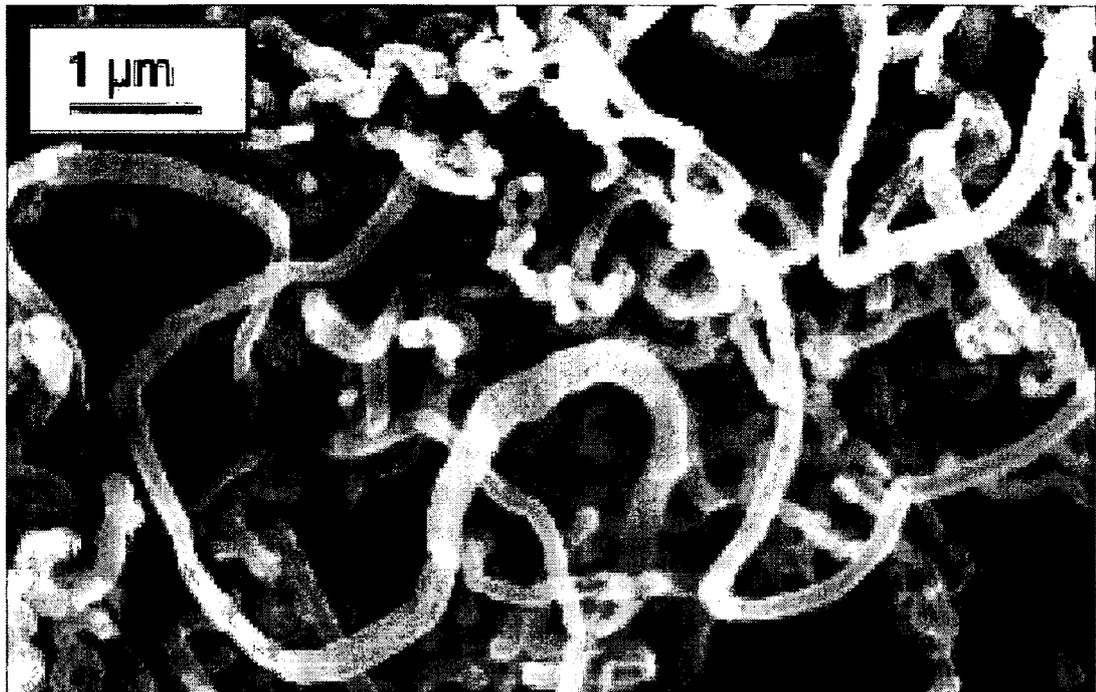


Figure 2

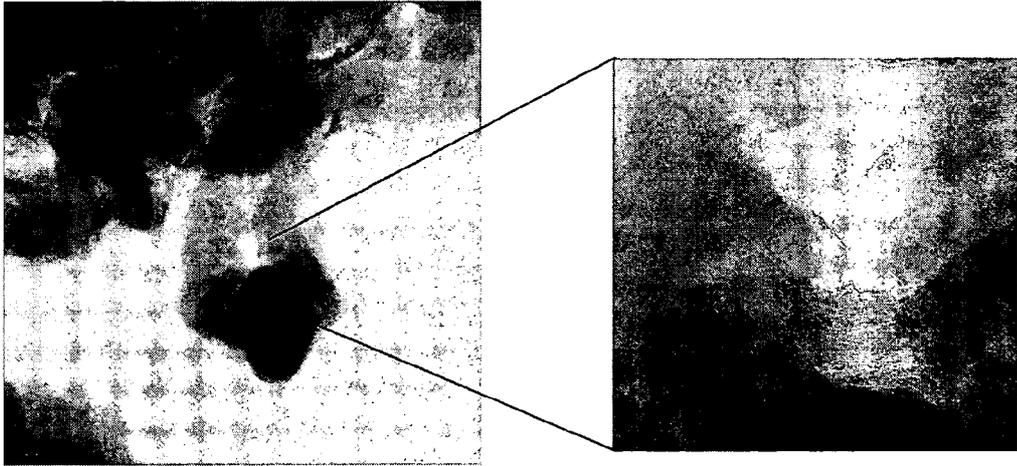


Figure 3

