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Instrument: Specific Cooperative Research Project for SMEs

PUBLISHABLE FINAL ACTIVITY REPORT

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Partners:
INASMET (SPAIN)
GRUPO ANTOLÍN ING. (SPAIN)
ESVRES MATRIÇAGE (FRANCE)
ACORDE (SPAIN)
IMT (ITALY)
ICMCB (FRANCE)
MARION TECHNOLOGIES (FRANCE)
ALLIANCE (FRANCE)
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Glossary

Al/SiC: Aluminium Silicon Carbide

CNT: Carbon Nano Tube

CTE: Coefficient of Thermal Expansion

GaAs: Gallium Arsenide

GaN: Gallium Nitride

GANF: Grupo Antolin nanofibres

SWCNT: Single-wall carbon nanotube

SEM: Scanning electron microscopy

Si: Silicon

SiC: Silicon Carbide

TC: Thermal Conductivity

TEM: Transmission electron microscopy

VGCNF: Vapour-Grown Carbon Nano Fibre

XRD: X-ray diffraction

WCu: Tungsten Copper

1 PUBLISHABLE EXECUTIVE SUMMARY

1.1 PROJECT DESCRIPTION AND OVERVIEW OF OBJECTIVES

Currently there are two major relevant problems to be solved in the electronic industry. In the short term, the first problem is the substitution of lead in all electronic components (mainly in solders). The second problem is the improvement of heat management in electronic devices. This is the best way to improve power, reliability and efficiency of existing products (Si, SiC and GaAs semiconductor technologies) while facing the challenge of the miniaturisation of electronic components (power microelectronics) and new developed semiconductors (GaN). Higher operating temperatures and frequencies are the main targets. Therefore the improvement of the housing of new electronic components is crucial for the near future of the electronic industry.

The electronic industry in Europe is a sector which is, on one hand, experiencing a strong competition from "low-cost" countries outside the European Union (mainly from the Far East) for the production of cheap components. On the other hand, Europe has a dependant position with respect to "high-technology" countries such as Japan and USA, these being the main providers of high-technology products such as new semiconductors, advanced materials for electronic packaging, etc. So, there is a clear need for the European Industry, and more specifically to SMEs, to strengthen their competitiveness to compete advantageously with Far-East countries while leaving step by step their dependant position from Japanese and American suppliers of strategic products. European SMEs of these sectors find the need to improve the quality of their products, to optimise the processes and to accept new challenges of new products developments, this way improving their competitiveness by offering higher quality products while reducing costs derived from a higher production rate of advanced components.

The HeatConductives project has focused on the improvement of the efficiency and reliability of electronic systems by the use of innovative highly heat-conducting materials and products formed by the combination of copper and new carbon nanofibres and nanotubes of outstanding thermal conductivity. Conventional and innovative manufacturing processes have been developed during the project to produce thin foils and 3D near net-shape components. Through these methods, new highly heat-conductive composite materials have been produced with the target of improving the performance in comparison to those products available today.

The project target has been to meet the demands of the electronic industry for a heat-sink material with the following advantages:

- Two to six times higher thermal conductivity than conventional and state of the art electronic packaging materials available today for power electronics.
- Low Coefficient of Thermal Expansion (CTE) which can be tailored to specific application requirements
- Adaptation of highly productive fabrication methods of monolithic materials such as tape casting (for thin sheets and foils) and Metal Injection Moulding (3D shapes) to the production of composites in order to enable an easier industrialisation of final products while lowering costs
- Good machining characteristics to enable the use of high speed conventional steel tools
- Three to five times cheaper, and improved performance, compared with current state of the art materials such as AlN, Al/SiC, AlSi, CuMoCu or WCu.

