Executive Summary:

The ambition of the MULTILAYER project was to develop a new platform for the large-scale production of micro devices based on a technology we call 'Rolled multi material layered 3D shaping technology', which uses the concept of tape casting combined with advanced printing techniques. A set-up has been established and the feasibility of mass manufacturing for this developed solution has been assessed. This technology will enable high-throughput manufacturing of complex 3D-micro parts while using a layer-by-layer approach. The layers can be given specific structures composed of any combination of printed patterns, channels and open or filled cavities each manufactured with very high precision. The resulting micro devices will have ceramics as the basic building material which is a clear advantage in applications that require high temperatures, aggressive environments, particular dielectric materials, a low thermal conductivity and long term reliability. Furthermore, the ceramic tape technology developed enables structuring with spatial resolutions under 10 µm on tapes which can be as thin as 10 µm.

It has to be noted that the MULTILAYER project did not intend to fully develop new production technologies, which would have been far too expensive, but to adapt, hybridize and further integrate technologies that have been already demonstrated. The main innovation brought by the project l lies in the integration of technologies that are seen as very promising from an industrial point of view but that are not yet compatible with large scale and low cost manufacturing of ceramic multifunctional micro devices. This approach guarantees the impact of the MULTILAYER project on the industrial participants by reducing the cost of development.

The 'Rolled multi material layered 3D shaping technology' has several advantages:

- it is an efficient mass production tool with an output of over a million units in a single fabrication series,
- it has the flexibility to manufacture a wide variety of possible component designs,
- it allows the incorporation of different materials as different layers thus enabling the manufacture of multimaterial MULTILAYERed packages with a high degree of integration, the process will be extremely reliable with the facility for each layer to be rigorously inspected.

Project Context and Objectives:

The market of Micro-Electro-Mechanical Systems (MEMS) had an annual growth of 16% between 2004 and 2009 to an annual turnover of 56 billion dollars (43 billion EUROS). The widespread development of non silicon multifunctional MEMS is now linked to the development of new manufacturing routes, which tackle the main drivers brought by the end-users:
- cost reduction
- miniaturisation
- massive integration of functions

The current generation of mass-marketed non-silicon micro devices is mainly obtained by classical replication processes, micro injection and to a lesser extent hot embossing of polymer materials. The additional steps from material to product, namely functionalization, cutting, assembly, but even quality controls are considered as other building blocks and therefore implemented more or less independently along the process chain. This type of manufacturing process does not offer possibilities to build very complex multi functional 3D parts and are not suitable for inorganic materials (ceramics, metals).

Consequently, for very complex multifunctional ceramics 3D complex parts, a solution for mass marketing had to be developed.

A relevant solution consists in cutting the design of the micro device in several different layers which are individually structured and treated and then ultimately assembled. This type of technology offers no limitation on the complexity of the part to be designed and a potential important for the miniaturization of the micro parts. This is the idea of the so-called 'MULTILAYERed technologies' for the fabrication of micro devices so the MULTILAYER project intends to develop.

The first objective of the project is to develop the needed technologies for the manufacturing of a new generation of multifunctional micro devices with highly complex 3D structure for mass marketing. For that, the project aims to set-up the platform MULTILAYER 'Rolled multi material layered 3D shaping technology' for several fabrication routes, in order to provide a reliable set of technologies. This platform will be assessed in the frame of the project and the relevance for different kinds of 3D multimaterials products has been evaluated,

2) Fabrication of a set of demonstrators to validate the MULTILAYER platform:
The MULTILAYER platform will offer the potential to address already existing markets, offering new products at extremely reduced costs. As an example, the project will offer the possibility to reduce the manufacturing costs of cooling systems for automotive lighting systems by a factor of ten compared to existing solutions. Moreover, the project will give birth to a reference solutions for the manufacturing of other emerging large scale markets like microfluidic (medical application, microreaction,…), integrated device packaging with embedded MEMS and optical fibres, microreactors, bioreactors, RF applications, high efficient cooling systems (integrated heat pipes, micro heat-exchangers …), micro sources of energy, actuators and sensors and different types of multimaterial microparts at very large scale.

These demonstrators are presented in the figure 4.

Project Results:

To achieve this global objective, the consortium focused on:

1. Definition of materials, processes and products specifications and requirements with the final objective to define the overall technical approach and ensure a coherent framework for all the industrial applications targeted by setting references for further assessment. This constituted the main focus of SP0 (led by CRF).

2. The objectives of SP1 were to provide the tapes that were used to make the prototypes developed within SP6 and to provide knowledge and know-how that were the input to industrial scale processes that was developed within SP5. Starting with the input from SP0 and existing formulations, tapes have been developed with properties suitable for embossing, printing, lamination, debinding and sintering in collaboration with the tasks in SP2, SP3 and SP4. The developed tapes required plasticity and deformation properties that well exceed current formulations. The tapes have higher precision for exact structuring and high definition printing. The processes developed are environmentally sound (water based) and accommodate a wide range of materials. This constituted the main focus of SP1 (led by IVF).

3. Development of innovative tooling solutions and novel processing chains that combine the capabilities of different replication technologies. Tooling is one of the critical stages in scaling up the production of micro components and is the main factor in determining the product development lead-time. In particular, the research involved the development of tool-making techniques for fabricating large area stamps for HE and HE rollers and rollers for gravure printing. In addition, this SP addressed open research issues associated with the development of techniques for structuring, handling, alignment and orientation of green tapes. This constituted the main focus of SP2 (led by CU).

4. Development and adaptation of the technologies of printing to be part of the process MULTILAYER. More precisely, it concerns the formulation printing inks adapted to the processes and the substrates (ceramic tapes, prepared in SP1), in order to fulfill the specifications on the different case studies provided by SP0. Different types of inks have been tested and developed: sol-gel inks and suspensions of active materials. The different inks were adapted to the different technologies envisioned within MULTILAYER, namely inkjet printing, screen printing and high definition printing. This constituted the main focus of SP3 (led by CEA).

5. Development and bundle the post treatment processing steps necessary for the component development in this project. 3D structured green tapes have been laminated. Debinding and sintering routes has been developed not only for single tapes but also for material compounds achieved by MULTILAYER technique and inmould labelling. Stresses arising during the thermal treatment have been predicted by simulation. Furthermore, one topic was the mechanical influences upon sintering of cutting, handling and stacking which is necessary for qualifying the developed techniques for a high throughput production. This constituted the main focus of SP4 (led by IKTS).

6. Automation issues of the technologies developed in SP1-4. They have been transferred from the laboratory to production environments, which

required applied research and development from a different perspective as the one taken in SP1-4. It also included the integration of selected processes into standard or new production processes. On the basis of specifications, developed by SP0 and SP1-4, specific technological routes have been defined for each of the 6 demonstrators (case studies). It included respective equipment adaptation and modification. Finally an assessment of the up scaling potential of the technologies developed and used in the project has been carried out, along with a benchmark and cost evaluation of these production technologies, taking into account the respective market requirements. This constituted the main focus of SP5 (led by KMS).

7. Manufacturing and characterization of intermediate prototypes and final demonstrators taking into account the knowledge, nano-materials and processes developed in sub-projects SP1, SP2, SP3, SP4 and SP5. The objective was the development of high electrical, optical and thermal performances substrates to be applied in a wide range of applications with a significant potential impact on many industrial areas. The work was clearly oriented towards defined products and applications directly related to the industrial end users involved, namely Microwave components for Tera-Hertz applications, Thermoelectric device for domestic applications, Cooler for automotive lighting system, Multi fluidic component, Ceramic embossing tool insert for micro optical structures, Fluidic MLC-based sensor for medical applications. This constituted the main focus of SP6 (led by CRF).

