PROJECT FINAL REPORT

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4.1 Final publishable summary report

Executive Summary

Light is one of the most fundamental and integral parts of modern living. It is required in almost every aspect of life ranging from general illumination over simple signalling systems such as traffic lights to complex information transmission for example in monitors, displays and TV-sets. In recent years, light applications have become increasingly more sophisticated. Luminaires have developed from simple illuminators to lighting elements, integrated into complex building and interior concepts, designed to create high quality, functional environments. Large area, high resolution displays are becoming more and more common in everyday life and are used to provide information, advertising and entertainment. Monitors and TV sets at the same time are becoming smaller, while offering high quality images and more and more complex functionalities.

Structured and planar light guides posse ideal properties as optics for the lighting engineering. Thereby complex and 3-dimensional microstructures make a visual functionality possible. The production of large-area components with micro structured surfaces confronted industrial production processes with so far irresolvable problems. Flexible micro structuring with step and repeat hot embossing processes provides the opportunity to eliminate the production-related deficits of previous processes. Within the context of the research project »FlexPAET« an adaptive hot embossing process and its integration in a process chain of a cost-effective production of planar lighting optics was developed.

The developed machine demonstrator imprints systematically the structures of complex micro tools into a thermoplastic substrate. In contrast to the conventional process of hot embossing, singular structural elements are put together piece by piece on one surface. In surfaces up to 1x2 m² the machine can imprint microstructures with a positioning accuracy of 2 µm. Concerning flexibility and speed unknown opportunities with regard to the production of visual functionalised surfaces result. The optical function of the embossed component is measured directly in the machine system by means of integrated metrology. Thus errors in the optical design can be detected directly on the machine. An algorithm compares the optical function of the embossed component with the required values. In this manner, the system identifies those positions on the surface where the structure has to be improved. The optimisation process will be proceeded until the measured optical properties correspond to the required specifications.

The process is part of a replication process chain that fits to mass-production. Similar to the approach of CD and DVD production, form tools were produced out of the embossed component by means of galvanic electroforming processes, enabling the cost efficient production of high quality optics.

FlexPAET covered the entire production process, starting with the optical design, the production of master substrates, the measurement of the optical behaviour and iterative remachining of the masters, material development, and mass replication technologies. The developed technology enables economic production of advanced light guide products for LED lighting.

Context and Objectives

FlexPAET addresses the limitations of state-of-the-art micro machining technologies and optical design calculation methods with respect to the production of optically functionalised elements. An advanced process chain was developed for the flexible, self-optimising fabrication of highly complex, large-area micro structured surfaces. In this process chain, illustrated in Figure 1, optically fully functional master structures are manufactured directly into thermoplastic substrates by means of Adaptive Embossing Technology. A specifically developed advanced step embossing process prints a structural pattern into the substrate. Utilising in-situ metrology, the optical performance of this master substrate is analysed, compared to the design requirements, and an optimisation algorithm determines necessary rework on the substrate. Rework iterations are repeated until the performance of the master substrate matches the design specifications, thus constituting an adaptive, fully self-optimising production process. The final, completely functional master substrate is then used to produce a mould in order to replicate the structure. Galvanic processes were optimised for the specific requirements of micro structure forming including large-area substrate sizes. Finally, these moulds were used in replication processes such as injection moulding, injection embossing, and roll-to-roll embossing, allowing for high-volume production of optically functionalised elements.
Furthermore, and beyond the scope of optically functionalised elements production, by bridging the gap between conventional micro manufacturing technologies and cost-effective high volume production, Flexible Patterning Technology provides a means for utilising advanced micro technology in consumer products and applications. Due to the holistic research approach which integrated mould making and mass replication, the proposed technology is extending the range of micro fabrication process capabilities to encompass a wider range of materials and geometric forms in order to produce a new generation of innovative, high value added products.

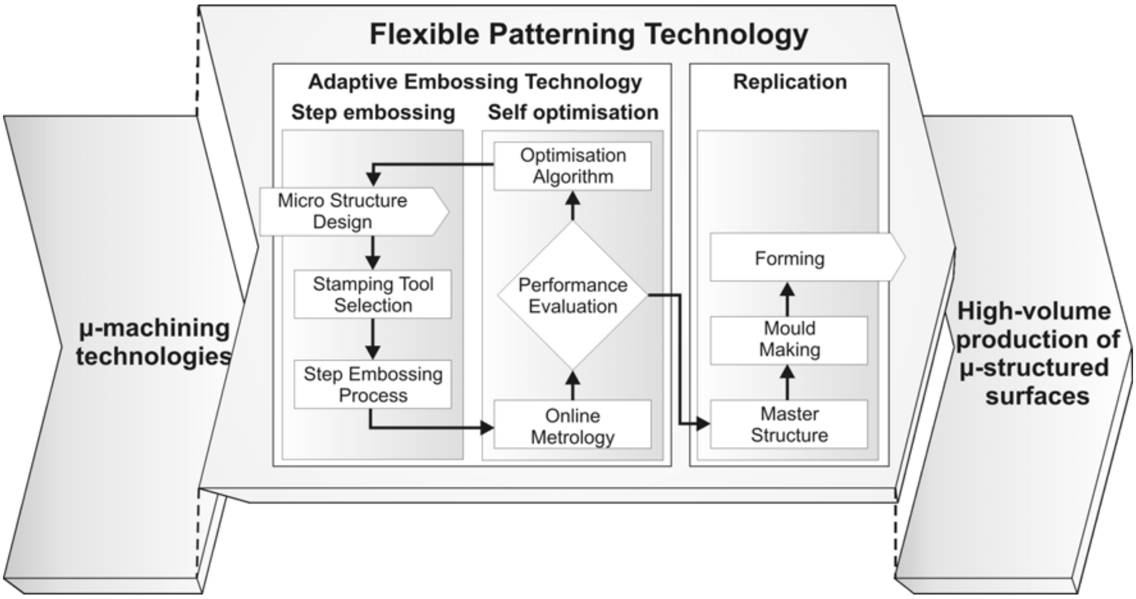


Figure 1: Flexible Patterning Technology – bridging the gap

Step Embossing

A process based on step embossing or step imprinting technology constitutes the core of the developed process chain. The basic principle is depicted in Figure 2. In this novel concept, micro structured stamping tools are used to emboss or print complex matrices of standardised micro-structural elements into thermoplastic substrates. Each embossing tool features a uniquely designed optically functional structure. These structures are replicated in a predetermined location of the substrate surface. The embossing locations for the individual structures are calculated by a specifically developed algorithm, based on the required optical performance of the substrate. The combination of tool structure, position on the substrate surface and tool orientation provides a high degree of structural flexibility for a broad range of substrate sizes, unmatched by any available state-of-the-art micro machining process today. In principle, this proposed patterning method is comparable to conventional surface mount technology based on a “pick-and-place” process:

- A stamping tool is picked from the tool tray with a manipulator arm.
- The tool is being heated.
- The manipulator moves the tool to the programmed location.
- The tool structure is embossed into the substrate surface.
- The manipulator moves the tool to the next location.

After embossing every programmed location for the specific tool, the manipulator moves the tool back to the tray and the process continues with the next tool in the same manner.
Figure 2 illustrates the step embossing process. Each tool features a different geometry (square size), thereby gradually varying the structural pattern which is imprinted into the substrate surface.

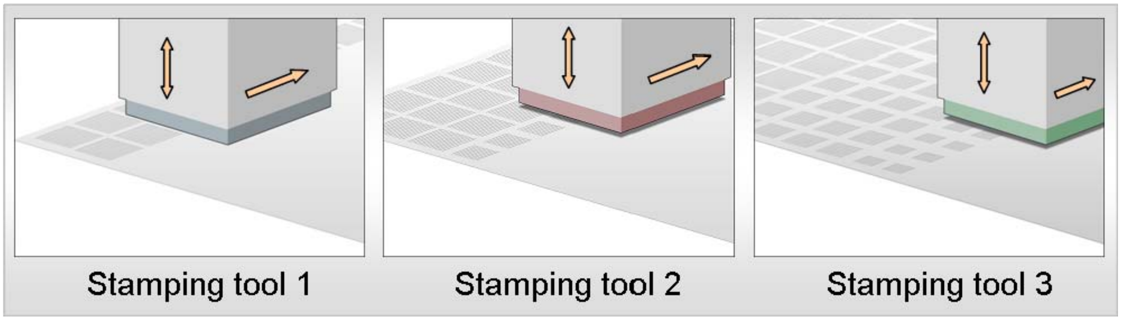


Figure 2: Step embossing with different stamping tools

Self optimisation

When the entire substrate surface has been printed with the respectively structured tools, a process-integrated metrology system verifies the optical performance of the substrate in production. Light is launched into the substrate using application-relevant light sources and coupling points. A specifically developed luminance measurement system then determines the light output of the substrate. The measured output is compared to the specified performance required for the substrate and a specifically developed optimisation algorithm will determine necessary rework in order to match the substrate performance to the requirement specifications. After the first rework cycle is finished, the online metrology system again checks the substrate performance and potentially necessary further iterations of the structural pattern are determined by the optimisation algorithm. These iteration cycles are continued until the substrate performance matches the design requirements. Thus the proposed embossing machine constitutes a truly adaptive, self optimising manufacturing system.

