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CARBON NANOTUBES IN ART CONSERVATION

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Abstract

Ever since their discovery in 1991 carbon nanotubes (CNTs) have inspired scientists and developers of future technologies. They feature an electrical conductivity similar to copper, a thermal conductivity similar to diamond, and a modulus more than hundred times greater than steel. Many companies are working intensively on the development of CNT technology and applications. New catalysts have been developed which are capable of forming the tiny and thin-walled carbon nanotubes without any impurities. Based on these new industrial processes, cost efficient mass production has become viable. Perhaps one of the greatest technological potentials of CNTs at the present time lies in their electrical and thermal properties. CNTs are not only extremely light and robust, but can also efficiently heat up surfaces of any size utmost evenly with very rapid thermal response which can guarantee ultra-steady temperatures over large surface areas as well as short heating and cooling times. In order to use these properties in art conservation, the IMAT-project has been launched. The project is supposed to create a series of innovative and highly accurate mild and flexible heating devices for the conservation of various kinds of cultural heritage.

Keywords: *Nanotechnology; CNT; IMAT-heater; Mild heating; Art conservation*

Introduction

Ever since their discovery in 1991 [1], carbon nanotubes (CNTs) have inspired scientists and developers of future technologies. This is due to the unique material properties of the tiny nanoscale tubes composed of pure carbon. CNTs are the strongest and stiffest material known in the world and the only material that may be eligible to design a space elevator that would not break by its own weight. They feature an electrical conductivity similar to copper, a thermal conductivity similar to diamond, and a modulus more than one hundred times greater than steel.

CNTs can be regarded as molecular scale sheets of graphite (called graphene) rolled up to make a tube and can be described as a new member of carbon allotropes, laying between fullerenes and graphene. As widely recognized, Single Wall Nanotubes (SWCNT) consist of single seamless rolls of graphene [2], while Multi Wall Nanotubes (MWCNT) consist of two or more rolls [3, 4]. Properties of individual CNTs can be influenced significantly by their chirality (twist) and geometry. Held together by the Van der Waals force, CNTs tend to bundle in ropes, forming agglomerates, but depending on the production method ("growth") they can also form highly aligned structures.

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There are three commonly known processes for the synthesis of carbon nanotubes:

- Laser ablation process
- Arc discharge process
- Catalytic chemical vapour deposition process

The laser ablation process is based on thermal decomposition of a solid carbon source and is for several reasons regarded as typical lab scale process, especially due to the low efficiency and limited scalability of lasers. Also, the arc discharge process - which uses thermal decomposition of a solid carbon source as well - is associated with difficulties regarding the scale-up possibilities of the process and its economics. Today, most commercially available material is based on the so-called catalytic chemical vapour deposition process [5]. In this process, typically a gaseous carbon source decomposes on a solid catalyst particle at elevated temperatures. Depending on the catalyst and the process conditions applied, SWCNT or MWCNT are grown on the catalyst particle (Fig. 1), forming an agglomerated CNT-particle. The catalyst particle is deactivated during the reaction and remains in the product.

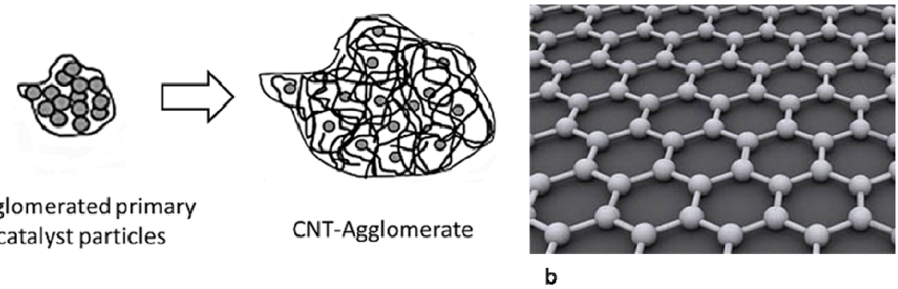

Fig. 1. Carbon nanotubes: a - Catalytic reaction for production of carbon nanotubes; b - Schematic image of graphene layer composed of hexagonally positioned carbon atoms.

The reaction, which typically occurs at temperatures above 500°C, can be conducted in different types of reactors. For use of solid catalysts common reactor types with moving beds like rotary kiln reactors or fluidized bed reactors are used since they provide better heat and mass transfer than fixed bed reactors. Furthermore, an agglutination of the product can be avoided allowing easy discharge of the product from the reactor. Often, a fluidized bed process is used which is characterized by a better mass transfer than rotary kilns and thus leading to higher space-time yield. In consequence, it allows a distinctly smaller reactor size.