8. The higher demands on precision and 3D monitoring in the MULTILAYER project require a much better laterally resolved thickness measurement. Even more demanding is the technique required for determining the embedded 3D structures in laminated sheets and the detection of de-bonding, cracks, warping and deformation. Suitable techniques for in-process monitoring at these conditions did not exist, but had to be developed in the project. Off-line inspection will be performed on intermediate as well as final items developed in the different sub-projects by employing standard lab techniques for dimensional measurements, surface finish, defects, dielectric and mechanical properties. In order to avoid hazard on nanopowder within the MULTILAYER platform, the CEA as coordinator of NANOSAFE project assisted the partnership on recommendations for nano-particles handling for raw material preparation and validation of fabrication procedure for ink and feedstock. This constituted the main focus of SP7 (led by KTH).

Description off the results/foreground by Sub-project.

SP1: Tape casting
The objectives of SP1 were to provide the tapes that would be used to make the prototypes, and to provide knowledge and know-how that would be the input to industrial scale processes developed within SP5.

SP0 provided the demonstrator requirements and together with existing formulations this was the basis for the tape development in SP1. The tapes should have properties that are suitable for embossing, printing, lamination, debinding and sintering. The processes developed should be environmentally sound (water based) and accommodate a wide range of materials.

Tape casting starts with dispersion, which is the subject of WP1.1, divided into colloidal dispersion methods and mechanical dispersion methods. Further, the dispersion needs an organic binder and other additives, and this formulation is the basis for WP1.2, together with the manufacturing of thick tapes by calendaring and characterization of the tapes. Characterization of the tapes was made in order to develop tapes with tailored properties. An important step in tape manufacturing is drying and this is more critical when water is used than organic solvents. Therefore WP1.3 was devoted to drying and cracking, with the aim of understanding cracking, in order to avoid it.

WP1.1 Nanopowders Suspensions
A good dispersion of the ceramic powder is achieved by milling to destroy any agglomerates and addition of dispersant to keep the particles separated. A good dispersion has low viscosity and viscosity has been used to evaluate the effect of milling procedures and dispersant concentrations. Dispersions have also been developed for ink-jet printing of Ag and SiGe.

Ball milling was used for the sub-micron powder (alumina and LTCC), planetary ball milling for nano-powder (zirconia and silica), and high intensity focused ultrasound for Ag and SiGe. In addition plastic processing was used for LTCC and silica, which were two materials more difficult to disperse by colloidal methods.

WP1.2 Tape Forming Methods
Thick tapes have been made by KeraNor using the calendaring process. Different binders have been tested for optimisation of tape properties for the sub-sequent process steps. Alumina, zirconia, LTCC and silica tapes have successfully been produced. Calendaring is preceded by plastic processing. It was found that nano-powders need higher shear forces, and that better uniformity was achieved the higher the shear force. Thick tapes have been found to be suitable for punching and laser cutting, but not for embossing or lamination. Instead structuring has been integrated into the calendaring process, so that the final shape can be produced directly in the production of the tape and embossing and lamination is not necessary.

Thin tapes have been made by water-based tape casting by IVF (alumina, zirconia and LTCC) and IKTS (alumina and zirconia). In addition, tapes with UV-curable binders have been made by IKTS. The tapes have been optimised for embossing, laser cutting, punching, printing, lamination, de-binding and sintering. In order for the optimisation to be successful, various tapes were sent to a number of partners and characterised in the following ways: release of carrier film, yield stress, elongation, DTA/TG, optical inspection, SEM microstructure, porosity, surface roughness and hardness.

Surface roughness, micro hardness and plastic deformation tests have been performed on sintered alumina. The results generated from alumina material under investigation is very promising for optical and other tool applications, where very low surface roughness is specified.

A Life Cycle Analysis (LCA) performed by IVF, comparing water-based tape casting with solvent based, showed that water based tape casting causes 43% less CO2-emmissions. Wedge-shaped tapes have been made by IVF for KTH for evaluation of optical properties. Tapes have been combined with in-mould labelling by IKTS and KIT-G.

WP1.3 Drying and plasticity modelling
The drying experiments performed at UCAM have shown that cracking is driven solely by the action of the capillary pressure. The stress state in the drying film material was found to agree closely with theoretical analyses based on fluid flow, ruling out other processes. The driving force for cracking was strongly controlled by the crack spacing, thickness and geometry of the film.

Using a new technique that allows the measurement of local stresses, it has been shown that deviations from the fluid flow predictions, observed near the pore-emptying front, are associated with pore-opening and cracking. The influence of pore-opening has been quantified by comparison to theoretical analyses of pore size distribution. The observed pressure drops due to cracking were shown to agree with theoretical analyses, yielding an analytical model for the crack driving force.

It has also been shown that the particles do not come into contact in the dried film, unless it is heated above 120 °C, but remain separated. This gives rise to a reduction in the elastic modulus by an amount consistent with the separation being associated with water molecules bound to the surface of the particle.

The change in properties of UV-curable systems has also been studied. It has been shown that there was no clear correlation between curing depth and time. Such behaviour might be associated with scattering from the ceramic particles in the tape.

SP2 Tape structuring
A) Tooling. The main goal was to develop innovative tool making solutions for large area stamps/rollers required for HE and gravure printing, and design and manufacture of reference tools for comparing the different replication processes.

As a result of the efforts of all partners novel hybrid tool making techniques were created, designed for optimal performance and enabling the manufacture of micro-tools rapidly and cost-effectively. Reference stamps/rollers were designed and manufactured. Development efforts were following initially chartered plan- going through a few development phases: design of experiment, trials, optimization. These reference tools reinforce the comparison of the investigated tape casting and advanced printing techniques in regards to their replication capabilities and throughput. More than 30 tools were created utilizing different manufacturing chains designed to address feature sizes, overall dimensions and accuracy. Feature sizes ranged from 100 micrometers up to 300mm organized in different patterns. Very important aspect of the work carried out was developing and implementation of rules for alignment and orientation as often multiple processing was required at different locations(partners).Not only we realized the process but also we managed to upscale it so id addressed the need for high throughput and low cost.

B) Tape structuring.
The main focus of this activity was to structure green ceramic tapes and structure casted slurries by UV light. Direct structuring methods were investigated in order to analyze existing and feasible structuring processes. Laser structuring was investigated employing different laser sources - from microsecond to picosecond pulse durations. Optimization of the laser material interaction was performed in order to retain high process accuracy and high throughput.

C) Embossing.
The main goal was to develop solutions for performing room temperature embossing. For this purpose tapes with nano sized or very fine grained powder developed in SP1 were utilized. Functional concept for the cold embossing system was developed based on the requirements of the material as well as the technological solutions.
Once the process was defined a machine was designed and realised to carry out test for the cold embossing process. A feasibility study was conducted in order to identify tools compatibility, material response and process parameters. After the completion of the preliminary tests enough information was gathered in order to perform cold embossing for the demonstrators with required accuracy.

D) In-mould label technique. The main task was the development of a combined process based on in-mould labelling technique and enhanced powder injection moulding, i.e. combining ceramic tapes with injection moulded complex shaped parts. For that purpose ceramic tapes were inserted into an injection moulding tool and completed by injecting a 2,5D or 3D component. All associated tooling components were developed in order to orient and retain the inserted part. Further features as holding of the ceramic tape within the tool were also considered at the manufacturing.

Shrinkage of the injection moulded parts during debinding and sintering must be adjusted to the shrinkage behaviour of the tapes. In order to achieve that blends of powders with different particle sizes and different solid loadings of the feedstocks were developed. Furthermore, the types of polymers used for the thermoplastic feedstocks needed to be adapted to the polymers used in the tapes for simultaneous debinding. Different kinds of binder systems for extraction debinding and for thermal debinding were utilized.

The feedstocks were characterised by torque measurements, high pressure capillary viscosimetry and by all mechanical and thermal data necessary for mould-filling simulation. Ceramic green tapes were inserted in injection moulding tools by means of a handling device. By subsequent injection moulding the same or another type of material was joint to the ceramic tape. The injection moulding parameters needed to be adjusted to the demands of both ceramic green tape and high shaping accuracy. The merging area between the label ceramic and the injected ceramic was comprehensively investigated and the accuracy of the 3D microstructures determined and optimized.

