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PROJECT FINAL REPORT

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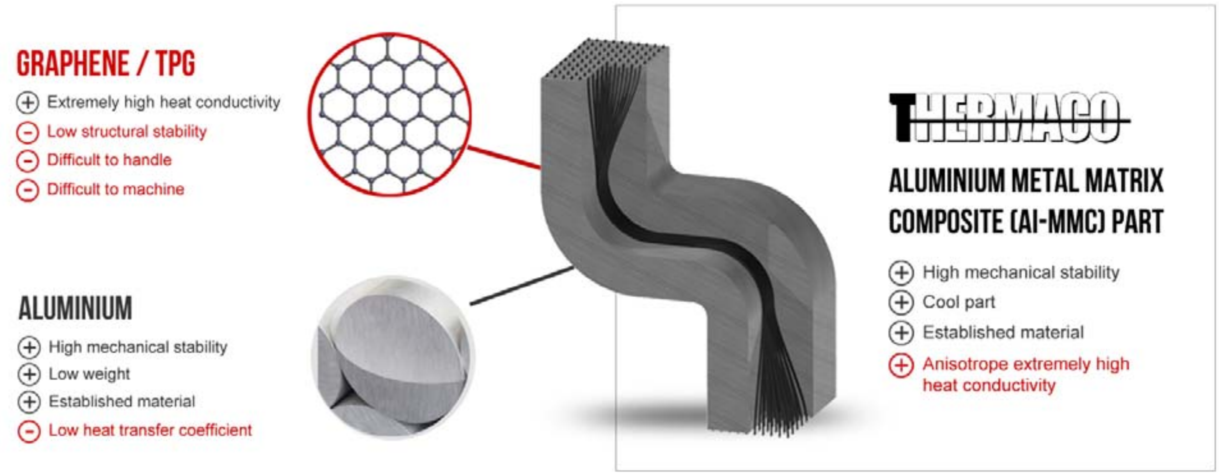
4.1 Final publishable summary report

Executive summary

The heat evacuation problem is omnipresent. For many technologies in which heat generation limits the performance of systems it may be a serious obstacle hampering their advancements. Finding effective and efficient solutions to address this problem still remains a demanding challenge. However, recent developments in science and technology offer some promising innovations to make a change. Newly developed heat conductive materials such as graphene or highly oriented pyrolytic graphite (HoPG) are carbon-based materials. They are perfect thermal dissipation agents. Their conductivity values are of up to ten times that of aluminium and five times that of copper, which are the current industry standards. However, their mechanical properties hinder their standalone applications. THERMACO addresses this challenge.

Inserts made of graphene or pyrolytic graphite can be inserted into an aluminium envelope of high strength and low weight to function there as "thermal highways". This allows creating smart aluminium metal matrix composite part - or AMC - a heat conductive material of unique thermal properties. Imagine the heat generated by the source being channelled into, transported along the thermal highways and dissipated, for example, at a common, central heat sink or cooling system with great efficiency, eventually even without the part itself becoming hot!

To make this vision become reality, a combination of knowledge and expertise from such areas as material science, design and simulation, advanced industry-standard casting and adapted finish and surface microstructuring processes is needed and brought together within THERMACO.



THERMACO focuses on heat evacuation applications in fields such as power microelectronics, e-mobility or (renewable) energy generation as well as highest performance combustion engines, using and researching new heat conductive materials.

Based on this, THERMACO provides manufacturing technologies to integrate them into extremely efficient solutions, using Aluminium Metal Matrix Composites (Al-MMC) with Graphene- and HoPG-based inserts, applicable in many key technologies and products bolstering several sectors in Europe. Challenging real life applications of the "thermal highway" concept within the project involve technology leaders such as Infineon and Lamborghini. With consortium members Graphenea, a company on the forefront of European Graphene production, Specialvalimo and NRU as innovative casting providers and CECIMO and KIM as multipliers, industry relevant research and development is ensured. The scientific expertise of Università di Bologna, Technion, IETU and Technische Universität Chemnitz adds extensive in-depth process knowledge and allows THERMACO to develop into a technological breakthrough and a change of concept in many heat management applications.

Summary description of project context and objectives

Composite materials are, due to their improved properties compared to traditional metals or polymers, now used in more and more technologically advanced products. Recent developments on carbon-based materials such as Graphene, introduced into composites, could even further expand the application and foster the realisation of significantly improved high-tech parts. With regard to their incredibly high thermal conductivity, they raise high expectations as to deliver new solutions and allow functional integration in areas now limited by the heat generation of core parts. It is scientific consent that the key challenge in many leading edge applications is the thermal system management. Further system integration, higher system performance and the need for cost reduction are limited today by system temperature conditions. To solve this, new, affordable products with dramatically improved thermal behaviour are a must to remove this bottleneck.
Composites incorporating those novel materials could deliver a breakthrough solution in this context. However, because of a lack of satisfactory machining and manufacturing technologies, they cannot yet be implemented. So far, complicated and cost-intensive multi-part cooling systems have to be applied, hindering a further functional integration or power increase.

THERMACO aims at providing manufacturing technologies for extremely efficient solutions in heat evacuation based on Aluminium Metal-Matrix Composites (Al-MMC) with Graphene-based inserts, applicable in and bolstering many key enabling technology sectors in Europe.
The enormous demand for such manufacturing processes can be demonstrated by looking at relevant industrial sectors: for one target sector, Micro-/Nanoelectronics, the “Pyramid of Wealth” shows its importance as a major enabler for innovation and economy. In Europe Micro-/Nanoelectronics leverage an electronic market of €230 Billion. Europe is leading the electronic production worldwide in the segments of Automotive (27% of electronics for Automotive is coming from Europe) Industrial (30% of electronics for Industrial is coming from Europe) and Aerospace. Power electronics, power modules and components are key elements for automotive and industrial applications. However, innovative electronic systems, especially in the environment of automotive and industrial, are extremely cost sensitive with demands for highest reliability.
Focussing on another major industry, especially in automotive and even more in e-vehicle applications, size and cost play an important role. Water-cooling modules are hard to integrate in vehicle systems. Moreover there is a trend towards the integration of power electronics and electric machine. Further integration can lead to a significant increase of efficiency and reductions of production costs and weights (of special importance for e-vehicles). Unfortunately, a further integration of engine and power electronics leads to an increase of heat and mechanical loads, raising the demand for new heat dissipation solutions.
In many other key technological areas such as power electronics for e-mobility, renewable energies, smart grids, or LED lighting, limitations in heat evacuation and heat management hinder further integration and downsizing as well as material and cost saving. Europe as technological driver of innovation in those relevant fields is more and more challenged by competitors and under pressure of producing lower cost parts, with higher quality.
The KET initiative of the European Commission has addressed these applications including multiple KETs by defining “Micro-&Nanoelectronics”, “Advanced Manufacturing Systems” and “Advanced Materials” as key technologies for the European economy. THERMACO focuses on those extremely relevant areas.
Delivering the proposed new, much more efficient heat evacuation solutions will therefore significantly boost the competitiveness of a wide range of European high-tech and cutting-edge industry sectors.

As stated, conventional materials have reached their limits, newly developed materials such as pure HOPG (highly oriented pyrolytic Graphite) and Graphene are aimed at extremely high heat conductivity, but so far are not usable for structural parts, because their mechanical properties are unsatisfactory (HOPG) or they can only be produced in very thin layers in the nanometer range (Graphene). However, their outstanding heat conductivity properties (Graphene of up to 2000W/m*K as compared to copper with 400W/m*K) are calling for a development to exploit these.

To overcome current limitations, the THERMACO project proposes an innovative process chain to produce high-strength, selectively reinforced Aluminium Metal Matrix Composite (Al-MMC) parts with carbon based thermal reinforcements. For the first time, THERMACO will allow a knowledge-based design and layout of structural heat-conductive parts with integrated Graphene-based thermal highways; it provides specially adapted manufacturing technologies for reliably and cost-efficiently producing those advanced composite parts by enhanced casting. These are backed by detailed casting simulation, taking into account the anisotropy of Graphene as a complete novum. Furthermore, guidelines for surface microstructures for an optimised heat transfer from the heat source to the thermal highways are calculated. Additionally, enhanced machining strategies, incorporating novel cutting and ablating processes adapted to the composite material to machine these structures and the final part with highest precision and beyond state-of-the-art are developed within THERMACO, providing innovations throughout the complete process chain.

It is clear that these demanding challenges can only be met by incorporating multidisciplinary knowledge and through a synergy of expertise in the areas of design, material development and processing. A holistic approach integrating the complete process chain is essential – it is obvious that these objectives cannot be achieved by one organisation. Furthermore, the specific know how is not available on a regional or national level. Thus, a European approach is compulsory. In THERMACO, 2 large scale industrial end-users, 5 industrial technology providers (5 SME) and 4 RTD partners from Germany, Israel, Italy, Spain, Belgium, Finland and Poland have committed to collaborate and develop the best suitable manufacturing technology required to produce a high-strength, extremely heat-conductive composite part for breakthrough applications in markets of key enabling technologies such as power electronics, e-mobility and resource efficiency in automotive engines.

THERMACO spans the whole product and process lifecycle, starting from the determination of needs for MMC parts in terms of shape and structural integrity, continuing over simulation and design of the thermal connections via especially micro structured surfaces as well as the form and alignment of the carbon based inserts inside of the part.
With these unprecedented results, THERMACO allows for a knowledge-based design and layout of structural heat-conductive parts with integrated Graphene-based thermal highways for the first time. Based additionally on the following choice of best casting method for different product groups and batch sizes (gravity or investment casting), an optimised mould can be designed and machined, while in parallel the best suitable heat conducting Graphene/HOPG material chosen.
With its holistic approach, THERMACO uses adapted manufacturing technologies for reliable and cost-efficient production of the composite. The gained knowledge allows for an optimal integration of thermal inserts into structural Aluminium cast parts. The required casting process is developed using sophisticated casting process simulation to minimise part loss and guarantee a stable process. For the best achievable efficiency, the finish machining of the composite parts is done using enhanced machining strategies in micro cutting and force-free ED/EC ablating processes. Here, vibration assistance and tool edge design provide the ground for a fast, reliable precision machining of the required micro structures. Tool-wear free ECM is applied for a selective machining of the structural Aluminium material without affecting the carbon based inserts. Of course, the parts are characterised regarding mechanical strength and thermal properties, using state of the art measurement technology and specially designed test rigs. Particular focus is set on recycling aspects of the composite materials and assessment of the environmental impact.

The THERMACO holistic approach is reflected in figure 1, clearly showing how the full spectrum of critical R&D tasks is addressed.

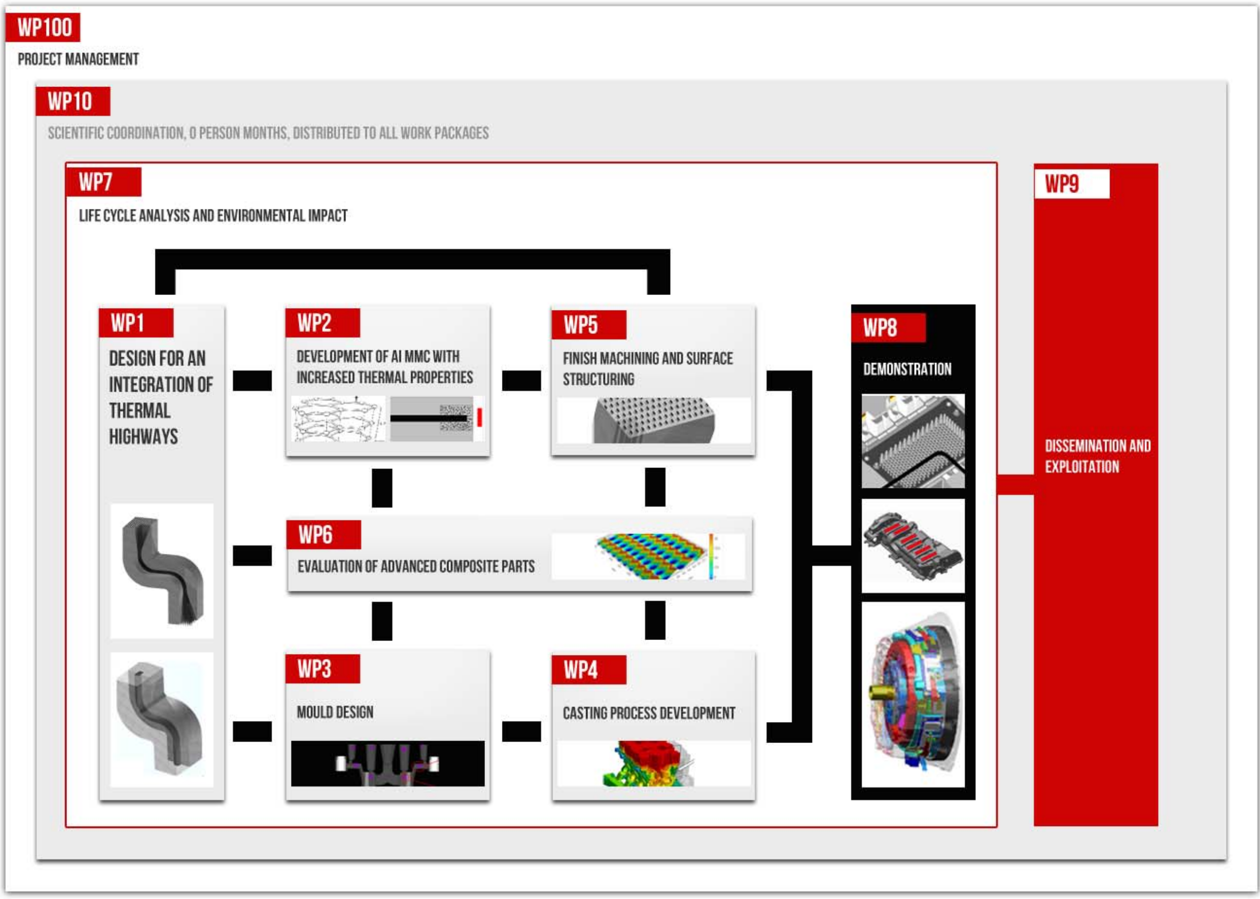


Figure 1 - THERMACO holistic approach

The THERMACO developments provide industry with a unique opportunity to introduce completely new, integrated product designs into the market that were until now unthinkable of.

