Final publishable report

1 Executive Summary

Lithography based additive manufacturing technologies (AMTs) allow the creation of complex, 3D parts with arbitrary shape, excellent surface quality, good feature resolution and high precision in just a few process steps. Recent developments in high performing light sources; i.e. Digital Light Projectors (DLPs) and ultra-short pulsed lasers led to AMTs development into high performing standardized products; robust economical and ready for industrial use. Together with recent advancements in the field of photocurable resins, lithography based AMTs have grown out of being only prototyping techniques. Quite contrary, several AM parts may outperform goods fabricated by conventional technologies.

The project photopolymers customized for additive manufacturing (PHOCAM) addresses two promising lithography based AMTs, Digital Light Processing (DLP) and Two-Photon Polymerization (2PP). Both of these technologies overcome two major obstacles impeding AMTs from a broader use; insufficient mechanical properties and low resolution.

Facing mechanical properties, DLP enables the fabrication of arbitrary shaped parts made of silicon nitride and aluminium oxide ceramics with up to 99.6% of theoretical density. Excellent properties (>500 MPa biaxial bending strength), high resolution (25 µm) and excellent surface quality were achieved on geometries that cannot be manufactured otherwise. Foundry cores for turbine components and yarn guides for textile industry were fabricated. Consequently, a new business line was established in the course of the project.

Covering the resolution issue, 2PP, the second key technology of the PHOCAM project, facilitated the fabrication of mm to cm sized constructs at features below 100 nm resolution. Optimised material systems and setups permit the fabrication of high-aspects (>90:1), the highest building speeds reported (>500 mm/s) and customized mechanical and biological properties. Moulds for computer tomography devices and ossicular replacements were successfully built and tested.

The research and development of the PHOCAM project renders parts produced with both engaged technologies competitive to existing devices. Yet, potential AMT interested parties face serious challenges; the comparability to existing technologies is complicated; there is no expertise on building an organisation around AM and specific skills are necessary preparing computer designs for manufacturing. Within PHOCAM, a supply chain was modelled around the DLP technology, including all stakeholders from suppliers and manufactures to customers. Quality standards were defined for easy comparability of AMT parts and software tools were developed allowing easy handling of designs files, their repairing and job-file preparation. An online platform was established acting as a form of e-commerce for AMT parts. Designs are uploaded and customers automatically receive relevant quotes from manufacturers.

Dissemination and exploitation of PHOCAM activities was focused on industrial translation. A start-up company (Lithoz GmbH) was founded which now commercializes PHOCAM technology in the field of engineering ceramics. The successful PHOCAM activities in the field of innovative light engines and textile machinery components also led to industrially used products.

2 Summary description of project context and objectives

Additive manufacturing technologies (AM) is an automated technique for direct conversion of 3D computer aided designs into physical objects using a variety of approaches. AM technologies are simple and flexible processes that allow creating very complex and customised 3D objects in just a few process steps. AMTs are the only manufacturing technologies, where the material properties of the object evolve simultaneously to its geometry during the fabrication. No additional tools are required. These prospects, together with the fast increasing availability and the fast decline in price of AMT machines, triggered off a real hype for this fabrication technology.

The catalyst for the hype of AM is the envisaged access to goods customized according to a personal design. Instead of buying given products from a bulk created by large-scale manufacturing, people foresee buying said parts from a company that will create single ones through AM. The fast growing accessibility of AM give companies the capabilities to realise their ideas without necessarily having the infrastructure in place.

Yet, despite the rapid development in AMT and it's credited highly disruptive aspect, it has hardly found its way to mainstream use. Apart from few exceptions, most AM applications are related to its initial purpose and terminology: rapid prototyping, the quickly creation of simple objects meaningful for a particular related product, parts that support the design process without being necessarily applicable.

After roughly 30 years of AM, challenges preventing related technologies from a broader use remain. For some applications, where the obtainable complexity would be beneficial, AMs cannot meet the required material properties. For others, where AMT's 3D capabilities would lead to increased performance and functionality, the feature resolution is insufficient.

Within the project Photopolymers Customized for Additive Manufacturing (PHOCAM), the consortium relied on two core-technologies capable of overcoming these issues. One one hand, Digital Light Processing (DLP) facilitates the fabrication of arbitrary shaped ceramic 3D structures, at high feature resolution and directly in accordance to a CAD. Novel DLP based AM machines are presented that integrate high performing digital light projectors and customised optics. Dense (>99.5% relative density) ceramic parts with dimensions of 80x40x110 mm^3 and down to 25 µm feature resolution were built at speeds as high as 8 vertical millimetre per hour. Photocurable materials with up to 50% solid loading of alumina oxide and silicon nitride powder were developed. The material systems presented not only facilitate the fabrication of parts with smooth surfaces, hollows and undercuts but also favour excellent material properties such as biaxial bending strengths of above 500 MPa. Hence, the findings of the consortium enable this technology to add excellent material properties to the advantages of AMT.

The second lithography based AMT the consortium relies on is two-photon polymerisation (2PP). It is shown that 2PP allows fabricating features below 100 nm while still permitting the fabrication of parts in the mm to cm region. Optimised material systems and novel setups were developed to meet high demanding geometry requirements (high-aspect ratios >90:1), comparably high building speeds and different mechanical and biological properties. It is shown that this technology adds high resolution and unique 3D capabilities to the advantages of AM.

Fabricating, testing and optimizing parts for various applications, the PHOCAM consortium has shown that these technologies offer much more than simply creating non-applicable prototypes. Ceramic parts fabricated by DLP can be used as turbine blades and yarn guides that were evaluated and tested during the project. 2PP can produce high aspect moulds for final grid fabrication for computer tomography devices. Furthermore, it offers possibilities to fabricate highly customized total ossicular replacement prosthesis.

These findings show that AM and the presented technologies in particular, have grown out of just being non-functional prototyping technologies. They are competitive processes that deserve a place on the market. However, only few are aware of the potential technological advantages and the customer benefits offered. Although potential customers and manufacturers might be better off turning to these novel fabrication techniques, they rather stick to less attractive but established and widely used processes due to insufficient know-how, comparability of technologies, willingness to switch and trust.

To address the comparability issue, the consortium presents a quality management concept intending to ease the comparability between different AMTs as well as between AMTs and conventional manufacturing technologies. On the one hand, this concept should make the AMT process more reliable and more applicable for industry. On the other hand, it AMT benefits get transparent for potential interested parties.

To address the know-how issue, the consortium developed novel software tools to ease the handling of AM machines. The tools provide easy modification and preparation of computer-aided designs, sophisticated automated repair of damaged files and their straightforward preparation for manufacturing. As almost all AMTs work on a similar layer-by-layer principle, the presented tools are quite universal to a variety of machines.

As both presented technologies are not yet applied in industry, there is no expertise on the development of an organisation around an AMT, which might hinder a supplier from investing. The consortium models a whole AM supply chain defining processes and stakeholders from the order to the final product. An organisational guideline, universal to AM parts is presented. Based on case studies, conventional production technologies are compared to AMTs over the whole supply chain to assess the differences in respect to costs, flexibility, quality and delivery time.

To provide access of AMT parts to a wider public, the consortium presents a web-based platform allowing the communication between costumers, requiring AMT parts and the manufacturers, possessing different technologies and providing different services. The platform ensures the complete ordering process from uploading the CAD model to payment procedures and can act as a form of electronic commerce, where customers can buy parts over the internet without any intermediary service leading to potential reduction of prices and delivery times and thus more competitive AMT products.

The PHOCAM consortium promoted the research results obtained within PHOCAM with the goal to establish industrial interest groups. Additionally, the PHOCAM consortium established an IMS MTP action with partners from EU, USA and Switzerland. These activities successfully helped to establish additional industrial links beyond the PHOCAM core consortium. Further dissemination activities were related to trade fairs (Rapidtech, Euromold, Photonics West) were PHOCAM partners initiated a booth or gave highlighted presentations. The PHOCAM consortium was also very active in academic dissemination activities.9 peer reviewed journal papers were published, in addition to 7 contributions to proceedings. PHOCAM partners gave 15 talks presenting results obtained within PHOCAM and 1 best paper prize was awarded to one of those presentations. Overall, 8 students got their academic degrees (PhD, MSC and BSc) from work performed within PHOCAM.

In addition, one patent application originating from PHOCAM research is pending with TU Wien as patent owner.

3 Results

3.1 WP2 Software for supply chain management

During the project, a prototype web platform for DLP and 2PP processes has been built which provides a complete customer workflow from geometric CAD model upload to quote comparison, part ordering and payment.

The uploaded model is automatically checked for errors and repaired if necessary and possible. The manufacturer chosen by the customer can automatically create support structures and DLP process specific slicing jobfile directly usable for printing. The role of PHOCAM platform in the supply chain is shown in Figure 1.

Web interface

The user interface of the PHOCAM platform is a web application (Figure 2) where the customer can register and then log in after a successful registration. After the login, the customer can upload her/his CAD models (typically STL models), with a selection of requirements which need to be fulfilled by the printers defined into the platform — technology (currently DLP and 2PP), material, quality. The CAD model is saved into the platform data base, automatically verified for correctness for production and quotes are calculated for printing the model on a suitable subset of printers defined.