Summary of the achievements:
- Novel Tool-making solutions for the fabrication of stamps/rollers with complex 3D shapes;
- Solutions for tape structuring employing different direct rapid machining/structuring techniques;
- In-mould labelling techniques for incorporating of 3D structures in ceramic green tapes developed and tested;
- Ceramic green tapes provided with 3D micro structures by micro in-mould labelling
- Embossing techniques for patterning tapes with high resolution, high accuracy and high throughput (cycle of less than 30 seconds) at room temperature.
- Suitable processing conditions established for evaluated techniques.
- Cooperation between partners established and sustained.
- All technology solutions transferred to demonstrators realization

SP3 Tape printing

The aim of the sub-project 3 so called Functional Printing was to develop and adapt existing individual printing technologies to a large scale production of micro devices. This intent implied to use innovative printing tools which requiring specific ink developments, in particular the use of nanopowders.

Up to now, screen printing is selected in printed electronic sector for mass production.

However, there is a new industry demand for finer printed patterns to manufacture next generations of micro devices.

To this end, screen printing is already a limiting factor in industrial processes, both in terms of achieved resolution (100µm maximum) and also in terms of production rate compared to a roll to roll process.

MULTILAYER project includes in its objectives the transfer of the screen printing process to a rotogravure printing and inkjet printing to reach a higher accuracy and productivity.

The SP3 is divided in 3 work packages entitled:
Inkjet Printing (WP3.1), aim at a small scale very fine details
Screen Printing (WP3.2), aim at a larger scale compared to ink-jet but with less accuracy
High definition printing (WP3.3), aim at a roll to roll process (flexography)

The next paragraphs expose the objectives and the outcome of each work package.

WP 3.1 Inkjet printing

The object of this work package was first to evaluate the jetting performances of selected inks then, to work on jetting devices and tape surface management in view to improve the printing resolution. Lastly, specific inks were developed by the project partners and then characterized. (Electrical conductivity, adhesion, dimensional control) (D3.1.4, D3.1.5, D3.1.6).

MSE has defined and supplied to MULTILAYER's printers the test layout for ink-jet printing.

Pagora studied surface properties of green tapes manufactured by other partners. Tapes surface energy, porosity and roughness have been characterized.

The project's objective was to reach a resolution less than 10 micrometers. To this end, Altatech has studied the effect of the printing nozzle diameter on the achieved resolution. A specifically developed 10µm diameter nozzle has been used for these tests. (D3.1.2)

CEA worked also on tool development to improve the resolution of inkjet, using a CeraPrinter X-Serie (256 nozzles, printhead resolution: 30µm) from Ceradrop company.

After a device development, various design (ring resonator, long line and serpentine) were successfully printed on sintered LTCC substrates. Printed details of 60µm have been reached and validated in terms of electrical properties. (D3.1.6)

Otherwise specific silver inks have been developed by Pagora and Cranfield to facilitate the printing. Indeed, to reduce the head clogging, silver nanoparticles were synthesized thanks to a new-water based route. Moreover the addition of SiO_2 nanoparticles to improve the adhesion to the substrate has been also evaluated and validated.

To finish, Pagora has worked to enhance the dimensional control of tracks by printing in recesses.

The technologies and know-how for performing prints with very good dimensional control and electrical characteristics are now available.

WP 3.2 Screen printing

The objective of this workpackage was to develop new types of conductive inks suitable for screen printing (D3.2.1, D3.2.2) and also to evaluate the functional assessment of deposited inks. (D3.2.3)

Using the MSE test layout, Pagora and CRF have set the Screen printing parameters allowing achieving the printing of the desired silver patterns with a satisfactory resolution and quality. This development was undertaken using water based printing paste, specifically developed during the project. From its side, MSE has defined efficiently the one-step sintering process of the green tapes and the silver printed patterns. Lines with low electrical resistivity values (1.8.10-8 to 6.0.10-8 Ohm.m) close to that of bulk silver materials were performed.

CEA has developed two thermoelectric inks suitable for screen printing. One based on SiliconGermanium powders and one based on Bismuth Telluride powders as active material. For the demonstrator requirements, the bismuth telluride ink was selected for its ability to generate a higher Seebeck voltage at room temperature compared to the silicon germanium material. The evaluation and optimization of thermoelectric properties have been done, just as a study of contact resistance between thermoelectric patterns and the metallic contacts.

As a result, the screen printing process has been considered as an efficient process for the printing of conductive lines for the demonstrator 2 and 3 (Thermoelectric sensor and cooler for automotive lighting systems).

WP 3.3 High definition printing

The main task was to improve the printing resolution by investigating other printing processes as photogravure and flexography. (D3.3.1, D3.3.2) These methods allow to print thin film (less than1µm by pass) with a high speed rate but limited to flexible substrate. (Compatibility with demonstrator 6 process) Lastly, the partners evaluated the functional properties of the deposited ink. (D3.3.3).

Liquid silver inks adapted for rotogravure and flexography were formulated and optimised. The inks were successfully printed on LTCC tapes by rotogravure as well as by flexography. Regarding these results, the possibility of a scale up of the flexography process using a pilot press has been validated by Pagora.
Very low electrical resistivities were achieved after sintering (performed by MSE); varying from 6.3.10-8 to 19.3.10-8Ohm.m depending on silver content, number of passes and line width.

Valorization of technical results
The sub-project 3 has been result-full and has led to a rich dissemination. Indeed, the MULTILAYER achievements concerning the functional printing have been communicated through 8 oral presentations at international conferences, 8 publications in journal, 1 poster and 1 patent:.

SP4: Post treatment assembly

The objective of SP4 was to develop and to bundle the post treatment processing steps necessary for the component development in the MULTILAYER project. 3D structured green tapes were laminated. Debinding and sintering routes have been developed not only for single tapes but also for material compounds achieved by MULTILAYER technique and inmould labelling. Stresses arising during the thermal treatment were predicted by simulation. One major topic dealt with the mechanical influences upon sintering of cutting, handling and stacking which was necessary for qualifying the developed techniques for a high throughput production.
SP4 was subdivided into three work packages. WP4.1 started in M01 and last until M45, whereas WP4.2 and WP 4.3 started in M12 and had been finished in M24.

Main results of the subprojects

The lamination process has been completely adapted to the requirements needed in the MULTILAYER project.

Multistep lamination of 3-D LTCC modules with cavities and closed channels has been carried out by using uniaxial lamination. Thereby the influence of the lamination pressure on the quality of the final structure was investigated. The attained laminated tape structures were investigated and verified by a non-destructive scanning acoustic microscopy (SAM) analysis was carried out in a Sonoscan D-6000 equipment, working in the pulse-echo mode at a frequency of 100 MHz.

Alumina green tapes, developed within the project, were laminated by various lamination methods: isostatic, uniaxial and cold chemical lamination. For producing large cavities and inserted channels the possibility of using sacrificial pastes has been examined. Various parameters and their influence on the inserted channel structures were investigated. The best results have been achieved with uniaxial and cold chemical lamination, which can be scaled up to high through put production.

For lamination of green tapes by means of ultrasonic waves a laboratory ultrasonic welding device was used. The equipment is termed "multi-press MP351 with generator SL35" and it is fabricated by Rinco Ultrasonics AG (Switzerland). The used ultrasonic frequency was 35 kHz. The tapes can be joined directly between sonotrode and support or polyethylene foils can be used a protective foil. By using ultrasonic welding an integrally joining between green tapes can be achieved. This lamination technique is limited to small tape contacting areas. It is more suited for joining than for a large-area lamination.

Commercially available lead-free and low melting solder glasses which are suited for sealing alumina ceramics have been tested within the scope of realizing joining temperatures lower than 550 °C. It had been shown by the experiments that actually no lead-free commercial solder or sealing glass is available suitable for a sealing process below 500 °C. But, the G018-250 (SCHOTT) shows a sufficient sealing quality at a minimum temperature of 520 °C. The experimental glass 2816 (Ferro) shows the potential for realising dense seals at temperatures below 500 °C. Both types of solder glasses were used for sealing the housings of Demonstrator #4 "Multi fluidic device".