In the fluidized-bed process (Fig. 2) the catalyst is fed into the reaction zone. Hydrocarbons are fed through the bottom being the fluidizing gas as well as the carbon source for the reaction. The reactor is heated through the walls. Waste gas, mainly hydrogen, is disposed by incineration after particle separation. The product is discharged through the bottom of the hot reactor, cooled down and filled into drums for shipping. Due to the high efficient catalyst in case of MWCNT synthesis, the product has a high purity and can be used “as grown” without further costly treatment steps. In case of SWCNT synthesis, catalyst yields as well as specificity are much lower, so that extensive cleaning from catalyst residues and by-products is inevitable. Generally, a completely closed reactor system is used in all processes, mainly due to the need to avoid a potentially explosive atmosphere, and because of product safety reasons.

The product discharge system and the packaging unit are fully automated in order to minimize any potential for exposition of operating personnel.

Depending on their production process, CNTs can have a length up to several millimetres and their diameter usually is in the range of 5-20 nanometers (Fig. 3), so that they usually have a length to diameter ratio in the range of several thousands. When they are produced they are highly entangled and agglomerated. High mechanical forces are necessary in order to break them apart and disperse them evenly in a liquid or coating material.

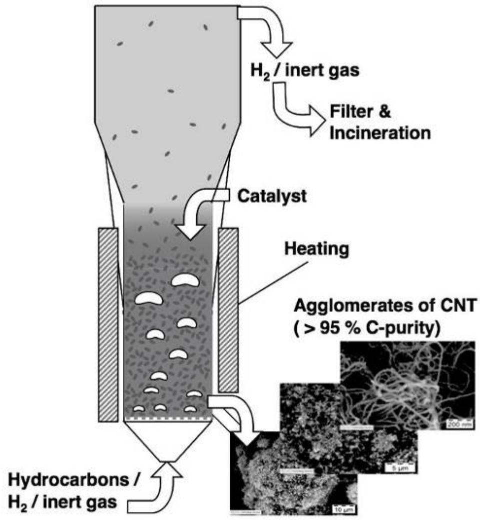

Fig. 2. MWCNT fluidized bed production process of Bayer.

During the drying process, re-agglomeration occurs and new entanglements are formed which will keep the CNTs and the CNT coating together even under mechanical strain. Therefore, such CNT coatings display an astonishing high elasticity and flexibility even at a very thin coating thickness, especially when these structures have been fixed within a chemically cross-linked coating system. Carbon nanotubes are extremely long and thin hollow nanofibers in which the carbon atoms are bonded together in graphitic structures that are the origin of the high electrical conductivity of the nanotubes. CNTs are the best field emitters of any known material and they can carry an electric current density of 4 x 109 A/cm2, which is more than 1,000 times greater than metals such as copper. CNT thermal conductivity along the axis has been measured as high as 3500 [W m^{-1} K^{-1}], although in theory [6] it could reach a value equal to 6600 [W m^{-1} K^{-1}] which is 2.5 times higher than diamond.

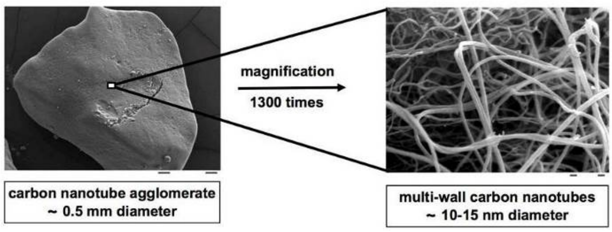

Fig. 3. Entanglement in extremely long and thin multi-walled carbon nanotube agglomerates.

CNT Applications

Many companies around the world are working on the development of CNTs-based technologies and applications [7-10]. New catalysts have been industrialized which are capable of forming the tiny and thin-walled carbon nanotubes without any impurities. Based on these new industrial processes, cost efficient mass production has become worthwhile. The main fields of application today are the use as filler and reinforcing agent in polymers and other materials, leading to electrical conductivity and high mechanical strength. CNTs are particularly interesting for various applications in cutting edge electronics, optics and material engineering.

While CNTs are revealing ever more remarkable features that will enable the creation of a broad range of "smart" materials and products with revolutionary characteristics, most researchers agree that perhaps the greatest technological potential at the present time lies in the electrical and thermal properties of CNTs (e.g. to generate heat in a way unachievable with other traditional technologies). As a matter of fact, CNTs can efficiently heat up surfaces of any size uniformly in very rapid thermal response that can guarantee ultra-steady temperatures over large surface areas as well as short heating and cooling times. For traditional materials, the change in temperature is usually slow and delayed due to their large thermal mass. In contrast, the thermal response of CNTs can be very fast even up to the incandescent state. In order to use these properties in art conservation, the IMAT-project [11-13] was launched. The project's goal, as partially described in [11], is to create a series of innovative and highly accurate mild and flexible heating devices for the conservation of various kinds of cultural heritage. Highly entangled CNTs embedded in a chemically cross-linked binder matrix are the basis for the coating system to be developed for the IMAT Project. Accordingly, the main aim of the present work is to describe how CNTs can be effectively applied in the Art Conservation field by creating a range of efficient and innovative heating devices.