After the customer has chosen a manufacturer and a printer and proceeds with the order, the manufacturer is given access to the CAD model. At this step the manufacturer can either use the automatic operations available in the platform (support structure generation, slicing and jobfile generation) or she/he can download the model and manually prepare the model for printing. Manual work may be sometimes needed to, e.g., control shrinkage of specific models. For manual tasks the manufacturer can use her/his favorite computer software, like DeskArtes 3Data Expert.

Quote calculation

After the customer has uploaded a model proper for printing, a list of quotes is automatically generated for all printers which fulfill the technology, quality and material requirements chosen by the customer, and which have a printing area big enough to contain the desired number of copies of the model.

For each quote, the following information is shown: approximate total time from order to delivery, total cost, information about the printer and manufacturer. From this list the customer can choose the most suitable one based on cost, time, geographic location, etc. and contact the manufacturer for further processing and, eventually, a delivered printed model (Figure 3).

For the prototype implementation, the “broker” approach was chosen. This means that the web platform has an active role only when the customer is choosing the manufacturer from whom she/he decides to order the print job. After an order has been initiated, all communication between the customer and the manufacturer takes place either outside the PHOCAM platform, or using messages within the platform but not involving the platform itself.

“Manufacturer area of conflict” and a distributed approach to quote calculation

In a web application where multiple manufacturers provide competing quotes for the production of customer's model, an **area of conflict** arises: manufacturers are unwilling to give their confidential production information to the web application provider. Further, to be able to give an accurate quote based on real-time supply chain data, the manufacturers need access to their in-house information systems.

Within the PHOCAM platform, the solution to the area of conflict is distributed quote calculation. The calculation algorithms can either be stored into the web platform or, as the preferred method, accessed as scripts from the manufacturers' own web site. Communication between the platform and the quote calculation script is implemented with a mutually agreed, encrypted parameter format. Verification of message origin is also checked on both the web platform and the manufacturer site script (Figure 4).

In case the manufacturer wants to test the platform, or does not have a suitable web server and agrees to have the production data stored into the platform data base, the quote calculation script can also be set up locally on the PHOCAM platform. From the point of view of the platform the implementation is similar to the distributed approach, including message encryption and verification of origin.

3D model analysis and preparation

A necessary part of the platform, the 3D CAD model upload, analysis, repair and print preparation is handled by the **repair module**, a specialized version of the DeskArtes 3Data Expert software. In the PHOCAM platform architecture the repair module can reside either in the same physical server as the user interface and the data base modules, or it can be installed in a separate server, for example for a better control of processor work load.

The repair module reads the CAD model from the PHOCAM data base, verifies the model, repairs it in case any problems have found during the verification, and saves the repaired model back into the data base (with a reference to the original CAD model), along with sufficient information about the model properties for quote calculation and printing (mainly volume, dimensions and possible error data).

Later, after receiving the job order from the customer, the manufacturer can use the automatic support structure creation and jobfile generation tools of the platform or download the model and proceed with preparing the model for printing with the normal 3Data Expert version (Figure 5)

During the PHOCAM project, the 3Data Expert repair software has been significantly developed. Some main improvements, which will also be available to the 3Data Expert user base, are a 64-bit implementation (allowing handling of substantially larger models than the 32-bit version), enhanced support structure generation and efficient fixing of complex or badly corrupted topology.

3.2 WP3 Materials development

Lithography-based AMTs are layered manufacturing approaches, where liquid photopolymerizable, i.e. light-curable resins are solidified selectively with ultraviolet, visible or infrared light. The aim of WP3 was to design and optimize these photopolymerizable resins to achieve parts with mechanical properties, precision and surface quality that fit the requirements of PHOCAM's end users (WP6). Hence, for Digital Light Processing (DLP), suitable slurries, i.e. ceramic powders dispersed in a liquid photosensitive organic system had to be developed. For two-photon-polymerization, curable systems that can be processed at very high resolution had to be found.

Introduction

Projector mask processes use a video beamer to image one cross-section of the desired part onto the surface of a photosensitive resin to be exposed. In this technology, a digital light projector (DLP), consisting of an array of micro-mirrors (digital mirror device, DMD), projects a 2D pixel-pattern onto the material. Depending on the focusing objective and the amount of micro-mirrors, the resolution can be up to 40 µm laterally and 15 µm in Z (doi: 10.1002/adem.201200010). In Phocam, we use this technique to process formulations filled with ceramic particles (Figure 6).

These photocurable resins consist of (1) different ceramic powders, (2) monomers and crosslinkers that can be polymerized, i.e. solidified, (3) solvents and (4) dispersing agents that alter the amount of ceramic powder addable to the system (solid loading) and finally (5) a photoinitiator that starts the polymerization, i.e. the solidification of the monomers upon illumination with light.

After processing by means of DLP, the organics get solid; a "green part" is obtained that consists of an organic matrix filled with ceramic particles. To obtain fully dense ceramics, the part now has to undergo thermal treatment. First, in the drying process, one evaporates residual diluents. In debinding, the organic matrix decomposes at temperatures between room temperature and 500°C. This procedure is finished by a final sintering step at high temperatures (Figure 7). This way, the fabrication of fully dense ceramic AM parts is facilitated. Though a variety of different ceramic materials can be processed in this manner (10.1002/adem.201200010), only two types were relevant for PHOCAM. Alumina oxide was used for the fabrication of yarn guides used in textile machinery applications. Silicon nitride parts were required for targeted applications including ceramic foundry cores and turbine blade.

In the following two sections, the consortium reports on work done optimising these two ceramic materials for their intended purposes.

3.2.1 Aluminium Oxide Slurries

Preparation

A mixture of commercially available polyfunctional acrylate-based monomers (15–25 g) was used as the reactive system. By adding 0.05 g of a highly reactive photoinitiator, 1 g of a dispersant, an absorber and 6–10 g of polypropylene glycol as a non-reactive diluent, the organic premix was obtained. To achieve a homogeneous mixture, the organic components were stirred magnetically at room temperature. Alumina powder with particle size in the range of 0.2-2 µm (BRO) was used. A solid loading of 50 vol% of ceramics could be achieved. The viscosity was adjusted to 7-20 Pa s in order to be processable in DLP based AMT.

Results

Representative green bodies and sintered parts fabricated by lithography based AMT have been investigated. All parts were seen to exhibit adequate shape and dimension accuracy (Figure 8). Density, mechanical strength and a brief comparison to conventional manufacturing processes, are summarized in Table 1. Fractography analysis was used to investigate the microstructure of the fracture surfaces of sintered bodies.

Viscosity: For the successful processing of ceramic filled resins with the presented DLP system, a maximum viscosity of approximately 20Pa•s is allowed. Alumina's viscosity, in contrast to that of other ceramics, shows clear shear-thinning effects. Regardless of the high starting viscosity at low shear rates, the viscosity of the presented alumina-filled slurry at the relevant shear rates during the DLP process is sufficiently low.

Density Measurements: of the sintered samples were performed by using the Archimedes method. A density of 3.97g/cm³ was achieved which corresponds to 99.6% of the theoretical density (**deliverable 3.1**). Within PHOCAM, a homogeneous dense microstructure could be achieved on alumina samples.

Mechanical properties: The biaxial bending testing method was used to determine the mechanical properties of the sintered parts. Additionally, 3-point-bending test bars in different orientations were manufactured to assess possible anisotropic effects that could be inherent in the applied layer-by-layer based DLP-based fabrication process. The alumina specimens fabricated showed a flexural strength of 516 MPa (**deliverable 3.1**), respectively a Weibull modulus of 13. These results may compete with the flexural strength of conventionally processed alumina materials (see Table 1) confirming a sufficient densification of the alumina samples and furthermore the absence of e.g. large voids or defects (microcracks) within the sintered microstructures.

3.2.2 Silicon Nitride

Preparation

In the first step, different ceramic powders were tested according to their suitability for DLP based AMT. Initially, the organic composition of Al_2O_3 formulations was used with the the new type of ceramic powders.

Starting point was formulation consisting of the organic composition from an Al_2O_3 reference slurry. The ceramic powder was a mixture between Silicon Nitride (Si_3O_4), Aluminum Oxide (Al_2O_3) and Yttrium Oxide (Y_2O_3). Two different slurries, varying in their solid loading were prepared. To increase the solid loading, improve the processability of the slurry and the final parts' quality, other base monomers and solvents were used in the course of the investigations. Three different slurries, varying in their solid loadings were prepared.

Structuring results

To ensure attachment between single layers, the layer thickness was adjusted to 25 µm. TS-29 turned out as a promising resin. Green bodies with high resolution were fabricated (see Figure 9). Under- and overexposure problems, seen in previous Silicon Nitride slurries were reduced. Selecting the powder type and composistion the high resolution 3D parts could be obtained.
However, the required solid loadings for pursuing a successful sintering process were not achieved. For obtaining fully dens ceramic silicon nitride parts, further research is needed.