This general objective of producing heat sink materials will be achieved through the achievement of several partial technical objectives summarised in the following table:

OBJECTIVE	*PARTIAL OBJECTIVES*
New heat-sink materials and products	Development of novel highly conductive low cost vapour grown carbon nanofibres (VGCNFs) and carbon nanotubes (CNTs).
	Production of feedstock for MIM and Tape Casting with copper, VGCNFs and CNTs. Development of the method to coat VGCNFs and CNTs with copper.
	Development of metal matrix composite 2D and 3D manufacturing processes (tape casting and metal injection moulding)
	Validation of the technologies developed by the production of industrial components, mounting, assembling and evaluation of electronic devices

Table 1: General and partial objectives of the Project

1.2 *LIST OF CONTRACTORS*

The contractors involved in the project were the following:

Consortium Overview				
Role	**Organisation Name**	**Partner Nº**	**Country**	**Business Activity**
End-user	ACORDE	A 2	Spain	Design and manufacture of microwave components, equipment and systems for satellite and terrestrial communications
End-user	SEMELAB	A 3	UK	Semiconductor device manufacturer
Composite manufacturer	ESVRES MAT	A 4	France	Design, manufacturing and sale of precision parts for electro-technical equipment
End-user	IMT	A 5	Italy	System Engineering for Space Application
Carbon nanofibres producer	MARION TECHNOLOGIES	A 6	France	Production of "tailor-made" materials and nanostructured powders for industrial uses
Composite manufacturer	ALLIANCE	A 7	France	Metal Injection Moulding of components for the electronic and automotive sectors
Carbon nanofibres producer	GRUPO ANTOLÍN ING.	A 8	Spain	Design and production of a wide range of components for the automobile industry. Production of carbon nanofibres, which is its main role in the project.
RTD Performers				
Materials researcher	INASMET	A 1	Spain	Materials and Process development
Materials researcher	ICMCB	A 9	France	Materials and Process development

Table 2: List of contractors

1.3 *PROJECT COORDINATION*

The project coordination has been carried out by Javier Coleto from INASMET.

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1.4 PROJECT STRUCTURE

The project was divided into seven key work packages as shown in the table below. The main objectives and the methodologies employed by the project partners to achieve these objectives, as well as the results and achievements arising from the key work packages are described in Section 2 of this document.

WP1	Definition of Requirements and Specifications
WP2	Production of Highly-Conductive Carbon Products
WP3	Mixing of Cu and C. Coating Process
WP4	Fabrication and Sintering of Green Body Components
WP5	Production and Characterisation of Prototypes
WP6	Technical and Economic Evaluation
WP7	Project Management and Coordination

Table 3: Project work packages

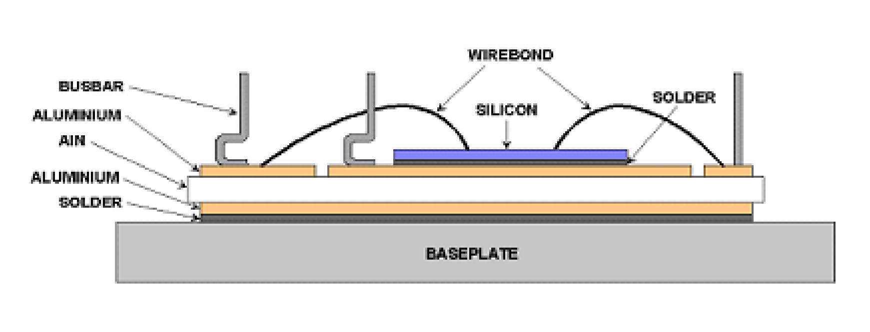
2 PROJECT OBJECTIVES AND MAJOR ACHIEVEMENTS

2.1 DEFINITION AND SELECTION OF PROTOTYPE DEMONSTRATORS

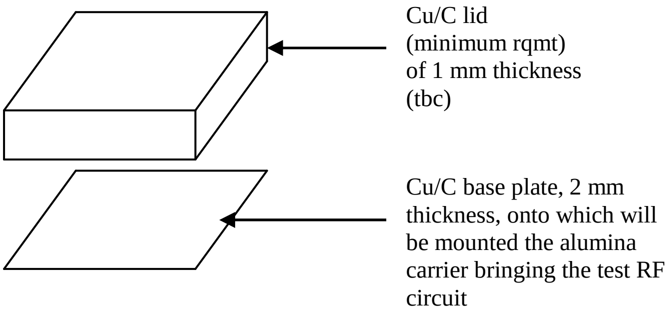
WP1. Technical requirements and end-users specification: In the first months of the project the demonstrators to be produced at the end of the project were defined by the end-users (SEMELAB, IMT and ACORDE). Three different types of electronic packaging components were defined for manufacturing. The most suitable manufacturing routes for producing the final prototypes of each of these demonstrators were selected according to respective part's geometries. The three end users highlighted the target parameters of their selected demonstrators.