The IMAT Project under the EU's Seventh Framework Program for Research (FP7)

The creation of new improved conservation materials and sophisticated "smart" instrumentation is of central importance in the advancement of the best practices in the art conservation profession and preservation of artworks and other cultural heritage assets [14].

The Intelligent Mobile Multipurpose Accurate Thermo-Electrical Device (IMAT) Research Project (2011-2014), selected by the European Commission and made possible with the financing under the EU's Seventh Framework Program for Research (FP7), now at its timeline midpoint, has advanced cutting edge technology of carbon nanotubes while designing a series of innovative, state-of-the-art precision instruments for mild heating, designed specifically for art conservation, in the form of lightweight, flexible, transparent and breathable film-like mats. The nano-mats are driven by a programmable mobile touch screen console with that will give the operator the ultimate control over the temperature and heating pattern that is unprecedented in art conservation, and will be advantageous in diverse structural treatments on cultural heritage assets, in dealing with local, global or specific conservation problems, allowing conservators to easily, and with unsurpassed accuracy, apply mild heating locally and over very large areas. The portability and low energy consumption will make the IMAT an ideal multi-use instrument for work in the field or in the laboratory, indispensable in the treatment large scale works, in areas of limited access or in emergency response conditions. The IMAT project aims to resolve at its core the pressing need for accurate mild heating in conservation methodology; this is accomplished by inventing a long awaited mobile and accessible nanotechnology to become an integral part of the conservators' tool box and to expand the technical capacities of conservators worldwide. With such a device, it is possible to open new, yet-to-be discovered possibilities in treatment methodology and to enable communities to safeguard their heritage and sustain their culture for the future generations. Sophisticated and accurate instrumentation allows conservators to treat artworks within the margins of minimal intervention and risk, while achieving the maximum result.

The IMAT Project develops an entirely new mobile nano-technological device, composed of portable mild heating mats and precision controls, which will bring the latest advances in carbon nanotube technology, electrical engineering and industrial manufacturing to the service of the most recent developments and demands in cultural heritage conservation.

The IMAT Project responds to a critical omission in current treatment instrumentation for accurate, selective and mobile devices for mild heating, which is essential for success in most structural treatments of paintings, works on paper, textiles and other cultural heritage assets. These accurate mild heating mats are being designed in ultra-thin, transparent, and woven forms, and also as gas permeable membranes to permit the migration of vapours and airflow so often used in combination with mild heating in conservation treatments. The project involves art conservators during the design, development and field-testing phases so as to gain the best insight into design improvements, to optimize the range of potential applications of the IMAT and to formulate new conservation methodology associated with the new technology. The IMAT Project was conceived with a research-based objective and with a bottom-up design format, unique in the field, to be mirrored in the development of the associated treatment methodology in order to improve the quality, accessibility and cost effectiveness of a fundamental tool for art conservators globally. The IMAT heater's thin profile allows it to be easily inserted under the stretcher or "sandwiched" with other materials used in diverse structural treatment (see Figure 4a). Moreover, the accuracy and low temperature capabilities of the IMAT will be useful in structural treatments, when heating is frequently applied (see Figure 4b).

a b

Fig. 4. IMAT heater: a - thin profile; b - example of a structural treatment where heating is frequently applied.

The research group is composed of a consortium of experts from the fields of thermo-electrical engineering, nanomaterial science, and industrial design to join the conservators who conceived the IMAT project (and who will become the end users), conservation product retailers, and specialty publishers to form an interdisciplinary consortium that will create the instrument in prototype form, develop new methodology, disseminate knowledge generated during the project, and deliver a market-ready and much needed conservation tool. Università degli Studi di Firenze (UNIFI, Italy) is the coordinator of the project, which is led by paintings conservators Tomas Markevicius and Nina Olsson. UNIFI has developed the console and temperature controls for the new device. Future Carbon GMBH (Germany) is responsible for the development of the innovative nano-coatings, which is carried out in close collaboration with Sefar AG (Switzerland) and the UNIFI. Stichting Restauratie Atelier Limburg-SRAL (the Netherlands), Laura Amorosi (Italy), Lorenzo Conti (Italy), Lietuvos Dailės Muziejus (Lithuania) and Istituto per l'Arte e il Restauro Palazzo Spinelli (Italy) are responsible for the field testing of the IMAT technology, while Nardini Press S.r.l. (Italy) will contribute in the dissemination and C.T.S. S.r.l. (Italy) in marketing in order to make the finished device available for the conservators.