To streamline the usage of these breakthrough innovations and ensure the facilitation amongst European industry, dissemination and exploitation support takes place via specialised European knowledge transfer partners.

The THERMACO process chain, integrating the full range of developments throughout the project and delivering a complete approach for manufacturing of the advanced composite material parts, is shown in figure 2.

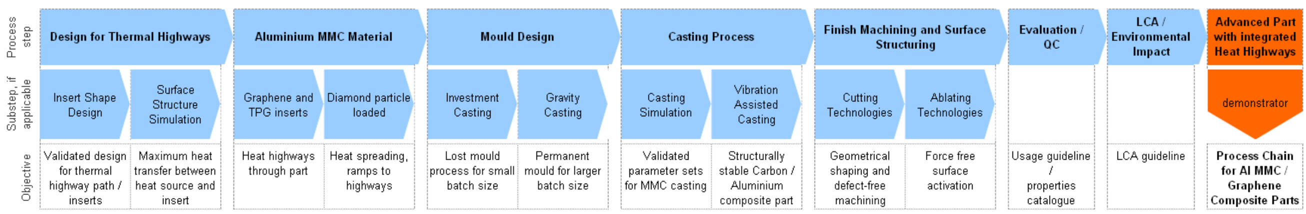


Figure 2 – THERMACO process chain for machining of thermal conductive Al Metal Matrix Composites

To prove the impact of the research and development, the findings are industrially assessed in demonstrators with applications in the extremely demanding automotive engine, e-mobility and power modules sectors. Furthermore, proof-of-principle demonstrators were prepared.

Project objectives

In order to tackle the identified challenges and critical problems, THERMACO provides significant innovations and breakthrough solutions to achieve the following objectives:

- Deliver knowledge-based design/layout guidelines for extremely efficient Aluminium Metal-Matrix-Composite parts with integrated carbon-based thermal highways
- Develop reliable and efficient manufacturing technologies for Aluminium Metal Matrix Composites with integrated thermal highways including
    - Production strategies for Graphene based thermal highway inserts to fulfil demands on dimensions, efficiency and handling
    - Placement and handling strategies for Graphene thermal highway integration into casting moulds
    - Detailed casting process simulation to enable reliable mould design
    - Investment and gravity casting process development to enable Aluminium casting around thermal highway inserts without damage to the inserts
- Develop design definitions for surface micro structures to ensure an optimal heat transfer from heat source to the thermal highways
- Develop optimal manufacturing processes for precision finish machining and surface structuring of Aluminium Metal Matrix Composite parts with carbon based thermal highways including
    - Precision cutting processes (milling, vibration assisted turning, turn-milling)
    - Electrochemical machining (ECM) processes to selectively uncover the thermal highways on the part surface for optimised connection to the heat source
    - Electroerosive machining (EDM) processes to force-free machine surface microstructures for increased thermal conductivity
- Deliver Life Cycle Analysis and environmental impact information on novel Aluminium Metal Matrix Composites with integrated carbon based thermal highways
- Develop complete process chain to manufacture composite parts with thermal highways and increased properties to enhance cooling efficiency by factor 20 (compared to standard Aluminium)
- Secure and exploit intellectual property from generated knowledge to bolster competitiveness and market strength of consortium partners and European industry

Description of the main S&T results/foregrounds

Design for an integration of thermal highways:

Thermal highways insert shape design and path optimisation

With steady-state FEM simulations we could show that macroscopic inserts with anisotropic thermal conductivity integrated into metal baseplates can be used to improve the heat dissipation of high performance power modules. It is necessary to adjust the insert geometry and orientation to achieve an improvement compared to plain metal baseplates. If the insert is optimised the chip temperature can be reduced by more than 8 °C, nearly doubling the chip lifetime. Without optimisation of the insert orientation heat spreading is shown to be detrimental for the given example because of the increased heat congestions at the inner IGBTs. Improvement compared to plain metal baseplates is only possible for inserts with high thermal conductivity in vertical direction. Modern power modules and their baseplate are shaped in such a way that only a very small amount of material doesn't take part in the heat dissipation. Thus, an increased heat spreading in horizontal direction only leads to an increased overlap and therefore to a heat accumulation. The conventional method to evaluate heat dissipation via an average thermal resistance value fails whenever anisotropic materials are involved. It is necessary to take a look at individual chip temperatures to fully comprehend the influence of the insert. The thermal contact conductance plays a major role in the performance of baseplate. If the TCC between insert and matrix is below 400 kW/($m^2 \cdot K$) the insert is not able to absorb heat and acts as a void instead.

To dissipate heat from an electric device like a power module or a similar heat source to the cooling area, conduction as transfer mechanism is often in use. The effective heat transfer by conduction requires materials with high thermal conductivity, like Graphene or highly oriented pyrolytic Graphite (HOPG). Highly oriented pyrolytic Graphite is an anisotropic, highly thermal conductive material and is composed of several layers of specifically arranged Carbon sheets. High thermal conductivity exists in in-plane direction of the layers. In perpendicular direction to the layers HOPG has a very low thermal conductivity. With integrating those materials as thermally conductive layers into an Aluminium matrix to lead the heat through the AMC parts, thermal energy can be transferred very fast out of or through the base material. Shaping the HOPG inserts allows for manipulating and optimising the heat transfer from the heat source to a predefined heat sink.

Previous simulations and investigations showed the magnitude of influence of the thermal resistive layer at the boundaries between HOPG and Aluminium. Because of the short distance from heat source to heat sink the benefit of the faster heat transfer inside the HOPG was diminished by the resistive layer between the materials. By applying the anisotropic material to longer distance setups from heat source to sink, the much larger heat conductivity can be beneficial. To investigate the influence of HOPG on thermal long distance effects, different models were created and compared to models without HOPG.

Surface structure simulation and definition for optimised heat transfer

Due to the advancing development, control of the thermal system management is one of the key challenges in many leading edge applications. Further system integration, higher system performance and thus the possibilities for cost reduction are limited today by system temperature conditions. New, affordable products with dramatically improved thermal behaviour are a must to remove this bottleneck. Structured surfaces offer possibilities to adapt several characteristics systematically, e.g. tribological properties and thermal behaviour. Within the project, a guideline to design and optimise component surfaces regarding their thermal properties by using micro-, meso- and macro-structures is developed.

To achieve the best possible thermal conduction between solids, high surface qualities with minimal roughness and waviness must be present. Thus, air inclusions and contact problems should be avoided.
In order to achieve a high heat transfer coefficient out of the solid material, liquids or gases can come to application. It should be noted that the Nusselt number values and therefore the efficiency of heat transfer of structured geometries is always higher than for the smooth, unstructured surfaces, what makes them preferable in this setup.
The variation of pin size dimensions and the distance between the pins have an influence on the heat transfer for forced convection. As noted by many researchers, for the dimensioning of structures such as a stepped circular pin fin array to enhance the heat transfer performance, the effect of heat transfer performance only becomes considerable if the ration of height to diameter of pins is larger than 3.0. Furthermore, it can be suggested that rhombic shaped pin-fins yield higher heat transfer rates and higher pressure loss in comparison to circular pin fins. Considering the distance between the pin-fins, for both in-line and staggered arrangements the Reynolds number is increasing with increasing Nusselt number. The maximum heat transfer occurred in flow-direction at a ratio 2.94 of distance to diameter of the pin. For the perpendicular direction to the flow-direction, the best ratio was achieved at 2.2. In most cases staggered arrangements achieve higher values of heat transfer than in-line arrangements.
To improve the heat transfer for laminar and turbulent fluid flow, the surface roughness can and should be increased. However, in case of slowly flowing fluids this can lead to sticking affects which are undesirable. If the surface of the heat sink is structured with micro channels, more heat can be transported through decreasing the hydraulic diameter of the channels. From a design point of view however, the hydraulic diameter is limited to the maximum pressure drop of the fluid. Air cooling requires high heat transfer surfaces which can be achieved – for forced convection – by increasing the roughness. The arrangement of pins should be preferably staggered, since their thermal resistance is lower than in-line arrangements.

Development of Al MMC with increased thermal properties

Material development – Graphene for heat highways

Graphenea synthesises Graphene in two different formats: Graphene films on any substrate via CVD (1 atom thick film), and Graphene powder. For THERMACO project the two approaches were taken into account.
For the composites preparation, big quantity of material is usually needed, thus, the powder is the recommended format. In this sense in GRAPHENEA two are the suitable Graphene materials available: Graphene oxide and reduced Graphene oxide. In the case of the Graphene oxide, oxygen groups have been attached to the Graphene structure and, as a consequence, it has a very high dispersibility in different matrices. However, these functional groups break the honeycomb Carbon lattice structure and Graphene oxide becomes an insulating material. To restore part of these properties the Graphene oxide can be reduced chemically and the conductivity is recovered. However, the loss of oxygen groups makes this material less compatible with different matrices, and it has a higher tendency to aggregate.
The synthesis of the GO is based on the Hummers method where by using a strong oxidant the oxygen functionalities are attached to the structure by covalent bonding. The honeycomb structure is broken (loss of the conductivity) and the interplanar distance increases what makes the forces between the flakes weaker (easy to exfoliate). If reduced Graphene oxide is then needed, a chemical reduction is carried out. During this reduction the material tends to agglomerate due to the loss of Oxygen functionalities and part of the sp2 structure is recovered (conductivity).
On the other hand, the use of CVD Graphene was also studied within the project. In this approach the Cu catalyst is first annealed at 1000ºC to remove the native oxide. At the same time the Cu grains are reorganised. Then methane is decomposed and the Carbon atoms start to create the Graphene monolayer network due to the low suability of the C in the Cu. For some application a transfer

process is needed to obtain the monolayer Graphene film on top of the desired substrate. However, in this case, the Graphene was evaluated directly in the Cu (fabrication of Cu/Graphene inserts) what makes the approach commercially more interesting.

Material development – Graphene loaded Aluminium for heat ramp and spreading
From the two Graphene materials selected for the composite fabrication, the rGO was the most suitable one due to its powder format, easy to be mixed with the Aluminium matrix. The Aluminium powder and the rGO were blended in a ball mill at different loadings (5 and 10 wt%). After the powder mixing, the composite was fabricated by extrusion (T: 350-450 ºC, P: 412-550 MPA) in ITT. The optical inspection and the thermal conductivity were carried out by UNIBO. The rGO was successfully dispersed in the matrix and the mixtures were homogeneous. Nevertheless, even if the dispersions were homogeneous agglomerations were observed what indicates that the material was not well exfoliated.
Laser flash technique was used to measure the thermal conductivity but, unfortunately the values obtain in the composites were lower than those obtain in the net Aluminium. The decrease in the thermal conductivity can be due to the surface resistance between the metal and the Carbon material as well as the non-exfoliation of the rGO.
For investment casting, it´s important to burn out and sinter the ceramic shell. The shell surface layers have to be free of wax residues or other particles. HOPG as a burning and sintering inlet material had to be tested for burning process. It was analysed in atmospheric process conditions for heat treatment and burning tests. A peel off reaction layer by layer shows an expansion growth of volume. On the top layer a bubbling reaction structure is seen from 400°C upwards. The HOPG begins to dissolve from 700 °C and ends with an ash content which was not measureable. The standardised atmospheric conditions offer HOPG the possibility to oxidise and in result destroy the geometric matrix itself. The burning process was also tested an evaluated with inert gas (argon) for non-oxidizing conditions. The result was a stable non modified HOPG inlet without visible bubbling or peel off reactions. This technology offers a better choice for higher inlet temperatures in process.

Mould design and production
Permanent mould
The mould is essentially the core of the foundry technology. In order to properly design the mould to accommodate thermal inserts there was a need to retrofit the casting simulation to accommodate an-isotropic heat flow "lanes" incorporated in the heat flow simulation. To do this, simple HOPG-Aluminium (cylindrical) samples have been studied and modelled in a finite elements manner. Once a correlation between the modelling and the experimental heat flow has been achieved the calibrated modelling tool was used for both applicative design of solutions and solidification simulation. For gravity die casting the mould was fitted with slits to hold the inserts in position while casting and simulated for best feeding, raisers, shrinkage etc. The results of these activities where tested in the "test bench mould" by attaching thermocouples in different spots in the mould. After several experiments that these have been monitored, the casting simulation's temperatures in the same locations have been compared to the measured ones.
The results have confirmed the accuracy of the computer aided mould design in gravity die casting.
Following the conformation and the know-how accumulated in the test bench activity the industrialisation of gravity die casting of THERMACO parts was done by designing an industrial mould for SPJO's experimental production.

Lost wax casting - mould design
The developed split shell process offers a production capability for Aluminium MMC with an investment casting process. The modification of this process begins in modifying the wax pattern. This wax parts get a flexible parting line in areas of disassembly. The mould parting lines have to be prepared on the wax pattern. They are optimised with thin adhesive tape to comply with the realistic

process conditions. This substitutes the thin wax parting lines and opens the flexibility for investment casting.
In case of high thermal conductivity of HOPG Inserts, wax trees have to be modified. Due to the cooling rate of the HOPG, bigger risers and sprues for the casting tree are needed in boundary layers between insert surface and aluminium melt. If the cooling factor will not be corrected, the rate of cold run and porosity will increase, which results in instable process quality like porosity and shrinkage. The core process of investment casting, shell building with ceramic slurry, is still an unmodified process. After the dipping and drying process of ceramic shell has ended, dewaxing of wax pattern is the next step. It is done in a dewaxing furnace at a process temperature of more than 120 °C. At the end of this process, there are still areas of wax and inclusions. These areas have to be removed. The ceramic surface has to be clean and smooth to prevent shell cracking and inclusions for casting process.
Burning out remaining wax material, inclusions and humidity from the shell is combined with sintering the mould material. This takes place at 800°C to substitute material on the surface and to strengthen the ceramic shell structure. The split shell process prevents oxidation of HOPG and guarantees the quality of casting and component quality. After sintering is completed the investment shell cools down. The next step is demoulding the ceramic shell on the parting line and preparation with sandblasting material to open the mould pieces and insert the HOPG stripes. The HOPG inserts have to be positioned in the split shell, so the stripes have to be prepared with grooves at the core print. Ceramic glue will fix the stripes in the shell and the shell itself.