3.2.3 Selection of 2PP resin

Using high-performance 2PP-photoinitiators it should be possible to increase the processing speed of 2PP, which will significantly increase its productivity to approach an industrially significant level. In order to assess the suitability of photoinitiators and photopolymer systems for 2PP microfabrication, methods have to be established which allow screening of the efficiency of monomer-initiator combinations in the context of high throughput, large processing window and geometric quality of the final parts. During the first project year two different methods for evaluating 2PP-structures were developed. The first method is based on optical assessment and is giving immediate response about the applicability of the material for 2PP. An example for the comparison of two resins by optical assessment is given in Figure 10. The second method involves the measurement of the double-bond conversion within the fabricated 2PP-structures, it provides quantifiable results about the efficiency of the photoinitiator with a given monomer system, and thus allows to compare different photopolymers in a quantitative way (Figure 11). In parallel an attempt to improve the resolution of the 2PP technology by tailoring the selected material composition was made. With the help of additives aimed at increasing the degree of cross-linking the resolution was greatly improved.

Two groups of resins were analyzed: Organic resins with photoinitiators developed at TU Wien and inorganic-organic hybrid resins with commercial photoinitiators. It turned out that the organic resins exhibit a significantly larger processing window. In contrast, hybrid resins have a smaller processing window, but lead to structures with higher resolution. Sub-100nm features could only be achieved with hybrid resins.

Based on the observed results the hybrid organic-inorganic materials will be accepted as the basic materials system in the framework of this project, since the focus lies on high-resolution structures with large aspect-ratios.

3.3 WP4 Lithography based additive manufacturing systems

3.3.1 Hardware for 2PP-based manufacturing with new autofocus system

An autofocus module was successfully integrated and operated in the two-photon polymerisation setup (Figure 12). It sends a probe beam through the objective onto the sample and detects the reflected light on the inverse path. The wavelength of the probe laser was chosen in a way that is does neither affect the photopolymer nor interfere with the sample illuminations. The integration requires a fine tuned adjustment of objective, camera, laser divergence and autofocus to match them all. It was found that a data acquisition approach with sample scanning before production provides valuable support in substrate defect detection and process automation.

The built height could be dramatically increased by the widened objective working (WOW) range technique. This technique is based on moving the objective within a liquid photo resist, and it allows overcoming the limitations of the working distance of the objective used. The results shown in Figure 13 demonstrate a grid structure of 460 µm height written with an objective with a working distance of only 170µm. The image on the right demonstrates building of centimeter scale objects with the same technique. The results achieved in frame of this project were submitted in February 2013 for publication in Light: Science & Applications, Nature publishing group.

Summarizing, in this work package a build area of up to 100mm x 150mm was provided, the build height is even not limited by the working distance of the microscope objective used and may be 10mm or more. With a cross-linker enhanced Zr-hybrid material features of less than 100nm (62.5nm) could be demonstrated.

3.3.2 Hardware for ceramic processing using new LED based light engines

Introduction

Generally in AM, 3D objects are created by successively adding cross-sections of defined thickness on top of each other. In DLP based AM, these individual layers are fabricated using a DLP projector (light engine) in combination with a photosensitive resin (see section 3.2.1). When exposing this resin to light with a specific wavelength a spontaneous polymerization, i.e. the solidification of the material to a defined depth starts. The finished layer sticks to the computer driven building platform, which moves away from the surface. New liquid material is delivered underneath the solid layer and the illumination starts again. The procedure repeats until the desired solid object reaches its intended extent (Figure 14).

The heart of this technology, the DLP itself, is based on geometric matching masks that contain the information of the part geometry. The masks work like a slide; when illuminated, they produce a full-scale optical image of the part cross section. The accuracy of the fabricated part is determined by the precision with which the mask can be produced. The PHOCAM light engine (VIS) with its specially designed projection optics (INV) generates pictures using high performance LEDs as light source and a DMD chip (Digital Micromirror Device, Texas Instruments) as dynamic mask.

The aim of WP4, Task 4.2 was to provide a DLP-based system using LED-driven light engines with build size of 40x55x60 mm. This system should be capable of processing alumina- and silica based slurries at processing speeds of at least 5 vertical mm per hour. This system should be embedded in a software frame developed in WP2.
The second task was to design a second prototype with extended build volume.

Laboratory Prototype 1st generation

The heart of the prototype is a DLP projector, consisting of a 1080p DMD chip from Texas Instruments. This chip was non-commercial at the time of the prototype's completion. The resolution was 1920x1080 pixels. Using a high performing LED source allowed peak powers of 208,3 W/m^2 at 465,6 nm dominant wavelength. Patented tilting and coating devices as well as back illumination facilitated the processing of ceramic based slurries with high viscosities (<40 Pa s). Together with a 3.704x magnification objective, a pixel size of 40x40 µm^2 and a maximum building volume of 43 x 78 x 150 mm^3 was achieved. Processing speeds of up to 10 mm/h were possible.

Laboratory Prototype 2nd generation

A new equipment with extended build volume was developed. Several components of the system had to be adjusted or redesigned in order to fulfil the new requirements. A series of changes in the structure of the DLP system and improvements to the 1st prototype (Figure 15) led to the concept illustrated in Figure 16. Due to the lack of space, the coating system had to be changed to a linear one. All components were adapted to meet high stiffness requirements of the extended build-volume. VIS delivered a light engine based on a WUXGA DMD with a resolution of 1920x1200 pixels. For focusing, optics with bigger magnification ensured a 3 times larger X-Y- building volume of 115.2 x 64.8 x 160 µm^3 was achieved. Building speeds of upt to 8 vertical mm/h could be obtained.

For the sake of flexibility, the prototype was designed for easy change of optics. INV provided two objectives, one with 5,556x and one with -2,325x, leading to 60 µm^2 and 25 µm^2 pixel size, respectively. Hence, the system can be used for high resolution (25 µm) or large volume structuring with just minor adjustments. Table 2 summarizes the PHOCAM prototypes' specifications.

Software implementation

In section 3.1, software tools were presented that allow the completely automatic creation of a CAD file into DLP machine code. Over the PHOCAM platform, a ready-to use jobfile can be created that contains pictures (bmp) of the individual cross-section of the part and a jobfile, containing information on the sequence and process paramters (light intensity, illumination time,…). The prototypes are on the internet and have an own email client. Over the platform, jobs are directly sent to the printer. Over a VNC connection, the operator can start the machine over the internet. Besides re-filling new material, no direct interaction with the machine is required.

3.4 WP5 Light Sources

DLP system

This task for the research project PHOCAM is the development of projection systems that allow a certain level of exposure in a specified field for the photo polymerization with sufficient intensity. For such structuring projection systems it is favorable if the image plane is formed of individually switchable pixels. As suitable systems for controlling exposure, so-called light valve projectors are applicable.
With these systems, the light of a light source is influenced through appropriate arrays of individually switchable "light valves" so that it is depending on the switching position of each light valve to direct light into the image plane or absorb it at an appropriate point in the system.
Due to the need of short wavelengths at high intensity of light, light valves as switchable micromirrors (Digital Micromirror Device, DMD) are applicable.
Starting point of the development was the research of suitable, currently available key elements (light valve, light source) and to determine the size and fineness of the construction field produced with the proposed AMT test objects.
In the first phase it was decided to use the 1080p-DMD with 1920x1080 micro mirrors, each with 10.8 microns side length. In the second phase we were able to realize a light engine using a WUXGA DMD with 1920 x 1200 micro mirrors. .
At discussions with the project partners it was decided to adopt the lens with 60µm pixel size, which was designed in project phase one to be useable with the WUXGA DMD. This enables the manufacturing of demonstrator parts up to 82cm² base area. To enable the use of the PhlatLight PT120 as light source for the WUXGA (this LED has still the highest intensity and at the same time largely homogeneous radiation in the blue spectral range) the aspect ratio of the integrating rod was changed from 4,6 x 2,6 mm² to 4,6 x 2,9mm². The micro mirrors of the WUXGA - DMD have a tilt angle of + / -12 °, same as the 1080p - DMD. Since a significant challenge in the development of the projection system is the requirement of maximum achievable intensity, the resulting aperture angle can be utilized as much as possible.
By that the framework for the imaging system (illumination of the DMD) and for the projection lens is defined.
As it was at the development of the 1080p system, also the development of the WUXGA illumination system and the WUXGA imaging lenses could be started independently of each other. Basic criteria for the exposure (illumination) system are the light intensity and uniformity of the DMD illumination.
The demands on the projection lens are in addition to the light intensity and uniformity a flat image field, distortion free and with nearly diffraction-limited contrast.

In project phase one layer thicknesses of 50µm down to 15µm where be used. To enable the manufacturing of high resolution demonstrator parts it was decided to develop and built an imaging lens with 25µm pixel size too. As the minimal thickness of the layers is down to 15µm within the previous tests this gives the possibility to produce parts with uniform resolution in width and height. To be prepared for the use of newly developed UV-LED it was decided to design the lens useable also for near UV radiation (down to 360nm).

It was experienced, that even with the 40µm pixel lens it is not easy, to adjust the engine to the surface of the glass plate of the material vat accurately enough. And for the 25µm pixel lens it was expected to be even worse, because one cannot see this structure with unaided eye and the depth of focus becomes much smaller. So it was decided to develop a special lens to image the surface of the glass plate to some camera sensor. By use of this camera the projected DMD-image will be seen sharply only if it is focused into this plane. This lens was supplied with a lens holder, which allows positing it at every place within the new developed rectangular material vat without removing any part.
In anticipation of later necessity to produce parts with even higher resolution than with the 25µm imaging lens the optical design of a lens with 1:1 magnification was done. It is intended, that within some variations of lens distances (vario lens) image pixels of 10µm to 12,5µm can be imaged.
The development of the light sources involved two main parts, the design of the optics, done by In-Vision and the design of the electronics by Visitech.