Art conservators form the core of the research consortium, and have played a key role in crafting the parameters used in the design phase, consulting on materials during the development phases of the IMAT project, and will provide technical expertise in the field-testing use of production prototypes of the device and in the formulation of new methodologies. In particular, the IMAT will be tested and used in cases and conditions where currently available heating instrumentation is lacking or ineffective, and where the unique design features such as the highly accurate temperature control also at low temperature ranges, transparency, breathability, the thin design profile, flexibility, the variable size formats, portability, low energy consumption, and financial accessibility of the new device realize their greatest potential.

The field-testing partners were chosen from various origins, with regards to their conservation specialties, and range from research institutes and museum conservation laboratories to conservators in private practice. Field-testing partners are active in various European locations, where regional methodology traditions will create an even wider spectrum of technical application and enrich the results. Use for emergency treatment and for remote field locations will also be considered, conditions replicated, and corresponding methodologies developed, providing guidelines for procedures to be used in the event of the extreme conditions of post-trauma response. In Figure 5a, a diagram of possible use of the IMAT for a treatment using humidification and low pressure suction platen is shown. The lightweight and easily portable IMAT heat transfer system may be used in structural treatments of large format works, in emergency response, and in situ treatments as shown in Figure 5b.

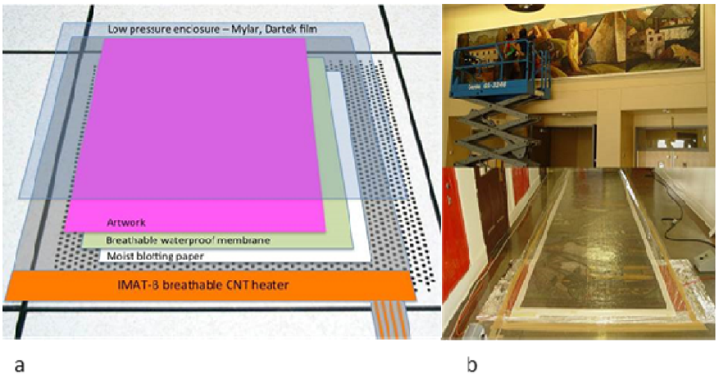

Fig. 5. Applications of IMAT: a - Diagram of possible use of the IMAT for a treatment using humidification and low pressure suction platen; the lightweight and easily portable IMAT heat transfer system may be used in structural treatments of large format works, in emergency response, and in situ treatments; b - The first applications of a flexible heater in the lining of a mural painting in Oregon, City, OR, USA.

The IMAT Design

The IMAT mild heater (Fig. 6) is an entirely new device with accuracy, along with other technical features, that cannot be matched by any other available heating tool in use in the field of conservation. Such advanced new technology, featuring custom-designed nanomaterials and the incorporation of other advanced materials, will open new vistas for the advancement of conservation methodology and techniques. Requirements of the ideal IMAT heater to be designed have been defined by the expert group of conservators who will have use the heater in their daily work. These design features are:

1. Portable, mobile, versatile and selective (allows possibility to apply heat selectively in the desired area).
2. Fast thermal response and highly accurate temperature control.
3. Ultra stable temperature and uniform heat distribution.
4. Transparent or translucent, permeable to gases: airflow, water vapours.
5. Soft non-tack surface, resistant to chemicals used in conservation and to physical stress factors related to frequent use.
6. Low power needs, safe low voltage at 36 V and 96 V.

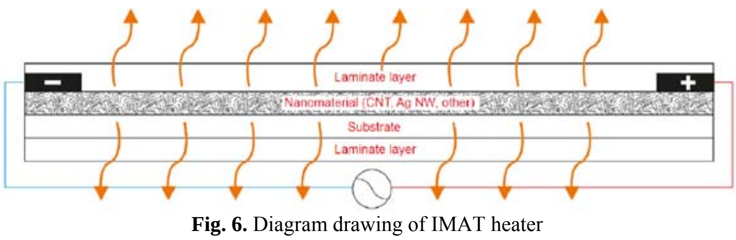

Fig. 6. Diagram drawing of IMAT heater

The design architecture of the IMAT device is composed of a conductive flexible film heater, made with CNTs or other nanomaterials, and an associated control unit (console) that also serves as a power outlet for the heater. The console includes an electrical “power box” that drives the heater, a digital touch screen console to control and program the heating process, and a thermocouple (TC) that is connected to the console via a Bluetooth (wireless) connection.

The IMAT architecture (Fig. 7) was planned to provide maximum versatility and mobility for the device in the most diverse treatment situations by separating the sensor, control pad, and power source elements of the console. For example, the heavier “power box” could be conveniently placed under the working table and the touch screen console could be kept nearby the treatment area. The wireless TC may be positioned easily in any location and the flat flexible connecting cable makes placement of the heater uncomplicated. In all aspects the IMAT design aims for miniaturization and simplification in the design solutions. The IMAT operates with a universal 110-230 V input and has two separate power boxes; 36V (for smaller heaters) and 96V (for larger heaters). In principle, the heaters can function with very low voltages, reaching 12-24V, but this is possible only for small sized heaters, while those very large heating mats exceeding several square meters may require voltages in the range of 180-230V.