Casting process development

Computer process simulation for mould design

UNIBO performed numerical simulation of the casting process in order to get the recommendations for the optimum arrangement of the moulds (both at the lab scale and on the final demonstrators) and of the casting parameters, thus defining the final layout of the castings. Simulations will be able to suggest the most important specifications for the castings design in terms of general dimensions, morphology of the HOPG insert, moulds design and process parameters, such as casting temperature of Aluminium matrix, mould preheating temperature, filling time).
During the second period of the project the activities about casting process simulation of advanced metal matrix-Carbon based inserts followed their path to maturity.
On one hand the activity of simulation parameter set-up basing on experimental data continued, taking into account all of the further production experienced carried out.
On the other hand, since the required robustness in casting production prediction was reached, the casting simulation was increasingly used as a purely predictive tool.
Casting simulations were extensively utilized for the design of the production process and tools of the final casting demonstrators.
The demonstrator production mould was defined starting from the "hard set" of information acquired from the lab scale mould development (Deliverable 4.1). The chosen general scheme of the tool was an H13 steel mould with a bottom-up filling, riser on the upper part of the casting and core print for HOPG holding during filling and solidification. The mould had to be used in an industrial-wise manner granting production robustness, ease and safety in the utilization. In this perspective it was endowed with fittings to automatic die-casting machines, ejector pins, ejector pins moving plates and a replaceable insert for HOPG strips positioning. Two different inserts were produced in order to allow the operator placing HOPG strip into one insert while the other one was mounted on the mould during casting solidification. At the beginning of the project no casting simulation software was available to account for thermal anisotropy of Carbon based thermal inserts. This was an important issue in the perspective of casting process design.
As an initial step a simulation protocol utilising two different simulation software (a multiphysics software delivering data to a casting process simulation software) was developed. Even though this protocol proved to be effective it was progressively abandoned since thermal anisotropy managing

capabilities were implemented into the used casting simulation software which proved to be accurate and robust.
All of the experimentally evaluated parameter and boundary condition gathered within the project activities (materials characterisation, heat transfer coefficients, heat surface resistances etc.) were integrated into the casting tool. Moreover, casting simulation tool responses were validated with the real ones, gathered during the several production activities carried out: simulated versus measured temperatures, casting defect position, microstructure etc. were compared and the casting simulation tool was set-up via a recursive trial-and-error approach.
Finally it can be stated that at the end of the development the casting simulation underwent during the project, it represents an effective and robust design tool for the production process of Smart Thermal conductive MMCs by casting.

Definition of casting parameters for composite casting
Defining the production (casting) parameters is essential for achieving optimised results and repeatable process.
In (gravity) casting the main variable production parameters are the pre-heating of the die and the liquid metal over heating (temperature wise). These will later on control the kinetics and chemical processes during the casting. For the composite casting it has been shown that a fast cooling will lead to interface cracks between the inserts (usually carbon) and the matrix, attributed to CTE difference and chemical compliance of the materials coupling. These were studied by designing and building a pre heated (controlled) mould for cylindrical composites samples with embedded heating elements to carefully evaluate different melt and mould temperatures. It was shown that a mould with over 400°C and melt of around 750°C will give optimised results.
In industrialisation of the technology the casting parameters were reduced to pre mould heating of 350°C (in steady production sequence) and around 730°C of molten Aluminium.
For the lost wax casting process, it is possible to industrially produce with much higher pre heated ceramic mould and thus obtaining a slower solidification and better interface. The working parameters where defined as mould above 650°C (in actual pouring time) and molten Aluminium of around 760°C.
Casting parameters were pre-performed by investment casting. There is a significant difference between test design and demonstrator design for Infineon baseplate. It differs in change of cooling rate of HOPG inserts. The ratio between the cooling influence zone of the test design and the demonstrator design was increased by more than 3 times. Problems in the cooling rate of the mould and demonstrator could result in shrinkage. These problems were resolved by preheating the mould-temperature. In fact, the preheating temperature of the mould and HOPG inserts rose up to 500 °C. Different revisions were made to find a wide spectrum of acceptable process parameters.

<u>*Finish machining and surface structuring*</u>
Final shaping by cutting processes
Advanced technological systems consistently demand for an increased performance and higher efficiency. Depending on the provided efficiency level, for example in electronics and powertrain applications waste heat is generated. As a consequence, thermoelectric and chemical effects can negatively influence the function of the system. In these cases the achievable performance level is mostly limited by the efficiency in dissipating the occurring quantities of the lost thermal energy. A promising strategy to enhance the thermal management and thus the overall performance is seen in specifically tailored material properties by using composite materials. Applying established lightweight materials reinforced with highly heat conductive phases (e. g. Graphene, Diamond) results in a significant increase of the thermal performance. According to results achieved during the ongoing project, the use of thermal highways consisting of highly oriented pyrolytic Graphite (HOPG) provides benefits concerning the heat dissipation and heat transfer thus influencing the thermal performance as well.

On the other hand the presence of the HOPG heat sinks results in a macroscopic heterogeneous structure of the workpiece material. The highly different material properties of the matrix alloy and the HOPG inlays result in challenges especially regarding the necessary machining processes with geometrically defined cutting edges.
Consequently, surface imperfections like voids in the area of the HOPG inlays as well as flaws at the boundaries between the matrix alloy and the HOPG inlays can occur, influencing the surface integrity of the workpiece. However, to achieve low surface roughness values and only minor surface imperfections the machining process has to be adjusted to the specific properties of the workpiece material.
Side milling tests varying the input parameters were realised to investigate the resulting surface integrity. Especially the achievement of comparably low surface roughness values and only a small number and small size of surface imperfections is of major interest.
The evaluation was based on qualitative as well as quantitative methods. Regarding the quantitative methods for evaluating the surface roughness Rz is selected as a characteristic value. Furthermore, the Rz values were determined for ten profiles in both measuring directions, parallel and perpendicular to the HOPG inlays. As the chosen profile parameter is typically determined for five separate sampling lengths within each profile, the parameter allows a comparably detailed insight into the local appearance of surface imperfections. On the other hand, more extensive areal deviations in the surface structure were detected as well.

Investigations were realised to identify the influence of different geometrical features of a cutting tool on the generated surface. For side milling tests a compound material consisting of the cast Aluminium matrix alloy A356 and embedded HOPG inlays was used. A major interest lies in the influence of specific geometrical features of the minor cutting edge when generating the surface in the machining process. Accordingly, a fractional factorial design was used including three different stages for the rake angle as well as the clearance angle. In addition, each tool geometry was used in combination with two different feeds per tooth to identify interactions between process parameters and tool geometry. The main goal is achieving low surface roughness values for the generated surfaces on the Aluminium matrix as well as on the HOPG inlays. Number and size of voids and other types of surface imperfections should be kept at a low, insignificant level.
Comparable to the Deliverable D 5.1, especially when applying a low feed, the most significant irregularities are noticed on the surfaces of the HOPG inlays. However, as the feed per tooth increases there are significantly higher roughness values on the surface of the Aluminium matrix as well, depending on the tool geometry applied.
Summarising, in terms of an appropriate rake angle for a feed per tooth of 0.01 mm an angle of about 5° was identified as most beneficial in the investigated area. Although slightly higher roughness values occurred on the surfaces of the Aluminium matrix, the lowest roughness values on surfaces of the HOPG inlays as well as the lowest overall roughness out of ten profiles are achieved with this configuration. Nonetheless, as the feed is increased to 0.02 mm, a neutral or negative rake angle results in more advantageous surface properties, emphasizing the meaning of the interactions between process and tool geometry. Referring to the applied clearance angle, for all feeds per tooth the lowest roughness values as well as the most beneficial surface structures are achieved using the lowest clearance angle of about 1°.
Concluding, based on the results given it becomes clear that the application of a modified tool geometry leads to distinct effects on the surfaces of the Aluminium matrix or the surface of the HOPG inlays respectively. The achievement of the required surfaces roughness values and a reduction of the formation of imperfections is especially challenging on the surfaces of the HOPG. One major problem can be seen in the random formation of breakouts leading to voids in the generated surfaces. Thus, further investigations must be focused on a deeper understanding especially of the specific chip formation when machining HOPG.

Final shaping by ECM and EDM processes
EDM: Different results were observed for the machining of the Aluminium-HOPG specimen with the two dielectric fluids. For deionised Water, a stable machining could not be realised. It was possible to start the process but after that a feed of the tool electrode could not be observed. Because of this, the process was stopped after a while. Although there are areas where a machining can be recognized, no clear grooves are observed in the figures. Especially for HOPG there is no clear erosion in the typical appearance of micro-EDM.
In contrast to this, clear grooves were realised by using hydroCarbon oil, indicating clear structures both for Aluminium and HOPG for all investigated discharge energies. Furthermore, a stable process was observed during the machining. Due to this observation, the following analysis was only done for hydroCarbon Oil.
The measured values for Aluminium are in the range of 96 µm to 103 µm. Based on the adjusted operation depth of 110 µm, this corresponds to a tool wear ratio of approximately 10 % to 15 % for the Aluminium. The depth for HOPG are in the range from 76 µm to 83 µm, with a tendency of an increasing depth by decreasing the discharge energy. The corresponding tool wear ratios for these values are in the range from 20 % to 30 % which is higher than for Aluminium.
The measured widths are also different between Aluminium and HOPG. For Aluminium values of about 193 µm to 199 µm were determined. Except for a discharge energy of 8.9 µJ the values for HOPG were much higher in the area from 209 µm to 228 µm. This indicates a larger discharge gap for the machining of HOPG.
The difference of the wear behaviour of the tool for both materials can be observed by the rising height value at the transition from Aluminium to HOPG.
As can be seen there is a clear transition of the groove from HOPG into Aluminium without any damages. This was also observed in the other machined grooves. The optical image indicates a lower surface roughness for HOPG than for Aluminium due to a smoother surface of the ground.
For the analysis of the surface roughness the parameters mean roughness Rz and average roughness Ra were determined. For both materials, Aluminium and HOPG, the average roughness Ra increases with an increasing of the discharge energy. Compared with each other better results appeared for HOPG with values till 0.28 µm for a discharge energy of 4.5 µJ. The increase in Ra is also for Aluminium much higher than for HOPG.

ECM: As in EDM, the sample specimen was a solid Aluminium block, with a length and width of 18 mm and a height of 3 mm. In the Aluminium, two HOPG sticks are embedded. For investigating the machinability, straight-lined removals were applied using Jet-ECM.
The dissolution behaviour of the composite material was investigated with different nozzle motions speeds. The straight-lined removals were arranged perpendicularly to the HOPG inserts. The length of each removal amounts to 15 mm with a lateral distance of 1 mm.
By varying the nozzle speed, a varying removal depth was expected in the basic Aluminium material. At lower nozzle speeds larger removal depth was expected due to longer impact of the removal process. In addition, the influence on the removal width was investigated. Due to the active dissolution of the basic material, an increasing removal was expected at lower nozzle speed. The electrochemical dissolution characteristics of the embedded HOPG were completely unknown before these investigations. Hence, the fundamental electrochemical machinability was investigated.
Considering the Aluminium basic material it can be derived that the removal width increases with decreasing nozzle speed. On the HOPG hardly any influence can be detected at nozzle speeds of 500 µm/s and 1000 µm/s. Only at the slowest nozzle speed of 200 µm/s a slight removal can be seen.
Considering the oblique view, a slight increase in erosion depth at decreasing nozzle speed can be derived in the Aluminium basic material. In the HOPG no erosion can be detected.
The resulting roughness also seems to increase at decreasing nozzle speed due to the inhomogeneous dissolution of the Aluminium basic material. In addition, the HOPG machined with the slowest

nozzle speed of 200 µm/s shows a very high roughness, which seems to be considerably higher than that of the Aluminium basic material.
As can be seen there is no clear transition of the groove from HOPG into Aluminium. This was also observed in the other machined grooves. Furthermore, the SEM-image indicates a higher surface roughness for HOPG than for Aluminium. The removals were measured with a 3D-Laserscanning Microscope Keyence VK-9700. From the resulting measurements cross-sectional profiles were derived in order to measure the machined depth and width.
From the cross-sectional profiles of the Aluminium the removal width and the removal depth were determined. The removal width was measured in a depth of 2 µm from the initial surface as the electrochemical removal does not create sharp-edged shapes. The removal depth is calculated from the distance between the third and the 97th percentile of all points of the respective cross-sectional profile in order to exclude too large influences from the high surface roughness.
It can be derived that the erosion depth increases significantly at decreasing nozzle speed. The factor by which the erosion depth increases is nearly the same factor by which the nozzle speed decreases. According to the measurement results the removal width amounts to approx. 300 µm, which is three times the diameter of the applied electrolyte nozzle. As can be derived from the deviation of the single values, the removal width is not as much affected by the nozzle speed as the removal depth. Only slight deviations of approximately 6% around an average of 297 µm were detected.
The roughness of the structures was measured on a length of 2 mm in the material using a Gauß-filter with a cut-off-length of 0.25 mm. In the Aluminium basic material a higher nozzle speed leads to a lower surface roughness, as can be derived from the values of Ra and Rz.