In Figures 17 a - c the different developed optics are schown. The pictures demonstrate the optical layout and the mechanical housing of the Phase 1 optics (resolution 50 µm), the Phase 2 optics for extended build volume and the Phase 3 optics with higher resolution (25 µm). Also, the optical design of a lens system in the range of 1:1 magnification (pixel size 10 µm) is presented (Figure 17 d). Up to now we have only made the optical design but this puts us in position to react to a rush demand.

As mentioned above the other main part of the light engine besides the optics is the electronics. For the different light engines (Phases 1 – 3) the "electronics" comprises

1. A Texas Instruments DMD mounted on a supportive DMD electronics board designed and developed by VIS.
2. An electronics „Formatter Board“ based on Texas Instruments‘ Discovery 4100 DLP chip set, designed and developed by VIS, including an application Field Programmable Gate Array (FPGA) with dedicated application firmware (FW) developed by VIS to include USB interface to the signal source.
3. An LED monochrome light source based on Luminus‘ ble PT120 LEDs, implemented with integrator optics to collect the light as efficient as possible for the physical size of the DMD.
4. Illumination optics based on a new design by Visitech based on TIR prism and optimized for the physical size of the DMD and with an optomechanical interface suitable for the projection lens designed and developed by INV.
5. Power supply, mechanical housing, etc to make a complete stand-alone product.

Starting from the Phase 1 engine (1920 x 1080 pixels) new DLP electronics has been developed for higher resolution DMDs (Figure 18). Electronics for WUXGA (1920 x 1200 pixels) is finished in design and manufacturing. The design utilizes similar generic design as for the Phase 1 Light Engine, but Firmware to support the higher number of pixels, and thus higher data rates, have been developed.

New LED control and driver electronics for “Light Dosing” has been completed in design and manufacturing. Visitech’s Light Dosing™ technology ensures precise and long term stable light intensity by using optical feedback to calculate the appropriate light dose for each colour depth bit plane.
The new LED control and driver electronics is based on a new concept for digital control of the LED, for which VIS has applied for a patent. Further implementation and application of higher resolution DMDs depend on the providing of higher resolution DMDs by the producer to VIS.

2PP system - Selection of fs-Laser

A market screening for available femtosecond lasers was performed. The lasers should have suitable power (>200mW) and sufficiently short pulses (<100fs). Figure 19 shows average laser power versus pulse duration for selected laser models. In addition they should be reliable turnkey systems that require low maintenance. The price should be 50k€ or less. From a list of more than 200 laser models three notable models were identified:

- Toptica Femtofiber pro NIR, 100fs, 150mW, 80MHz, 45k€
- HighQ FemtoTRAIN IC-800-200, 70fs, 200mW, 80MHz, 55k€
- Femtosource Integral 50-300, 50fs, 300mW, 85MHz, 75k€

With respect to all specifications and the financial budget the HighQ FemtoTRAIN laser was recommended.

3.5 WP6 End user applications based on advanced ceramics

3.5.1 Advanced ceramics for customized products for textile machinery

In WP6 we refer to end user applications based on advanced ceramics. Metal oxides, especially aluminas and some zirconias had to be screened which are feasible for Phocam-feedstocks. Certain requirements had to be fulfilled. For textile guiding components, the presence of agglomerates caused poor surface smoothness and caused damage to filaments and capillary breaks. By making refinement of various processes to reduce the agglomerates in high purity alumina powder we stabilized the production as well as the product quality.

We found that high-efficient jet mills and wet medium agitation mills for nanoparticles are necessary to reach fully desagglomerated feedstocks. Generally speaking, the process of desagglomeration of powders must be done with a great deal of caution. Because the smaller the original particles are, the more care for avoiding both regeneration of agglomerates and contamination is required.

During progress of the project, textile parts had to be designed and build. After the first promising results of the physical parameters of the sintered alumina we selected textile processes where new components will be installed in future machines or are installed in state of the art textile machinery. These so called jets, nozzles, guides and oilers where designed in cooperation with customers in the enduser market (guides), with the help of an external expert (consultant for TD-jets) and with the OEMs (oilers etc..) and build on the optimised DLP machine.

Selection of components

After the first promising results concerning final density of alumina we could go on by designing the different jets and yarn guides. Bröll decided to pick 4 different levels and requirements of the components.

Oiler: This type of geometry and microdesign was used as key part for a comparison of DLP to LPIM and CIM. Of course in CIM, due to the immense cost of the mould, we considered already the more mature product design. We were able to test all three production lines under industrial conditions and found that we could cope with all three production methods to get comparable results concerning the required properties: homogenious preparation of a POY yarn. To show the typical process we used CAD of Oiler => STL => Silicon forming => feedstock of same material

=> debinding/sintering => analyse and compare this part with DLP part. (geometry, surface, physical data, tribological data, effect on yarn/component contact).

TD-Jets: Seven designs where developed which contributed to a further understanding of the interaction between airflow and yarn friction on this part made out of alumina. We conducted inhouse trials in respect to friction and air consumption.

Eyelet guide: Some designs where created and 2 were choosen which could help the carbon fiber industry to use ultra-low friction guides.

Vortex parts: Here we had the most challenging and complex parts. The original idea of the design came from a customer in Asia. We supported the customer by implementing this part in ceramics, but again the tribological conditions are different to metal. The bores were extremely difficult to manufacture in green or hard machining. Again the interaction between alumina and yarn and high turbulent air flow is of main importance. No faults at the bore outlet are allowed.

In all these selected parts the “up-to date” technology and economical effort would have been so immense that it would not have been possible to optimize, develop nor install such components.

Very important was the outcome of:

- evaluating the “natural” topography for suitability in textile processes
- defining, modifying and designing the surface topographies which reduce friction in contact with textiles.
- benchmarking the relevant results against CIM and LPIM component.

Testing of selected textile machinery parts, based on alumina, manufactured with the developed DLP, was the main task 6.1 in WP6: end user applications based on advanced ceramics.

But beforehand a few obstacles in respect to unreproducable distortion and slurry quality had to be overcome (Figures 20 and 21):

Other issues were:

- optimizing debinding and sintering to avoid delamination effects and other faults
- check of reproducability (3 to 6 parts of each design were manufactured and geometrical compared)
- post machining some crucial plains on certain jets to fulfill their running behaviour by drilling, grinding, polishing etc.
- study behavior of surface properties after finishing
- benchmark of jets against serial product

Optimizing debinding and sintering to avoid delamination effects and other faults

During the project we learned how to choose the manufacturing strategy to get the most accurate shape and topography in the crucial areas of the components. We could stabilize the feedstock manufacturing.

Delamination along the build-up slices has many causes. The interaction between used complex organics and debinding strategy in the green state is of main issue. Through experimental work and analysis of DTG, TGA and dilatometry the crucial time and temperature dependent factors for thin (< 3 mm wall thickness) and thick parts (< 10 mm wall thickness) could be extracted. We could adjust two special debinding cycles for each. If debinding works properly, sintering is no more a cause for delamination but for density, contamination and colour.

Check of reproducability

To check tolerances and deviations in geometry from part to part, three to six ceramic TD jets of each design were manufactured and geometrical compared (Figure 22).

The most important parameters were eyelet diameter, roundness and blow hole area for the relevant textile process parameters as well as energy consumption and some outer dimensions for the latter assembly with the protection housing (Figure 23).

The positive result of this analysis was, that the deviation of tolerances is no more bigger than with traditional manufacturing methods. We believe that this is due to the fact, that the build up process is rather free of stress – hardly any orientation in x/y-direction and adjustable z-component. The main deviation is most likely dependent on debinding and sintering parameters.

Post machining

Despite the fact that the geometry with DLP can be manufactured in an acceptable way, certain products need very sharp edges (radii < 0,05 mm), very round holes (dr/r < 0,01) or highly polished surfaces (Ra < 0,1 µm) which cannot be maintained in precision through the debinding and sintering processes.
Therefore these requirements can only be fulfilled by post machining namely grinding, drilling and polishing with diamond tools.

Again it could be shown that with a perfect produced DLP ceramic part the post machining can be realized in the same way as a part produced with ceramic injection moulding or uniaxial pressing.
We expected polishing as most crucial but in fact the measured density is the most influencing factor on the reachable quality in roughness and brightness on the polished surface. When the density of the ceramic reached 99,5 % of theoretical density - which was possible - the quality of the polished surface was absolutely satisfying (Figure 24).

Behavior of surface properties after finishing

To evaluate the very relevant parameter “friction” for the manufactured components we measured this against 9 different yarns and more than 10 topographies. Some of these results are foreseeable for an expert through measurements of roughness and microscopical inspection of the finished surface etc. but some are not.
The measurements were done with a Rothschild friction meter at 100 m/min and most different smooth and hairy, flat and twisted, synthetics and natural fibers as well as staple and endless yarns.
The results have shown that polished DLP parts have the same friction values as the parts manufactured with other process routes.
The natural surface of a DLP product has a quite different response, but nevertheless it might be an interesting one for certain products.