The IMAT heater is a multi-layered construction composed of a substrate, covered first with a conductive nanomaterial coating, and then finished with an exterior protective coating, which also provides the non-tack surface and electrical insulation. Each IMAT heater has integrated parallel electrodes and when voltage is applied, the current is uniformly distributed over the conductive layer of the nanomaterials and heat is instantly generated evenly over the entire surface. The IMAT heater has a soft, non-tack and smooth surface.

One of the main IMAT objectives is to achieve efficient and uniform low voltage heating. The research work has allowed for the invention and development of a series of IMAT prototypes, obtained using a conductive CNT coating material in order to achieve low voltage heating even in large heaters, to be tested in the field.

In order to attain the target temperature at low voltage, an extremely high conductivity in the coating material was required, combined with a stable low resistance at the interface between coating material and electrodes, and an optimal configuration of the electrodes. In the research for the standard IMAT heater the main issue was to work with the highly conductive multi-walled carbon nanotubes (MWCNT).

To make the larger size heater work at low voltage, an increase in the conductivity of the CNT coating was main target. For the transparent heater, the research will focus on the use of single wall carbon nanotubes (SWCNT) and silver nanowires (AgNW).

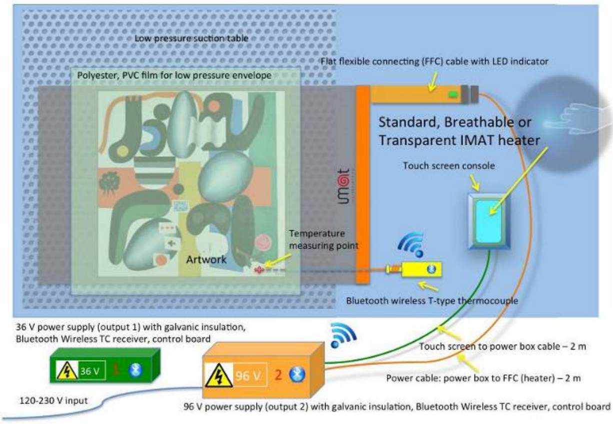

Fig. 7. Architecture of the IMAT heater: CNT heater, touchscreen console, power box, wireless thermocouple.

Depending on the thickness of the coating, electrical conductivity can be adjusted. In particular, as shown in Figure 8, experimental tests referred to the Carbo e-therm CNT show that the electrical resistance [Ohm/sq] decreases with increasing coating thickness (µm).

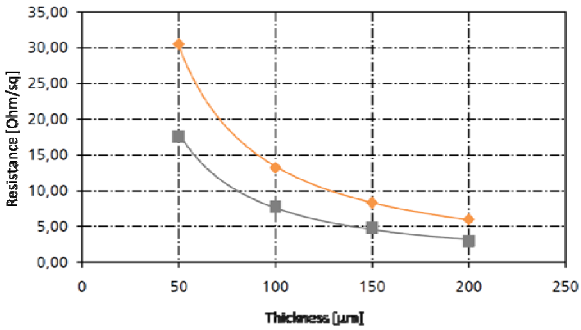

Fig. 8. Carbo e-therm resistance [Ohm/sq] vs. thickness [µm].

The design of CNT coating can be achieved by setting the required Power Density P_D [W/mm^2] and the surface A [mm^2] to be coated: first, the required power P [W] can be calculated as the ratio between P_D and A. Then, the sheet resistance R_Δ for a given applied voltage E is computed according to the following equation where L [mm] is the length separation between the electrodes of conductive coating:

$$R_\Delta = \frac{P_D L^2}{E^2} \tag{1}$$

Using the chart of Figure 9 the required thickness can be selected. Eventually, once the Power Density is selected, it is possible to estimate the reachable temperature.

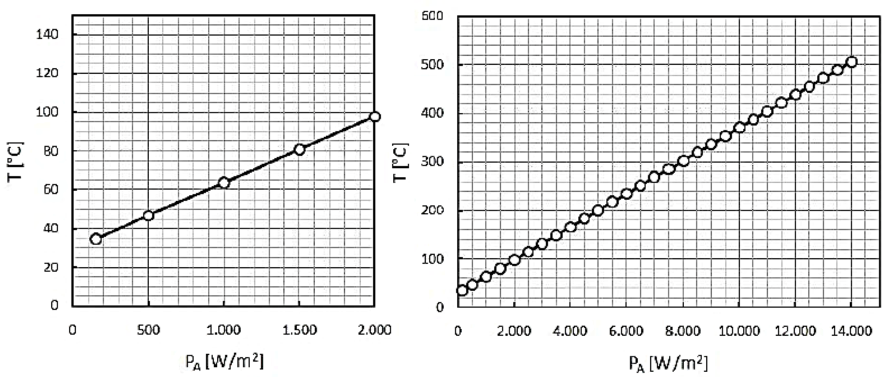

Fig. 9. Experimental Power density vs. Temperature chart.