Surface structuring by cutting processes

Ultrasonically assisted turning

Regarding advanced technological systems, there is a strong demand for increasing performance and efficiency. In many cases the achievable performance is limited by system temperature conditions. One strategy in increasing the performance of technological systems consists in the integration of a significantly improved thermal management. On the one hand development of tailored composites is required. A reinforcement of established lightweight materials with highly heat conductive phases (e. g. Graphene, Diamond) results in a significant increase of the overall thermal performance. On the other hand a considerable potential lies in an adapted micro structuring of functional surfaces, participating in heat transfer. A new approach in a highly efficient generation of predefined micro structures consists in an ultrasonic vibration assistance in cutting processes.
Ultrasonic sound is defined as a frequency of above 20 kHz. With reference to ultrasonic vibration assisted cutting processes typical frequencies used are in a range of approximately 20 kHz to 100 kHz. Ultrasonic systems consist of an ultrasonic generator and a transducer. The generator transforms the power supply voltage into a voltage with a high frequency, relating to the resonance frequency of the system. The transducer converts the electrical energy into translational vibrations using piezoceramic elements. At the transducer’s end face the sonotrode with an indexable insert tuned to the resonance frequency of the system is mounted. In face turning an ultrasonic vibration assistance can be applied in three basic directions.
An ultrasonic vibration assistance in the direction of the passive force results in a variation of the depth of cut. Consequently, the surface of the specimens exhibits a corresponding surface structure. Additionally, the geometry of the micro structures depends on the feed, the tool geometry and the ratio of cutting speed and vibration frequency. Independently of an ultrasonic vibration assistance there is a kinematic roughness in the radial direction. These roughness values depend on the corner radius and the feed. The additional ultrasonic vibration assistance leads to a micro structuring in the circumferential direction. The theoretical height of the micro structures in the circumferential direction corresponds to the double of amplitude. The width of the micro structures in the radial direction corresponds to the feed. The dimension of the micro structures in the circumferential direction complies with the ratio of the cutting speed and the vibration frequency.

Face turning of the specimens using a constant cutting speed requires an adaptation of the spindle speed and leads to micro structures with equal dimensions in the circumferential direction. Another approach consists in face turning applying a constant spindle speed. With decreasing diameter, this results in a reduction of the dimensions of the micro structures in the circumferential direction.
A further variant consists in an ultrasonic vibration assistance in the cutting direction. This involves a variation of the cutting speed. An ultrasonic vibration assistance in the cutting direction is applied to improve the cooling conditions in the cutting zone requiring a disengagement of the tool and the specimen.
Furthermore, an ultrasonic vibration assistance can be applied in the feed direction. This results in the generation of sinusoidal micro structures within the feed marks. The dimension of the micro structures in the radial direction corresponds to the vibration amplitude of the tool. The period of the sinusoidal micro structures in the circumferential direction can be calculated.
Besides, an ultrasonic vibration assistance can be realised simultaneously in more than one direction to combine different effects.
Referring to thermal devices, investigations in the generation of surfaces with high values for the developed interfacial area ratio Sdr are performed. With reference to the basics represented, an ultrasonic vibration assistance in the direction of the passive force is supposed to be beneficial for achieving high Sdr values.
For the experiments specimens with a length of 15 mm and a diameter of 28 mm made of the Aluminium alloy AA5754 were used. A bore on the face side of the specimens clamped with a pushing collet system enables machining with constant cutting speed. The tests were realised using a SPINNER precision lathe with an integrated ultrasonic device. The resonant frequency of the ultrasonic device amounts about 24 kHz.
For turning tests CVD (chemical vapour deposition) Diamond tipped indexable inserts with a polished rake face were used reducing the tendency for the formation of built-up edges. The inserts have very sharp cutting edges with a radius of about 3 µm. The type of the inserts was CCGW with the size 120404. The inserts have a corner angle of 80° and a clearance angle of 7°. The corner radius constitutes 0.4 mm. The cutting edge angle of the installed inserts was 95°.
All cutting tests were done using emulsion cooling with a concentration of approximately 5 % in order to reduce the tendency for built-up edge formation.
For face turning with and without ultrasonic vibration assistance an increase of the feed leads to significantly higher values for root square mean height. The strong increase of the root square mean height can be explained by the increase of the theoretical roughness. Furthermore, the generated surfaces exhibit a lot of voids especially for higher feeds. For medium and high feeds an ultrasonic vibration assistance involves slightly higher Sq values, caused by the micro structures. However, a low feed leads to a considerable higher value for root mean square height due to distinct squeezing of the material.
The developed interfacial area ratio of the surfaces generated without an ultrasonic vibration assistance exhibits a similar trend compared to the root mean square height. However, for all feeds tested an ultrasonic vibration assistance results in significantly higher Sdr values caused by the micro structures. The highest value for the developed interfacial area ratio was obtained in face turning with the lowest feed. Comparably to the Sq value, this results from the squeezing of the material.
Independently of an ultrasonic vibration assistance the radial feed marks can be seen distinctly. The distance of the feed marks corresponds to the feed values. An ultrasonic vibration assistance evokes the generation of circumferential micro structures. The dimension of the micro structures in the circumferential direction complies with the calculated values for dc. Moreover, the number and the size of the voids in the generated surfaces can be reduced markedly by machining with an ultrasonic vibration assistance.
Furthermore, the influence of the ultrasonic vibration amplitude on the surface structure has been investigated. An ultrasonic vibration assistance leads to a micro structuring of the surfaces and consequently to a significant increase of the developed interfacial area ratio. Beyond that, an increase

of the amplitude entails a slight raise of the values for Sq. This can be explained by an increase of the height of the micro structures for a rising amplitude. A further influencing variable for the surface structure is the cutting speed. There is a strong decrease of the developed interfacial area ratio with increasing cutting speed. This results from a reduced number of micro structures for higher cutting speeds, because of the increasing dimension of the micro structures in the circumferential direction dc. The SEM micrographs show the size and the number of the micro structures distinctly. The dimension of the micro structures in the circumferential direction dc corresponds to the calculated values. For the root square mean height there is small increase with a rising cutting speed. This can be explained by strongly changed effective working angles of the cutting tool. Because of the very high vibration speed, the working clearance angle becomes very small and temporarily even negative. This effect intensifies for small cutting speeds and prevents a deep penetration of the tool into the surface of the specimen.

Investigations in face turning with an ultrasonic vibration assistance in the direction of the passive force have confirmed the very high potential of this technology for a process integrated and predefined micro structuring of the surface. The main influencing variables for the geometry of the micro structures are the feed, the cutting speed, the amplitude and the tool geometry. An ultrasonic vibration assistance in the direction of the passive force enables a significant increase of the developed interfacial area ratio Sdr. A high amplitude and a low cutting speed are beneficial for the generation of surfaces with high values for Sdr.

Turn milling

Referring to advanced technological systems, there is a steady demand for increased performance and efficiency. Frequently the achievable system performance is limited by system temperature conditions. To improve the thermal management and thus the overall performance one strategy consists in an appropriate choice of workpiece materials such as tailored composites. The use of established lightweight materials reinforced with highly heat conductive phases (e. g. Graphene, Diamond) results in a significant increase in the thermal performance. Moreover, high potential lies in the specific structuring of functional surfaces participating in the heat transfer. A new approach consists in the efficient generation of predefined surface structures using a novel turn-milling process.

In general turn-milling represents a combination of both milling and turning processes. Besides a main spindle carrying the workpiece turn-milling machine tools include an additional milling spindle. The cutting velocity vc therefore mainly results from the rotational speed of the milling tool and is hardly influenced by the rotational speed of the workpiece. Depending on the orientation of the directional vectors of the centre axes of the main spindle and the milling spindle different variants of turn-milling processes can be distinguished.

In case of (centric) orthogonal face turn-milling the directional vector of the centre axis of the milling cutter is orientated perpendicularly referring to the directional vector of the workpiece centre axis. Furthermore, depending on the offset between both axes the process can be distinguished into centric or eccentric turn-milling.

During the tool engagement the vectors of the circumferential feed or the circumferential feed rate respectively and the cutting speed are superimposed. The directional vector of the cutting speed is variable depending on the angular position of the cutting tip during the tool engagement. Consequently the cutting speed increases depending on the feed rate according to the feed in the circumferential direction and depending on the orientation of the directional vectors of the circumferential feed and the cutting speed.

In the machining process there are two feed components, one in the radial direction and another one in the circumferential direction referring to the workpiece face side. In orthogonal face turn-milling the linear feed in the radial direction frad is realised alongside the centre axis of the milling cutter. Moreover, the feed is defined per revolution of the workpiece.

However, the circumferential feed fcircum depends on the ratio of the rotational speeds of the tool and the workpiece, the tool geometry and moreover the effective workpiece diameter. As the milling cutter approaches the centre axis of the workpiece the effective workpiece diameter decreases during the machining process. In order to achieve a constant circumferential feed the rotational speed of the workpiece has to be adapted depending on the actual workpiece diameter.

Another approach consists in face turn-milling with a constant rotational speed of the workpiece. With decreasing diameter of the workpiece, this results in a reduction of the dimensions of the micro structures in the circumferential direction. As a result of the superposition of the radial feed and the circumferential feed the generated surface exhibits corresponding two-dimensional surface structures according to the feed applied in each feed direction.

Another variant is the tangential face turn-milling. Similar to the orthogonal face turn-milling the directional vectors of the axes of the workpiece and the milling cutter are orientated perpendicularly to each other. In difference to the prior described variant the radial feed motion is realised perpendicularly to the centre axis of the milling cutter. The circumferential feed is achieved analogously compared to the orthogonal turn-milling. On the contrary to orthogonal turn-milling the cutting speed is not influenced by the circumferential feed rate, as the directional vectors of the cutting speed and the circumferential feed are orientated perpendicularly to each other.

A further variant is the coaxial face turn-milling characterized by parallel centre axes of the workpiece and the milling cutter. A novel approach consists in machining with a defined inclination angle β of the milling spindle combined with the orthogonal or the tangential face turn-milling.

In orthogonal face turn-milling the saw tooth-shaped profiles appear in the radial direction with the ellipsoidal structures alongside the circumferential feed direction. In difference to orthogonal turn-milling, tangential turn-milling using end milling cutters results in a saw tooth-shaped surface structure of the workpiece in the circumferential direction. In the radial direction the surface structures are represented by ellipsoidal dimples with a cross section representing the corner geometry of the cutting tip. However, the structuring of the workpiece with an inclined milling spindle leads to a significant increase in the surface area with the number of structures depending on the feeds used in the radial direction and the circumferential direction.

With an increased inclination angle the most significant increase results for the maximum height in the direction perpendicular to the radial feed direction. In difference to that in the radial direction a remarkable change of the Rz value is given only with the inclination angle increased to 19°, whereas the Rz values for 7° and 13° are almost identical.

This is attributed to the inclination angle particularly influencing the development of the saw tooth-shaped profile in the direction of circumferential feed, whereas the ellipsoidal structures in the radial direction are less affected by the inclination angle. With an increased inclination angle the overall height of the saw tooth-shaped profile from the highest peak to the lowest valley is increased thus resulting in higher Rz values.

Moreover, the overall length of the profile paths is changed compared to a not machined surface taken as a reference. Assuming the other process parameters left unchanged this influences the resulting surface area of the machined surface. Increasing the inclination angle results in a significant increase of the Sdr values and the Vm values. This can be attributed to a remarkably stronger pronounced saw tooth-shaped profile in the direction of the circumferential feed as described above. Especially the increased material volume results from the combined increase of the surface area as well the increased average height of the profile.

As the circumferential feed increases the most significant increase in the maximum height of the roughness profile appears in the direction perpendicular to the radial feed. This is attributed to the theoretical roughness of the saw tooth-shaped profile being directly dependent on the feed in the circumferential direction. Yet there is an increase of the Rz values in the direction of the radial feed too, although there is no theoretical dependency on the circumferential feed.

Depending on the superposition of the single surface structures resulting from each cut of the tool locally significantly higher structures occur. The effective cutting motion in face turn-milling can be described with a spiral. As the effective diameter of the spiral changes permanently for each point of the spiral the number of surface structures placed on adjacent arcs changes steadily thus leading partially to the above described superimposition of surface structures. These superpositional effects influence the roughness profiles in the radial direction. The circumferential feed in turn is taking influence on the superposition of the surface structures consequently affecting the maximum height of the roughness profile in the radial direction resulting in increased Rz values for the radial feed direction due to increased circumferential feeds. Moreover, it is remarkable that with an increase of the circumferential feed the number of maxima on the structured surface is significantly reduced. On the other hand the local maxima are significantly stronger distinct with an increased circumferential feed. Furthermore, it can be found that the length of the spiral arc equal to the distance between adjacent circumferential structures represents the double of the circumferential feed. As a double-edged tool was used this indicates that the machined surface was generated primarily by only one of two cutting tips. This effect can be attributed to deviations between both cutting tips regarding their trajectory.

Besides the surface roughness profiles in each feed direction there is an influence on the surface area and the (standardised) material volume.

There is a rather slight increase in the developed interfacial area ratio with increasing circumferential feed. On the one hand the length of the profile paths increases with increasing feed, yet the number of structures per length unit is decreased as the feed is increased. The material volume varies in a comparable range of values, however the least material volume during the tests was achieved with a circumferential feed of 0.1 mm.

In addition to the inclination angle and the circumferential feed the influence of the radial feed on the micro geometry of the surface structures was investigated. There is a remarkable increase of the Rz values in the direction perpendicular to the radial direction as the radial feed is increased. However there is only a slight increase of the maximum height of the roughness profile in the radial direction as the feed is increased from 0.05 mm to 0.1 mm. A further increase of the radial feed to 0.15 mm leads to no significant increase of the Rz value. The increase of the Rz values in the direction perpendicular to the radial direction is attributed to mainly two effects. On the one hand the increase of the radial feed leads to a more distinct generation of the surface structures which results in more significant differences of the height of the highest peaks and the lowest valleys. On the other hand the geometrical pattern of the structured surface changes as the radial feed is increased.