- **Semelab -** IGBT Half Bridge circuit power module baseplates (600V, 400A).
  - Dimensions: 100mm x 60mm x 3.5mm
  - Manufacturing route: Hot-pressing.
  - Thermal properties: CTE: 6-9 ppm/ºC (currently 15 ppm/ºC)
  - Mechanical properties: Crack resistance at mounting holes (~2.5Nm torque)

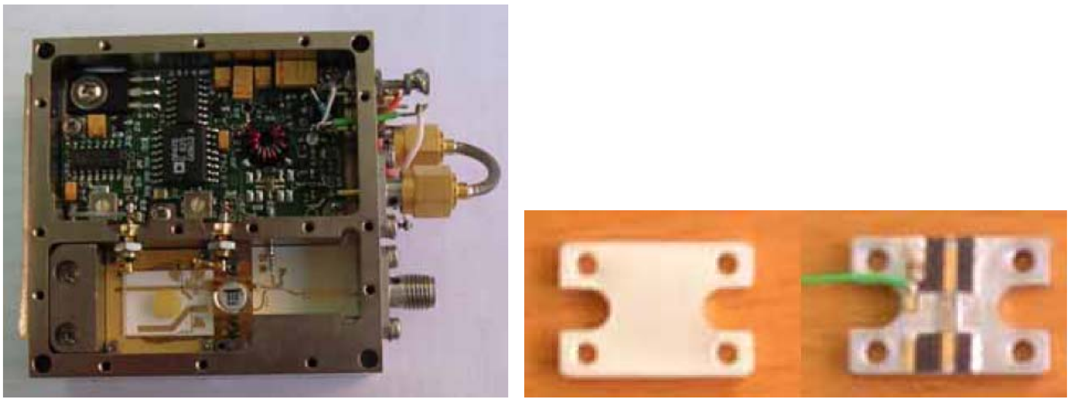
- **IMT** – an electronic package for the housing of RF/MMIC devices. The main aim was to improve the thermal properties of the entire electronic package whilst maintaining the electrical performance.
  - Dimensions: 25 x 25 x 12 mm
  - Manufacturing route: Metal injection moulding (box), tape casting (baseplate).
  - Thermal properties
    - CTE: 7-9 ppm/ºC (currently 15 ppm/ºC)
    - Thermal conductivity: ~ 600 W/mK (currently 200 W/mK)
  - Mechanical properties: Thermally stable up to 200ºC



(a) Semelab demonstrator



(b) IMT demonstrator



(c) Acorde demonstrator

Figure 1: HeatConductives project demonstrators

- **Acorde -** high power MMIC designs, for integration into different housings.
    - Dimensions: 15 x 10 x 0,5 mm
    - Thermal properties:
        - CTE: 6.85 to 7 ppmºC
        - Thermal Conductivity: > 150 -200 W/mK
    - Density: 2 to 3 g/cm^3
    - Electrical conductivity: < 10^{-6} Ωm
    - Easy CNC handling
    - Easy machining of features (recesses, pedestals, slots etc.) .
    - Thermo-mechanical stability up to 300ºC

2.2 PRODUCTION OF HIGHLY CONDUCTIVE CARBON PRODUCTS

WP2. Production of Highly-Conductive Carbon Products: The structure shown by the carbon nanofibres is determined by the manufacturing conditions, such as the catalyst and parameters used (temperatures, gases flow…).

This structure can be also altered by means of processes performed in a post-production process, such as the graphitisation treatment, in order to improve their properties. Fibres from Grupo Antolin Ingenería present a high graphitic level (around 70%) even though no post-process is performed.

The carbon nanofibres usually present an important grade of agglomeration due to their manufacturing process, becoming entangled during the growing process (thickness increasing phase by means of chemical vapour deposition). This makes their subsequent separation difficult. Standard fibres debulking methods include damped milling and pressing. Those methods have demonstrated their inefficiency to achieve a total debulking.

The high aspect ratio (L/D) of the carbon nanofibres and their small size induce Wan der Waals forces between the nanofibres dispersed in an aqueous media, leading to the formation of small clusters. These problems and their low solubility made their dispersion in liquids difficult.

In addition, the carbon nanofibres produced contained impurities from the Ni catalyst used in the manufacturing process. These impurities are detrimental to the proper composite material in terms of physical properties.