The debinding process of zirconia and alumina tapes based on water soluble binder systems such as of tapes with UV-curable binder systems were investigated thoroughly. The pure binder systems such as the green tapes were thermo analytically characterized by DTA, TG and DTG measurements. It could be shown that the presence of the oxide powders in the tapes decreased the burn-out temperature of the organic binder systems remarkably in comparison to the pure binder components. Debinding of the water based binder systems could be carried out without crack formation in the green tapes. For one of the two investigated UV-curable binder systems the heating rate had to be reduced for attaining crack-free tapes.

A further task of SP4 was to develop new and innovative solutions for co-debinding of multimaterial components. The key challenge was to achieve crack-free debinded parts within a reasonable debinding time. Co-debinding routes should be developed by means of supercritical CO2 and for parts made by inmould-labelling. The experiments had clearly shown that supercritical carbon dioxide can be considered an efficient extraction medium for low molecular weight species as paraffins or waxes contained as binder components in both, injection moulding feedstocks and tapes. Supercritical CO2 can generally penetrate a solid sample faster than liquid solvents because of its high diffusion rates, and can rapidly transport dissolved solutes from the sample matrix due to its low viscosity.

Furthermore, co-debinding of multi component parts produced by in-mould labelling were carried out as a sequence of two steps: solvent and thermal debinding. The solvent debinding is necessary to extract a certain amount of binder inserted to the feedstock. During storing inside solvent the inmould labeled green tape starts to swell. Moreover, a pure thermal debinding of the multi component parts was investigated. As a result of these investigations a thermal debinding route had been chosen with very low heating rates and dwell times in the low temperature region.

Beside debinding and sintering of tapes made of very fine grained powders and co-sintering of multi component parts were defined as tasks for SP4. Thermo analytical investigations were the key methods for this development work. Moreover, microscopic and FESEM investigations were carried out for characterization of the sintered parts. Tapes made of zirconia powder with a primary particle size of 70 nm could be densified up to 99 % of theoretical density, with a primary particle size of 30 nm up to 97 % theoretical density. From these results appropriate sintering profiles were established for the corresponding case study components.

For in-mold labelling the shrinking behavior between tape and injection moulding feedstock had to be adjusted very precisely. This had been done by several optimization loops for adapting the solid content of the feedstock to the solid content of the corresponding tape. The thermal treatment process had been supervised by radiographic images of the components in the green, in the debindered, and in the sintered state. Thus, it was possible to detect the source of possible defects very precisely. Finally, defect-free sintered in-mold labelled components with micro embossed surfaces had been attained by applying a novel co-sintering route.

A semi-empirical model of sintering has been successfully implemented into Finite Element software in order to estimate the distortions of MULTILAYER samples. This model requires the characterization of shrinkage properties, using dilatometry, during sintering in order to determine relevant input parameters for each material. It was evidenced that sample distortion and internal stresses cannot be avoided in such structures. In practical tests these results have been confirmed. Loading of the sample during sintering and adjusting the material properties to reduce the mismatch of shrinkage rates are likely to reduce such effects. Numerical simulation can be used to guide the MULTILAYER design accordingly.

Cutting tests were conducted for three different green tapes. By these tests different cutting methods were performed: Cutting with geometrically determined edge and cutting with geometrically undetermined edge (resin bond blade). Analysis of shape deviation of cut edge was realized by measuring removed and displaced material at entry and exit side of material with an optimal microscope. For cutting green tapes the principle of a gate shear seems to be a feasible solution.

For evaluating methods for retrieving green tapes from its carrier tape, necessary analysing methods for forces were designed in SP2. Subsequently a test rig was designed and realized. The tests performed in the test rig resulted in small forces, which are necessary to retrieve the green tape from its carrier tape. As final result of WP 2.1, retrieving the carrier tape using a wedge showed promising results and is regarded to have the most potential for an automated solution. The automated solution for this handling technique was demonstrated in SP4. The results showed that this principle for retrieving carrier tape automatically from very thin green tapes was feasible for upscaling in SP5.

Since conventional vacuum technologies cause intolerable distortions of the green tapes, for force regulated handling solution low negative pressure has to be used. For designing the handling system, pumps, pressure regulation valves, the suction plate and a system for regulated suction were selected. For the principle of regulation a system was chosen which compensates two air-currents, one sucking and one blowing air current. For gripping green tape, a resulting sucking air-current was induced by reducing the blowing air-current from standard level. For depositing the green tape, a resulting blowing air-current was induced by reducing sucking air-current and raising blowing air-current from standard levels. For realizing the force regulated handling system, the force regulation by adjusting air current with controlling the permeable pipe cross section for inducing suction or blowing was integrated into a software system. The regulation was realized by a three-step controller, which was programmed in the DasyLab-Software, which is also used to collect the data from measuring air-current flow values. For regulating the suction for handling green tapes, the system has to detect, when a green tape has been gripped. Results of tests to grip various sizes of green tape sheets, resulted in a drop in pressure corresponding to the size of the gripped green tape sheet. Furthermore, automatic regulation of handling pressure during gripping green tape was realized.

According to the considered design from SP 2 the system for aligning green tapes was realized. Stages of high precision were integrated into the system as well as two CCD cameras of high resolution. For aligning green tapes with the realized system, following results were achieved: For green tapes which are provided with an accuracy of ± 50 µm in X- and Y- direction there can be provided accuracy of 0.8 µm in X-direction and of 1.2 µm in Y-direction. These accuracies can be provided with a likelihood of 99.99 %.

Blanking was investigated as a possible bonding principle using a pierced pocket as tape connection (Form Fit). After the tapes were positioned under the test rig they were pierced with a cone-shaped or a cylindrical die and investigated if there is any noticeable connection. In conclusion it can be stated that the tapes are far too brittle that any connection between them can be achieved by blanking.

Joining with electrostatic forces was investigated. The bonding force was inspected by two scenarios: a) Electrostatic field OFF during separation and b) Electrostatic field ON during separation. However no reliable connection can be established between two tapes neither with switched off nor with switched on electrostatic field.

Examination whether mechanical fixing devices can fix the position of green tapes during stacking were investigated. This solution provides a fixation during stacking only. Therefore it has to be combined with a solution which fixes the tapes during sintering. Possible solutions are adhesive bonding and spot welding. A combination mechanical fixing and adhesive bonding is a promising solution.

Investigation of Heated Tool Welding for fixing two tapes was performed. Additionally a determination was made whether an alternating welding spot improves the post sintering results. The results of these tests show that Spot welding with an alternating spot is a promising solution.

Based on the considerations prior to the tool definition and the experiences gained in the trials carried out a concept for an automated IML process has been developed. It covers the manufacturing steps from tape delivery until shipment of the final sintered parts. For handling a robot system equipped with a vacuum gripper seems to be the most promising solution.