Regarding the investigated range of values a higher radial feed leads to a more homogeneous form of geometrical pattern of the structured surface. Moreover, as described priory the diagrams presenting the maximum height of the roughness profile are based on the average out of ten roughness profiles for each feed. As the surface pattern becomes more homogeneous the calculated Rz values for each single roughness profile approximate as well finally leading to an increased average Rz value especially in the direction perpendicular to the radial feed direction. The increase of the Rz value with the radial feed increased from 0.05 mm to 0.1 mm can be explained with a more distinct generation of the local maxima compared to the remaining machined surface. With a further increase of the radial feed no raise of the Rz values appears. In both cases (frad = 0.1 mm, frad = 0.15 mm) at least one local maximum is acquired by almost every section of measurement of each of the ten roughness profiles in the direction of radial feed.

The interfacial area ratio is basically not affected by a variation of the radial feed. However, there is an insignificant raise of the Sdr value with the radial feed being increased from 0.05 mm to 0.1 mm. A further increase of the feed to 0.15 mm results in almost identical values for Sdr compared with a radial feed of 0.1 mm. In difference to that there is a significant increase in the material volume as the radial feed is increased. This is mainly attributed to the more distinct generation of the ellipsoidal structures in the radial direction.

Investigations in face turn-milling with an inclined milling spindle have confirmed a significant potential of this technology for an integrated and predefined micro and meso structuring of the workpiece surfaces. The main variables influencing the surface structure that were investigated in the

experiments are the inclination angle of the milling spindle, the circumferential feed as well as the radial. A suitable combination of these process parameters thus allows a significant increase in the developed interfacial area ratio Sdr. Especially a high inclination angle of ideally up to 45° would be beneficial for the generation of high Sdr values at the same time representing the most relevant parameter in influencing the developed interfacial area ratio. The influence of the feeds on the Sdr value is less significant compared to the inclination angle.
However, in the investigated range of values especially a high circumferential feed of 0.15 mm resulted in the highest Sdr values. In difference to that high Sdr values could already be achieve with a radial feed of 0.1 mm. A further increase of the radial feed then lead to no significant increase in the Sdr value. In a next step the results shall be transferred to smart thermal conductive composites. Especially the possibility of a significant increase of the interfacial surface area ratio offers a high potential for both an increased heat conduction as well as an increased heat transfer.

Surface structuring by ECM and EDM processes

Graphene coated Copper using EDM

The experimental investigations were performed using a HydroCarbon Oil as dielectric fluid. The sample specimen was a Copper foil coated with a Graphene layer. The experiments were performed by sinking of a flat tool electrode with a width of 200 µm and a length of 12 mm into the workpiece. Most influencing parameters in Micro-EDM are electrical parameters like open circuit voltage, pulse duration and discharge energy as well as the type of dielectric fluid. The experiments were performed by variation of the discharge energy and the operation depth and the use of HydroCarbon Oil. A stable machining could be observed for all investigated discharge energies. This is indicated by grooves with a clear structure. Independently, the machined area shows the typical crater like surfaces which attest the realisation of a machining by micro-EDM.
For a measuring of the ablation depth the machined area was measured on both sides and the difference was determined from depth of the grooves and the height of the deformation of the other side. The determined values for the erosion depth are in the range from 15 µm to 17 µm, which is lower than the thickness of the not machined Copper foil. These values correspond to a tool wear of about 20 % to 30 %, which are in the typical range for micro-EDM. For a more precise determination are investigations necessary with a different experimental setup. However, these values demonstrate the feasibility for machining this material combination. Increasing the discharge energy leads to a rising width of the machined grooves. This is attributable to the increasing discharge gap due to the rising discharge energy.

Graphene coated Copper ECM

As in EDM, the sample specimen is a copper foil, with a length of 8 mm, a width of 4 mm and a thickness of 18 µm. On the copper, a 0.3 nm Graphene coating is located. For investigating the machinability, straight-lined removals were applied using Jet-ECM. The dissolution behaviour of the foil was investigated with different nozzle motions speeds. Varying the nozzle speed, a varying removal depth was expected in the specimen. At lower nozzle speeds larger removal depth or a cut in the foil was expected due to longer impact of the removal process. In addition, the influence on the removal width was investigated. Due to the active dissolution of the material, an increasing removal was expected at lower nozzle speed.
The electrochemical dissolution characteristics of the Graphene were completely unknown before these investigations. Hence, the fundamental electrochemical machinability was investigated.
At the Copper foil it can be derived that the removal width decreases with decreasing nozzle speed. At a nozzle speed of 200 µm/s the foil is cut. By cutting the foil the removal width decreases to the diameter of the applied electrolyte jet. It can be derived that the erosion depth increases significantly at decreasing nozzle speed. The maximum of the erosion depth, with 18 µm, is reached by a nozzle speed of 200 µm/s. According to the measurement results the removal width decreases slightly with decreasing nozzle speed. When cutting through the copper foil the removal width is 89 µm.

In this study it was shown that Jet-ECM is an applicable and efficient procedure for machining a Copper foil with a Graphene layer. From the realized experiments it was derived that the Copper foil as well as the Graphene can be machined using Jet-ECM. The straight-lined removals with different nozzle speeds resulted in different erosion depths and erosion widths. Hence, it is possible to structure the surface of the Copper foil. With lower nozzle speed, a cut in the foil can be realized. The structuring and cutting of the Copper foil could be realized more efficient by variating the process parameters.
The experimental investigations revealed that Jet-ECM is suitable for structuring and cutting Copper foils with Graphene layers by using the selected processing parameters.

ECM structuring of Aluminium loaded with Diamond particles: Simulation
To increase the efficiency of heat transfer and cooling systems, high thermally conductive materials have to be developed. At present, a commonly used material for heat transport applications is Aluminium. Aluminium has high mechanical stability, low weight but also a medium high heat transfer coefficient of 180 W/(m·K) (for A356). Monocrystalline Diamond with more than ten times higher thermal conductivity than Aluminium could offer an additional solution for thermal transport applications. By combining Aluminium and monocrystalline Diamonds to composite materials, the positive properties of each material can be used. Therefore, an Aluminium Matrix composite (AMC) reinforced with monocrystalline Diamond particles was created. It is known that with rising grain size of Diamond the thermal conductivity of the AMC is increasing. However, also the machining becomes more challenging with such big particles, i.e. cutting processes are not feasible due to the high tool wear. Due to this fact non-conventional machining has to be assessed.
Electrochemical Machining (ECM) is an appropriate ablating process for manufacturing components with small tolerances to the end shape. In case of the investigated material combination with Aluminium as base material reinforced with Diamonds the machining is more difficult. The reinforcing Diamonds are not electrical conductive and due to this cannot be dissolved by ECM. Within the machining process only the Aluminium matrix will be dissolved and the Diamonds will precipitate out of the matrix. To get a better knowledge of this process a special simulation model was developed. The materials used are Aluminium-alloy A356 and monocrystalline Diamond particles with a diameter of approximately 100 µm. The percentage of Diamonds within the Aluminium is about 40 vol%.
For investigation of dissolution behaviour of Aluminium-Diamond-Matrix by simulation various simplifications have to be made. Simulation of a big AMC component is to complex and time intensive. Due to this a simulation model was developed which concentrates the dissolution behaviour in a unit cell. Aluminium is the base material with just one integrated Diamond. The top of the Diamond is pointing out of the Aluminium surface covered by electrolyte. The electrolyte is necessary of electrochemical machining. The model is reduced to essentials. It is used to investigate and better understanding of the special dissolution behaviour. By reducing the model geometry to rotary symmetric design the computing effort also will be reduced. For even more simplifying the model the Aluminium domain is neglected. This simplification can be done because of the consideration of special boundary definitions. By implementing density ρ, valence z, molar mass M and specific ablation volume the dissolving behaviour can be defined by Faraday's Law. By using the electrodeposition module these parameters can be applied to the defined edge of the electrode. Due to this the definition of Aluminium as domain is not necessary any more. The geometric specs of the Diamond are 50 µm for radius rD and 70 µm in height hD. The domain of electrolyte is defined to have a radius of rE = 95 µm and 100 µm in height hE. The electric conductivity of the electrolyte (NaCl) is defined to be 130 mS/cm, the cell voltage is defined to 10 V. First approach for meshing is a triangular mesh shape. For the whole geometry the mesh size was constricted to 6.25 µm. Edges relevant for ablation, which are coloured in blue, are defined to have a maximum element size of 3.35 µm. Within these mesh settings the whole mesh consists of 1000 mesh elements. Refining the mesh elements causes numerical instability. To avoid numerical instabilities the

simulation had to be done with the coarse mesh. Simulation of the unit cell by using the electrodeposition module was done successfully. The applied cell voltage of 10 V at the surface of the work peace can be recognized. During the machining areas with increased current density can be observed. This area is located at the boundary of the Aluminium matrix and the Diamond particle. The area with highest current density causes maximised ablating at boundary of the two work peace materials. Due to the not electrical conductivity of Diamond just the Aluminium matrix is affected and dissolved. It can be recognised at the start of the simulation $t = 0$ s the normalised minimum current density is 120 A/cm² and the normalised maximum current density is about 135 A/cm². at the ablating process the minimum normalised current density varies between 65 A/cm² and 30 A/cm² the maximum normalised current density between 200 A/cm² and 180 A/cm². These fluctuations can be explained by the coarse mesh of the simulation model. In the area of maximum current density mesh moving occurs mainly around the Diamond particle. Actually the moving mesh can be seen equal to the dissolution of the Aluminium matrix. Considering the cross cut plots of FIG a time point $t = 0.7$ s can be estimated the particle will be removed half the way out of the matrix. At this time point the simulation stops due to numerical instability. Similar simulations done previously and successful with different aspect ratios and other materials and parameter combinations showed comparable results in behave of dissolution. However until now it was not possible to simulate the removing process of the whole Diamond particle. The reason for this can be found in the Diamond grain size of the model. Ablating experiments to consider the dissolution behaviour of the MMC can verify the results of the simulation until the point of $t = 0.7$ s. The results of the simulation show the special behaviour of dissolution of Aluminium material surrounding the not electrical conductive Diamond particle. A maximum current density can be recognised at the border of Aluminium and Diamond which leads to higher material dissolution at these areas. Due to numerical problems the simulations could not show the removal of a whole Diamond particle. Therefore the parameters and the precondition for the solvers have to be optimised to find numerical solutions.

Machining of surfaces for optimised heat transfer

Surfaces are boundary layers between two media, which can fulfil several functions. To achieve these, modifications of the surface are necessary. In terms of an efficient thermal management the heat dissipation/absorption can be regulated with special structured surfaces. Microstructures provide an opportunity to improve the heat transfer by a bigger surface and a turbulent flow.

This paragraph shows the production of one specific microstructure with several ablating machining strategies. Therefor the achievable accuracy will be shown for each process. As additional process Laser beam machining is presented, to have an overview of the most important ablating processes.

One function of structured surfaces is to improve the heat dissipation from the heat sink to a fluid coolant. As described in Deliverable D1.5 – "Design guidelines for surface structuring"- the arrangement and form of the structure has a big influence of the effectivity. An arrangement in reversed order of the structures seems to be the most effective. Additionally Diamond-formed (spare rotated for 45°) pin create a higher heat transfer.

To have effective pin dimensions, a multiphysics simulation was carried out. Here the temperature on the bottom side of the work piece is considered, which corresponds in reality to the temperature inside the workpiece. The distances between the several pins are as a function of the pin-size, which was varied from 10 µm to 500 µm. For the structured surface a pin-diameter of 50 µm is chosen. The base material is the cast Aluminium alloy AlSi7. Here the above defined structure will be machined with each described process. Therefor different machining strategies for each process are used.

At the Jet-ECM process the machining is done with a 100 µm steel nozzle. Therefor a zig-zag- path of the nozzle is used to machine the pined structure. The use of a smaller nozzle diameter is not feasible. The advantage of a more precise structured surface is accompanied by a large working gap, which means that the required depth of 150 µm is not reachable.

For the Laser machining a rectangular form around the pins is ablated. In the next step the remaining un-machined surface is covered with a so called "picture". The area of the whole picture will be

automatically filled and machined. Here layer by layer (each layer is about 6µm thick) is ablated to reach the final depth of 150 µm.
For the Micro-EDM both a sinking and milling strategy are possible. A strip electrode with a thickness of 40µm is used for the sinking method. Here the process is divided into three several sinking steps. First the sloped sinkings are machined with an angle of 98°. Finally the horizontal sinking is done to remove the remaining material. By simultaneously moving of the axis, complex shapes can be produced. For this an electrode with a diameter of 90µm is used and layer-wise with a thickness of 10µm each ablated.
With Jet-ECM it is not possible to reach the requested structures. Due to the big nozzle diameter the zig-zag-lines are not exactly mapped and the pins are not formed. Additionally, the current density has its maximum in the centre of the jet and diminishes within increasing diameter. This leads to a minor removal at the outer area, which can be seen at the rounded pin-profile. Due to arc-overs during the parametrization it was not possible to reach the required depth of 150 µm.
For LBM and µEDM it is possible to machine the required structures. The LBM structure shows a rough surface which results from the punctual material ablation and the re-solidification of part of the molten material. Due to reflections of the laser beam also some material is removed from the top of the pins. The sides of the pins are nearly vertical.
For the structure of the µEDM method two different results are shown: For the EDM sinking with a strip electrode not the whole material was removed, so that additional pins occur in a symmetric arrangement. Due to the small possible size of the electrode of 40µm not the whole area could be covered with the three machining steps. Single sinking of the electrode can be seen next to each pin and in between. Additionally the end of the electrode is sharpened due to tool wear, which leads to a reduced material removal width. The pin structure machined with µEDM-milling has a smooth surface with rectangular pins. Due to the optimised machining strategy, the tool wear is compensated and thereby no roughness on the bottom surface arises.