From this point of view it was extremely important to seek treatments that promoted de-agglomeration as well as to remove the impurities coming from the manufacturing process. With this aim, the most interesting methods were based on functionalisation consisting of the introduction of functional groups (C=O) in the structure of the fibre by means of chemical bond and heat treatments consisting of submitting the carbon nanofibres to high temperatures.

The guidelines for purification of the carbon nanotubes are based on the results obtained in collaboration with Marion Technologies. The purification was carried-out by washing with strong acids. Since the Marion nanotubes possess a low number of walls (single, double and triple-walled CNTs), it was important not to use acids that would lead to excessive damage of the wall structure. That is why the purification with nitric acid was discarded.

In this case, the CNTs were grown on ceramic substrates by the CVD method, employing two metal catalysts. The yield of CNTs on the obtained feedstock was about 15 wt. %. Thus it was crucial to eliminate both substrate and catalyst without any damage to the CNTs structure.

Different graphitisation treatments have also been performed at lab scale and at different temperatures ranging from 1600ºC to 2800ºC. Microstructural characterisation showed that impurities coming from gases and catalysts have been removed from as-cast VGCNFs. Moreover, a slight improvement on the disentanglement has been observed. These results have been confirmed by a graphitisation treatment performed at 2700ºC under controlled atmosphere in an industrial furnace (Carbon Lorraine, France) on a sample of 2 kg of VGCNFs from Grupo Antolín.

The improvement of the physical properties of the carbon nanofibre was indicated by the level of graphitisation of the fibre. The results showed the suitability of the heat treatment in terms of thermal and electrical properties. It was demonstrated that graphitisation in an industrial furnace in this instance has lead to better results than those achieved at lab-scale. It must be pointed out that with this heat treatment a complete purification of the carbon nanofibres was also achieved as all metallic impurities are eliminated at the temperature used.

2.3 MIXING OF COPPER AND CARBON PRODUCTS

WP3. Mixing of Cu and C. Coating Process: In order to develop the two manufacturing routes addressed in the project, a suitable feedstock has had to be prepared. The most important characteristic of feedstock suitable for the envisaged applications is good dispersion of copper and carbon nanofibres. Two main approaches for achieving this have been addressed:

1. Mixing of copper and carbon nanofibres: In order to obtain an even distribution of the nanofibres inside the mixture, several procedures have been developed such as suspension of carbon nanofibres and copper powder in fluids and mixing of carbon and copper in dry high-energy ball mills. Unsatisfactory results were achieved and it was decided to focus our efforts on the coating route.
2. Coating of carbon nanofibres with copper: By means of the electroless plating route, different trials were carried out in order to achieve an optimal dispersion and coating of the carbon nanofibres. One of the main challenges to obtain a good coating was the dispersion of carbon nanofibres in the plating baths and many efforts were dedicated to this task. Presumably due to the particular structure and surface of the carbon nanofibres supplied by GAI, disentanglement and dispersion have proven to be more difficult than expected.

The best way to obtain CNFs/Cu composite powders (as studied within the HeatConductives project) has been by electroless plating. The benefit of electroless plating is that the process can be scaled up to obtain higher yields of the composite powder.

However there have still been difficulties to overcome for the incorporation of CNTs:

- Excessive clustering
- Large surface area, which leads to oxidation

Electroless plating was selected among other coating technologies because of its simplicity, lack of expensive facilities and its possibility to obtain disperse fibres individually coated with copper. The process involves the activation of the non-active surface to enable coating. This is the case for the GANF material.

Activation was done by the immersion of the material in two consecutive activation baths. The first was a sensitization bath followed by an activation bath.

The use of these aqueous solutions allowed the dispersion of the fibres and individual coating in order to form a homogeneous composite powder. This was done by the use of surfactants and ultrasonic stirring. Agglomeration was seen to occur at concentrations greater than 1.5g fibres per litre of solution.

Excessive levels of the surfactants in the plating solution led to poor homogeneity of the coating (in some cases it led to the complete removal of the coating).

Lower volume fractions led to better homogeneity of the coating, due to the intrinsic mechanism of the electroless process. However at higher volume fractions (up to 40%) good coating morphology was also successfully obtained.