Galvanic Mould Making

In the following step, a mould is formed off the fully embossed master structure. This mould is used to replicate the master structure for high volume production. Developing advanced galvanic processes for the replication of micro structures, the mould is produced by building a nickel shim consisting of multiple functional layers onto the substrate surface. This nickel shim consist of a precise negative image of the surface structure. The coating process starts with the metallisation of the micro structured substrate surface, the application of an extremely thin metallic layer onto the substrate surface in order to provide electrical conductivity of the surface. The metallisation of the master is realised physical vapour deposition process. Subsequently, the nickel layers are deposited which constitute the actual mould. After the nickel deposition process is finished, the master substrate is delaminated from the mould and the mould is cleaned. The mould making process is illustrated in Figure 3.

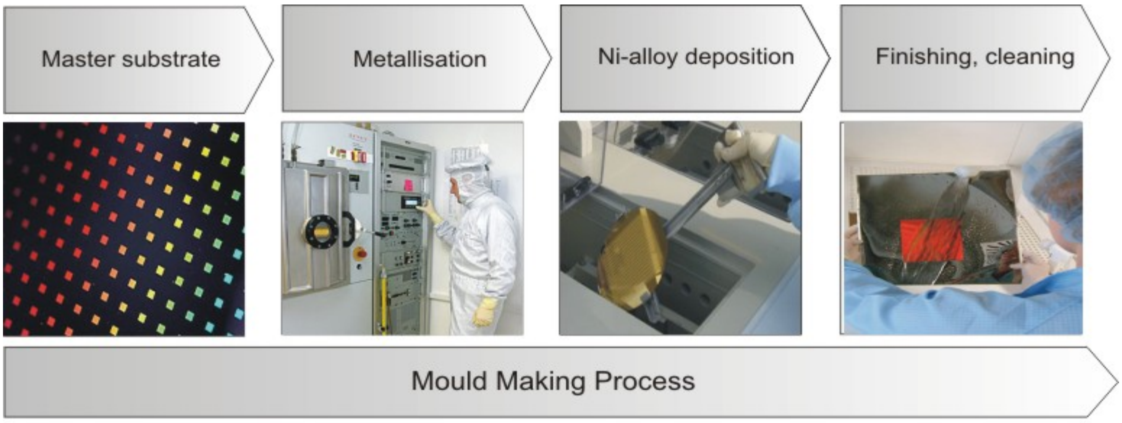


Figure 3: Galvanic mould making process

Forming

For the final step of the process chain, high volume replication processes was developed based on thermoplastic processing technologies such as injection moulding, injection embossing and roll-to-roll embossing. Injection moulding and injection embossing technologies use molten thermoplastic material, which is injected into a cavity containing the mould made from the master substrate in the previous process step. As the material solidifies, the micro structure of the mould are embedded into the substrate surface. In roll-to-roll embossing processes a liquid lacquer is coated on a base film which then is structured by a nickel shim which is bend around a cylinder to be a drum. While the coated film is in contact with the structured drum, the lacquer is cured by means ov UV light. Deep investigations for the injection moulding process were performed during the project while roll-to-roll embossing was just demonstrated to be generally a suitable process for mass replication of the microstructured substrates. Process development was focuses on the precise replication of micro structures as well as the processing of large substrate sizes without compromising the replication precision. The three mentioned replication technologies were optimised and evaluated with respect to their qualification for the production of optically functionalised elements .

Cost modelling

Concurrently with the technological development of the process chain, a cost model was developed, providing a means to accurately predict production cost for the production of optically functionalised elements. This method was designed to anticipate product cost with respect to high volume production based on data that was retrieved during the early laboratory or prototype phases of the development process. The development process followed a three-phase approach. In the first phase, economic potentials were estimated based on similar products and technologies. In the second phase, cost drivers were identified and detailed, simulating the complete manufacturing process. In the third and final phase the individual product perspective were integrated into the cost model.

Figure 4 summarises the objectives of the FlexPAET project, emphasising the dilemma between new and emerging illumination demands and the limitations of state-of-the-art micro machining technologies and successful development results.

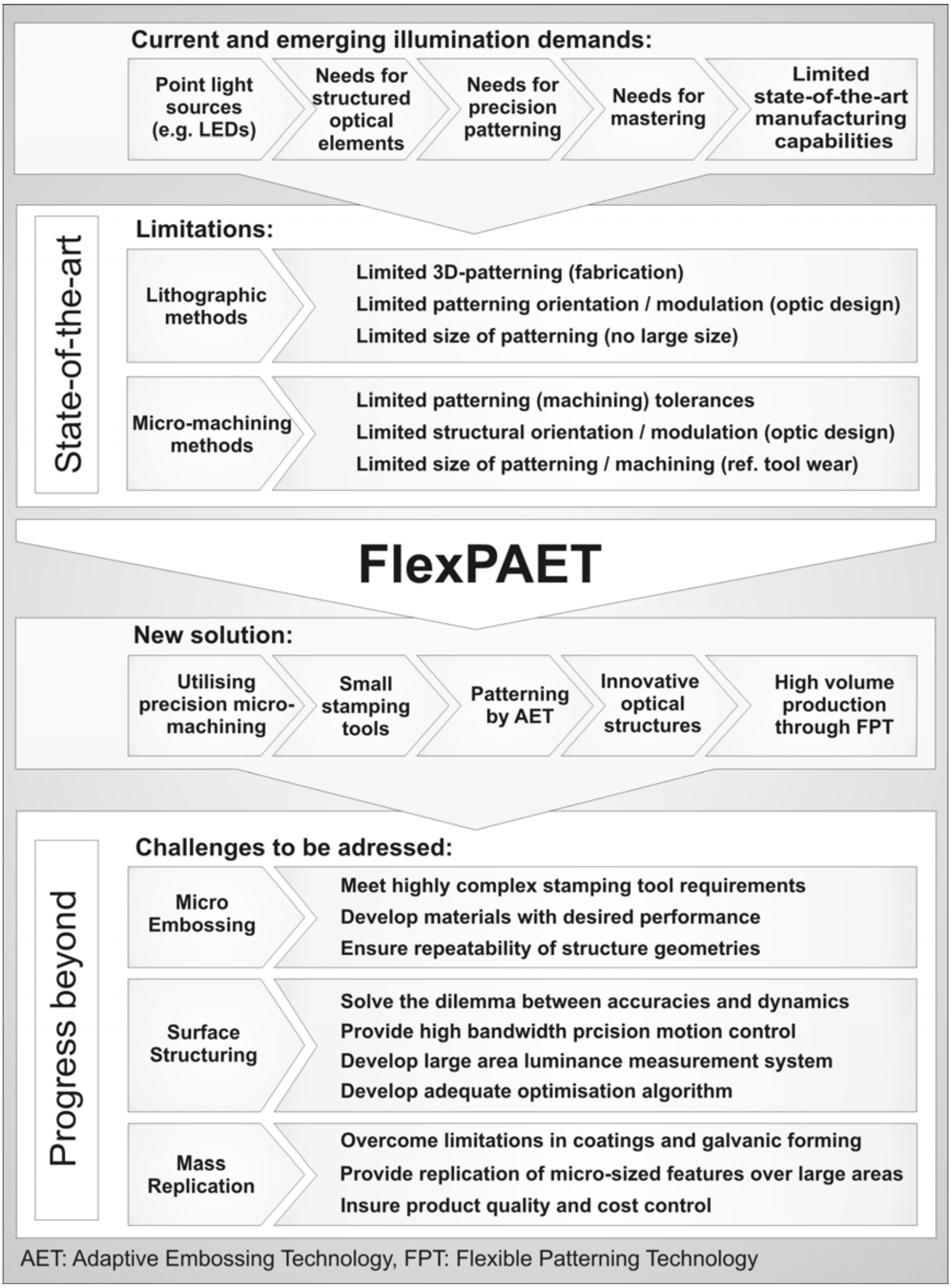


Figure 4: Objectives fo FlexPAET

Main S&T results and foregrounds

Product Specifications, Definition of Demonstrators

Within FlexPAET several different kinds of microstructures were developed and tested. The first structure type forms diffractive optic elements (DOFs). By the help of those elements light can be out coupled from a light guide in a controlled direction Figure 5. Basically, the later described algorithm for the design optimisation bases on automatically optimization of the number and position of the DOFs on the substrate. In addition to the DOFs, pyramidal structures, spherical tools and prismatic structures have been manufactured within the project. Pyramidal structures will be used by Zumtobel for lighting applications. Figure 6 shows the principle of an application of the pyramidal structures. As depict, the products which can be produced with the FlexPAET technology can be used for light guide optics and for transmissive optics.