Final shaping and surface structuring for (improved) chip/substrate contacting

The chip / substrate contact has a big influence on the lifetime of every semiconductor product. The contact needs to be mechanically stable and needs to be able to resist high currents as well as high temperatures and high temperature fluctuations. The temperatures fluctuations result in high stresses on the contact and the silicon chip. The contact between silicon chip and direct copper bonded substrate is established via a soldering process. The state-of-the-art backside metallisation is copper. Silicon has a rather low coefficient of thermal expansion of 2.6·10-6 K-1 compared to most metals. Aluminium, which was used as backside metallisation before copper has a CTE of 23·10-6 K-1, copper of 17·10-6 K-1. The different coefficient of thermal expansion between the chip material and the backside material results in a different, temperature depending, elongation of chip and metallisation layer. Since they are mechanically fixed to each other they cannot expand freely. Hence tension is build up in both layers depending on the difference in CTE, the temperature change (algebraic sign and magnitude) and their young's modulus. This tension results in a warpage.
The ambient temperature plays also a role in the magnitude of the warpage. The lower the ambient temperature is, the bigger is the warpage during the first few cycles after switching the device on, until a steady state is reached. For automotive and industrial power controlling applications the chip-substrate contact needs to be able to function within a wide range of ambient temperatures. One possibility to reduce the warpage is by reducing the thickness of the backside metallization. However the backside metallization also acts as a form of temperature capacitor. During the pulsed operation of the chip the backside metallization absorbs a big part of the generated heat, which is then dissipated towards the substrate and baseplate. If the metallization layer is too thick the warpage and the Rth is increased. Hence there is an optimal thickness for the metallization layer depending on the pulse form of the chip and the material properties of the chip and the metallization layer itself.
Therefore the only possibility to reduce the warpage is to develop new materials with improved performance, meaning lower coefficient of thermal expansion while having constant electrical and

thermal properties (resistance, thermal conductivity, etc.). One possibility is to replace plain copper layers with composite layers made from copper and a Carbon modification. The synthesis of copper and Carbon nanotubes composites via a electrochemical plating process has already been reported. However Carbon nanotubes are quite expensive to manufacture, hence we focused on the synthesis of copper-Graphene nano-platelets (GNP) composites using a similar method. Compared to CNTs GNPs have the advantage of having an increased thermal conductivity in two instead of only one direction. Using a Co-deposition process a Cu-GNP layer can be manufactured with one process step. This process is easily scalable to mass production. It is important to create a layer with a high GNP filler fraction and a homogenous surface.

Overall the R&D into co-deposition of copper and Carbon modifications is still in an early development stage. In order to evaluate the possibilities of such composite layers a simple sample layout, allowing easy, cheap and fast sample production and characterization is necessary. We used Si wafer with a thin copper seedlayer. The seedlayer is several nm thick and deposited via physical vapour deposition. For the electrochemical deposition a pulse plating tool was used. We succeeded in the synthesis of a low-priced alternative to copper-Carbonnanotube composites. Instead of CNTs we were able to create a Cu-Graphene-nanoplatelets composite via an electrochemical reverse plus plating procedure. A filler fraction of up to 50 % could be achieved with an optimized pulse form. The SEM cross-section shows that GNPs were integrated into the Cu layer and not just adsorbed on the surface. Investigation of the warpage of such a composite layer yields a significant improvement compared to the warpage of a plain copper layer. Unfortunately the composite layer shows a very high roughness. Before further investigation into the performance of this composite layer is possible a more homogenous layer needs to be achieved. We plan to optimize the pulse shape and the electrolyte bath composition using tensides, leveler and complexing agents to improve the layer quality even further.

Measurement of heat transfer rate

We measure the heat dissipation in electronic devices using anisotropic materials. These materials, like highly oriented pyrolytic Graphite, have a very high thermal conductivity in two spatial directions and a low conductivity in the third direction. Most real life power modules consist of several IGBTs (insulated-gate bipolar transistor) and FWDs (freewheeling diode) pairs connected to each other via wire bonds. The chips are soldered onto a direct copper bonded ceramic plate (the combination of which is called DCB) which serves as electrical insulator and heat spreader. The DCB is soldered on a baseplate (Al/Cu). The power module can be mounted to a heat sink or Water cooling system of various forms, which is usually provided by the customer depending on his application system. The performance and lifetime of a power module strongly depend on its ability to dissipate the heat generated by the chips. According to a rule of thumb the lifetime of a product doubles if the chip temperature is decreased by 10 °C. Heat is generated by the chip and dissipated through the whole power module to the cooling system/heat sink at the bottom. The heat dissipation can be quantified by the thermal resistance Rth [K/W] of the package (lower Rth means better heat dissipation), which is inversely proportional to the thermal conductivity λ [W/(m·K)] of the materials used.

One of the major obstacles for future generations of power modules are the increasing demands on system integration and power density. Both are accompanied by increased chip temperatures and hence decreased product lifetimes. The heat dissipation limit of conventional materials like Cu or Al is nearly reached. Hence for future devices novel materials with increased thermal conductivity need to be investigated. One solution is the enhancement of the thermal conductance of the baseplate by using new materials with a lower thermal resistance, like THERMACO metal-matrix composites using ‘Highly oriented pyrolytic Graphite’ (HOPG). HOPG is a highly ordered Graphite phase created by annealing turbostratic Graphite. HOPG has a thermal conductivity of above 1500 W/(m·K) in two spatial directions and 10 W/(m·K) in the third.

Especially the smaller size of future generation of power modules is a major challenge for heat dissipation. By decreasing hot spot temperatures the life time of electric components can be increased and their environmental impact improved. While heat dissipation problems of the next generation of power modules still can be solved by adjusting the overall structure of the module, the next but one generation will depend on new materials: Copper, the most commonly used material for heat dissipation reaches its limits. Metal matrix composites are the most promising candidates to alleviate this problem.
An important point of interest concerning the usability of HOPG as inserts in metal baseplates is the brittle behaviour of Graphite. During the assembly process of power modules the different coefficients of thermal expansion (CTE) between insert, baseplate, chip and direct copper bonded (DCB) substrate lead to internal mechanical strains. To compensate for the difference in CTE the baseplate needs to be bent before the assembly process. Furthermore during usage of the power module the baseplate is deformed periodically because of the pulsed load. It is unclear if the brittle HOPG insert within a metal baseplate can withstand these deformations. The THERMACO project uses thinner Graphite stripes with high thermal conductivity in the vertical direction in contrast to the state-of-the-art heat spreading. The strain on the inserts is reduced using insert geometries which neither cover the whole length nor width of the baseplate. We investigate the long term stability of these cast Aluminium metal matrix baseplates via thermal cycling and transient plane source as well as scanning acoustic microscope measurements.
Using transient plane source measurements, scanning acoustic microscopy and thermal cycling experiments we could show that the interface between Al matrix and HOPG inserts degraded slightly over time. The degradation is very small, so that after 1010 thermal cycles, corresponding to 505 h of thermal cycling, have no measurable effect on the lateral thermal conductivity of the composite baseplates, the degradation is only visible on the SAM images. We could also show that the measurement position plays a major role in the heat dissipation properties of the baseplate. Only if the sensor is positioned centred on the inserts an improvement compared to the plain metal baseplate could be accomplished. For all other positions the thermal contact conductance between insert and matrix are too low to exchange heat between insert and matrix. Without further optimization of the interface and without correct placement of the heat source the inserts act as voids and have a detrimental influence on the heat dissipation.

<u>*Measurement of mechanical and micro-structural properties*</u>

Tomography

The purpose of the mechanical tests is to characterize the prototype of the demonstrator and evaluated its structural strength in operating conditions. In order to evaluate HOPG inserted casting, mechanical properties and micro-structural characteristics have been in depth investigated. The tests that were performed are explained as below. In a first test the finned plate demonstrator, with and without HOPG inserts, were subjected to tomographic scans, to evaluate any internal defects and in particular to probe on the interface areas between Aluminium and HOPG. A second test, finned plates with HOPG inserts were subjected to a thermal cycles to stress and to evaluate any defects, which may occur during the operating conditions, due to different thermophysical properties of the two materials. Metallurgic analysis took place to investigate the surface microstructure and the insert-metal interface area. Finally, the demonstrator was assembled and tested in operating conditions and evaluated for its structural strength. The tomographic scan is performed as follows: the workpiece is placed on a rotary table and an arm is moved by a system of axes, to which is connected the x-ray source and the imaging unit that takes a lot of pictures at each rotation step of the workpiece table. The acquisition is processed by the software and is possible to get a qualitative and quantitative information of the presence of defects within the component through an evaluation section by section that allows to detect precisely limits and defects. To evaluate the presence of internal defects on finned plates the tomographic scans have been done. Both Aluminium and

Aluminium/HOPG finned plates are taken into account. The presence of internal defects is direct linked to the structural strength of the demonstrator.
The analysis of the images shows that in the most of the interface zones no appreciable defects are to be found. This should ensure good cohesion between the two materials, so a high value of heat exchange coefficient is expected.

Thermal shock

The aim of the test was to investigate the Aluminium/HOPG interface and the Aluminium microstructure. The plate with HOPG inserts was subjected to the thermal shock. The test provides that on the plate, thermal cycles from -30 °C to 140 °C are carried out, to generate thermal stress. 30 minutes to -30°C and 30 minutes to 140°C with instant step, into two different chambers (1 cycle in an hour), so up to four days that is 96 cycles. The high temperature test is similar to the operating temperature of the finned plate demonstrator. The thermal shock results showed that the demonstrator remains unchanged and the thermal cycling has no visible effect on the Aluminium matrix and on HOPG inserts.

Metallography

Finned plates with HOPG inserts are subjected to metallographic investigation: both pre thermal shock and post thermal shock. Three samples are obtained for each finned plate; then the samples are incorporated in the resin and they are mirror polished to investigate them at the microscope. There is a first investigation under the microscope on the sample surfaces to highlight the Aluminium/HOPG interface areas. Good and bad interface areas were examined. Afterwards the samples are attacked with acid in order to carry out a second investigation of their microstructure. From the micrograph is possible to see the gap between A356 and HOPG due to uncorrected cohesion between the two materials. Since the micrograph is done after the thermal shock, at the state of art it is impossible to know if the HOPG defects are result of the thermal cycle or result of production process. Likely the bubble defect was already present on HOPG insert and suffered an alteration after thermal cycling.
Due to the analysis of the micrographs bad interfaces and gaps between two the materials can found. In these areas the value of conductance will be low and this will result bad heat exchange. Even in micrographs where the interface seems to be good, a slight gap can be found. This reveals that an interface like metal on metal, characterised by high value of conductance, is difficult to achieve with this different materials like Aluminium and HOPG.
To highlight the A356 microstructure, the samples were attacked with HF 0.5% (hydrofluoric acid). The analysis shows the presence of Aluminium matrix with eutectic Silicon and primary Silicon particles. The eutectic Silicon seems to be little changed, probably due to a lacking quantity of Strontium in the molten Aluminium. Looking at the micrographs, the microstructure of the Aluminium matrix seems to be the same everywhere both near and far from HOPG/A356 interface, not affected by the presence of HOPG.

Structural investigations

Since metallurgic investigations, thermal cycling results and tomographic scans showed no particular defects, the casting campaign was evaluated positively. To evaluated structural strength of the finned plate demonstrator, the finned plates were assembled on bedplate; then they were tested in operating conditions. To assemble the demonstrator, laser welding is chosen, because the material thickness is thin enough to achieve a strong and durable connection. Laser welding with high power density and high cooling and heating speed, ensures negligible deformations. The laser welding process was done successfully without of any issues. The finned plate demonstrator has preserved its shape and its mechanical properties.
Test bench is performed in operating conditions at different engine speed from 1000 rpm to 7000 rpm. The bedplate demonstrator is subjected to vibration loads due to torsional vibration of crankshaft which are related to the combustion order of the cylinders and to the stiffness of the

crankshaft itself. Furthermore, the bedplate is subjected to bending forces due to the loads coming from the crankshaft pushing on the bedplate bearings. During the test no problems occurred and the demonstrator has endured structural stress.

The final geometry of the finned plate has been developed during the project in order to fulfil production, assembly and functional requirements. The assessment of the production process has been done with tomographic scans and metallographic investigations; the tests highlighted no defects for A356 finned plates. Instead for A356/HOPG finned plates the tests highlighted defects on A356/HOPG interface and inside HOPG itself. At the end the production process must be enhanced in order to avoid the detachment between the Aluminium matrix and HOPG inserts. Thermal shock investigation showed no modification in structure of the components. By micrographic investigation a uniform microstructure of the Aluminium matrix has been found. The assembly by laser welding of the finned plates on the bedplate has been done with no problems. Thanks to laser welding no deformations both on finned plate and on bedplate were inducted. From the structural point of view, the finned plate has endured the test with firing engine so under all the typical thermal and structural loads.