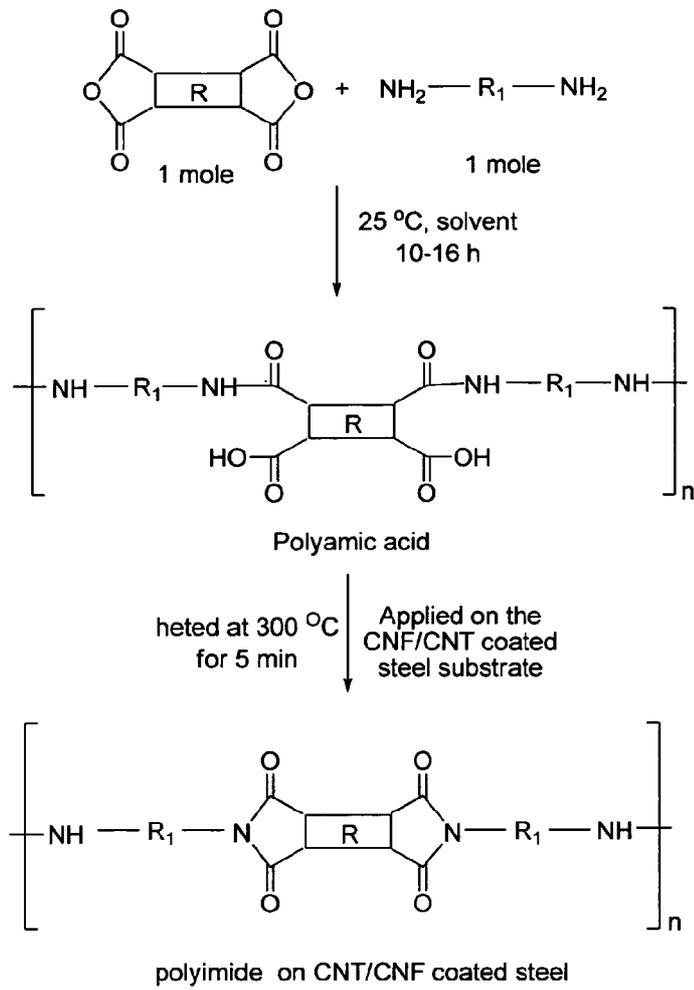


Figure 4

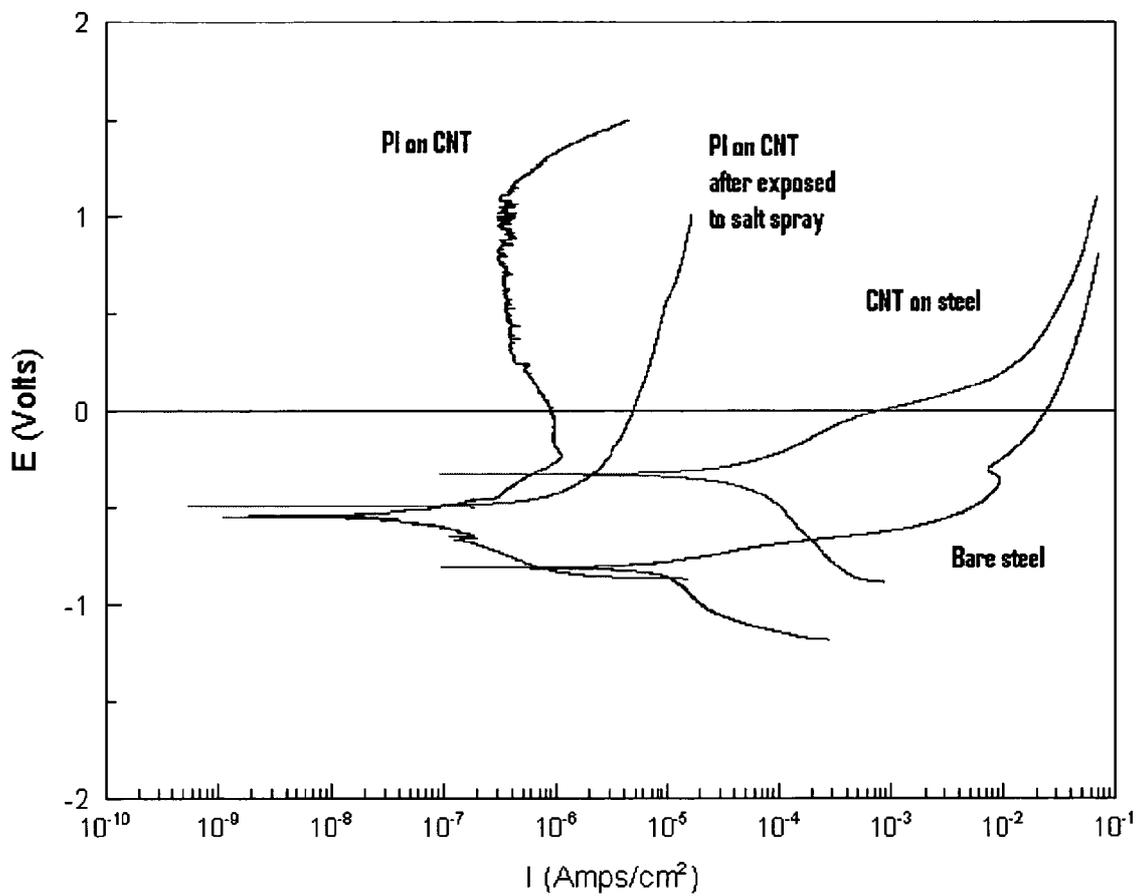


Figure 5

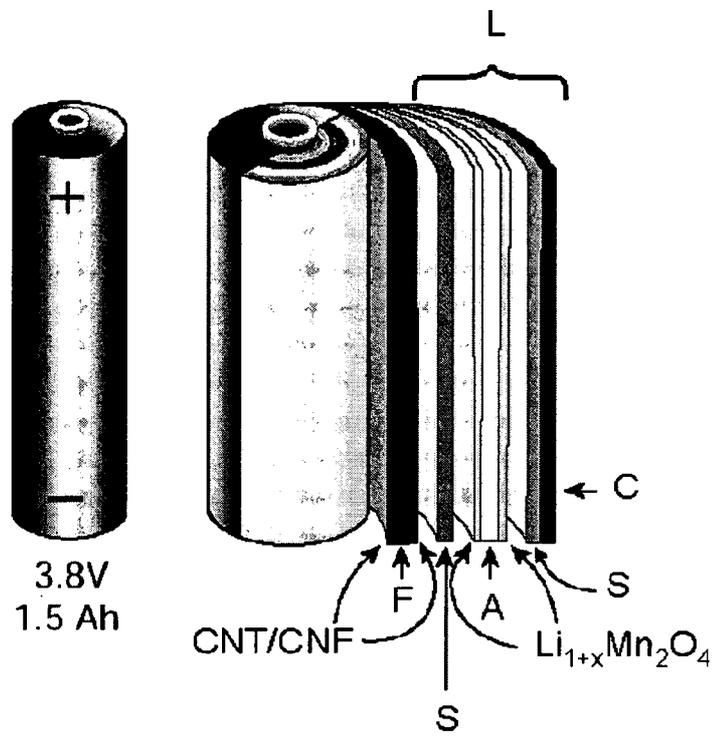