Benchmark of jets against serial product

Another question was: will the parts, manufactured by CIM (ceramic injection moulding) and DLP have the same running performance in respect to yarn quality?
And again: yes.

With Infrared measurements (Figure 25) we could show that the yarn contact temperature are absolutely comparable between and the textile parameters like yarn tension increase and capillary breaks was very similar

Potential Impact There is no doubt a hype to 3D-generative manufacturing at the moment. Not inclined to repeate the wide spread advantages (and doubts) for future individualisation strategies in design we can emphasize that this technology is also demarcating from heavy load, noisy and dusty working environments as well as assembly-line work. This work can be equally done by female and male people in all fields were ceramics is a preferred material to combine with others like jewelry, tribological issues, medical devices, automotive applications etc.
In short words: the manufacturing and final testing of selected ceramic components in alumina in an industrial surrounding has been successful. The implementation in industrial machines, the evaluation of their behaviour in their specific processes in respect to quality and tribological behaviour has shown, that these rapid prototyped ceramics products can be on a level comparable to traditionally manufactured parts.

3.5.2 Ceramic foundry cores for turbine components

The objective is to develop advanced ceramic materials applicable to additive manufacturing processes and to foundry core production for turbine blade casting application.
For a first technical approach to foundry core requirements and for geometry evaluation a simple demonstrator Sample C2, shown in Figure 26, was developed at SAG and produced in Al_2O_3 ceramic using the DLP at TUW.
From application side INCONEL 718 casting material has been replaced by INCONEL 939 at the very beginning of the project and for the foundry core itself silicon nitride has been defined as base material.

For the foundry core design, the ceramic material and for the additive process development a number of information was derived from turbine blade application and from casting requirements.
These include:
- Turbine blade component specifications
- Boundary conditions
- Foundry core material requirements
- Foundry core design rules.

The foundry core design was developed together with a SAG in-house partner and before the design was finished some component segments were developed to allow further process study. The two segments selected (S1, S3) are shown in Figure 27.

Summarizing this task in a first route silicon nitride slurries were developed, SLA-C processed and first specimens were sintered. With three different ceramics a melt flow test on IN939 (has replaced INCONEL 718) cast material was performed. Than it was switched to a second more common Al_2O_3 route and such slurry was used at SAG. With this alumina slurry foundry core segments were SLA-C processed. Fabrication tolerances have been evaluated and the process has been optimized and more precise segments were built by means of SLA-C processing. Debinding and sintering processes have been developed and specimens were sintered at 13,2% open porosity which meets the target of 10-15%. The shrinkage behaviour, key knowledge for such a process flow, has been studied on CPAR parts and on S1 segments as well (Figure 28).

Further development is needed for Si3N4 slurry approval and for optimization of the Al3O3 process chain. The usability of SLA-C processed ceramics as foundry cores for IN939 casting needs additional and substantial investigations.

3.5.3 Public demonstrator

Introduction Conventionally, BRO, like other textile companies, manufactures yarn guides using the low-pressure injection (LPIM) moulding technique. According to the results of TUW obtained within WP8, DLP reduces the complexity of the production while providing higher resolution and similar material properties. Manufacturing parts with DLP requires less process steps, decreases total process time and reduces costs**.**
In contrast to LPIM, however, DLP is not commercially used. This is due to the already existing and well-established production via LPIM on a commercial level. To compete on the market, DLP production must overcome entry barriers. In addition to available material and machine providers, software tools have to be developed that facilitate easy customer/manufacturer interaction. Here we demonstrate the manufacturing of a virtual yarn guide via the DLP technique.

Fabrication of a demo yarn guide using the developed preparation software

In contrast to LPIM, no mould has to be designed in DLP manufacturing of ceramics. One can directly design the desired part and directly manufacture (print) it. However, the computer aided design (CAD) has to be modified prior to manufacturing. First, a shrinkage has to be considered, the CAD has to be scaled prior to manufacturing. Furthermore, for some geometries, including yarn guides, support materials must be added to the CAD to ensure proper fabrication of overhanging features. As nearly all AMT proceed via a layer-by-layer technique, the part is then divided into several slices of predefined thicknesses. The thickness of these slices determines the resolution in the Z-dimension and the number of cross-sections that have to be processed within a fabrication procedure. For DLP, these slices are saved as a sequence of digital black and white images. The cross sections, i.e. the part of the slurry on the building platform that has to be solidified, is white, the intended share to stay uncured, black. A separate machine code ensures that the DLP displays an image while the building platform stands still. Then the DLP turns off, the building platform levels up and the next cross-section is displayed. The machine code and the picture files are stored in one jobfile.
Formerly, this jobfile was created the following way:

- Scaling and positioning the CAD and saving it in the STL format
- Creating support structures using a licensed software
- Slicing the CAD using a separate licensed software for conventional AMT machines and saving it as jobfile

The aim of the consortium was to automatize this procedure. Using knowledge from TUW regarding shrinkage and shaping of the supporting structures, parameter files were made that facilitate a partly automatized preparation of the jobfile, from the customer designed CAD model to the machine code that can be uploaded to the AM device. DESK 3Data Expert (see WP2) provided the necessary basis for this routine. Figure 29 shows the process steps involved when preparing a CAD for printing with the DLP technology. These steps were automatized within PHOCAM. Hence, only one mouse-click is necessary to convert the CAD file in a printable format.

3.6 WP7 End user applications based on flexible micro-fabrication

3.6.1 High-precision lattice mould for computer tomography device

Work package 7 is covered by two tasks. Both tasks are dealing with the same Two Photon Polymerization (2PP) process to be developed and to be used for two end users applications based on flexible micro-fabrication of high-resolution structures with features in the sub-micron range.

The objective of task 7.1 was to develop 2PP micro-fabrication for flexible lattice mould prototyping and manufacturing to allow final grid fabrication for computed tomography (CT) devices. The achievement of a large wall height to wall thickness aspect-ratio (significant higher than 90:1) is an essential part of this task. The objective is related to Siemens' CT scanner business such a way to continue with the development and to drive innovations for future product design.

A new phase-contrast X-ray imaging system is targeted and this principle as shown in Figure 30 needs high-precision grid devices. Such grids are metallic key devices providing high potential to increase CT performance.

The grid device (positive) requires an arrangement of thin metal walls with narrow distances. In this case wall heights up to 150 microns, a wall thickness and a wall distance of 1 micron each are required. These requirements apply for the lattice mould (negative) in polymer, too. In consequence the ideal mould in polymer should be of free-standing walls without supporting structures between the walls to allow high density noble metal deposition.

In this field the 2PP micro-fabrication process has to compete e.g. with LIGA (Lithography, Electroplating, and Moulding), an available fabrication technology for high-aspect-ratio microstructures. But, even LIGA did not succeed in the achieving of all lattice mould requirements so far.
A state of the art representative for a lattice mould development is given in Figure 31.
Beside the extreme aspect ratio and the 2 microns period the lattice mould requires thin walls arranged in parallel across an area of 50 mm x 20 mm.

The high-precision lattice mould was development along the supply chain as illustrated in Figure 32, but task 7.1 mainly was focused on Lattice Mould Design and on 2PP Process Development. The 2PP process specific materials were part of work package 3, whereas CT grid materials and final CT grid production were not part of the PHOCAM project.

The application requires a metallic thin wall arrangement. For good absorption the walls must have as less openings as possible and respectively as less dense noble metal missing, too. For the lattice mould that means any kind of supporting structure between the walls of the mould will result in an imperfection of the CT grid device. But, due to the extreme aspect-ratio from mould producibility point of view, there is no doubt about the need for supporting structures between the walls and the obvious aim is to minimize the volume of the supporting structure.
The volume can be minimized by considering the following opposed aspects:

- sufficient absorption and manageable imperfection requires less volume
- sufficient self-support and dimensional stability requires more volume

Design Based on first results from self-supporting free standing thin walls, built performed by LZH, cuboidial stabilizers of different designs and different patterns (see Figure 33) were developed and evaluated.

With a pattern design most suitable for the application including the option to raise the wall height up to targeted 150 microns three cubes (Table 3) different in size were designed for further evaluation and process studies.
Cube10 design was used to vary the stabilizer size. From three different stabilizer sizes with respect to application requirements cube10-1 resulted to be the most promising one (see Table 4).
Than cube10-1 slightly was modified to allow cubes to be added in both X and Y direction up to an area of 5mm x 2mm. Cube150 and the mould element (ME150-5-2), which only is 1/100 of the lattice mould for a complete CT grid device, is shown in Figure 34.

Fabrication Process To evaluate the PP2 process self-supporting thin wall heights were studied. For a wall thickness of 1.8 microns LZH found the limit of self-supported free-standing walls at 40 microns in height which is illustrated in Figure 35.
During study of the 2 microns period required it was observed structures that were in fine shape before development show additional distortions after development and electron microscopy (see Figure 36).