In order to manufacture the green body components and to use the feedstock produced in previous tasks, the adaptation of the manufacturing routes addressed in the project was started. Inasmet's activities focused on the optimisation and production of copper coated carbon nanofibres using an industrial pilot plant. The reason to develop the pilot plant was the requirement of large quantities of coated fibres for preparing feedstock for the Metal Injection Moulding and Tape Casting processes. This plant has allowed the move from laboratory scale to semi-industrial manufacturing. It was possible to obtain up to 400 g of composite powders (40vol% of VGCNFs) per batch.

2.4 FABRICATION AND SINTERING OF GREEN BODY COMPONENTS

WP 4. Fabrication and sintering of green body components: The following step of the project has been the fabrication of green-body components. Once the feedstock had been prepared, basic parameters were studied related to the manufacturing routes addressed in the project.

MIM green parts were not successfully sintered. Large air voids were formed inside the samples, inhibiting the complete sintering. This effect was probably due to the oxidation that appeared in the composite powders. At medium temperatures, the oxygen from the oxides can be removed, and reacted with carbon to form carbon monoxide (gas). A possible indication of the reaction with oxygen was superficial etching of the nanofibres.

Samples have been manufactured by means of Tape Casting and Hot-Pressing.

Several pressureless sintering trials were carried out with copper/20%vol. coated nanofibre material. The samples were cold-pressed and then heat treated at 600, 700 and 800ºC. Fibres were stripped of coating material above 700ºC. The density at this temperature was too low and suitable mechanical properties were not achievable.

Hot pressed samples containing 20 vol. % and 40 vol. % of reinforcement were assessed under high vacuum at 25 and 35 MPa, and 700, 900 and 1000 ºC.

A process temperature of 900 ºC and pressure of 35 MPa were found to be suitable parameters to achieve good properties in terms of densification and reinforcement distribution. Hot-press sintering showed the best results of the processes assessed and was selected for the sintering of the samples.

Spark Plasma Sintering trials were also carried out. Samples containing 20 vol.% and 40 vol.% of carbon nano-reinforcement were assessed at CNRS-Cirimat (Toulouse). Densities between 95 and 97% were achieved for 20 and 40 vol % VGCNFs at 400ºC and pressures of 75 and 100 MPa.

- Hot-press sintering has shown the best results and was the candidate process to carry out the sintering of the samples.
- Spark Plasma Sintering has shown promising results that must be improved focusing on the Cu/C interface. However this work was outside the timescales (and costs) of this project.
- Sintering without pressure has not shown suitable results due to the lack of interaction between the copper and carbon fibres.

The main finding of this study has been the necessity to improve the interface between Cu and C, particularly focusing on promoting a chemical interaction between the two components. If a proper interface can be achieved, better results will be obtained in the different sintering processes assessed, and this will lead to a proper material in terms of physical and thermal properties.

2.5 PRODUCTION AND CHARACTERISATION OF PROTOTYPES

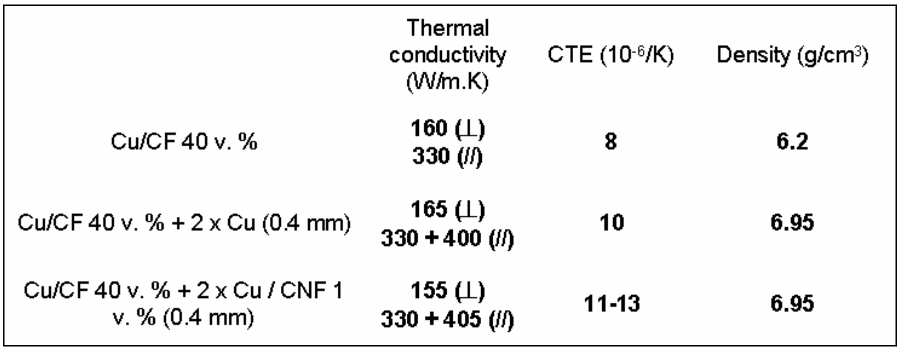
WP 5. Production and Characterisation of Prototypes: The following step of the project has been the fabrication of green-body components. Once the feedstock had been prepared, basic parameters were studied relating to the manufacturing routes addressed in the project. Samples have been manufactured by means of Tape Casting and Hot-Pressing due to the difficulties preparing samples via the metal injection moulding (MIM) and the pressureless sintering routes. The following results were obtained.