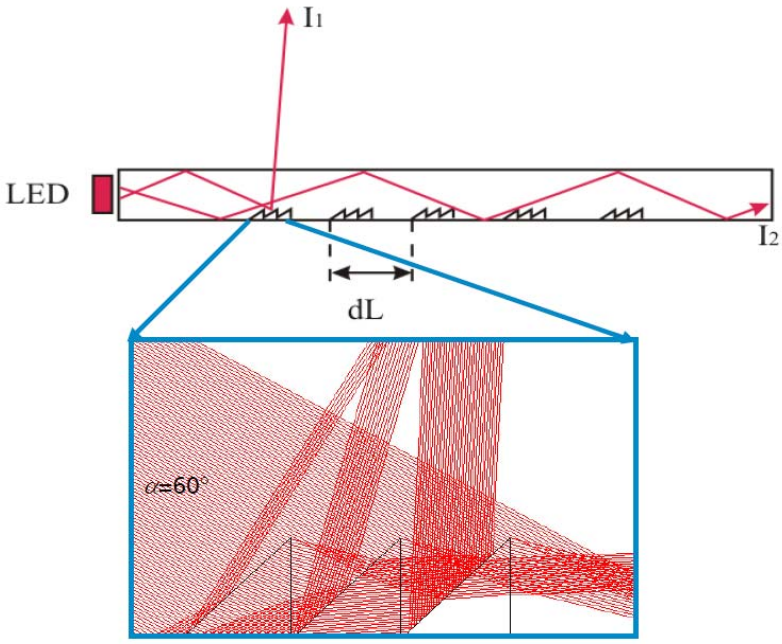


Figure 5: General principle of the DOE structures.

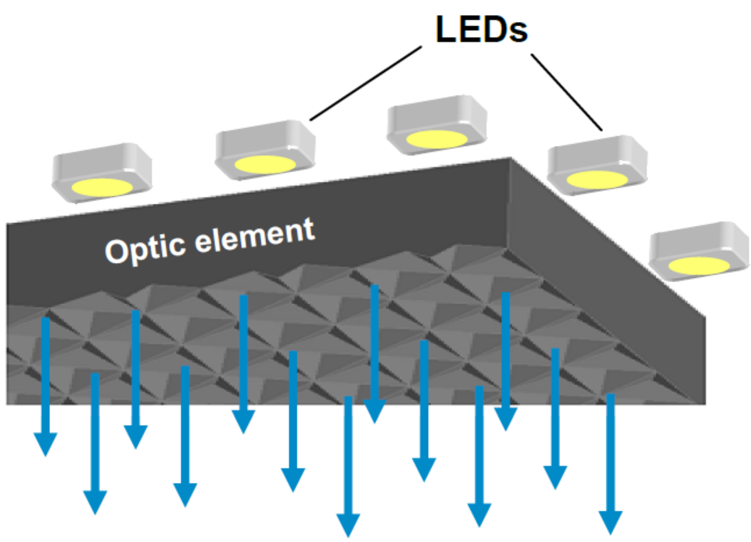


Figure 6:General principle of the pyramidal structures.

Material Development

Within FlexPAET two development strategies for material have been focussed. The first approach was to develop transparent material like. Since the possibilities to adjust the properties of those materials are strongly limited, within the second approach the focus was on the development of non-transparent material. The non-transparent material was adjusted with respect to the glass transition temperature (Tg) and to the electrical and thermal conductivity. The electrical conductivity was adjusted by the addition of nano particles.

The material selection, has been made in order to fulfil the requirements of the different steps of the process (embossing step, conductive coating process followed by the electro deposition and removal of the substrate to produce the final master).

Control Concept

Within the project, two basic concepts for the machine controller have been developed. For the decision process for selecting a suitable controller it was taken into account that, for the positioning unit, standard CNC functionalities like interpolated movement of several axes, interpretation of ISO-machine code as well as a standard HMI for machine control need to be available. In contrast for the embossing unit there is no need for standard CNC operations but for flexible adaption of the embossing movement. Therefore, the first control was split up in an industrial numeric control "Siemens 840D" and a flexible programmable real time control system "Bachmann M1". Figure 7 shows the control concept of the first control system

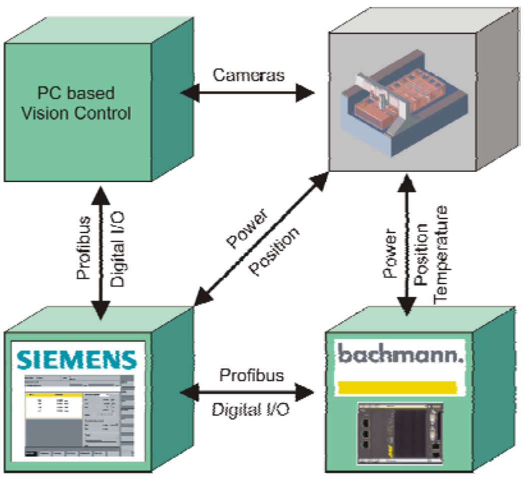


Figure 7: Control concept for the overall machine system

During the course of the project the system needed to be changed since the combination of the systems lead to some inefficient control structures. A second control system was therefore developed.

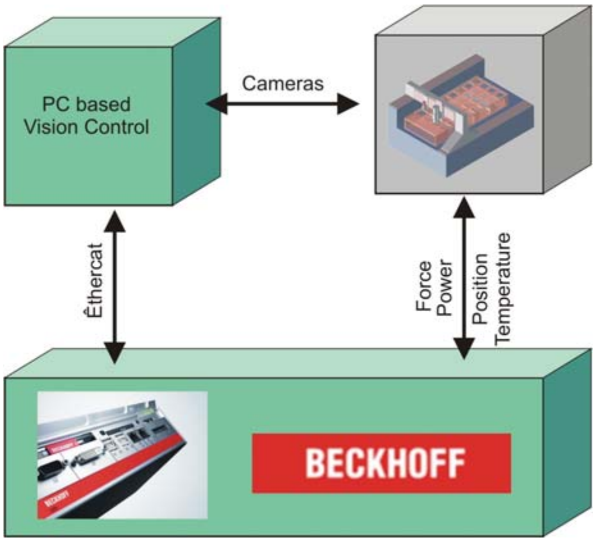


Figure 8: Control concept II for the overall machine system

Figure 8 shows the concept of the secondly developed machine concept. In contrast to the first concept, the controller bases on a Beckhoff automation system. This platform is able to control the main axis by standard codes while the embossing algorithm can be implemented flexibly on the same control system. In addition the EtherCat bus provides easy communication options between machine controller and camera PC.

Test Bench Design

The present chapter shows the design of the test bench for the embossing experiments. The travel of the test bench limits the size of the preliminary demonstrator to 270 mm x 285 mm. The machine system is capable to carry the embossing head which later was used with the final machine system. The test bench uses the same control system structures as later on the machine system used.

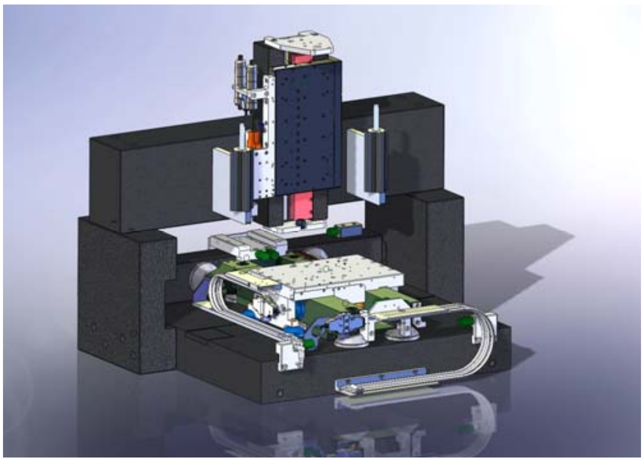


Figure 9: Test Bench for the embossing system

Final Machine Concept

Two principle concepts have been derived which suit the restrictions resulting from the intergration of metrology systems in the machine. First, a system where the metrology modules are mounted under a moving glass table has been developed. Secondly, a system where there is an additional metrology box which carries metrology devices has been worked out.

Glass Table Concept

This concept bases on the idea that structural parts of the machine table are made of glass. With the information about glass machining possibilities and restrictions of the camera system, the dimensions of such a system were sketched.

Figure 10 shows the rough machine concept.

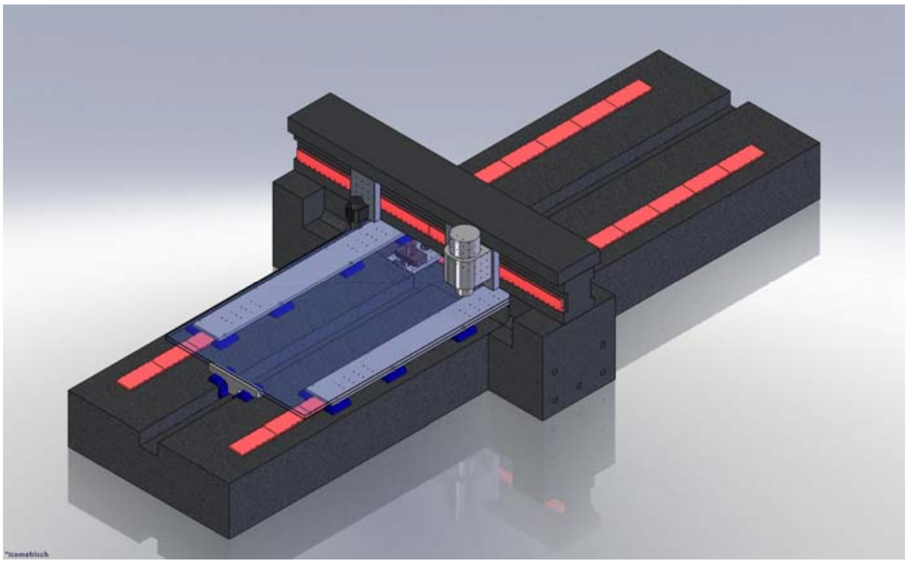


Figure 10: Glass table concept

As a further development the concept was changed that way, that not the entire table is made out of glass but a frame caries a glass plate. In this setup the table should be stiffer compared to the full glass table variant. In addition, the operating reliability should be better because the edges of a glass plate would be sensitive to impacts. The idea of bearings which are placed close to the machining zone was transferred in the setup as well. To win stiffness in the machining area while the table is relatively flexible, vacuum preloaded air bearings should be used. Those bearings should work at a working point where there is no additional external preload needed. Thus, there is no preload force which deforms the table when there are no external forces. Figure 11 shows the load and stiffness charts of a vacuum preloaded bearing. The charts roughly could be extrapolated to the operating point where the external load is zero.