Figure 37 shows that the building height can be extended up to 60 microns by a stable outer frame and single interconnecting lines.
In Figure 38 the aspect ratio of 90:1 for the required wall thickness of 1 micron and the period of 2 microns is demonstrated. The image at the left was taken at 45 degree angle. The structure consists of 11 walls, a length of 30 microns and a height of 90 microns to match MS4 milestone.
The walls are stable and clearly separated from the top to the ground due to stabilization by interconnecting lines.
Further parameter and design studies resulted in significant improvement of structure stability and allowed to extend the structure up to the build volume of the piezo system used. Figure 39 shows a cubic wall array of 100µm x 100µm x 100µm with an aspect ratio of 100:1 and regular walls. Spacers were placed horizontally and vertically every 12µm. The structure is slightly smaller at the top compared to the ground due to residual material shrinkage. This shrinkage could be partly counterbalanced with a thicker frame.
After further optimization Cube4a, as defined by SAG, were produced from Zr-hybrid material. For this a combination of laser scanner and a 63x immersion oil objective, NA1.4 was used. This allowed writing the Cube4a with minimal mechanical disturbance during the writing process.
However, the walls resulted not perfectly regular, since they have a tendency to bend and collapse with increasing distance from the spacers. This was not a result of an inaccurate writing process, because structures that were inspected before development showed perfectly regular walls. Distortion and bending of the walls happen accidentally during development, when small asymmetries in the removal rate of the residual photo material result in forces on the wall surfaces that bend the walls.
To compensate the insufficient support by spacers, similar wall arrays as Cube4a were produced, but the spacer distance was reduced to 50% which increases mechanical stability by four times more spacers.
It can be seen that the 60µm x 60µm x 60µm structure of the Cube4 modified design was fully produced, all walls are present and the walls show a regular shape even in the view of a 45 degree angle (see XYZ). Only slight asymmetries remained that result from material shrinkage especially at the edges and at the boundary to the substrate. The structure is free from the top to the ground and all the spacers are well visible (Figure 40).

Evaluation and Testing For evaluation of the latest as-built cube design LZH provided two sets of cube4 specimens. Laser powder used is in the range between 44mW and 22mW and the build speed is between 2mm/s and 0,5mm/s. The material used for these specimens is Ormosil. At the

6x16 set, only, three cubes were marked as best results and these cubes are named A, B and C (see Figure 41, picture left) and were used for evaluation.
For this set also SEM and dimensional measurements were performed at SAG. Some general dimensions of the cubes were measured and are given by a representative example as shown in Figure 41 at the right picture.
As reported by LZH the original cube4 design actually had to be modified due to stability issues. The arrangement of spacers used has a doubled density of the supporting structure what resulted in a significant better stiffness of the whole cube. The original cube4 design size is 60x60x59 cubic microns, whereas the representative example shows little smaller typically dimensions of about 57x54 square microns. Furthermore, the original design has a pattern of stabilizers only, but no arrangement of spacers, as used here in this cube4 modified design. The distance between the spacers (D) is about 14.2 microns. This is slightly larger as for previous thin wall samples with cross-wall support distances of about 12 microns.

Figure 41 at the right also shows the most relevant geometry targets: period (T1), wall thickness (T2) and wall distance (T3).
From the best cubes A, B and C dimensional measurements were taken and some characteristics of these cubes can be seen in Figure 42.
As known from earlier result also this three cubes show very similar characteristics. The cubes A and B show the same typical wavy walls in the same line, whereas cube B comes with a straight line. Another example of a conspicuous feature can be seen at cube C, the reduced wall distance at the red arrow. Here again cube A and B look very similar and regular (see at the white arrow).
All dimensional measurements were taken at the lower half of the cubes, since these parts are more regular than the upper parts and this results in extremely uniform values as summarized in Table 5.
The 2 microns period targeted is far and away from earlier results. The wall thickness is marginally better, but as respect to these geometry targets no improvement can be identified. In consideration of the fact, that here are no full cross-walls anymore, but just an arrangement of spacers, the result is remarkable and it really is amazing in Figure 43 to see this supporting structure of less volume between the walls.
Summarizing task 7.1 the photopolymer and the developer selected in WP3 has been suitable for micro-fabrication of fine structures. The design and the 2PP parameters were developed and allowed fabrication of thin walls with spacers of less volume. Specimens were evaluated, but at the end quality and built size were insufficient to complete a lattice mould and to perform lattice mould testing.
Further development of a design-to-manufacture and of the 2PP process parameters is needed. This development possibly should include the photopolymer, but quite certain the developer.

3.6.2 Patient specific middle-ear prosthesis

The aim of this task was to develop 2PP micro-fabrication for the manufacturing of patient-specific middle-ear prosthesis. Fabrication of Total Ossicular Replacement Prosthesis (TORP) and Partial Ossicular Replacement Prosthesis (PORP) require high precision and flexibility of the applied technology. In the first step a design of the prosthesis and scaling procedure in accordance to patient CT data was developed. A photopolymerizable material with adequate mechanical, sound transduction and biological properties was selected. In parallel optimization of TORP quality, process times and its scaling was performed. The mechanical and acoustical properties were evaluated.
Missing or eroded auditory ossicles in the human middle ear (namely malleus, incus and the arc of the stapes) interrupt the transmission of sound between the tympanic membrane and the stapes. A total ossicular replacement prosthesis (TORP) that is placed between the tympanic membrane and

the stapes basis restores the sound transmission. The prosthesis needs to be individually adapted to the dimensions of the person (see Figure 44, indicated in green).
The relevant dimensions and the installation situation have to be determined with help of computer tomography, which allows reconstructing and visualizing the structures in the middle ear and measuring the relevant dimensions. Figure 45 shows computer tomographic sections of the human head with focus on the middle ear. The ear specialist measures the dimensions that are required to define and adapt the individual implant.

Different TORP designs were considered. They are based and inspired by the design of commercial titanium TORPs, e.g. available by Kurz. The prosthesis (Figure 46) has a head piece, which is put in contact with the tympanic membrane. Holes in the headpiece allow visual control of the installation of the prosthesis during surgery. A sound transmitting rod connects the head piece with the thickened base of the prosthesis, which is placed on the base stapes (see Figure 44 for a sketch of the installation situation). The position stability can optionally be increased by small pins.
A set of design parameters was defined that allows automatic generation of an individual prostheses with a minimum of effort: diameter of the head piece d (head), length of the transmission rod l (rod) and diameter of the base d (base). Other design parameters are set to standard values, but can optionally be adapted. For processing the 2PP software was extended to allow the integration of software plug-ins, and a plug-in for the 2PP processing of total ossicular replacement prostheses was developed (Figure 47 and 48). The plug-in accepts the patient data as parameters that are entered into an input mask. The software checks this data for plausibility and uses it to create CNC code that is processed on the two-photon polymerization system.
Therefore, the TORP model is split into sliced layers, which are processed one after each other. The distance between the layers is defined according to the objective, the laser energy used and the corresponding voxel size. Each layer contains a section of the TORP model. The contour in each slice is hatched, and this hatching defines the path of the laser focus during the fabrication of the total ossicular replacement prosthesis. Even the hatching parameters are defined by the objective, the laser energy used and the resulting voxel size. The slicing and hatching parameters are predefined to reliable empirical values. They can be changed and adapted if required. When scaling the TORP the slicing and hatching parameters are kept fixed, but the assembly layers and contours are changed.
After material screening the design optimization and production of Total Ossi¬cular Replacement Prosthesis (TORP) were performed with the hybrid polymer Ormo¬comp. This material is originally intended for UV patterning in lithography and molding, however it even works fine for 2PP-structures that require good surface quality and larger dimensions at the same time at a relatively low shrinkage rate of about 5%. In a biological environment it offers the advantage that it is free of solvents and does hardly absorb water. Our tests have shown that it provides good stability for mechanical elements and can stand temperatures of more than 200°C. The temperature extension coefficient measured for this material of about $100 \times 10^{-6}\ K^{-1}$ can be neglected for the typical temperatures in the human body.
The TORP (Figure 49) were processed in the LZH two-photon polymerization setup. To allow pro¬duction of the high aspect ratio part in one step the 2PP-system was equipped with a 16mm lens. As light source 1nJ laser pulses of 520nm, <150fs at 80MHz repetition rate were used. Patient specific data was entered into the software mask and the model was automatically adapted, generated and built by the software module. The TORP structures (Figure 50 and Figure 51) were produced with a linear positioning axis at a speed of 18mm/s, which results in a production time of about three to four hours. This can be further sped up with a laser scanner which allows up to 50 times faster production of objects in the view field of the lens, but which is not available in the setup for this laser wavelength-material combination.

Measurement results on sound transfer proved that the TORP successfully transfers sound between two membranes (Figure 52). The transfer ratio measured is in one order of magnitude for all acoustical frequencies. With an artificial membrane qualitative data is provided, which cannot be fully representative of the situation an individual patient human ear.
Summarizing a photopolymerizable material with adequate mechanical, sound transduction and biological properties was selected. Optimisation of TORP design, quality and scaling was performed. The design as well as the fabrication of the patient-specific structures was done and the process time was determined. The mechanical and acoustical properties were evaluated. In the framework of PHOCAM it was not planned to do a clinical study with the prosthesis.

3.7 WP8 Supply chain and quality management

3.7.1 Supply chain management

In order to assess producibility in an industrial environment and to enable the selection of an appropriate AMT, it is necessary to know the requirements of the product as well as the technical specifications of the various manufacturing processes. Apart from the technical possibilities enabled by the various additive processes, for companies that intend to implement AMT it is important to identify the differences to conventional (industrial) value and supply chains (SC). To pave the way for lithography based AMT in an industrial manufacturing environment, the overall strategic objective of PHOCAM is the development of a customizable manufacturing platform (PHOCAM platform). The PHOCAM production platform is intended to give the customer and end-user the opportunity to evaluate lithography based AMT with respect to the requirements faced in industrial manufacturing. The PHOCAM platform enables the testing of its traits and potential without having to change all processes and allowing a focus on the product.