High conductivity and very low sheet resistance were critical in the design of the heater with the two opposing electrodes, where the longer distance between the electrodes requires increasingly higher conductivity. Yet, another challenge occurred while designing the IMAT textile heater with woven multiple comb electrodes, where the distance between the electrodes must remain short and hence a low conductivity was required. As a result, one of the design parameters of the research was to develop CNT coatings that achieve the required conductivity of the coating with precision, while maintaining stability and resistance to diverse external factors, such the heat required for subsequent lamination processes of the external protective layers.

IMAT Prototypes

In the search for practical solutions designing the IMAT prototypes that would meet the desirable technical and operational features for art conservation we decided that optimal results could be achieved if the IMAT device will provide at least 3 different types of heaters, which can be connected and operated from the same console (control unit) and will allow the conservator to select the required type, depending on the treatment.

During the project the following types of the IMAT heater have been invented and developed (Fig. 10):

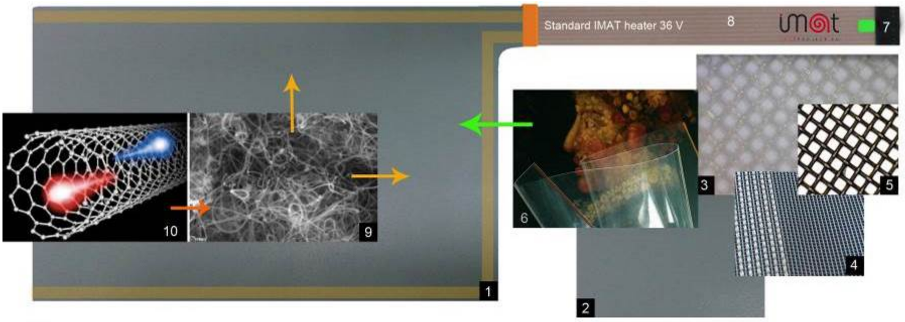

Fig. 10. IMAT types and structure. (1) IMAT mild heating device with electrodes and flat flexible cable (FFC) with connector and LED indicator. (2) Standard heater coated with silicone rubber, non-tack surface, grey colour. (3) Breathable transparent heater, polyester monofilament mesh, transparent (this result could be achieved coating with SWCNT or Silver nano wires. (4) Breathable semi-transparent heater, polyester monofilament mesh with woven-in electrodes. (5) Breathable and semi-transparent heater, polyester monofilament coated with carbon nanotubes. (6) Transparent heater, polyester film with SWCNT. (7) Flat Flexible Cable (FFC) connector. (8) FFC cable. (9) SEM image of carbon nanotubes (10) Schematic view of single walled carbon nanotube.

IMAT-S (Fig. 11) is a conductive low voltage heater with soft and non-tack surface, which is opaque and non-breathable.

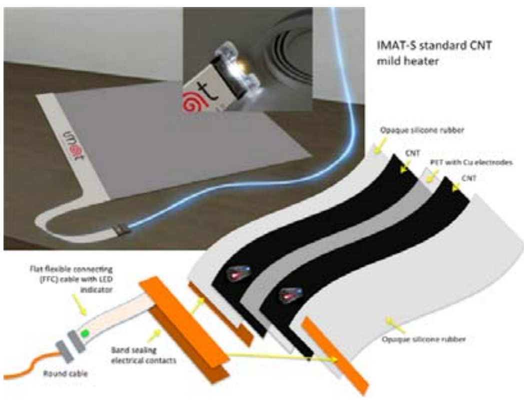

Fig. 11. Standard IMAT heater with protective soft silicone coating.

The IMAT-S is intended for the thermal treatments where visibility and breathability are not required. In terms of its use it is similar to the pre-IMAT prototypes, but the new added feature have been improved distribution of the heat over the surface, instant thermal response, improved accuracy especially at low temperature ranges, and notably low voltage power consumption, as well as easy handling which allows the heater to be rolled up for storage or transport to any location "in the field".

With regard to different requirements of the different IMAT heaters given above various systems and material combinations have been looked at. It is well understood that all heaters will consist of a multi-layered structure. While it may contain various layers, the main layers will consist of a substrate, the conductive CNT coating, and a protective-insulating coating on top. The conductive coating material itself as well as substrates and protective top coatings and their application processes have to make sure that all the requirements of the IMAT heaters will be met. Transparent polyester film is a good choice for the substrate, since polyester is the standard material for plastic films and usually gives good adhesion to any kind of coating due to its chemical base units which allow the formation of strong chemical bonds between coating and substrate. For the electrical supply two copper electrodes were glued onto one side of the polyester film and the CNT coating was applied by spraying.