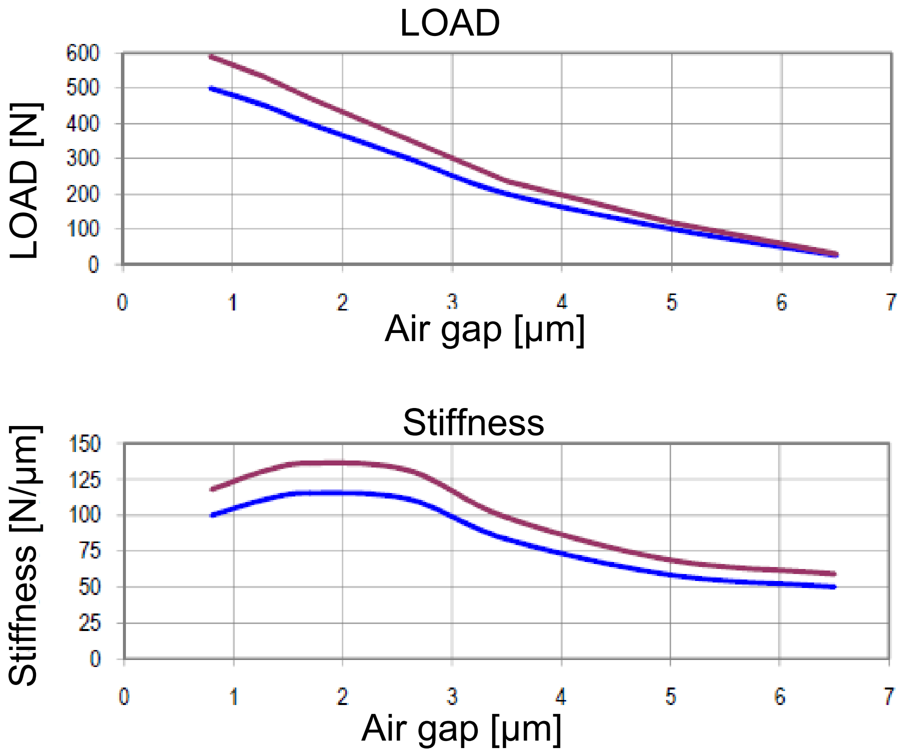


Figure 11: **Load chart of vacuum preloaded airbearing (Eitzenberger)**

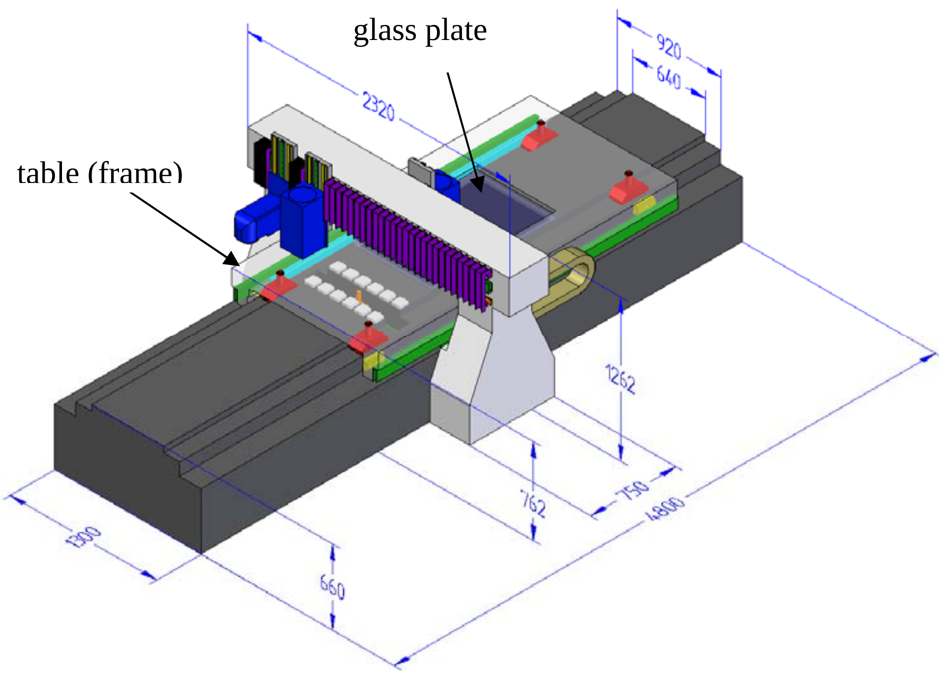


Figure 12: **Glass table concept**

The position of the camera system inside the machine bed is asymmetric. It is directly installed under the TCP and can travel along the y-direction of embossing system Figure 12 shows the rough dimensions of the system. The advantage of this concept is that the whole machine setup is relatively flat. Therefore the design can be stiffer and the linear encoders can be positioned closer to the TCP.

- The positing unit for the camera does not need an axis for the x-direction.
- The setup has some disadvantages which need to be taken into account:

- The glass plate is sensitive to shocks.
- Only low stiffness is achievable for the table due to limited thickness of the glass and low material stiffness.
- High production costs.
- Little experience in the design of structural glass components.
- Lack of accessibility of camera system.

Metrology Chuck Concept

The concept was detailed in order to see the resulting dimensions of the machine system. For the bearings a similar setup to the bearings of a JFA machine has been used. Figure 13 shows the example of JFA for the table guidance. Figure 14 shows the concept of the machine table equipped with a metrology chuck.

Figure 13: Bearing setup

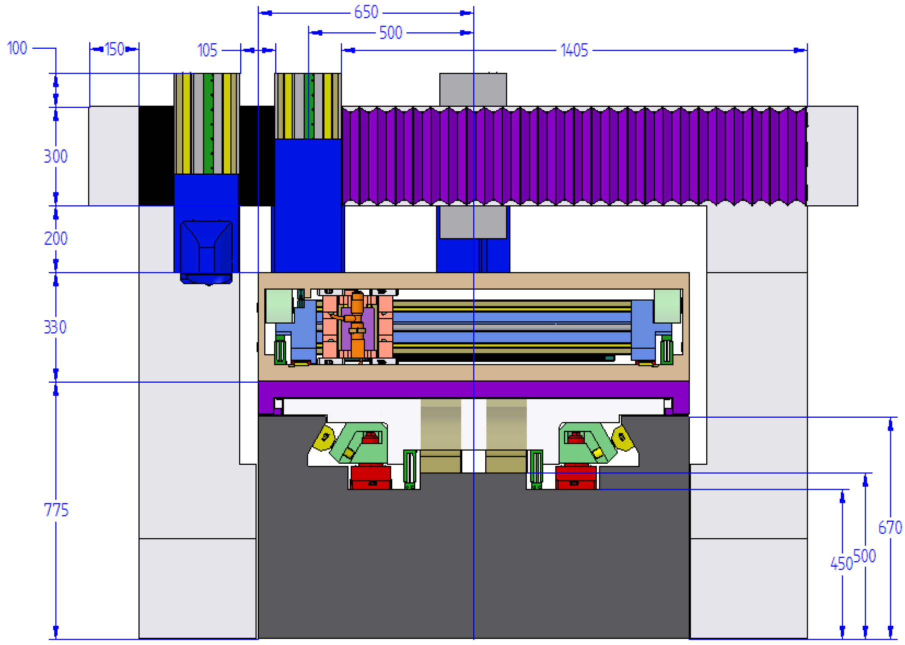


Figure 14: Concept for machine with metrology chuck

The advantages of this variant are

- Approved machine concept.
- Modular design enables simultaneous engineering of machine and metrology system.
- Better accessibility of camera system.
- No weakening of the base machine due to camera trench.
- The disadvantages are:
- More complex camera system.
- Large offset between machine basis table and TCP.
- Heavy setup with large offset between drives and centre of gravity.

Final Machine Concept

Figure 15 shows the final machine concept.