SP5: Processes
The objective of SP5 "Automation, Process Integration & Upscaling Assessment" was to investigate automation issues of the technologies developed in SP1-4, which dealt not exclusively with, but were rather focused on more fundamental technological investigations. For industrial applications, those technologies have to be transferred from the laboratory to production environments, which require applied research and development from a different perspective as the one taken in SP1-4. SP5 also focused on the integration of selected processes into standard or new production processes. On the basis of specifications, developed by SP0 and SP1-4, specific technological routes have been defined for each of the 6 demonstrators (case studies). Respective equipment adaptation and modification was carried out. The major scientific achievements can be summarized as follows:

- MULTILAYER ceramic technology processes, which have been investigated under laboratory conditions in SP1 to 4, have been adapted and transferred to prototype or industrial production for demonstrator fabrication.
- Several innovative technologies and technological aspects have been investigated and developed, such as:
  water-based tape casting as resource saving and pollution preventing tape production method
  integration of tape structuring processes already into the tape fabrication (tape casting) process
  economical thick tape production by calendering, combined with 3D structuring via embossing
  embossing of complex structures into green ceramic substrates for microsystems fabrication
  combined tape 3D structuring of ceramic green tapes, by integrating punching, embossing and laser ablation into standard LTCC production equipment
  damage- and stress-free handling of sensitive ceramic green tapes
  application of in-mould labelling process for combining the advantages of ceramic powder injection moulding and tape based processes
  high throughput rotary (flexography) printing on green ceramic foil
  automated carrier foil removal for high precision stacking of thin tape layers

- A structured compilation of MULTILAYER ceramic production technologies, which are needed have been used for the demonstrators, including their respective technological variants, is being worked out. This compilation addresses technological compatibility as well as it identifies needs for further technological development. A subject of special interest is the assessment of roll to roll compatibility of the respective processes.
- Technological routes (process chains) and practical manufacturing equipment
(pilot lines) have been defined and established for demonstrator fabrication at the consortium partner's laboratories.
- An assessment of the up-scaling (mass production potential) of each technology and
their respective combinations has been conducted, which also benchmarked MULTILAYER technologies against market requirements.
- The knowledge on MULTILAYER products fabrication gained within the project, combined with actual available market development data, has been summarized and condensed into a kind of „technology roadmap" for multi material multi layered ceramic microsystem products. The respective study has been published at the 4M conference 2012 (Vienna).
The following section contains a brief selection of the scientific and technological results achieved in SP5 "Automation, Process Integration & Upscaling Assessment". The structure of it follows the SP5 workpackage structure.

Description of the main S&T results

Results related to tape manufacturing

Water-based tape casting process
An environmental analysis, which was performed in the MULTILAYER project, comparing tape casting based on water or with organic solvents, showed that water-based tape casting causes 43% less CO2-emmissions than tape casting based on organic solvents. Water based slurries have been in the focus of MULTILAYER slurry development.

Integration of embossing processes into the tape fabrication process
A comprehensive compilation of embossing variants was conducted within the MULTILAYER project. Based on the results, feasible solutions for manufacturing the demonstrators were analysed. Embossing processes which were feasible to be integrated into casting processes were selected and necessary equipment was evaluated. Finally this work resulted in realized prototypes of integrated casting and embossing processes. Several alumina recipes have been performed with different alumina powders. These powders have different particle sizes and shapes. In parallel to the different powders, the additives and water amounts have been varying. The structuring of these tapes made of different recipes was successful.

Results related to tape cutting and structuring
Tape handling solutions for laser processing of ceramic green tapes
Handling of ceramic green tape has to be done without damage to the sensitive limp material, without compromising accuracy and (not to neglect) without blocking (too much) of valuable tape area. Challenges of ceramic green tape handling mainly originate from their properties, they are (depending on their thickness) flexible and deformable. Handling of green sheet laminates seems to be easier, for they are stiffer, but they are also heavier and sometimes warped, so the main requirement is here a secure fixation. Respective solutions have been designed, realized and tested within the MULTILAYER project.

Combined 3D micro structuring

For an industrial fabrication of MULTILAYER ceramic microsystems, often several tape structuring techniques are applied. A combined 3D micro structuring facility, integrating different micro structuring techniques in one process, is desirable both for technology development and ceramic microsystems production, allowing ceramic green tape structuring with highest flexibility. Such a system has been developed within the MULTILAYER project allowing system features as punching of vias and cavities, laser drilling / cutting / ablation, embossing (small area or sequential) and automated optical alignment and inspection.

Gripping system for loading and unloading of an injection mould

In the MULTILAYER project, an automated loading and unloading module for an injection moulding machine has been developed. Among the challenges to be solved were the feeding of the moulding machine with green tape, at a later working stage the product take out of the injection mould and further the integration into an existing production system that consists of an injection moulding machine and a mechanical robot handling system.

Results related to functional layer printing

Roll-to-roll flexography printing on ceramic green foil

In the MULTILAYER project, roll-to-roll printing on ceramic green foils has been carried out using a commercial 5 unit flexography printing press. Two kinds of substrates provided by Swerea IVF were tested: alumina and LTCC tapes. They were both laid on a carrier film, and rolled on a tube. The suitable internal diameter for the roll to be directly used in the printing press should be 70 mm. One pass printing was successfully achieved with both substrates (e.g. 25 m alumina green tape length and 10 m LTCC length) with a speed of 3 m/min and air pulsed dryers allowing solvent evaporation.

Results related to tape handling, stacking and lamination

Force regulated handling device for limp green tapes

Since conventional vacuum technologies can cause intolerable distortions of the green tapes, for force regulated handling solution low negative pressure has to be used. For designing the handling system, pumps, pressure regulation valves, the suction plate and a system for regulated suction were selected. For the principle of regulation a system was chosen which compensates two air-currents, one sucking and one blowing air current. For gripping green tape a resulting sucking air-current is induced by reducing the blowing air-current from standard level. For depositing the green tape, a resulting blowing air-current is induced by reducing sucking air-current and raising blowing air-current from standard levels. Since sensitive pressure sensors were not commercially available to measure such low pressures with good signals, sensitive flow sensors measure the value of air-current for regulating handling force.

Automated carrier foil removal

Within the MULTILAYER project, automated carrier foil removal, which is essential for high volume production, has been intensively investigated. Suitable technical principles have been identified and a special test rig has been developed and used for tests on several materials. The results of the retrieving tests that were executed with this test rig showed that the used principles for retrieving the foils automatically are feasible for up-scaling of the process. Three different variants to take off the carrier foil have been developed and realized in cooperation between KMS and KIT(-U). In all variants the ceramic green sheet is retained in a horizontal position by a vacuum suction plate.

Prototype of an automated stacking solution
Further, a prototype of an automated stacking device including several variants of automated carrier tape removal and temporary fixation of single green sheet layers during stacking has been developed within the MULTILAYER project in close cooperation of KMS and KIT (-U). The prototype features, among others an automated carrier foil removal unit with all 3 previously described methods installable.

SP0 and SP6: specifications and Demonstrators

The SP0 was oriented to the definition of materials, processes and products specifications and requirements with the final objective to define the overall technical approach and ensure a coherent framework for all the industrial applications targeted by setting references for further assessment.
The objective of this report is the definition of specifications for the six demonstrators to be developed for the validation of the MULTILAYER approach:
- Microwave Tera-Hertz components for environmental monitoring sensors (DEMO#1);
- Thermoelectric devices for domestic applications (DEMO#2);
- Cooler for automotive lighting systems (DEMO#3);
- Micro fluidic device for micro reactors, fuel cells or medical devices (DEMO#4);
- Micro structured ceramic tool insert for embossing tools (DEMO#5);
- Fluidic MLC-based sensor for medical applications (DEMO#6).

The requirements have been selected considering physical and geometrical properties of tapes and pastes to finalize the prototypes.
The definition of physical properties allows starting the selection of ceramic, semiconducting and conducting materials to be used for the fabrication of the MULTILAYER structures. For all the application a feedback from SP1 allowed to select the most suitable materials.

The preliminary definition of geometries and patterning features, which have been finalized after the completion of the design activity (figure 24 and 25), allows to the definition of the correct process chain to guarantee the device fabrication (figure 26).

For thermoelectric and automotive demonstrators are particularly important costs issues and then economical constraints have been defined.

The detailed specifications reported have been used to design the different demonstrators by means of the simulations and the CAD design of the different layers composing the final devices.

The objective of this report is the definition and description of the characterization tests and procedure for the final validation of prototypes and demonstrators. The industrial users selected a proper list and combination of analysis within electro-optical, mechanical, electro-mechanical, optical and lifetime tests to have significant data from the device performances. The potential economic and social impact of the MULTILAYER outcomes will be validated by the full characterization of the 6 demonstrators.