Life cycle analysis and environmental impact assessment

LCA

The main aim is to investigate and assess environmental and health aspects of the new material on two levels: technological processes of material production and utilisation and recycling of the thermal MMC materials and final application of the materials in the selected potential applications (WP8). Life cycle assessment (LCA) for the materials produced is performed to demonstrate environmental impacts and benefits associated with this process during its lifetime. A set of parameters are established to describe all relevant processes of the material production, its use in final products and utilisation of components, materials and waste. The processes of production are investigated and the environmental impact assessment (EIA) procedure is performed in close relation to LCA. Relevant environmental impacts are identified based on the material and energy balance (LCI) of developed technology description, parametrisation and measurement results. The results from technological work packages are used in analyses and assessment of consequences of the material and the technological processes when it is implemented on commercial scale. Results of new material application are compared with the results of the current conventional solutions in the selected applications (based on chosen functional unit) and the environmental benefits are determined. Data structure and requirements were prepared in the first period and were verified accordingly to the THERMACO project developments. 2 THERMACO MMC concepts were evaluated and characterised considering technical aspects of their potential application. The Life Cycle Inventory was extended to copper material and data for the concept of THERMACO Copper-Carbon MMC were also prepared. Moreover additional technological processes were characterised as essential for production of THERMACO inserts. Results of the technological work packages were reviewed to focus further work and select the most promising concepts. For selected key THERMACO MMC (Aluminium - Highly oriented pyrolytic Graphite MMC, Aluminium-Diamond powder MMC, and Copper-Graphene MMC) there were further developed LCIs for respective production technologies of the basic materials and production processes of the MMC materials. The inventory was based on the draft LCIs prepared in the first period, extended literature studies, information delivered by partners, review of LCA databases and industrial data, theoretical calculations, expert judgement. Final input – output matrices for the key THERMACO MMC materials were prepared as excel sheets. Final LCI was prepared for scenarios of production of demonstrators.

Life Cycle Assessment was performed for the selected key THERMACO materials. Comparisons were made for THERMACO materials and the respective currently used solutions (copper and Aluminium components). They were assessed as to their overall impact with the basic impact categories (e.g. energy, ecotoxicity, human health) and in terms of Carbon footprint. SimaPro software was applied to perform the assessment. The THERMACO concept was positively evaluated showing lower impact for the MMC materials than for metal components. Sensitivity analysis was carried out to identify the key processes and aspects. It was confirmed that the high impact is allocated to the production of Carbon material. In case of copper high impact is related to producing primary copper. Processes of THERMACO insert production have in comparison very low impact. The analysis is also sensitive to the recycling rate of materials. Two demonstrators were assessed in Life Cycle perspective taking into account effectiveness measured during the project and identified potential environmental benefits of their application. It was proved that it has lower environmental impact than the baseline case. Results of the performed assessment were reviewed and discussed with partners. Quality of the assessment was evaluated using a multi-criteria approach, expert judgement and Monte Carlo analysis. Data prepared for analysis was documented and the results summarized.

Environmental Impact Assessment

Environmental data were further collected to characterize Carbon materials (Highly Oriented Pyrolytic Graphite, Highly oriented pyrolytic Graphite, Synthetic Diamond powder, Graphene sheets) and manufacturing technologies in the whole value chain of THERMACO inserts production. It included production of the Carbon materials and manufacturing of Metal Matrix Composites from Copper, Aluminium and Carbon materials.

Models of industrial production for the selected THERMACO MMC materials were developed considering information gathered from partners regarding production processes and the materials used during production and utilization of the THERMACO components. They were characterised in quantitative and qualitative way based on descriptions of machinery, technologies, physical and chemical processes and materials used with identification of environmental impacts and characterisation of environmental performance. In the assessment aspects of transport, usage of final products and waste utilisation were also considered.

The environmental characterisation was based on extended literature study, EU and national environmental regulations, industrial reports, technical information, environmental audits and expert qualitative assessment and contacts with industry.

For the three THERMACO MMC materials the key environmental aspects were analysed for each step of production and the environmental impacts (resources, air, waste Water, waste emission, noise, hazards) and potential risks were assessed concerning occupational health and environment. Based on the assessment of the MMC materials production of THEMRACO demonstrators on industrial scale was assessed with a set of sustainability criteria.

In the assessment efficiency of environmental management measures for all respective impacts was characterised and evaluated. According to the results recommendations for mass production of THERMACO inserts were formulated. The EIA results also show that the highest potential impact can be related to production of Carbon materials and their processing along the value chain. The best industrial practices can mitigate the potential impact on human health and environment to an acceptable level.

The results of the assessment were discussed with partners, and the results were documented and prepared as EIA report.

Management scenarios were formulated for utilization of waste materials and by-products during production, and for the components used in the envisioned applications in the final products. The baseline scenario was developed based on the analysis of legal requirements and overviews of the current situation in recycling of End of Life Vehicles and electronic appliances in Europe and contacts with the waste management companies. Based on expert judgement and analysis of post-consumption waste utilisation trends in Europe appropriately three post-consumption waste management scenarios were proposed including: reuse of the THERMACO components and recovery and recycling of the materials. Recycling and waste management options for the material were studied based on the partners experience and the material characterization prepared in technological WPs. Literature data on MMC materials reuse and recycling was collected and analysed. The waste types from manufacturing and utilisation of the products were investigated, characterised in qualitative and quantitative way, classified and assessed for the effectiveness and efficiency of existing and prospective management schemes. Study on components reuse, material recycling and/or waste management was performed for the three selected THERMACO materials and at the same time for the prototypes application. The scenarios were assessed with a set of sustainability criteria. It was shown that currently there exists essential barriers to reusing, recovering and recycling of the Metal – Carbon MMC materials as a whole and only metals can be recovered and recycled in an efficient way. The results were summarised and presented in final report on Environmental Impact Assessment and Waste Management, Final EIA and Waste Management Report.

Demonstration

We manufactured high performance power modules using composite baseplates as well as one plain metal baseplate. The warpage of the baseplate origin from the soldering process were bigger than expected and lead to problems in the characterization procedure. As expected the plain Al baseplate shows the biggest warpage. The HOPG inserts improve the mechanical stability of the baseplate, therefore reducing the warpage. Replacing the matrix material with mechanical more stable materials like AlSiC or copper will reduce the warpage even further. Creating composited baseplates with these materials could lead to further decrease of the warpage compared to state-of-the art baseplates. Comparing the THERMACO baseplates with state-of-the-art baseplates shows similar heat dissipation properties. If the warpage is compensated, e.g. by a pre-bending step, we expect improvements compared to state-of-the-art baseplates in regard of heat dissipation, warpage and long term stability.

About bedplate demonstrator, the finned plates both Aluminium and Aluminium with HOPG inserts have been realized. Some samples of finned plates representative of the entire production were subjected to mechanical testing to test the resistance to high temperatures, typical of the engine operating conditions, and to assess the success of the production process. After the casting process, the mechanical machining on finned plates have been realised. t the same time the bedplate has been subjected to mechanical machining for the realization of the housing for the finned plates, allowing the direct contact between the baseplate and engine Oil. In addition to the pockets, the thermocouple holes have been realized; the thermocouples are necessary to record the Oil temperature both upstream and downstream of the finned surface. The assembly of the plate was performed by laser welding. Two bedplates were subjected to mechanical processing and subsequently they were assembled with finned plates; one for the bench test with Aluminium finned plates and one for the test with finned plates with HOPG inserts. With post-processing operations it is possible to calculate the dimension of the finned plate surfaces using the information derived from tomographic scan, both Aluminium and HOPG side. The obtained surfaces by scan are compared with 3D CAD to match the maths of the finned plate. The match between tomographic scan and CAD is elaborated from the software in global way automatically by the least squares method, which minimizes the distance between all the surfaces of the finned plate. The dimension analysis is evaluated only for the Aluminium matrix, both A356 and A356/HOPG finned plate, because its geometry depends on the production process. It’s necessary to take into account that the CAD comparison has been done without considering the modifications of the geometry on the finned plate, e.g. made to evaluate the extraction from the mould and the casting system to guarantee the correct filling of the shape. According to the method of matching, if you consider two symmetries of the piece, there is a colouring such as to ensure the compensation of the deviation where it is possible (e.g.: base-left side and base-right side).
After several CAD evaluations, an EDM machining was made to realize the cylinder head demonstrator. To perform the machining, copper electrodes of the desired shape were made: an

electrode for the thermocouple hole (it is necessary to measure the temperature of the exhaust valve bridge), and one for HOPG pocket. Starting from a HOPG plate, the inserts were cut. Then they were assembled to their pockets with interference to avoid decoupling during operating condition due to Aluminium thermal expansion. During the assembly operations, with the aid of endoscope, it was possible to check the right position of HOPG insert in its pocket. Mechanical and EDM machining have been done. About finned plate demonstrator, the laser welding process was done successfully without of any issues. The bedplate has preserved its shape and its mechanical properties; in fact according to the dimensional analysis, the deviation from – 0.2 mm to +0.2 mm of the surfaces of finned plate gives no functional or assembly problems, validating the casting process.

Public 3D demonstrator

There are 5 different demonstrators for simulation, analysis and presentation of different Aluminium Matrix Composites. A Stereolithographic (SLA) demonstrator was built as a sample for a unidirectional HOPG insert test device. It demonstrates the complexity of MMC Material with investment casting process. It´s built up as an assembly of 5 separate pieces for measurement and tests demonstrations. A functional demonstrator was cast as an Aluminium Metal Matrix Composite for measurement and test demonstrations. It shows the complex possibilities of 3D- guided Thermal Inserts with investment casting.

As a test demonstrator for Aluminium MMC heat conductivity measurements, a block was manufactured by vacuum gravity casting.

This demonstrator was done by split shell technology. The HOPG are fixed just at one side and the other was free of moving. This allows the HOPG to crack and break off within casting process. To avoid this, the gating system was prepared to fill the mould with the bottom up principle.

To measure and investigate the 2 boundary layers between aluminium and HOPG a composite layer sample was evaluated and cast. This demonstrator has a difficult gating system, caused by the small boundary layer/ wall thickness between HOPG, Aluminium and HOPG. It was the first sample which was tested without the split shell process. The HOPG comes as an insert in the silicone mould to cast the wax pattern around that. The burning of the ceramic shell is done by a modified burnout process. The Aluminium casting was done at very high mould temperatures (680 °C). The reason was the critical solidification of very thin Aluminium layers. The quality of the test sample was controlled by cross section and structural examination. The result was a successful fulfilment of high quality components without any pores and shrinkage.

Copper Demonstrators with the standard baseplate design were cast as the last version of baseplate samples. The casting parameters of the copper demonstrator are totally different to Aluminium baseplate demonstrators. Copper has a melt temperature which is twice times higher than Aluminium. Also, the thermal conductivity is significantly higher than of Aluminium.

This results in 2 essential facts: 1. Oxidation rate of copper is much higher than of Aluminium, because of high melting temperature; 2. Risk of cold run, porosity and imperfections is very high. The melting tests where done in inert atmosphere at melting temperature of 1200 °C. The shell moulds have to be heated up to more than 700 °C. This has to be done under insert atmosphere. As a risk protection the shell heat was enclosed by a thermal coat to minimize the risk of cold run and porosity. The quality of the casting process could be seen after machining the finished baseplates. There was just a small number of mistakes like porosity or inclusions.

To dissipate heat from an electric device like a power module or a similar heat source to the cooling area, conduction as transfer mechanism is often in use. The effective heat transfer by conduction requires materials with high thermal conductivity, like Graphene. Graphene is just one layer of Carbon atoms and due to this very thin and not easy to handle. To make it more stable and even better for handling, the combination of Copper as base material and Graphene as coating was investigated. As seen in the deliverable D2.4, it was possible to grow Graphene direct on top of the Copper foil without of any transfer process. The simulation also showed the potential of Graphene coated Copper foil in rolled shape. One big benefit of rolled Copper foil as thermal highway is the

handling of the material. The needed dimension can be achieved in the rolling process and the rolled material can easily be cut to length. It is not brittle or sensitive like HOPG or Carbon based material in general. The Copper foil has the size and shape of a 4” wafer, with a thickness of approximately 12 µm for the foil and even thinner coating of 0.3 nm.
The first step will be the cutting of the wafer shaped foils into stripes to roll them and create some kind of rod. The rod of Graphene coated Copper foil than can be tested and compared to a rod of Copper foil without of any coating, if the coating affects the thermal conductivity.
For comparison of thermal properties an almost equal rod rolled from Copper foil was produced, except for the coating.
Thermal experiments are conducted to compare the thermal conductivity of rolled Copper foil with Graphene coated to rolled Copper foil without any coating. By assuring the different Copper rolls have the same diameter and the same length, the comparison of thermal properties is possible. In preparation for the thermal measurements, thermocouples have been mounted to the rolled Copper rods and they have been surrounded with rubber material to prevent any damage during clamping in a holder. The optical unit of the laser beam machine is centred over the rolled Copper foil in defined distance. The laser beam is used as heat source with constant energy input.
The results from simulation of rolled Copper foil have been promising good results in terms of thermal conductivity and therefore for the use as thermal highway. It could be approved that the handling and production of rolled Copper foil with sheet thickness of 12 µm is feasible. Thermal measurements have been conducted by using LBM as heat source. Thus, it can be ensured that in all samples the same amount of energy is applied. All measurements are performed multiple times and were evaluated afterwards. The results from the thermal measurement are different from the results of the simulation. This is also a result of research thus until now there is no basic knowledge about such materials. Unfortunately the values for the rolled Copper with Graphene coating are 13 % less good as the thermal conductivity for rolled Copper foil without of any coating. Due to this, further experiments for casting the rolled Copper foils into a matrix of Copper have been neglected. However the results can be used to evaluate the thermal simulation and implement the thermal results of into simulation to achieve better simulation models and to improve the results of the simulation.

Engine based demonstrators

Demonstrators have been produced and tests were performed to test the real use of HOPG in an engine component in operating conditions. Another way to take advantage from the higher cooling effect of the HOPG insert could be to reduce the cooling flow rate in order to increase the engine efficiency. These conclusions are supported by analytical calculations on thermal resistances. The demonstrators and the entire project have highlighted that HOPG is a material with a high thermal conductivity. With two demonstrators two different strategies of use of HOPG insert have been evaluated: co-fused solution with forced air convection and interference solution with cooling water. At the state of art the interference solution with cooling water is the best solution to take advantage of HOPG properties, because a tight solid contact and water flow rate are characterized by a high heat transfer coefficient. The results keep open to further investigations on the cylinder head application.

The potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results

Exploitation of project results and wider project dissemination to enable partners to maximize the commercialisation of results post-project includes four international one day industry seminars, five scientific or technical papers and five to ten publications or conference proceedings. Any foreground IP that is developed in this project is first fully protected prior to any dissemination actions.
The partners have joined this project to develop the technology and to commercially benefit from its wider uptake and commercialisation; as such they are all actively involved in this work package. Use is made of latest guidance from the EC on how to maximise the impact of research, development and demonstration projects to ensure that the results are effectively used, through exploitation and dissemination.
Whilst all partners input into this Work Package, KIM use their expertise in market analysis and commercialization techniques, particularly through appropriate IPR strategies, while CECIMO, as a European-wide industry body will contribute greatly to this WP with their ability to ensure targeted dissemination activities and directly engaging stakeholders. The THERMACO IP owning industrial partners will lead the exploitation and commercialisation of the project results.
During this second reporting period, the IPR management activities have become more intensive since to exploit the project results, a proper Intellectual Property Rights (IPR) protection strategy is required. The IPR Manager's activities have been to ensure that all Foreground IP is identified, that all Foreground IP is assessed and that all Foreground IP is protected, as appropriate, before any public disclosure or that a protection strategy is set.
IPR management carried out during the project
In any European project is necessary to focus on the identification of the developed knowledge, its value and its management. A proper management of the IP developed during a European project offers a result able to be exploited. In order to achieve this, THERMACO participants leaded by the exploitation manager, KIM, have managed the intellectual property through the following scheme:

- A proper identification of the results;
- A successful and preventive elaboration of an IPR management plan in order to detect and prevent potential issues related to the definition of IP ownership; transfer of the ownership and the access' regime to the background and foreground of the project;
- A good elaboration of an IP protection and exploitation strategy.

All the detailed information in this regard can be found on "Deliverable Intellectual Property Rights (IPR) Management Strategy".

Dissemination of project results
All partners have been very intensely working on disseminating project news and achievements to the industrial and scientific community. They have been selecting the most adequate events like trade shows (i.e. EMO Milano 2015), conferences giving a presentation or participating to a poster exhibition (i.e. Industrial Technologies 2016, Composite Innovation 2016, Thermec 2016, Nano Israel 2016, Cooling Days 2015, EuroNanoForum 2015). Moreover, various scientific publications and articles were published (i.e. CECIMO Magazine, Spring 2016).
In addition to that the website was regularly updated and social media were used to address project novelties. Besides, an updated informational flyer "THERMACO on the go" was distributed to project partners with an aim of distributing it to their networks.
Finally, a project video was produced discussing project results and explaining how Aluminium Metal Matrix Composite (MMC) can innovate other industries.

Conceiving of written materials for dissemination

During the second reporting period, the consortium has been using the pack of materials prepared during the first reporting period:

- Leaflet
- Poster with and without mention to the ERAMEC cluster
- Folders
- USB

Moreover:

- KIM has designed a new leaflet were an update of the project achievements was explained. This leaflet was printed and send to all partners (100 copies each).
- A second set of project USBs was printed and distributed among partners to use as giveaways in congresses and conferences.
- Several newsletters have been prepared with the collaboration of all the partners and send to the stakeholders identified for THERMACO.
  - Project newsletter 2: May 2015. 1285 subscribers.
  - Newsletter specific for EMO promotion: October 2015. 1228 subscribers.
  - Project Newsletter 3: May 2016. 1195 subscribers.
  - Project Newsletter 4: August 2016. 1188 subscribers.
- IETU has leaded the preparation of a video

Design and up-dating of project website

The website, www.THERMACO.eu, represents the main “business card” of the project (stakeholders, research community, civil society, etc.). For this reason, during the first months of the project, the design of the website was built upon a visual communication (photos, web pages are easy to browse, information is kept short and links to relevant information (websites, publications, related projects) are included.

The Website is divided into two main sections:

Public section. The aim of the public website has been to serve as an official information channel. It provides clear and concise information on THERMACO activities, including: overview of the project, methodology, work plan and outline of work packages, history of dissemination activities, clustering activities, partnership, news, links to other interesting websites and contact details.

Private section. The private zone for exclusive use of the Partners (to access with a login and password), aimed at providing partners with a dynamic working tool that overcomes geographical distances. The private website has acted as an Interactive Communication tool for all project related information, such as actual progress and milestones, deliverables produced, events organization and repository of materials and documents.

During this second reporting period, KIM has been responsible for the integration of new content and doing regular content up-dates.

Dissemination amongst the project participants and their close business partners

Project partners have been duly informing its network on the project’s progress. During the last reporting period there were 5 THERMACO Newsletters issued: May 2015, October 2015 (special edition for EMO Milano International Machine Tool Fairs), May 2016 and August 2016. Each edition was sent to approx. 1200 subscribers.

Moreover, adequate communication was executed via social media: Twitter, Facebook, etc.

In summer 2016, each partner received 100 copies of an updated project leaflet with a purpose of distributing it to its networks.

In the last reporting period CECIMO has been regularly informing its members 15 National Associations and their member companies about the progress of THERMACO project. It took place

twice year during CECIMO General Assembly that accounts on average 50 people as well other smaller meetings of average 15 people:
Moreover, in the last edition of CECIMO magazine there was an article published presenting the latest project progress – 'Opening ways for new materials with extremely high heat conductivity' (June 2016). The magazine is distributed in 500 hard copies to CECIMO members (national associations and machine tool companies), EU institutions, academia, research stakeholders, etc.

Wider dissemination to industry
During this reporting period the consortium continued with the organization of the planned seminars/workshops in order to inform the public about project progress and findings. Attendees to this events originated from industry, academia and research.
The industry seminars were as follows:
1. CECIMO organized for THERMACO a booth during the EMO 2015 International Machine Tools Fairs in Milan, 5-10/10/2015.
Moreover, THERMACO was presented at the R&I Conference on 9th October at EMO Milano 2015.
2. IIT organized for THERMACO a stand within the Israel EC NCP to disseminate the Project within the Nano Israel 2016 on the 22-23/02/2016.
3. KIM organized a collaboration with the Composites Innovation Conference 2016 in order to become sponsors of the conference and have access to wider possibilities for dissemination within the conference. UNIBO attended the event representing the consortium.
EMO Milano 2015 – booth and conference
The EMO exhibition registered more than 1.600 companies on 120.000 m². The leaders in this ranking were Italians, closely followed by Germans, Taiwanese, Chinese and Swiss exhibitors. In total 150.000 visitors from approximately 100 countries visited the EMO Milano show. Figures speak for themselves and it also validates the fact why the consortium has chosen this exhibition to demonstrate the THERMACO project results.
THERMACO joint CECIMO booth with the Lamborghini engine that was a very attractive demonstrator. On average CECIMO booth had 200 vistors/day. THERMACO project partners were actively present during the exhibition to inform visitors about project's findings.
On 9 October 2015, CECIMO and its partner organized a joint international conference focusing on communicating INTEFIX experiments along with other project results. Around 90 people and 10 speakers registered to the event. The audience included people from various countries and industries. THERMACO was presented by the project coordinator Henning Zeidler of TU Chemnitz.
Moreover, on 14th June KIM has organised a final THERMACO event for within the framework of the annual KIM conference. 2016 edition was entitled "Innovation as a business growth driver". TUC, ITT, UNIBO, IETU, NRU, LAMBO, CECIMO and KIM attended. A roundtable was organized where, THERMACO, together with other FP7 and H2020 projects were presented.
In addition to that CECIMO has been informing its members during the biannual General Assembly meetings participated by the National Associations and companies' representatives (approx. 50 people). Besides, few smaller meetings of working groups, etc. took place gathering on average 15 people.
- CECIMO General Managers Meeting in London, 11-12 May 2015 (presentation);
- CECIMO General Assembly Meeting in Brussels, 2-3 December 2015 (information about project's progress);
- CECIMO Technical Matters Meeting in Brussels, 4 May 2016 (presentation);
- CECIMO General Mangers Meeting in San Sebastian, 12-13 May 2016 (presentation);
- CECIMO General Assembly Meeting in Fuschl-Am-See, 18-21 June 2016 (presentation, project factsheet).

Dissemination to the wider public
IETU produced a project video targeting a non-scientific audience, explaining the advantages and applications of the THERMACO technology. IETU cooperated with KIM as IPR Manager and CECIMO as Dissemination Manager in planning and organizing dissemination activities

Review of the dissemination plan and exploitation plan
IETU maintained database of project stakeholders and reviewed of the key dissemination documents including Policy brief (D9.7) Final Plan of Use and Dissemination of Foreground (D9.6). IETU team participated in "KIMconferences 2016: Innovations a business growth driver", Barcelona (Spain) June 14th, 2016 presenting THERMACO results.

Exploitation of project results
During this reporting period, a final exploitation plan has been established with the collaboration of all partners. To do so, the roadmap in which each technology was evaluated according to close-to-market criteria has been reviewed, and the information updated and refined, as explained in the Task 10.3.1 “Technology assessment”. In regards to the Exploitation Plan, a study of the market has been performed in order to characterize it and evaluate the real needs. Afterwards, an exploitation strategy for each output and for the whole THERMACO process and for each technology individually has been designed, defining the main sectors of application and selecting the target entities for the marketing actions.
All this analysis can be found described in detail within deliverables “D9.6. Final Plan of Use and Dissemination of Foreground” and “D9.4. Intellectual Property Rights (IPR) Management Strategy”.
In a first phase, KIM has evaluated THERMACO’ results based on their potential innovation and their ability to reach the market. To do so, KIM elaborated a Technology Request Form that all the partners involved in the development of foreground filled in explaining several aspects of the foreground developed and classifying the results according to their degree of maturity and development. The Technology Request Form is divided in four parts:

- Technological aspects: title, partner’s contribution to the development, Technology readiness level (TRL), Generic Maturity Level (GML).
- Intellectual Property and Knowledge protection aspects: Ownership of foreground, existence of external collaborations, related invention in the partner portfolio, existing IP references, mechanisms of IP protection foreseen, and publications.
- Applications: key applications; target/preferred geographical markets, main market barriers.
- Expected exploitation plan: expected exploitation intentions, indicate if the technology could be the bases for a spin-off/start-up and which partners should be included.

Thanks to the information given by all partners, KIM has obtained the necessary information to detect what is the intention of each partner in the development of an IPR protection and the related expected exploitation plan. Consequently, KIM has been able to recommend an adequate IPR protection and exploitation strategy for each technology and for the whole process.

Market analysis
During the second reporting period, a market analysis has been performed. The complete market analysis can be found in Deliverable D9.6. Final Plan of Use and Dissemination of Foreground here, a brief summary is explained.
Market needs

- Thermal management of electronic devices is an issue of increasing relevance since the increased complexity of modern electronic devices involves a problem associated with excessive heating of these components during operation.
- 55% of component failures of electronic complex devices are due to thermal issues.
- Challenge to be overcome by the industry, which seeks oriented solutions to the incorporation of new materials with very high thermal conductivity values, with a dimensional control to the

equivalent semiconductor devices in operative temperatures, with a lower power consumption, smaller, reliable and with lower costs. This is only possible with an optimal heat dissipation produced.

Market data

- The electronics market was estimated in USD 31.6 million $/year in 2012.
- From a global point of view, the world thermal management market has grown rapidly since 6 years ago.
- In 2010, it reached USD 7.500 million, reaching USD 8.000 million in 2011 and is forecast to grow about 3.000 million dollars until 2016, yielding a compound annual growth rate (CAGR) of 6.4% Between 2011 and 2016 which shows perfectly the importance in economic terms.

Sectors of application: sectors dealing with heat evacuation

- Main sector of application:
  - Electronic packaging materials to improve heat dissipation
  - Automotive industry to develop lighter vehicles with fewer corrosion problems
  - Space applications to offer an enhanced spacecraft performance: lighter weight, enhanced stiffness, and material strength.
- Other potential sectors
  - Led lighting: adequate and efficient heat dissipation.
  - Renewable Sources: solar energy collection, hydro and wind power (turbines and alloy materials), geothermal energy thanks to conductive properties (smarter heat management)

European geographic landscape

- Europe is expected to witness moderate growth rates in near future on account of rising automotive, power and aerospace industry in the region.
- In general, the evolution of the demand for MMC's in Europe, will advance in line with the ground transport sector (firstly automotive industry) and aeronautic sector. Both of them are considered priority sectors in the evolution of the Aluminium Metal-Matrix Composites (Al-MMC) with Graphene-based inserts.

Geographic landscape outside Europe

- North America dominated the global metal matrix composites market in 2013 and is expected to remain the largest regional market until 2020, owing to rising demand from aerospace and automotive industries in the U.S.
- Latin America and Africa are expected to witness significant growth over the next seven years on account of growing electronic/thermal, power and defence industries in the region.
- Asia Pacific is anticipated to witness rapid growth over the foreseeable future owing to increasing metal matrix composites demand in automotive and defence sectors, from emerging countries such as China and India.
- Major demand is anticipated to come from economies such as China, Brazil, India, U.S. and Israel.

In conclusion, this data and the more detailed data specified in the deliverable D9.6, shows that there is a clear market need for solutions such as the one proposed by THERMACO and that European countries have an opportunity to evolve and position themselves as a leader region or in an equal position to North America. That could bring a lot of economic growth and relevance to Europe in this particular field. For this reason, it can be concluded that research in the line of THERMACO must be continued in Europe, as well as improvement of manufacturing technologies and development of the market opportunity if we want to position ourselves as a leading region.

The address of the project public website, if applicable as well as relevant contact details.

Project website: http://www.thermaco.eu

Project logos:

The project video is available on tube channels and linked via the website:
http://thermaco.eu/noticia/thermaco-final-video-released/
or directly on youtube: https://youtu.be/YLZZcGWOhZE

The project was coordinated by the professorship Micromanufacturing Technology of Technische Universität Chemnitz, Prof. Dr.-Ing Andreas Schubert (coordinator) and Dr.-Ing. Henning Zeidler (scientific manager).

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