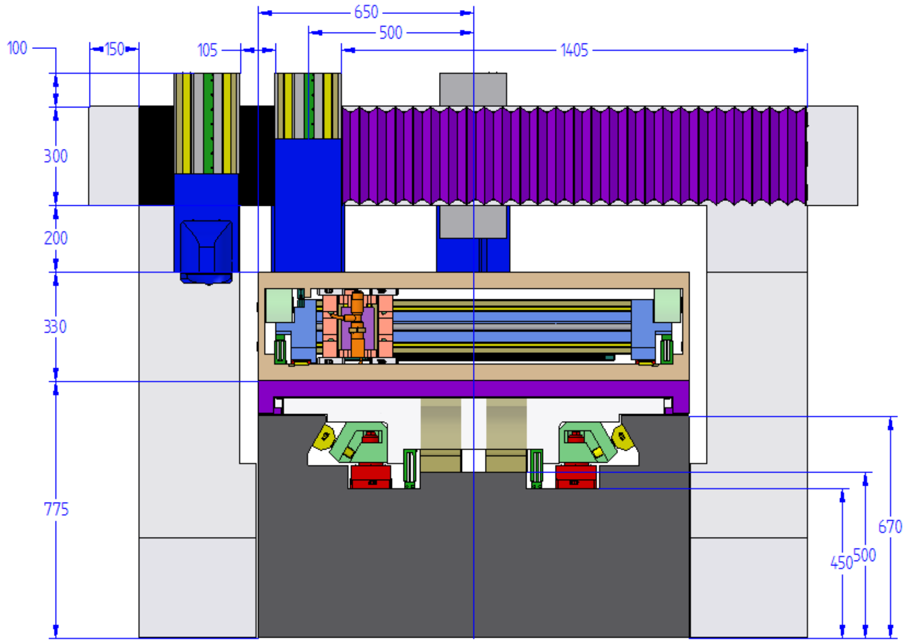


Figure 15: Concept for machine with metrology chuck

Figure 16 shows the finalised machine system with detailed axes. In addition to the embossing axis, there is the microscope axis at the same side of the Y-bar of the machine. On the opposite side, there is an axis for flycutting

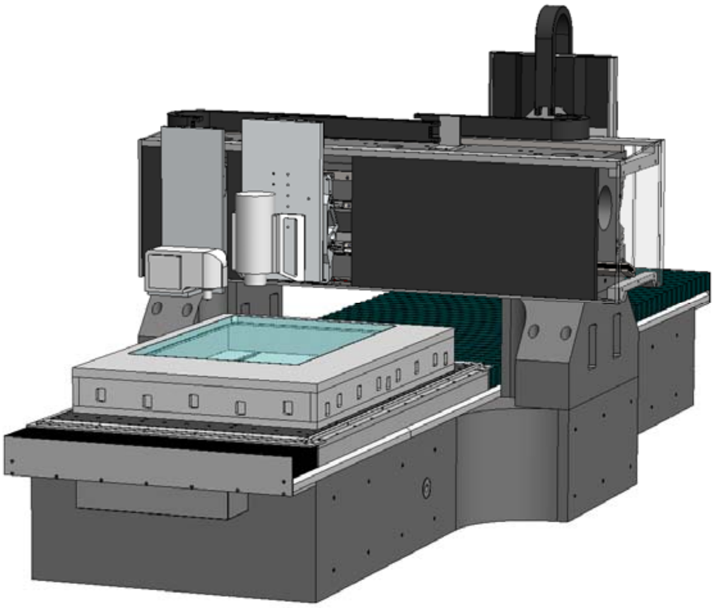


Figure 16: Detailed finalised machine system

Figure 17 shows the machine base. The entire base machine is made out of granite.

Figure 17: Machined machine base

Figure 18: Machine table (X-axis)

Figure 18 shows a photo of the machined X-axis For weight reduction, through the entire table holes have been drilled. In this manner, it was possible to achieve a light-weight table, machined out of granite. Thermal properties and accuracy of the material is outstanding but for machining, special know-how needed to be developed. In addition to the X-axis, a lightweight design was chosen for the Y-Axis as well. A fully integrated Y-Z-combination was machined out of a special aluminium alloy with low coefficient of thermal expansion.

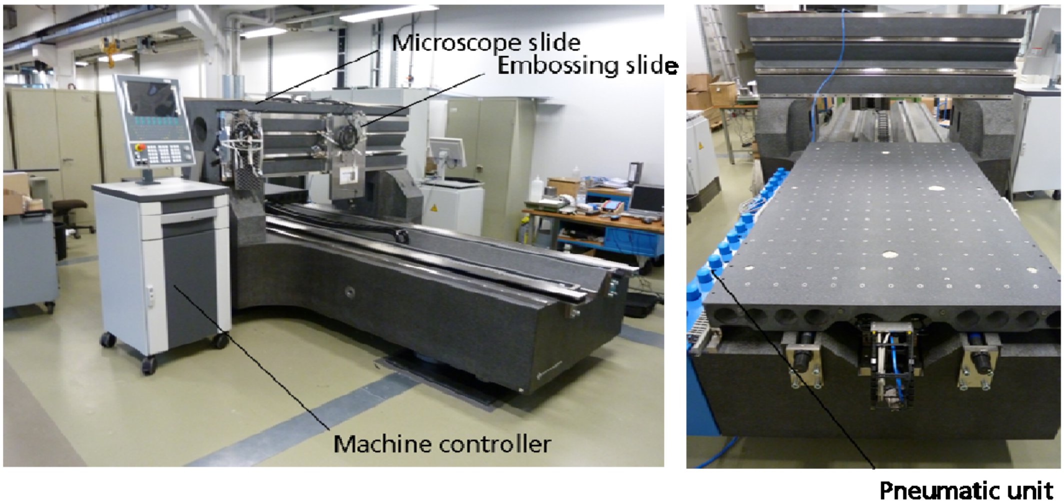


Figure 19: Basic setup for machine system

Figure 19 shows the basic setup for the machine system, including all main axis. **Figure 20** depicts the entire adaptive embossing system with the integrated embossing systems, the metrology chuck with the integrated camera, a conoscopy system, and a confocal microscope.

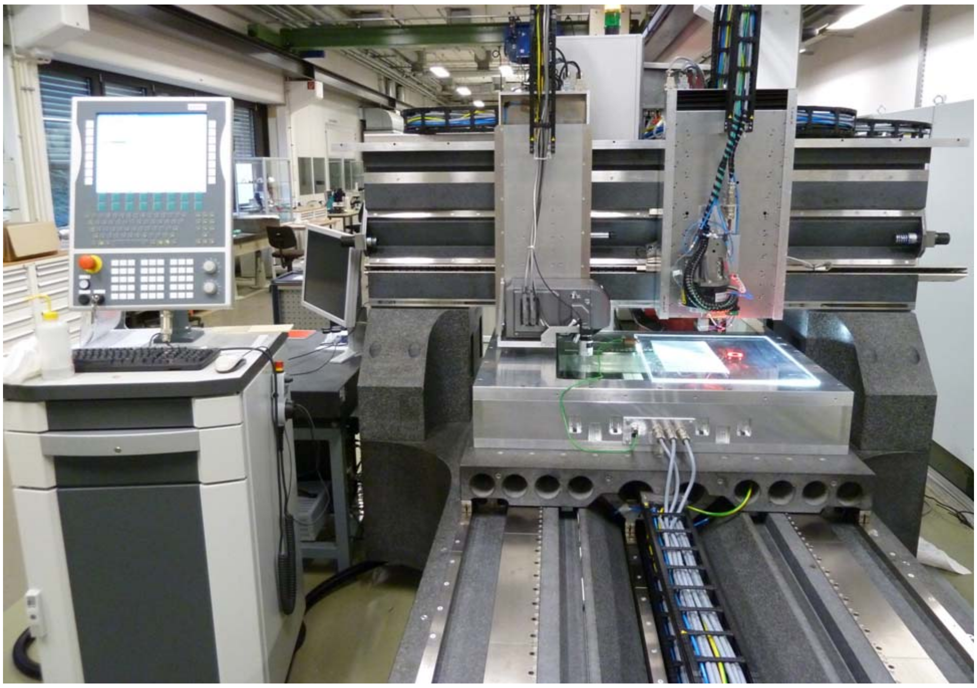


Figure 20: Final machine System for adaptive embossing

Metrology

The metrology system for the machine to be developed in FlexPAET project must comply with the specification for an online analysis of the stamping tool and the stamped substrate. Thus, the requirements for the system have been divided in these two major groups: Tool related Process Control specifications and Substrate related Process Control specifications. Within each of these two Process Control specifications, several subsystem requirements have been defined.
Besides the specific Process Control requirements, available volume, required components for embossing process, component costs and embossing process capacities bring limitations to the implementation of all the desired Process Control systems, and therefore, some prioritisation has been developed for the requirements in order to define which of the requirements are necessary or desirable, and of these, which are to be implemented first if possible.