SP6: demonstrators

The objective of SP6 is to develop high electrical, optical and thermal performances substrates to be applied in a wide range of applications with a significant potential impact on many industrial areas. The specific activities related to the SP6 have been: Integration of MULTILAYER high performances substrates in the end user assembling processes to finalize the demonstrator fabrication; Characterization of the final demonstrators on the basis of the validation test protocol defined in SP0 and Costs analysis of each case study to define the optimal conditions between cost efficiency and technical results. The work is clearly oriented towards defined products and applications directly related to the development of 6 final demonstrators:

- Microwave components for Tera-Hertz applications (Demo#1 by Omnisys)
The final version of demonstrator number 1, a transition from microstrip to waveguide using a MULTILAYER circuit and LTCC technology has been manufactured. Measurement of the demonstrator shows that LTCC technology can be used up to 100GHz with good result in terms of low loss. The high precision manufacturing capability needed for accurate manufacturing is available within the consortium. The cost assessment shows that there is a cost reduction opportunity for high volume circuits. Especially for applications were high integration between very high- and low-frequency components is needed.

- Thermoelectric device for domestic applications (Demo#2 by LEGRAND)
The final demonstrator, introduced during M48 meeting, is functioning. It embeds last sample of thermoelectric sensor manufactured by CEA. A fine tuning on the electronic schematic has also been done in order to setup level of comparison for electric voltage generated by the sensor. Legrand improved also current consumption of its ZigBee transmitter down to 580µJ. But this level is still too high to be powered by a thermo electrical energy harvester.

- Cooler for automotive lighting system (Demo#3 by CRF)
The final big rounded demonstrator is realized on the basis of specifications defined in SP0. Technologies for the production of demonstrator already identified within the consortium are used for the realization of final prototype. The process chain established previously is important for the realization of the final working demonstrator. Characterization in terms of light efficiency, thermal dissipation and lifetime supports the preliminary results of positive demo performances. The cost evaluation demonstrated that the low cost manufacturing process allows to achieve a substrate cost reduction compared to commercially available and standard components.

- Multi fluidic component (Demo#4 by IKTS)
The micro fluidic component with enclosed channel structures is realized on the basis of specifications defined in SP0. The inserted channel structures are made of alumina green tapes, based on water based binder system. By uniaxial cold embossing and laser ablation channels are structured into the green tape. Subsequently the structured tapes are laminated (cold chemical and uniaxial lamination). Afterwards the tapes are heat treated and finally mechanical treated to achieve the needed dimensions. At least the parts were inserted to a still existing housing element and hermetically sealed by glass soldering. The parts were checked in practical tests and by radiographic and computer tomographic investigations.

- Ceramic embossing tool insert for Micro optical structures (Demo#5 by BPE)
In comparison to conventional replication tools the ceramic inserts have a higher wear resistance and a higher stiffness which shall provide tighter tolerances and higher value added for the final products. The demonstrator 5 is ready for production. The production means and process, here micro milling of hard sintered ceramic are present and the production costs have been calculated to the lowest. The demonstrator has been tested at different temperatures, the polymer end product as well as glass end product has been produced in low quantity and is stable for high number production. The marketing and production can start.

- Fluidic MLC-based sensor for medical applications (Demo#6 by MSE)
The demonstrator embeds 3D Structures and cavities. This product can be used to detect the flow, pressure or electro-chemical reactions. Based on manufactured demonstrator #6 LTCC sensors, a final pilot line #6 could be defined. Existing equipment could be modified successfully to meet all the requirements. Also new equipment like the uniaxial press could be excellent implemented into the pilot line. Two process variants, embossing and laser structuring, necessary for realizing the fluidic channel could be successful developed. The LTCC based sensor show an excellent sensitivity and very short response time. Both new developed MULTILAYER processes will give a remarkable cost benefit. Based on the defined process chain for pilot line of demonstrator #6 also the throughput of each equipment was calculated. To compare the throughput and see the bottle necks the maximum of pieces per hour are ascertained. For an upscaling potential there could be a good opportunity for the embossing process, if in a sufficient way a multi up embossing tool could be manufactured to decrease the process time.

SP7: Inspection control
The processes involved in the MULTILAYER project cover ceramic tape casting, micro-structuring, sintering, multi-material layering, 3D printing, lamination, post-treatment and assembly. Several of these processes are by themselves well developed manufacturing processes with already existing process control methods. Vision systems are used for positioning of stacked sheets and for assembly of components. Thickness monitoring is also a routine technique in tape casting. However, the much higher demands on precision and 3D monitoring in the MULTILAYER project require a much better laterally resolved thickness measurement. Even more demanding is the technique required for determining the embedded 3D structures in laminated sheets and the detection of de-bonding, cracks, warping and deformation. Therefore, the main objective of SP7 has been to develop suitable techniques for in-process monitoring at these conditions since they do not exist at present.

Off-line inspection is also considered and performed on intermediate as well as final items developed in the different sub-projects by employing standard lab techniques for dimensional measurements, surface finish, defects, dielectric and mechanical properties. The outcome of the development of optical tools for process characterization will have a major impact on the recommendation for a roll-to-roll inspection system.

A safety assessment of all equipments developed (handling ultrafine or nanopowders) within MULTILAYER in particular by measuring the presence of ambient ultrafine or nanopowders have to be insured. Based on the results, recommendations are provided regarding the conception of industrial tools to insure the protection of the persons around the equipments.

The subproject SP7 consists of four workpackages dealing with: (7.1) Analysis and modelling of feature response; (7.2) Control of process; (7.3) Inspection off and on-line and (7.4) Safety.

The technological development in SP7 has been progressing very well and even beyond initial expectations. Samples of two typical materials; alumina and zirconia were selected at an early stage.. They differ in geometrical dimensions, porosity, sintering states, and embedded structures, and are investigated for geometrical dimensions, surface finish, defects, dielectric, optical and mechanical properties. The materials information necessary for modeling the optical response of embedded 3D structures are obtained. For an IR-transmission based system with suitable detection technology, the "transparency windows" of alumina and zirconia have been determined and best detector technology for achieving good lateral resolution as well as good contrast separation has been established by IR-camera analysis.

Also, access has been provided to several Optical Coherence Tomography (OCT) systems for evaluation purposes, and the modelling of OCT-images has been strongly improved by the collaboration with the Russian based scientists Mikhail Kirillin and Ekaterina Sergeeva. For developing an OCT-technology that is suitable also for thicker alumina and zirconia samples, a system operating at 1.7µm is evaluated at Harvard Medical School in Boston and the obtained results agree with theoretical prediction and show that 1.7µm OCT system provides larger probing depth for high-scattering alumina and zirconia. The result indicates that OCT technology combined with a dedicated image processing program is promising for in-process 3D monitoring of the embedded 3D structures in laminated sheets and the detection of de-bonding, cracks, warping and deformation in ceramic micro manufacturing.

Different non-contact techniques suitable for the inspection and control of the roll-to-roll processes are summarized, including OCT, IR-transmission and reflection measurement, dual optical distance sensors, X-ray computed micro-tomography, IR-transmission combined with IR-camera, optical profiler, camera inspection and laser scanner.

As one of the objectives in SP7 is to improve inspection techniques, it is crucial to analyse the measurement data as precisely as possible in order to ensure a high-quality process control and inspection. Data representative of imaging systems such as optical microscopy, scanning electron microscopy and high-speed camera imaging, have been analysed with new algorithms developed at KTH by Peter Ekberg for dedicated image processing providing sub-pixel precision. Data representative of surface roughness and thickness are compared with measurement results obtained using different instruments and tools in order to verify systematic errors in measuring principles and methods. Moreover, conformity is checked with certain standards for use with commercial optical profilers. Feedbacks are provided to the artefact manufacturers.

Based on the evaluations and findings of various inspection techniques a hybrid automated 3D monitoring system has been proposed for the in-process inspection and quality control. The system consists of a monitoring centre with dedicated data processing and function control program and four major inspection units -- the ViaCon®SCAN Inspection system, IR transmission imaging, optical coherence tomography (OCT) system, and dual optical distance sensors. Based on the off-line inspection results, development of multi-sensor Coordinate Measurement Machine measurement strategies are required in order to quantify and optimize both the tool-making and the foil production results and processes.