The presented report gives an overview about the influences of the implementation of AMT technology in industrial companies and the introduction of a production platform such as the PHOCAM platform on their value and supply chains. The presented SC-concept and SC-framework describe the relationships between the stakeholders as well as the role of the PHOCAM-platform in the SC.

Impact of AMT and platform implementation on the supply chain

Dependent upon, what type of AMT technology is employed, a variety of ramifica-tions on a department or section within a company are possible. If the implementa-tion of AMT is done using the developed production platform, the effects are primarily felt in organisational and logistical factors. Basically the implications can be distinguished into four categories:

- organisational effects (e.g. changes in production support and production lo-gistics processes, changes in after sales services / spare part warehousing and spare part provision, introduction of new quality standards)
- logistical effects (e.g. altered transport routes between customers and produc-tion, changes with respect to waste and disposal, raw material form and stor-age)
- production based effects (e.g. changes in production process steps)
- technological/ product related effects (e.g. changes in design phase with re-spect to construction / choice of material)

Production platform based supply chain concept

Supply chain management considers in general the development of interfaces be-tween companies in an entire corporate network. Essential tasks and goals are im-proving customer orientation, synchronization of demand and supply, flexiblization and demand driven production and reduction of stocks along the value chain.

Against this background, the implementation of the PHOCAM platform will support the acceptance of AMT in the commercial arena. PHOCAM enables the testing and pilot application of AMT in an industrial environment and helps to keep the organizational efforts in the supply chain low and the resulting benefits high. This is promoted by an automatic and standardized web-based procedure for fulfilling customer's demands. The scope of investigation is limited to interaction between producer and customer / supplier.

The PHOCAM-platform, integrated in the supply chain, is a self-regulating, flexible production system that negotiates between the manufacturer and the customer. The platform is responsible for the essential digital information flows between the two main stakeholders – the manufacturer and the customer.

In addition, through the interaction with several potential manufacturers, starting with a customer request, the production (of products of multiple customers) is distributed over several producers (production smoothing effect). An offer is chosen with respect to cost, necessary or possible delivery date, or other customer requirements. At the same time, the competitive situation is intensified and an ideal customer oriented SC is established. The use of very flexible AMT technology in combination with the implementation of a production platform represents an extremely flexible, efficient but also robust manufacturing opportunity for customers. Through the order-focused/ customer focused orientated production that boasts very early customer decoupling points, stock along the supply chain can be kept very low be. The intended objectives are comprehensively met by the developed manufacturing platform.

The design of operational processes inside the PHOCAM platform (situation of integration in Fig. 53) as seen in Fig. 54, shows the single process steps inside the PHOCAM platform linked with the customer and manufacturer interaction.

It is oriented to the customer with the following main characteristics:

- Platform for different manufacturers
- Real-time data handling and quote calculation
- Real-time STL-file verification and repair function
- Real-time print job initialization

The PHOCAM platform is designed as a system to support the customer as an end user or system supplier, who needs to build a product, which is predestinated for additive manufacturing and designed accordingly (high geometric complexity, material, small batch size, etc.).

Framework design - SCM platform framework for AMT integration and implementation precedure

This project doesn't deal with optimization of existing supply chains. In fact, a general framework (Fig. 55) for the supply chain and platform system is to be defined, to enable a flexible production of high complex and high quality products by a customer oriented central production platform.

The PHOCAM platform framework is divided into five layers (access layer, operating layer, system requirements layer, platform layer and DB-Layer), each responsible for a different role within the framework. Dependent on relevant user characteristics within such a layer, each layer and where expedient, is systematized into further modules.

- The Access Layer provides system availability and accessibility, which consti-tute the possibility for different users to enter and interact with the platform.

- With system entry secured, the data communication takes place within the Operating Layer. The Operating Layer is responsible for the operating activi-ties, i.e. to convert the format of inputs to the system and the format of outputs to the different interfaces.

- The System Requirements Layer is responsible for the processing of com-mands with information based on either the inputs delivered from the Operat-ing layer or the shared data accessed over the Platform layer.

- The Platform Layer is responsible for the semantic retrieval on databases or data warehouses and it interacts thus besides with the System requirements layer as well with the Data-Base Layer.

- Out of the data variability provided within the Data-Base Layer, relevant data is accessed over limited requests matched through a semantic web technolo-gy with the defined application system requirements. The Platform serves in this sense as a data selector and distributor based on defined structures within the web. Accordingly to user characteristics in data base sources, the Data Base Layer is set up by the modules Manufacturer Data, Customer Data, Quotes Data, and Repair Data.

The implementation of the PHOCAM-platform has to undergo seven implementation stages, reaching from the Data collection to the Testing platform (Fig. 56), on its way towards an official launch, which are characterized by data collection, identifying necessities for “service platform”, identifying manufacturer and customer requirements, development of the “service platform” (PHOCAM platform), implementing and testing the platform.

3.7.2 Quality management

Quality control standards are important to ensure a sustainable and reliable production chain and respective products. Within the project quality control standards for products made with Additive Manufacturing techniques are described among the Additive Manufacturing process chain. Figure 57 illustrates the Additive Manufacturing process chain and respective methods for quality observation.

The production chain consists of four major sections each coupled with adapted quality control methods (Figure 57).

The first section deals with virtual part design and its conversion into a suitable data format for Layer Manufacturing machines. Basically, the part designer has to ensure, that the general suitability is provided to build the part in a layer-by-layer fashion. Up to now, there are no automated standards developed to inspect virtual models. In order to allow the upload of the model data to a particular machine, the conversion of the respective data to the data type STL is necessary. Through a process entitled triangulation, the volume data is converted into a surface model. There are a few automated processed available to observe the triangulation process, as e.g. the company DeskArtes provides the software package 3DataExpert, containing automated “Verification” and

"Repair" tools. Slicing of the virtual model is done automatically, but the way, the part is to be sliced at its best, is to be decided by the particular machine user.
Second section is the Building process and its preparation, followed by cleaning of the green part and, if required, post processing steps (*section three*). For polymer-based Additive Manufacturing, different techniques exist in order to monitor the quality of the formed polymer network in terms of crosslinking and functional group conversion, and thus the mechanical properties. The converted bonds can directly be detected using Infrared-Spectroscopy or, in an indirect way, through heat development upon reaction (DSC).
Section number four is receiving of the ready-built part. There are a few ways based on different techniques to observe the quality of the ready-built part. Visual inspection based on Optical Microscopy, Scanning Electron Microscopy or Micro Computer Tomography can be used to detect the geometrical precision and local deformation of the physical object. Especially the Computer Tomography Technique offers a fully spatial analysis, even of internal sections that may not be monitored by other techniques (Figure 58). The mechanical properties can be distinguished by established techniques, e.g. measurement of strength, hardness and others.

The AMT processes engaged from PHOCAM partners achieve very good results within the positional accuracy. In terms of contour accuracy, however, the tested parts show different results for horizontal and vertical orientation (Table 6). Horizontal shape deviations due to lateral overcuring are easily compensated by recalibrations of the light exposure unit, that are valid for the entire set of layers unit. The parts show excellent results within the horizontal orientation as long as they do not belong to ceiling structures, where vertical overcuring contributes to strong shape deviations. In the vertical direction the influence accumulated overcuring due to superjacent layers has to be considered. Consequently the positioning of critical geometric features in the vicinity of ceiling structures should be avoided. Good results have been achieved for the homogeneity of the density and suppression of other defects such as micro-delamination and pore distribution.

4 Impact and dissemination strategies

The primary objective of PHOCAM was the introduction of lithography based AMT into an industrial manufacturing supply chain. The strong industrial background of the consortium in combination with experienced scientific key researchers helped to set up an innovative supply chain model which fulfils the economic and engineering boundary conditions. The incorporation of three industrial end-user applications was instrumental to test the economic and operating efficiency of the proposed approaches at an early stage of development.

4.1 Impact of the performed work

The table below summarizes the impact of the performed work with respect to the original call text. As indicated, a number of achievements, well aligned with the original call text, were successfully tackled.

4.1.1 Expected impact according to call:

First time right, flexible and efficient manufacturing systems

4.1.2 Relation to PHOCAM

Both core technologies (Customized ceramics, on-demand micro-manufacturing) provide innovative approaches for the fabrication of high value added products (key components for textile machinery, turbine components and CT tomography). Both technologies can fabricate customized geometries on a flexible on-demand basis and are significantly more efficient regarding material usage compared to existing manufacturing approaches.

4.1.3 Achievements

Due to the developments in the field of innovative light engines and the excellent progress in the field of highly-filled ceramic photopolymers the consortium was able to fulfil a number of challenging requirements in the targeted industrial applications. The use of high-power LEDs as light source for light engines in lithography based manufacturing has become standard in this field. The PHOCAM partners INV and VIS are now capable of providing state of the art light engines for this field. The ceramic materials developed by TUW have set a new standard regarding strength and reliability. A bending strength of >500MPa for alumina has been achieved, which is currently the world record in this field.