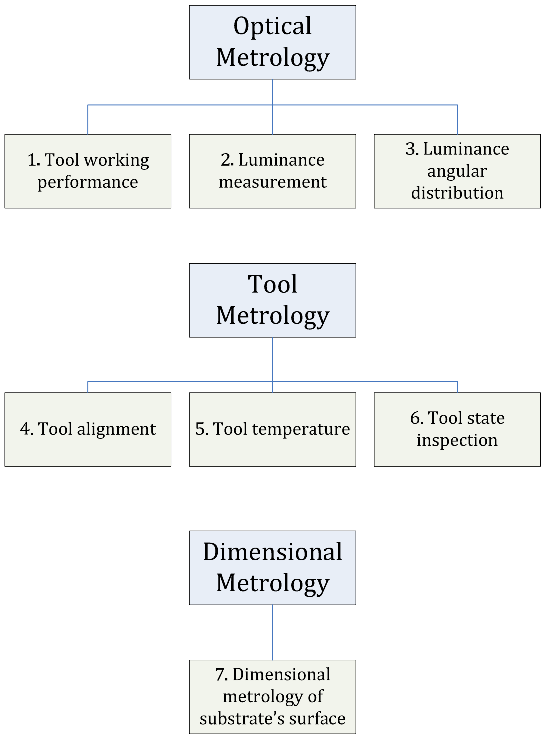


Figure 21: Specifications of the metrology system.

Online detection of microstructures

One of the first requirements to be fulfilled was a metrology system for online inspection of the stamping process. The intention is to perform an inspection of the stamping in order to obtain some information about the stamped areas before the process continues. Each stamped structure can be inspected just after the stamping process from a camera system which is situated inside the metrology box. By means of this information of the structured area it can be evaluated if the process should continue, or something is wrong with the results. Thus, only a rough inspection where big errors could be acknowledged online would be performed.

This subsystem obtains the information on the structured area through image capturing. A camera obtains an image of each structure just after stamping is performed. This image is compared with a reference image of an optimum structure. This comparison gives a rough estimation of the performance of the stamping process. If the image of the structured area differs from the reference image of a correctly stamped structure, some errors have occurred. This procedure shows that an error occurred, but no information is given related about why this error appeared. This subsystem is used to assure that easily acknowledgeable errors have not occurred in the stamping process, and if so, stop the process and investigate the reason why the error happened and what to do to avoid it, preventing further erroneous stamping.

Tool alignment measurement

The need for several tools requires a tool changing procedure to be defined for the machine. Then, misalignment errors could appear in this process. A metrology subsystem is to be developed in order to inspect the accuracy of the tool exchange process. This subsystem captures an image of the tool after the exchange has taken place. Location of reference features are compared with a reference image of a correctly aligned tool.

Tool State inspection

The objective of this specification is to analyse the state of the surface of the tool in order to avoid operation with a damaged tool. This component operates in a similar manner to the tool alignment measurement. Additionally, an image of the tool before removal can be captured in order to acknowledge its state.

Luminance relative value map

The objective was to evaluate the luminance distribution in the substrate when the light is coupled in, as it is in the final operation of the manufactured component. The goal was to obtain a measurement of the luminance of the full substrate in order to guarantee that no dark or bright areas are present during operation.

The system is composed of a camera and a lighting device. This lighting device is formed by the final LED's to be used in the product operation, which would be turned on and off for the image obtainment.

For the analysis of the outcoupling behaviour of the patterned light guide plates, a system for sensing the outcoupling efficiency was designed. A special optic was selected for the integration in the metrology chuck. In experimental series the outcoupling behaviour of light guide plates with different structures was tested.

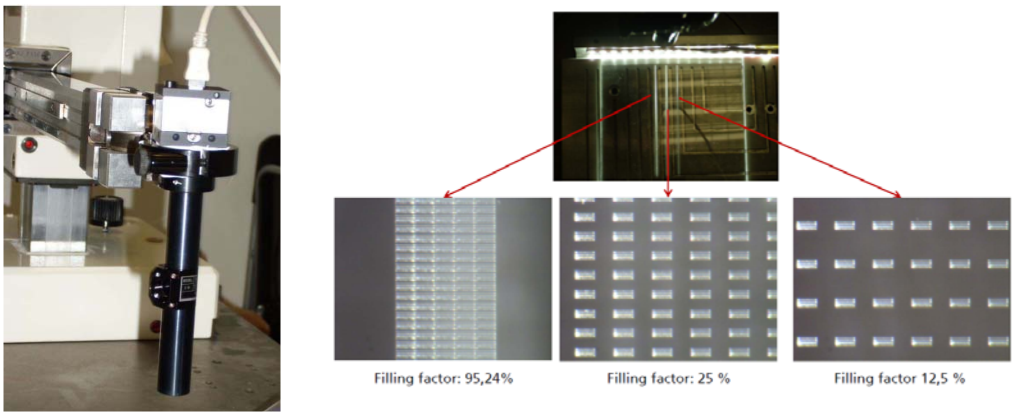


Figure 22: Metrology experimental setup

Figure 22 shows the experimental setup and a substrate which has been tested. Different filling factors where investigated. The luminance over the outcoupling length was tested. Figure 23 shows the trend of the luminance for substrates with filling factors of 95,24%, 25% and 12,5%.

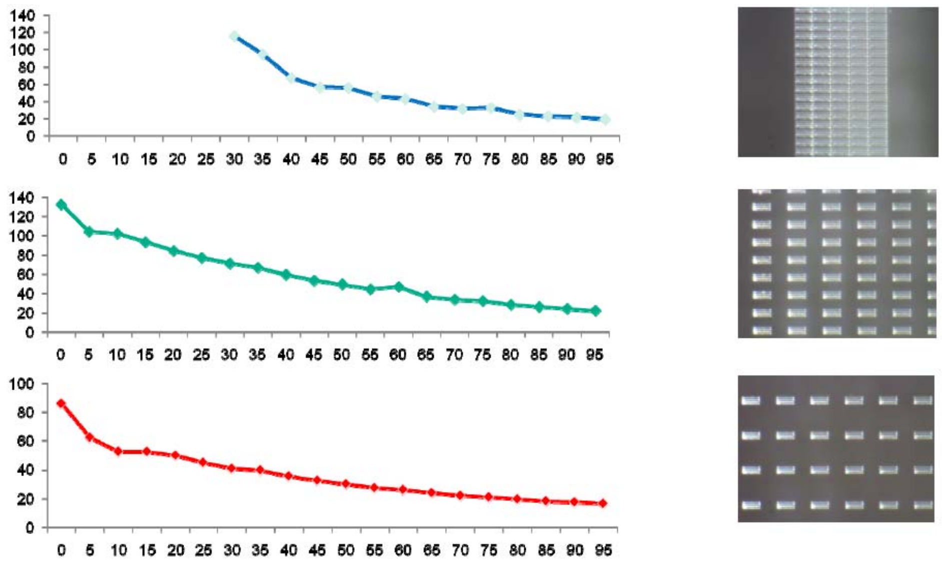


Figure 23: Metrology experimental setup

Luminance angular distribution map

Evaluate angular distribution of the light passing through the substrate. The objective was to assess the deviation of the light coming out of the substrate. Two possibilities have appeared in order to evaluate angular distribution of light in the substrate. On one hand, a conoscopic system was envisaged. This system could evaluate the angular distribution of light for each measured point. But two major problems arise, such as the cost of this component in the market, and its implementation on the machine. The size and features of such a system exceed the capabilities of the machine under development. On the other hand, a goniometric system could be developed to evaluate the angular distribution. Costs and light source and ambient light separation are the main drawbacks of this system. Finally, a low budget consoscopic sensor, basing on a CMOS-Camera and a pinhole optic was implemented in order to achieve conoscopiy measurerments. A setup by a camera system and a special purpose optic was developed. The optic consists of a pinhole and lenses of the suitable projection of the light on the CMOS chip of the camera. Figure 24depicts the setup and. Figure 25 the measurement results of the low cost concoscopy system.

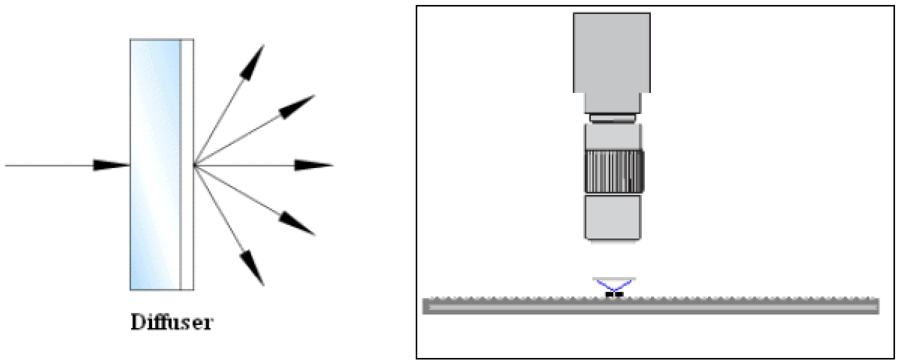


Figure 24: Setup for low cost conoscopy measurements

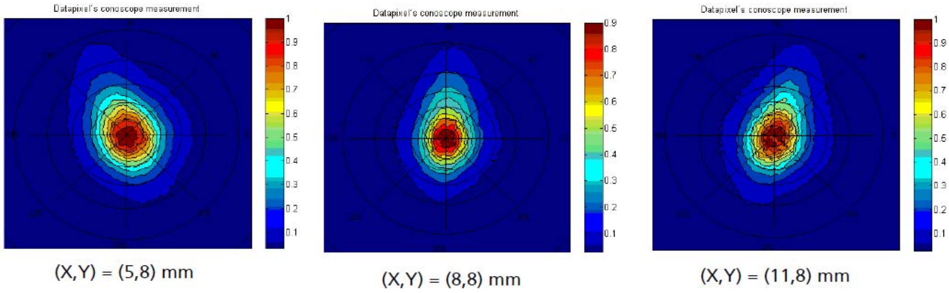


Figure 25: Measurement results of the low cost conoscopy system

Dimensional characterization of the substrate surface

Characterise the structures embossed in the substrate. The goal is to obtain high precision metrological information of the substrate for process performance evaluation. A confocal system has been integrated in the machine for the substrate surface characterization. A major issue regarding this component was the implementation in the machine and its performance. The technical requirements, such as vibrations, luminance, of such a microscope mean that it can only be used independently, while the rest of the machine is stopped. Thus, this system has been implemented for further inspection of the substrate after the embossing, and it will not be used in an on-line basis.