Based on the recommendations on manipulation of ultra-fine powders such as ceramic powders, it is possible to protect workers against nano-aerosols by implementing existing solutions of today (as assessed in Deliverable D 7.4.2). The same solutions could also be applied when using ultra-fine powders for the preparation of inks to be deposited onto the ceramic substrates. These results have to be taken into account for the industrial tools (in line with SP5 activity) in order to insure the protection of the persons around the equipments.

In summary SP7 has been very successful with lots of new research results and guidance for future realisation of roll-to-roll in-process metrology and inspection based on IR-technique for ceramic tapes and embedded structures in them.

SP8: Exploitation, Dissemination and Training within the MULTILAYER project

The importance of exploitation, dissemination and training was formalised in the MULTILAYER project by including the activities within a separate sub-project. Exploitation was concerned with protecting the intellectual property arising from the project and continuously monitoring and updating the considerations of companies on the exploitable technologies and products developed within the project. Dissemination activities were designed for business and application sectors, technology providers and academic communities. Training involved the exchange of knowledge between process specialists through the development and operation of a training programme.

Exploitation

During the full duration of the project, a continuous work has been made on the preparation of the exploitation of the results. At month 6, an exploitation seminar has been organized just after the 6month review meeting. It allowed to identify results which have been followed during the project. Between this seminar and the final meeting (48month meeting), some results have disappeared and some have appeared. All this activity on exploitation has been regularly reported within deliverables D8.1.4 (review annually).

18 results have been finally reported concerning all the activity of the project (not only related to the demonstrators developed). Among these 18 results, we imagine to make commercialization of 13 of them (refer to the chapter on Exploitation).

Dissemination

The decisions on which information could be disseminated were made following discussions at six-monthly project meetings covering progress made, new findings and their dissemination within the consortium. Suitable vehicles for dissemination were developed:

MULTILAYER project web-site:

Two web sites have been used during the project. A CEA internal web-site, e-Doc, was used for document archiving, including presentations given at progress meetings and minutes of meetings. For this web-site access to material was restricted to MULTILAYER consortium members. The other web presence was on the 4M web site and the open site was oriented to interest from outside of the consortium. Both these web sites have been effective for internal and external aspects to the project.

The success of disseminating information on the MULTILAYER project can be assessed from the written publicity made available outside of the consortium during the course of the project. Such documents included:

- More than 48 publications already published or submitted to journals or conference proceedings
- Six patents submitted with two of these already accepted
- More than 90 oral presentations on aspects of the project.
- Six posters describing the activities and objectives of the MULTILAYER project.
- Six newsletters were produced during the project which described the progress made at different stages. The newsletters were given to members of the User Group as a matter of course
- One MULTILAYER flyer was designed and printed and distributed to companies, work-shops and conferences.

User Group:
The establishment of a User Group, potentially interested in the technology being developed was able to provide feed-back to the consortium on the Technology Readiness Level (TRL) for the technology being developed.. More than 20 members were identified as interested by the results of the project.

Training:
Training was undertaken both within and external to the consortium. An important goal was to increase the skills and interest in the technology of young scientists and engineers in ceramic printing and associated technologies. The high involvement of consortium members starting out on their careers can be assessed by the number of qualifications obtained by student studying topics within the framework of the MULTILAYER project. Thirty-two students obtained qualifications as a result of the project. Their studies we enhanced by the opportunity to visit other laboratories within the consortium, sometimes for extended periods of study. More than 14 such visits were undertaken.

Technical workshops:
Workshops were organised coincident with project progress meetings. The topic for the workshops was determined by the technology development status at the time of the meeting. These workshops proved an excellent format for the discussions of particular technical issues. Six workshops were held open outside of the consortium. To communicate MULTILAYER results outside of the consortium partners participated in MULTILAYER Special Sessions within two 4M conferences (4M 2010, 4M2011 and 4M2012)

Potential Impact:

Increasing European competitiveness and its economic impact

The MULTILAYER project set up an efficient mass production method for microdevices enabling fabrication series over a million units. This process is cost-effective due to the combination of shaping and mounting procedure in one step and will reveal a high added value due to high complexity, increased accuracy of the multi-material, and multi-functional products. By using ceramic tape technology, the manufacturing processes can be configured continuously and with a high level of automation. Both factors implicate potentials for cost-effective production. Subsequent processes of structuring and lamination allows a high flexibility concerning design of the ceramic component and the potentials of cost-efficiency and high flexibility allow a fast production on demand for diverse micro-structured parts from small batches to high number of pieces:

Microwave components for Tera-Hertz applications (OMNISYS): The current use for THz technology is very limited due to the cost of building such systems where the waveguides are drawn as pipes in a process industry. With required precision these components are only possible to use in high end applications such as some space or military application. The impact of the technology in this project will dramatically reduce the cost of such system by building them in a way that is more similar to how other microelectronic devices are built. The ultimate market for THz technology in a near future is where each car will need several THz microwave components for a car anti crash radar, for short range communications with road installations (system for paying for road access, systems for information about congestions, road works detours and varying speed limits) for automatic update and communication with other cars (anti-collision, anti-congestion systems). Future security systems for terrorist surveillance or low intensity conflicts will need arrays of many detectors working in the THz range. It is well since a long time that the only reliable systems for remote detection that are not influenced by rain or fog are radar which means microwave. To use radar at short range to monitor people you need very high frequencies for two reasons. One is to have a safe system that does not expose people to radiation. At THz frequencies the electromagnetic radiation has very low penetration into any object (in the micrometer range). The other reason is that there is already a shortage for frequencies for communication without interference with other systems. THz gives access a new unoccupied frequency band and since the transmission of wave at this frequencies is very short range. There will be a large number of free frequencies at any location.

Future consumer products will have much more intelligence built into them and this will also require more local communication to implement new wireless function. All this adds up to a very large potential market for a THz technology that can be produced as efficiently and cheaply as today microelectronics.

Cooler for high-brightness LEDs (CRF): In the automotive application field, the economic impact of the MULTILAYER project is related to the fabrication of low cost substrates for high-brightness LEDs (HB-LEDs) developed by CRF and KeraNor. Such devices have a big advantage to reduce the size of the light when compared to traditional bulbs. However, LED's have the disadvantage to heat in service. The overall market is forecast to grow at an average annual rate of 21% to reach 4.7 billion dollars in 2007 (or 3,6 billion EUROS). Meanwhile, the market for HB-LEDs in illumination is forecast to grow at 44% per year, double the overall rate, to reach 520 million dollars in 2007 (or 400 millions EUROS). The most significant applications now being addressed by high-brightness LEDs include electronic signs, automotive lighting (from front light, taillight and courtesy lighting systems to dashboard), and traffic signals. The improved thermal properties of composite proposed by MULTILAYER represent a crucial improvement to develop a simpler and less expensive heat dissipation design resulting in a longer device lifetime. Moreover the coupling between these new substrates and the direct integration of LED sources shows a number of advantages and innovative features, such us low cost, modularity, miniaturization, high external efficiency and conformability. The approach proposed in MULTILAYER demonstrated that it will increase the speeding up of the penetration of LED technology in a wider range of key market segments developing cooler substrate at low cost, conformable and compact. The production of the ceramic cooler will be further developed and optimised by KeraNor, while the take-up for the automotive will be driven by CRF, through Magneti Marelli Group, 100% owned by Fiat Group. It is also expected that upon successful completion of this project, more market opportunities will actually open up further fostering the growth of the LED market.