2.5.1 SEMELAB - IGBT POWER MODULE BASE PLATE

The thermal and mechanical properties of the copper/carbon nanofibre base plate (Semelab design) were first assessed in the laboratory and the following results were obtained.

1. 5 plates in Cu / CF 40 v.%
2. 5 plates in Cu / CF 40 v.% + 2 x 0.4 mm Cu
3. 5 plates in Cu / CF 40 v.% + 2 x 0.4 mm Cu / CNF 1 v.%

The copper/carbon fibre mixtures were pressed at room temperature. Thin foils of copper or composite Cu/CNF were added on the 2 sides of the C/Cu composite material for groups 2 and 3.



	Thermal conductivity (W/m.K)	CTE (10^{-6}/K)	Density (g/cm^3)
Cu/CF 40 v. %	**160 (⊥)** **330 (//)**	**8**	**6.2**
Cu/CF 40 v. % + 2 x Cu (0.4 mm)	**165 (⊥)** **330 + 400 (//)**	**10**	**6.95**
Cu/CF 40 v. % + 2 x Cu / CNF 1 v. % (0.4 mm)	**155 (⊥)** **330 + 405 (//)**	**11-13**	**6.95**

Table 4: Thermal and physical properties of Semelab base plates

In addition there was no damage around the mounting hole regions on the plates for a screwing force of 2.5 Nm. This was the case for both the Cu reinforced plate and the Cu/CNF only plate.

The base plates were then mounted into the Semelab test rig and tested according to Mil-Std. 883. Two samples manufactured with the HeatConductives project (Modules D and E) were tested alongside control baseplates of aluminium silicon carbide (AlSiC) (current industry standard), and pure copper. The thermal resistance performances were as follows:

AlSiC Module	0.138 °C/W
Cu/C (Module D)	0.128 °C/W
Cu/CuC/Cu (Module E)	0.120 °C/W
Cu Module	0.117 °C/W

From these results it can be seen that the Copper/Carbon fibre composites have an improved thermal performance over a standard production module with an AlSiC baseplate. The original expectation was that these new materials would also out perform copper but this has not been the case.

Both CuC and copper baseplates exhibited levels of stress higher than that of AlSiC. This was evident in the final assemblies as indicated by the magnitude of concave bow of the baseplate after substrate to baseplate soldering. These levels of stress may have an impact on the long term reliability of modules.

As reference, the AlSiC baseplate exhibit low stress due to very close CTE match within the structure and remains flat after baseplate soldering.

The long term reliability of copper carbon composites has, in the past, been of some concern due to the difficulty in obtaining a good bond between copper and carbon during manufacture of the composite. During extended temperature cycling this bond can become compromised leading to degradation of both thermal and mechanical properties of the material. To this end Semelab is conducting an experiment of extended temperature cycling on the modules assembled for this project, which is ongoing (beyond the timeframe of the HeatConductives project). The results of this experiment will be made available to all partners on completion.

Overall the plates provided to Semelab had good dispersions of carbon fibres (controls) and carbon nanofibres. Development work within the project led to the production of perfect copper sintering that showed no detrimental interfaces between the materials.

2.5.2 PROTOTYPE CHARACTERISATION - IMT

For the IMT demonstrator a set of 25 x 25 x 12 mm^3 electronics packages were requested. The solution proposed consisted of 2 parts - a Cu/CF cover lid (bonded and plated) and a base plate in Cu/CF.

2.5.2.1 Cu / CF (K223HG) 40%

Thermal properties of the Cu/CF material:

- Thermal conductivity = 160 W/m.K
- CTE = 10 ppm/°C

Samples of 1 mm thick plates were manufactured by powder metallurgy and bonded together with an acrylic adhesive (maximum usage temperature of 150 °C). Three of the packages were nickel plated to ensure sealing of the component. Three (3) packages with nickel plating and 3 without plating were sent to IMT for analysis. The samples contained Cu/CNF (including new samples provided with copper matrix reinforced with 40% of carbon nanofibres and gold plating over Ni coating). The samples were tested in order to evaluate the thermal behaviour through both thermal resistance and thermography methods.