Figure 26 shows the image of a pyramid micro tool. Obviously the sensor information in the steep areas of the pyramid flanks are strongly limited, which results in noise and some peaks in the image of the tool profile. Anyhow, the geometry and the structure angle can be detected quite well. Additionally a tool state inspection, based on the characterisation of the embossed substrate, is possible by the help of the metrology system. A quantitative value for the surface roughness can not be detected in those slanted surfaces.

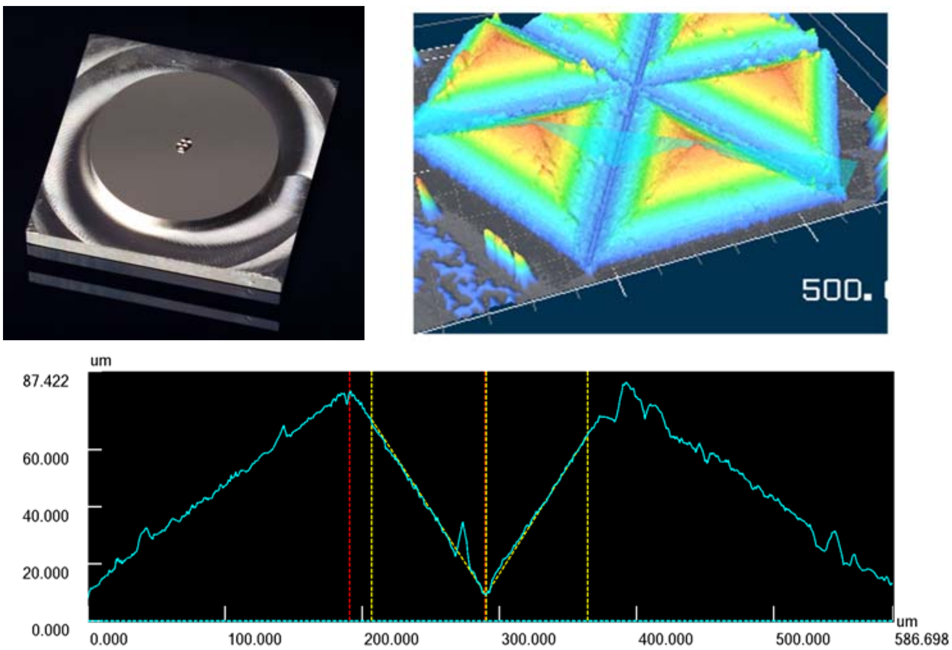


Figure 26: Imaging of a pyramid structure tool

In addition to metrology tests of the tool, embossed structures where characterised by the help of the microscope as well. The main task of the system inside the machine will be the analysis of embossed structures in thermoplastic material, thus it was analysed if embossed grating pixels and embossed pyramids can be detected with the confocal microscope. Figure 27 shows the results of the imaging. The imaging possibilities provide sufficient information for process optimisation of the embossing process. Size and angle of the structures as well as structure depth can be detected easily.

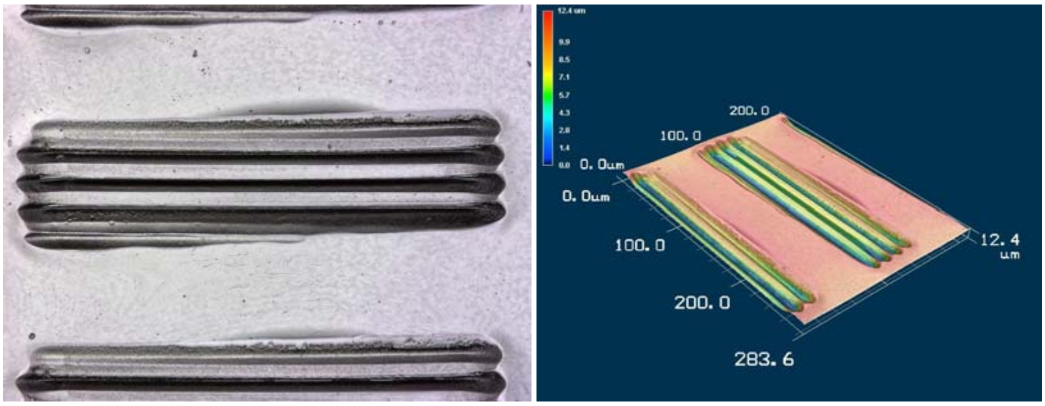


Figure 27: Imaging of embossed grating pixel

Due to the optical principle, the system does not provide profile information for very good surface quality on very steep slanted surfaces. For example geometry of the diamond machined tools for the grating pixel can not be detected in the areas of the ground of the groove. The upper part can be detected which is sufficient to analyse angle and pitch of the structures.

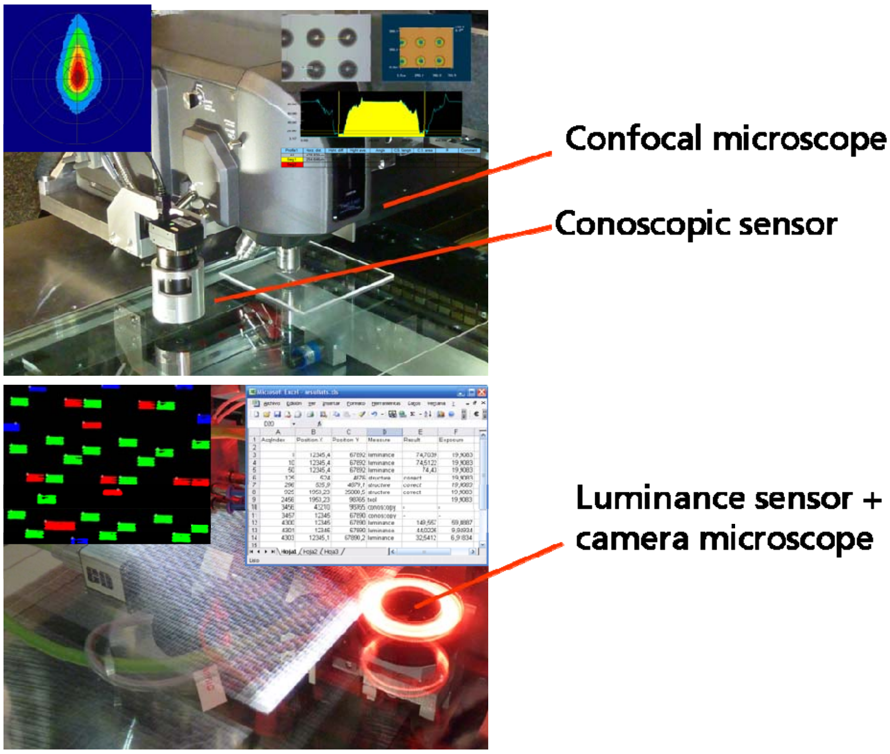


Figure 28: Metrology Systems, integrated in Machine

Figure 28 shows all elements of the metrology systems integrated in the machine setup for FlexPAET.

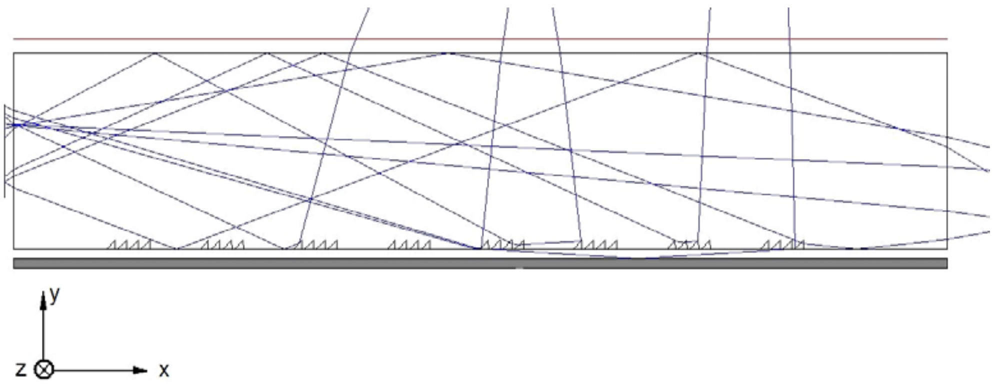
Optimisation Algorithm

A differential equation giving the distribution of scattering elements leading to a uniform irradiance along the waveguide was found and a method to determine the value of the outcoupling coefficient from the irradiance (or radiance) measurements was proposed. The validity of this model by performing ray tracing simulations on a waveguide with the scattering elements distributed according to the solution of the proposed differential equation was verified and a quantitative agreement between the analytical results and the simulated ones was found. Also this model has been used to directly calculate the output power of a given embossed waveguide. For optimization purposes, an objective function was defined and using the direct calculation of the output power based on the aforementioned model a simulated annealing algorithm for finding the distribution of the scattering elements giving a uniform radiance was proposed. Finally, the possibility to fit the luminance experimental data was discussed.