Thermoelectric device for building management (LEGRAND): In the field of building management there is more and more emphasis on intelligent processing for security and energy saving. This leads to increase the number of needed sensors in many places. To avoid using wires, those sensors or commands will send information by radio transmission techniques and these devices are powered by batteries. There is a strong requirement to avoid the use of batteries for two mains reasons: environment, and maintenance. In the field of office building there is the strong requirement to avoid any maintenance of lighting control device before a complete reorganisation of the area for example in an office open space. The cost of a punctual intervention in an office is considered almost the same as the change of all batteries of the area. An integrated 3D thermoelectric generator is quite a complex device to manufacture, and will only be economically viable if cost efficient processes like MULTILAYER are developed. In the project, it has been demonstrated that the technology is credible even the power produced is limit to imagine immediately the industrialization of the technology.

Micro fluidic component (BPE): Micro fluidic components will address the market of energy industry, chemical industry and will have a real impact on the safety of the reaction and will allow to reduce the time to market and allow the production of new more efficient energy and chemicals/drugs with a shorter time, the market size is several millions of units.

Ceramic inserts for embossing tools to be applied for micro optic components (BPE): These inserts will improve the cost effectiveness of the manufacturing processes to produce light guiding structures. The foreseen application of the developed tools will target refractive and diffractive applications for light guiding systems of day light, laser light and other certain radiation wave lengths. BPE expects an increase of the environmental protection and energy savings. Several millions of units have to be produced in case of technical success. The new products could advantageously replace existing day light lighting systems.

Fluidic MLC-based sensor for medical applications (MSE): 3D Structures like micro channels and cavities are needed in the field of fluidic medical applications. The sensor can be used to detect the flow, pressure or electro-chemical reactions. It is also necessary to connect the device to an outer media rail with suitable 3D connections. To realise small channels and cavities for high volume and low cost devices it is necessary to establish a high throughput technology like the two key technologies embossing or laser structuring. To print the metallisation for the electrodes on the base of the channels the standard screen printing process could not be used. Due to this reason a contact less process like the ink jet technology is needed or the screen printing process has to be modified in a sufficient way. To realise this applicable technologies, suitable tapes (compressible, embossable) and compatible pastes (inks) are needed. The expectation for this fluidic medical sensor is that a one time usable device is generated at a low price for different applications depending of the type of measurement with different sensoring pasts. The advantage should be that an easy coupling to the evaluation electronic device is provided and the sterilisation after use is not necessary any more.

For the realisation of this project the competence of a variety of partners is necessary. These types of partners are spread out to whole Europe; therefore a European approach of this project was mandatory.

The MULTILAYER project will not only provide EU micro devices manufacturer with a cost efficient manufacturing process, but also improve the competitiveness of technology providers of the process chain (KERANOR: tape manufacturer, KMS: gravure printing development , ALTATECH: inkjet equipment). Often the new technology developed with MULTILAYER can also be used in other sectors. For instance, in the case of quality control by inspection of ceramic multi-layers, it is indeed very similar to inspection of printed papers. Techniques developed in this project might therefore find applications at printing companies as well as in the paper and pulp industry.

Reinforcing the European knowledge base – European approach

The MULTILAYER consortium is composed of 19 partners from France, Sweden, Germany, Italy, United Kingdom, Norway, and Poland. Each partner has been selected due to its specific expertise, and considering the highly innovative aspect of the project, such a partnership would not have been possible to set up on a national basis. MULTILAYER will contribute to the strengthening of common European activities by bringing together unique European expertise in the µmanufacturing area.

The project has developed the field of ceramic processing. Ceramics are key components in new products that give better functionality effectiveness and wear resistance. The new understanding of drying of thin layers that we developed has a great impact of many other fields. The processing of concentrated nanoparticle suspensions is a general problem the needs to be solved to be able to develop practical use of new nano-based products. The results of the project will promote further research studies in the field of tape technology also with respect to other applications. The production of ceramic membranes by tape technology can gain a positive impact regarding cost-efficiency fabrication.

The project has furthermore allowed opportunities to gather new knowledge on the handling of large limp structures with micro specimens on the surface without harming the surface. A wide range of markets can be addressed by the developments made in the project. The developments can for example address all the markets of non-silicon microsystems and could be hybridized with CMOS technology to offer new materials in Microsystems. Display systems could for example benefit from these technologies as well as highly integrated solar cells or highly efficient micro sources of energy (micro fuel cell SOFC) or even large/thin SOFC. The acquired knowledge on process automation will affect other fields such as aeronautics industry. Production methods developed within the project can offer new opportunities for other products in high temperature applications. The automotive industry will also be affected since new and compact products can be developed using the automated layer technique.

The MULTILAYER project in not primary targeted to replace current LTCC technology. In spite of this the MULTILAYER project addresses some of the most important industrial demands for future development of this technique such as: reliable high definition printing, handling of higher thermal loads, higher accuracy in post processing, integration of a wider range of materials and better understanding of cracking and warping problems.

Associated Community societal objectives

Environmental impact:
Aqueous based tape casting processes are environmentally-friendly and they have also positive health-aspects for employees in comparison with the use of toxic organic solvents and yields to a highly positive environmental impact. According to RoHS (directive 2002/95/EG) the application of the heavy metals lead and cadmium in glasses is still allowed in cases where still no equivalent materials for a replacement exist. Proceeding research and development supports the attempt of this directive to avoid further use of these heavy metals in glasses for electric and electronic equipment. As a consequence minimised heavy metal contents in these devices have beneficial impacts on their recycling processes and will also decrease the deleterious effects on the employees of recycling companies. Additionally the environment pollution with heavy metals will be further decreased. This concerns not only the recycling process but also regions of the manufacturing route of these products as the glass melting process, the grinding of the glass frits or the joining and soldering process at elevated temperatures.

Savings in energy / material use:
Among the applications targeted by the MULTILAYER project, 2 of them are directly linked to the rationale use of energy:
Thermoelectric device (Legrand): detection of open doors or windows by self powered thermoelectric energy sensors is a key issue for energy management. Thermoelectric energy source could be of great interest for retrofitted market for wireless detection.

Cooler for automotive lighting system (CRF): the improved thermal properties of the new substrates for LEDs lighting systems will lead to a reduction in volume/thickness and increasing of lifetime of the devices resulting in reduced plastic consumption and environmental impact. Moreover, the energy saving related to LEDs, respect to the incandescent light, will also contribute to the preservation of natural resources tacking into account the huge expected penetration of LEDs systems by 2008 (up to 60% into the lighting market).

Moreover, development of efficient in-line quality control (such as been developed) will prevent material waste and immediate correction of manufacturing processes, before it goes out of control and produces scrap. By developing new tooling techniques, the MULTILAYER project will enable to cut the amount of materials required to produce a component.

Employment:
The MULTILAYER outputs will contribute to diffuse a novel approach to the manufacture of microsystems. The cost effectiveness of the approach is expected to foster the penetration of new devices into key markets. The opening-up of new market sectors is expected to significantly increase the employment opportunities in existing European companies and promoting the birth of new high-tech companies. Further, the number of people that will have the opportunity to buy/benefit from high-tech products at low price (display systems, car industry ...) will increase.

As an example, the results of the MULTILAYER project are expected to impact CRF at different levels. The first is the expected growth of the Micro & Nano Technology group at FIAT Research Center (currently composed by 40 researchers) to more than 60 high knowledge researchers working in the transferring of new processes, materials and devices to the different transportation sectors (FIAT Auto, IVECO, CNH, Magneti Marelli). The second very important aspects related to MULTILAYER is the increasing of the knowledge internally in the FIAT group allowing the increasing of the ratio internal/outsourced work with a related increasing of people employed inside the group in the field of materials and technologies for displays/HMI of several hundreds of units. Currently at Magneti Marelli Automotive Lighting more than 10000 people are involved in the fabrication and assembling of front and rear lighting systems. The development of new materials and the optimization of the standard technologies will allow Magneti Marelli to bring internally the majority of the process to fabricate such devices with resulting increasing of employment in the range of 15-20% in the next 5 years.

During the project, a list of 18 results that can be exploited has been identified. Among them, 13 will lead probably to a future industrialization a short or medium term.
The exploitation of each of them will contribute to impact the number of job created.

List of Websites:

http://multilayer.4m-association.org/