Figure 6

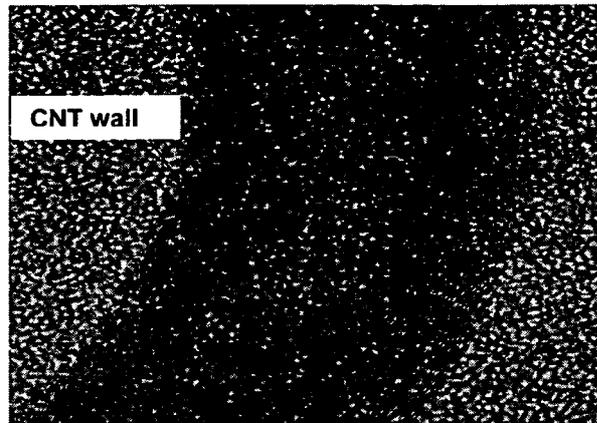


Figure 7

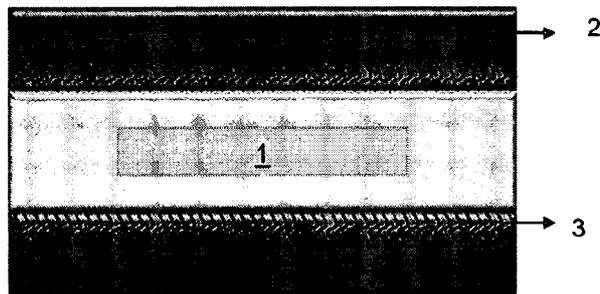


Figure 8