Based on earlier experiences, silicone rubber has a number of desirable features, with regard to chemical resistance, flexibility, and soft-feel touch. However, standard silicone grades require modifications in order to meet closer the IMAT wish list. Based on a flexible polyester film, the highly conductive CNT coating layer and a soft-touch protective silicone top coating a first prototype for the standard IMAT heater has been manufactured with a flat cable attached for electrical supply. Low viscous silicone coating systems as well as perforation afterwards to the coating process or use of permeable membranes have been explored for designing the breathable IMAT heater.

On the basis of the above considerations, a coating thickness of 40 μm has been chosen for the standard textile-based heater with an electrical resistance of 16 Ohm/sq. This is sufficient for a standard Din A4 size heaters to reach a temperature of 80°C.

IMAT-B is a conductive low voltage heater, opaque and permeable to gases, in particular to airflow and to water vapours. For the IMAT-B, a custom formulated carbon nanotube coating is deposited on an appropriate substrate, such as an open weave polyester textile. Such a textile, developed by SEFAR, is shown in Figure 12.

Essentially based on SEFAR PETEX 07-465/49 the IMAT-B is basically composed by PET (Polyethylene terephthalate) fibers i.e. by thermoplastic polymer resin of the polyester family with an intrinsic viscosity range equal to 0.40 – 0.70. In particular, two different sizes of fabric has been developed: wide and DIN A4 sized. For the wide fabric, warp is composed by 16 filaments/cm with a diameter equal to 200 μm. Weft has 10-20 filaments/cm with a diameter equal to 100-140 μm. This demonstrate that density of the fabric can be adjusted along weft direction. Electrodes are made of stranded copper wires Ag coated with a cross section equal to 0.7 mm2 and 20 mm width.

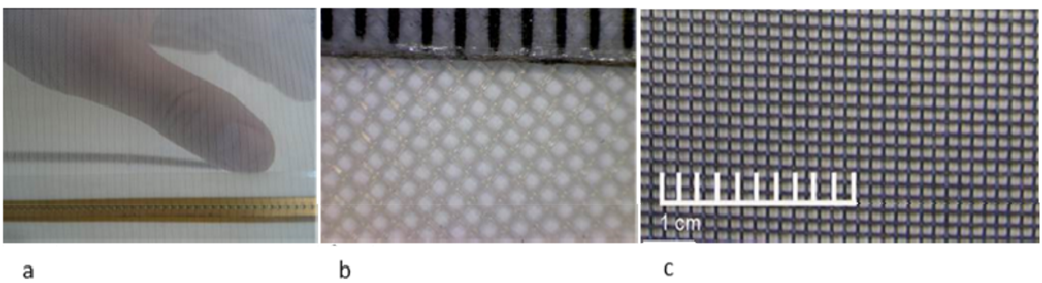

Fig. 12. Carbon nanotubes textiles: a - Image of Sefar AG hybrid textile with woven-in electrodes; b - macroscopic image under microscope of transparent monofilament textile used for the IMAT heater; c - the textile can be transparent if coated with silver nanowire or single walled CNTs and semi-transparent if coated with multi-walled CNTs.

IMAT-T is a conductive low voltage heater, which is transparent but not breathable or permeable to gases.

The development of a highly conductive and transparent CNT coating is still a major task. All transparent conductive materials that are available on the market still do not have sufficient conductivity in order to allow the design of transparent heaters in a larger size. Even highly conductive SWCNT coatings do not have sufficient conductivity for heating of large areas. However, there are transparent silicone grades available which are an alternative option for the transparent/translucent heater if used in combination with a thin conductive mesh. Thus, a first prototype for a transparent IMAT heater has been manufactured and is being tested in field trials.

All these prototypes already show a fast thermal response and easily heat up to temperatures in the range of 100°C and higher. Equipped with a corresponding control console it will be able to supply the desired temperatures up to 90°C constantly. The non-tack surface covered with a highly cross-linked layer of silicone rubber isolates the electrical current and has an excellent chemical resistance to water and other solvents for protecting the CNT coating. It also withstands any physical stress factors related to frequent uses. One of the IMAT objectives is to achieve an ultra-low voltage heating. For the low voltage heating high conductivity is crucial. There is still work going on to find an optimal formulation of the highly conductive CNT coating in combination with the optimal design of the electrodes so that very low voltages can be used for the electrical supply. Most of earlier studies on the conductive nanomaterials based heaters address designing small scale heaters only on glass or PET substrate for LCDs, automotive industry etc. The targeted scale and the physical properties of the substrates in the above industries are of little practical use for art conservation, where larger scale, highly flexible, chemically and physically resistant, soft and breathable and also transparent substrate and coating materials are required.