Sample	**ΔT (ºC)**	**Thermal resistance (ºC/W)**
Rough Aluminium	8	7,14
Anodised Aluminium	6	5,36
Cu / CNF	1	0,89
Cu / 40% CNF	0,5	0,45

Table 5 – Thermal resistance of test materials based on ΔT measurements

The thermal resistance measurements are shown in Table 5 and whilst the Cu/CNF material showed a large improvement over the aluminium controls, the results were higher than those results obtained by Semelab.

2.5.3 ACORDE - BASE PLATES

To obtain 15 x 10 x 0.5 mm^3 plates two processes were used: powder metallurgy and tape casting using two types of reinforcements - carbon fibres and carbon nanofibres. Thirty plates were prepared.

1. 10 plates by powder metallurgy of Cu / CF 40 v.% (machined by electro-erosion)
2. 10 plates by tape casting of Cu / CF 40 v.%
3. 10 plates by tape casting of Cu / CNF 20 v.% (coated by Inasmet)

	Thermal conductivity (W/m.K)	CTE (10^{-6}/K)	Density (g/cm^3)
Cu/CF 40 v. % (powder metallurgy)	**160 (⊥)** **330 (//)**	**9**	**6.2**
Cu/CF 40 v. % (tape casting)	**150 (⊥)**	**-**	**6.2**
Cu/CF 40 v. % + 2 x Cu / CNF 1 v. % (0.5 mm)	**200 (⊥)**	**-**	**7.6**

Table 6 – Thermal and physical properties of Acorde base plates

The thermal conductivity perpendicular to the material plane was higher than the need of *Acorde* (150 W/mK) regardless of the size of the fibres.

3 SUMMARY OF PROJECT

Table 7 shows the objectives set out at the start of this project.

OBJECTIVE	*PARTIAL OBJECTIVES*
New heat-sink materials and products	Development of novel highly conductive low cost vapour grown carbon nanofibres (VGCNFs) and carbon nanotubes (CNTs).
	Production of feedstock for MIM and Tape Casting with copper, VGCNFs and CNTs. Development of the method to coat VGCNFs and CNTs with copper.
	Development of metal matrix composite 2D and 3D manufacturing processes (tape casting and metal injection moulding)
	Validation of the technologies developed by the production of industrial components, mounting, assembling and evaluation of electronic devices

Table 7: General and partial objectives of the Project

The development of novel highly conductive low cost vapour grown carbon nanofibres (VGCNFs) and carbon nanotubes (CNTs) has been successfully carried out with products from both Grupo Antolin and Marion Technologies. The properties of these materials have been improved during the course of the project, particularly relating to the improvement of properties by graphitisation. The improvements seen when moving from laboratory to industry scale methods were very encouraging.

Production of feedstock for MIM proved to be difficult (due to issues with porosity and poor green strength) and the processing route had to be halted. However further work will continue outside of the HeatConductives project based on the findings of this work. The production of feedstock for tape casting with copper, VGCNFs and CNTs was successful. The copper coating method for both the VGCNFs and CNTs was improved during the project. The final products showed no visible interface between the copper and carbon fibres which was an essential step towards improving the thermal conductivity properties of the material. The best results were seen for the electroless plating technique developed at Inasmet.

Development of metal matrix composite 2D and 3D manufacturing processes (tape casting and metal injection moulding). The MIM route proved to be difficult (due to issues with porosity and poor green strength) and the processing route had to be halted. However further work will continue outside of the HeatConductives project based on the findings of this work. The tape casting technique was successfully used to produce thin films that were used to construct the final demonstrators. In addition, hot pressing was successfully used to manufacture several of the components in place of the MIM process.

Validation of the technologies developed by the production of industrial components, mounting, assembling and evaluation of electronic devices. All three components were successfully mounted and tested. The IGBT baseplate tests carried out by Semelab showed a 14% improvement of the thermal resistance of the copper/carbon nano fibres when compared to the standard AlSiC baseplate. This value was comparable with unfilled copper however the carbon fibre filled material has a closer CTE to the substrate material and is therefore more suitable than unfilled copper.

Overall the base plate materials did not show the large increases in thermal performance that were expected from this project. This is primarily due to the continuing problem of the interaction between copper and carbon. Whilst significant improvements have been made to improve the physical interface region between Cu and C, the lack of chemical interaction continues to prevent the optimum use of the good thermal properties of the carbon nanofibres. More work by the project partners is required to improve this interaction and this work will continue to be developed based upon the findings of the HeatConductives project.