4.1.4 Expected impact according to call

RM methodologies for high value added products

4.1.5 Relation to PHOCAM

Based on innovative light sources, new manufacturing equipment is developed that allows on-demand fabrication of high-added value products.

4.1.6 Achievements

The expected impact regarding high-quality products with excellent feature resolution and outstanding surface quality could be achieved.

4.1.7 Expected impact according to call

New supply chain approaches

4.1.8 Relation to PHOCAM

The consortium is developing a secure, internet based software framework which facilitates distributed, customized manufacturing on an on-demand basis. The system includes quality measures to ensure first-time right manufacturing.

4.1.9 Achievements

The new supply chain approach has been implemented into the AMT software platform developed by DESK. Especially the integration into a server-based supply chain model and the advancements in the field of file repair significantly enhanced the technological level of the software platform maintained by DESK. Several software modules which have been developed for PHOCAM are currently integrated into DESKARTES' commercially available software packages.

4.1.10 Expected impact according to call

Targeting health, consumer, automotive and high-end equipment industry

4.1.11 Relation to PHOCAM

The consortium develops end-applications which provide key-components for the European textile equipment, health and the energy industry. The developed manufacturing systems are based on key components developed by partners in the European electronics industry.

4.1.12 Achievements

The consortium successfully proved that lithography-based AMT can be used in industrial environments. The manufactured ceramic parts fulfil the requested requirements. An industrial translation of the developed materials and processes is running since beginning of 2013. The developed supply chain models are integrated into the targeted software platforms. A spin-off company has been founded who commercializes the developed ceramic filled resins and the developed hardware platform. Cooperations with international enterprises in the field of digital dentistry has been started, with the goal to establish PHOCAM technologies in biomedical engineering.

4.2 Dissemination

4.2.1 Publications

The following peer reviewed journal papers could be published based on results obtained within PHOCAM:

[1] K. Cicha, Z. Li, K. Stadlmann, A. Ovsianikov, R. Markut-Kohl, R. Liska, J. Stampfl: Evaluation of 3D structures fabricated with two-photon-photopolymerization by using FTIR spectroscopy Journal of Applied Physics, 110 (2011), 064911; S. 1 - 5.

[2] S.D. Gittard, A. Nguyen, K. Obata, A. Koroleva, R.J. Narayan, B.N. Chichkov: Fabrication of microscale medical devices by two-photon polymerization with multiple foci via a spatial light modulator, Biomedical optics express 2 (11), 3167-3178 (2011)

[3] K. Cicha, T. Koch, J. Torgersen, L. Zhiquan, R. Liska, J. Stampfl: Young´s modulus measurement of two-photon polymerized microcantilevers by using nanoindentation equipment, Journal of Applied Physics, 112 (2012), 094906.

[4] R.A. Rezende, F.D.A.S Pereira, V. Kasyanov, A. Ovsianikov, J. Torgersen, P. Gruber, J. Stampfl, K. Brakke, J.A. Nogueira, V. Mironov, J.V.L. da Silva: Design, physical prototyping and initial characterisation of “lockyballs”, Virtual and Physical Prototyping, 7 (2012), 287-301.

[5] A. Ovsianikov, Z. Li, A. Ajami, J. Torgersen, W. Husinsky, J. Stampfl, R. Liska: 3D grafting via three-photon induced photolysis of aromatic azides, Applied Physics A: Materials Science & Processing, 108 (2012), 1; S. 29 - 34.

[6] A. Ovsianikov, Z. Li, J. Torgersen, J. Stampfl, R. Liska: Selective Functionalization of 3D Matrices Via Multiphoton Grafting and Subsequent Click Chemistry, Advanced Functional Materials, 22 (2012), 16; S. 3429 - 3433.

[7] P. Tesavibul, R. Felzmann, S. Gruber, R. Liska, I. Thompson, A. Boccaccini, J. Stampfl: Processing of 45S5 Bioglass by lithography-based additive manufacturing, Materials Letters, 74 (2012), S. 81 - 84.

[8] J. Torgersen, A. Ovsianikov, V. Mironov, N.U Pucher, X.H. Qin, Z. Li, K. Cicha, T. Machacek, V. Jantsch-Plunger, R. Liska, J. Stampfl: Photo-sensitive hydrogels for threedimensional laser microfabrication in the presence of whole organisms, Journal of Biomedical Optics, 17 (2012), 10; 1 - 10.

[9] J. Torgersen, X. Qin, Z. Li, A. Ovsianikov, P. Gruber, R. Liska, J. Stampfl: "Hydrogels for two-photon polymerisation: a toolbox for mimicking the extracellular matrix", Advanced Functional Materials (invited), 2013, n/a-n/a.

4.2.2 Industrial interest group

In order to promote the research results of PHOCAM for a larger public and to gain awareness for the industrial interest group, the following actions have been taken:

The PHOCAM consortium organized a booth at the international trade fair **Rapidtech 2012** in Erfurt (Germany), where one of the developed machines in combination with manufactured ceramic parts was on display.

The results obtained in the context of miniaturized 3D-printers were presented at the **Photonics West 2012** in San Francisco. The goal of these dissemination activities was to attract US-companies to participate in the interest group and/or IMS-MTP action.

TU Wien made **two press releases** related to PHOCAM activities. The first press release[1] promoted the development of the smallest 3D-printer worldwide, and spurred substantial resonance, leading to several contacts for the PHOCAM industrial interest group.

The second release[2] (March 2012) was related to two-photon lithography and triggered substantial interest in the USA. During the **MRS-Spring Meeting 2012** in San Francisco, J. Stampfl made several follow-up visits regarding this press release. In detail, the following companies have been visited and/or meetings at TU Wien have been arranged.

Texas Instruments is a supplier of DMD chips, which are essential for providing high-end light engines. The responsible engineer at TI (Patrick Oden) has been contacted, and a meeting at the Photonics West has taken place.

Colop GmbH (Austria) is a manufacturer of stamps and is interested in 3D-printing technology which is capable of producing elastomeric stamp masters. A meeting at TU Wien was arranged, and the IMS MTP action was presented to the responsible executives at Colop.

Hewlett Packard (USA) has set up a 3D-printing group, operating from Barcelona (Spain) and Palo Alto (USA). The responsible people (Ed Davies) contacted TU Wien regarding the mini-printer press release. HP visited TU Wien, and J. Stampfl visited the HP-facility in Barcelona. In

[1] http://www.tuwien.ac.at/aktuelles/news_detail/article/7007/

[2] http://www.tuwien.ac.at/en/news/news_detail/article/7435/

February 2013 a workshop will be organized in Vienna, were HP staff from Palo Alto and Barcelona will discuss issues regarding photopolymerization with the team at TU Wien.

Glaxo Smith Kline (GB) contacted the PHOCAM consortium as follow-up of the 2PP press release. A team of three people visited Vienna in June 2012.

Ivoclar Vivadent AG (Lie) is an established research partner of TUW and is mainly interested in recent developments of light engine technology, as performed by Visitech and Invision within Phocam.

Lithoz GmbH (Austria) is a spin-off of TUW and licensee of TUW IP in the field of AMT. Lithoz is closely cooperating with Invision and Visitech regarding light engine technology.

Applied Materials (USA) is a supplier of semiconductor processing equipment. Their interest is mainly related to innovative structuring methods, as made possible by PHOCAM's 2PP methods. J. Stampfl visited Applied Material's headquarter in Santa Clara (USA) in March 2012 to discuss potential cooperations.

Phonak (CH) is a Swiss manufacturer of hearing aids and has interest in providing their retailers with localized manufacturing capabilities to produce hearing aid shells.

Nanomix (USA) is a US based company specializing on micro-fluidic solutions and is interested in innovative methods for micro-fabrication, e.g. two-photon lithography.

4.3 Overall impact

To summarize, the following achievements regarding impact, exploitation and dissemination have been achieved:

- The consortium established an industrial interest group and initiate an IMS MTP action. These activities significantly improved the international awareness of the project. Due to these activities, new research partners for the consortium have been identified, and new customers for the developed light engine technologies and hardware developments were found. Several new research projects in the targeted areas are currently running.
- The consortium successfully proved the industrial viability of the chosen scientific pathways. In the field of 3D-prnted ceramic parts outstanding results regarding strength, reliability and surface quality were obtained. These results led to the industrial translation of the developed methods in end user applications like textile machinery components. To guarantee the commercial availability of the developed materials and systems, a spin-off company has been founded (Lithoz GmbH) who currently provides the developed ceramic filled photopolymers and lithography-based AMT systems on a commercial basis.
- In the field of on-demand-micro manufacturing significant improvements regarding through-put and achievable feature resolution have been made. Several academic awards could be gained in this respect. Among other aspects, a researcher of PHOCAM (Dr. Ovsianikov) was awarded an ERC starting grant in 2012, where PHOCAM technology is screened for being used in life-science oriented aspects.

- Dissemination activities were done on an academic level (see list of publication), but also on a number of international trade fairs. Several press releases helped to promote the achieved research results on an international level. One press release regarding on-demand micro-manufacturing was specifically successful. A Youtube video associated with this press release was downloaded more than 450.000 times, and is currently the most popular Youtube video published by TU Wien.