IMAT Control Console

IMAT is powered and controlled by an associated control unit (console) that serves as a power outlet for the heater and controls, and both monitors and registers the heating process. The IMAT console (control unit) is responsible for the temperature control, for the accuracy and steadiness of the heating cycle and for the heating and cooling times. Because of the low thermal mass, the heating and cooling of the IMAT heater will be instantaneous and the heating software shall allow the temperature to rise or descend either instantly or gradually, in the time set forth by the operator. The controls will allow the target temperature to be set with an accuracy of 0.5°C, which is sufficient for most thermal treatments and will also allow the desired heating and cooling time to be programmed. The IMAT consists of three distinct components: IMAT Power box, IMAT Control Unit and IMAT TC Unit. IMAT Power Box (see Figure 13a) is the unit dedicated to regulation of the IMAT heater temperature. The Power box is the central unit to which all the other devices are connected. The IMAT Power Box is composed of the voltage power supply and the IMAT Main Board. This device analyses the temperature data coming from the TC Board, and then corrects and regulates the electric power with the classic approach of the PID-PWM regulation (Proportional Integrate Derivative Pulse Width Modulation) of its AC/DC Switching voltage supply source. Its configuration guarantees the galvanic insulation of the output voltage toward ground, and thanks to an embedded microcontroller unit, it can emit and display acoustic and visual signals to alarm the user of errors and malfunctions that can happen. The IMAT Main Board is an electronic board into which can be identified various section. The electric power for both the IMAT control and the power box circuit is derived from a MeanWell AC/DC Power supply that supplies 36V or 48V to the IMAT Main Board according to the output needs of the small and the large IMAT Consoles. More precisely, the small size IMAT Console requires only a single HRP-600 36V MeanWell Power supply. The large size IMAT console instead uses two identical RSP-1500 48V MeanWell Power supplies, connected in series to reach 96V total output. The Main Board Core is the ATxmega16A4U Atmel Microcontroller, a small microprocessor with additional internal peripherals integrated into the same chip. This device has 16kB of flash memory, 2kB of SRAM and a 12MHz CPU master clock.

Fig. 13. The IMAT components: a - The IMAT power box, here rendered, is subdivided in its mains components: the IMAT Main Board and the AC/DC Switching Power Supply which that assures galvanic insulation of the output voltage; b - rendering of the IMAT Control Unit; c - rendering of the IMAT TC Unit.

IMAT control unit (see Figure 13b) is based on the Xflar Core produced by Qprel s.r.l. It's an extremely compact ARM9-based CPU module working at 240MHz with 64MB of RAM and 256MB NAND flash memory (memories are expandable) with integrated peripherals. This module can be integrated with the Xflar Xpress board that add connections like Ethernet, buttons and USB unit and that can be expanded with a resistive touch screen to realize a complete touch console. Into IMAT Control Unit a Linux operating system build around ARM architecture is installed. A GUI (Graphic User Interface) has also been implemented.

IMAT TC Unit (see Figure 13c) is composed of the IMAT TC electronic board and a rechargeable lithium battery power source that renders it cordless and mobile. The TC Unit is equipped with a T-type thermocouple laminated with electrostatic film that serves as a detachable temperature sensor. This unit measures the IMAT heater temperature locally with a thermocouple and transmits data via Bluetooth to the IMAT Main Board.

Conclusions

Today, the application of CNTs for highly accurate heating remains a challenging task for CNT researchers globally, yet it also appears to be one of the most promising areas, where the new CNT qualities and potential could be revealed. IMAT is the first application of carbon nanotubes in art conservation. Although the scope of this research project is focused on the application of CNTs for mild heating in art conservation, the results of the IMAT technology could find interesting applications in other fields beyond art conservation.

The IMAT Project, now at midterm, enters a phase of intensive field testing of the CNT-based prototype heaters, which will render further improvements to the design for the final production prototypes, new methodologies for art conservation and paths for further research.

As finality, the IMAT project will make the new technology based on carbon nanotubes and other nanomaterials available to conservators and scholars in multiple formats: through the presentation of research at conferences, publications, as well as through a dedicated website (www.imatproject.eu), workshops and symposia.

The expected results of the IMAT project offer to conservators an essential, sophisticated, yet simple to use tool for their everyday needs; with its ambitious multi-faceted aspects of joint effort in interdisciplinary exchange, diffusion of knowledge, and end goal of improving the best practices of conservation of cultural heritage assets IMAT project epitomize many broad goals addressed by conservators and conservation scientists today. In particular, it emphasize the need to 1) continuously address and re-evaluate the objectives and demands of the field, 2) to integrate contemporary science with conservation practice and 3) to affirm cultural heritage conservation and conservation research as a professional pursuit, fundamental for its role to society.

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