The mathematical model of the light propagation in a waveguide with a given distribution of scattering elements

The mathematically modelled system is illustrated in Figure 29. This represents a PMMA waveguide which on the lower surface possesses an embossed distribution of scattering elements, each scatterer consisting in a series of four adjacent prisms designed by Oy Modines Ltd. Although in the simulations performed for testing the validity of the model this specific scatterer is used, this model is general and it can be used for a scattering element with any geometric characteristics. For visualization purposes the thickness of the waveguide presented in Figure 29 is 200 microns, 15 times smaller than the one of the actual waveguide. For the real calculations the thickness is 3 mm. In order to ensure that the entire scattered light comes out on the upper surface of the waveguide a mirror is placed under the lower surface of the PMMA plate. The main constrain of this model is that it describes a 1 – dimensional system in a sense that the light emitted by the source is collimated in the (x-z) plane as shown in the lower panel of Figure 29. A method to obtain a collimated radiation from an array of LEDs will be described in the next section. The scattering process is represented in Figure 30. An array of scatterers is considered and the input field I_0. At the scatterer with the index i the input field is I_i the scattered field is kI_i where k is the fraction of the input field scattered out the waveguide and the remaining field inside the waveguide is $(1-k)I_i$. For the next scattering element the calculations are done in a similar fashion as it is shown in Figure 30. In this way, knowing the configuration of the scattering elements and the outcoupling coefficient k, one can calculate directly the intensity of the field emerging from the upper surface as a function of the position of the scatterers as well as the irradiance and radiance quantities, respectively.

Using this model one can also find the configuration of the scattering elements in order to obtain a required distribution of radiance (or luminance in photometric units) of the upper surface of the embossed waveguide.



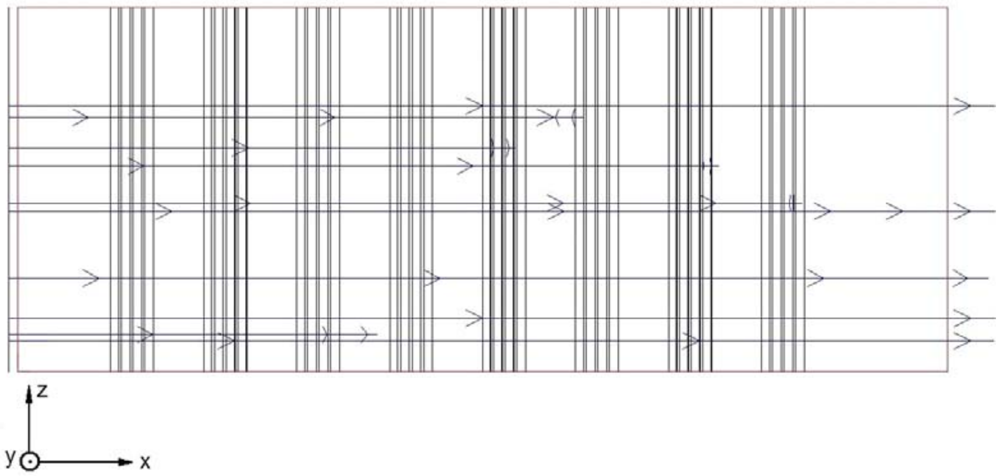


Figure 29: Upper panel: the cross section view of a waveguide with scattering elements embossed on its lower surface and a random distribution of rays interacting with the scatterers. Lower panel: top view of the waveguide showing the collimated beams in the (x-z) plane

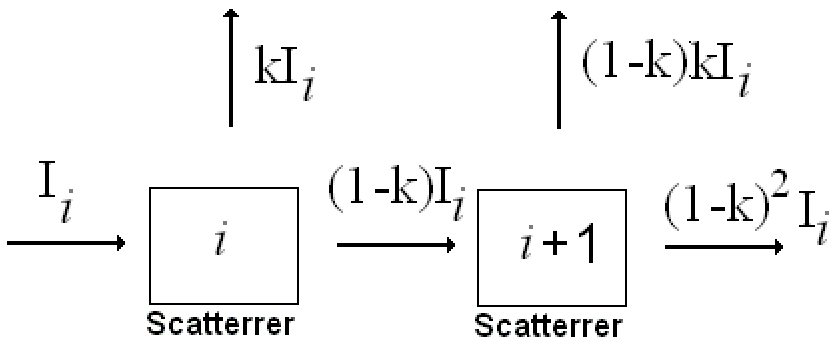


Figure 30: Schematic diagram of the scattering process.

In the following, an expression giving the scattered configuration corresponding to a uniform irradiance over the entire waveguide will be presented.
The amount of radiation Q scattered out of the waveguide over the unit length is equal with the variation with the direction of propagation of the intensity of radiation still confined into the waveguide. This assumption is correct if the absorption losses are neglected. The value of *Q* is proportional with the intensity of radiation *I* propagating in the waveguide which depends on the distance *x* and an attenuation coefficient α which also depends on *x*.

$$Q = -\frac{dI}{dx} = \alpha(x)I(x) \tag{1}$$

If α is constant then the field intensity inside the waveguide I(x) and the Q value will decrease with *x* on an exponential trend.

$$I(x) = I_0 \exp(-\alpha x) \tag{2a}$$

$$Q = -\alpha I_0 \exp(-\alpha x) \tag{2b}$$

In order to obtain a uniform field intensity Q exiting the upper surface of the waveguide over the entire propagation distance, it is necessary that the coefficient α has a dependence with propagation distance. The variation with x of the attenuation coefficient can be easily deduced from the above expression, since I(x) must depend linearly with x such that dI/dx is constant. If the length of waveguide L is considered necessary for complete radiation coupling out of the waveguide and I0 the launched intensity in the waveguide, the intensity function on distance is written as

$$I(x) = I_0 \frac{L-x}{L} \text{ and } Q = \frac{I_0}{L} \quad (3)$$

and α(x) is expressed as

$$\alpha(x) = \frac{1}{L-x} \quad (4)$$

The attenuation coefficient is proportional with *k* which represents the amount of radiation intensity coupled out of the waveguide by a single scatterer and the number of scatterers on the unit length. Therefore, the attenuation is written as

$$\alpha(x) = \frac{k}{\Delta x(x)} \quad (5)$$

Here Δ*x* is the spacing between two adjacent scatterers and its variation with distance is easily obtained from equations (4) and (5) and is given by the following relation

$$\Delta x = k(L-x) \quad (6).$$

One can see from the equation (6) that there are two parameters the length of the waveguide L, and the outcoupling coefficient k that completely determine the scatterer's configuration necessary for a uniform power over unit length over the entire length of the waveguide.
For an outcoupling coefficient *k* constant over the propagation length, the spacing Δ*x* varies linearly with *x*. One can notice that the density of scatterers increases with *x* and eventually tends to infinity when *x* approaches *L*. It is noteworthy that the relation (6) is valid also for an *x* dependent outcoupling coefficient *k(x)*.
For an outcoupling coefficient *k* independent of *x* , the scatterers position can be obtained as a function of *N* – order number of the scatterer with respect to the origin. This can be done using expression (6) by considering an iterative approach illustrated in Figure 31.

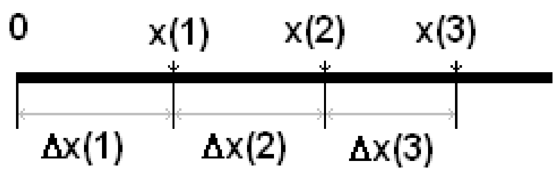


Figure 31: The coordinates *x* of the scatterers and the distances Δ*x* between two adjacent scatterers

Thus,

$$x(N) = \sum_{j=1}^{N} \Delta x(j) = x(N-1) + \Delta x(N)$$

and

$$\Delta x(N) = k\left[L - x(N-1)\right]$$

From the previous relations one can obtain

$$x(N) = kL + (1-k)x(N-1)$$

For the first positions *x(1)*, *x(2)* and *x(3)* one can write:

$$x(1) = kL$$

$$x(2) = kL + (1-k)x(1) =$$

$$= kL[1 + (1-k)]$$

$$x(3) = kL + (1-k)x(2) =$$

$$= kL[1 + (1-k) + (1-k)^2]$$

The general expression for *x(N)* is obtained in straightforward way

$$x(N) = kL\sum_{j=0}^{N-1}(1-k)^j \quad ,$$

and it can be written in a compact form:

$$x(N) = L[1-(1-k)^N]\,. \tag{7}$$

The position *x(N)* of the scatterers, the distance between to adjacent scaterers Δ*x* and their density are shown in Figure 25. In this case the length of the waveguide is 1000 mm and the outcoupling constant k is 0.0034.

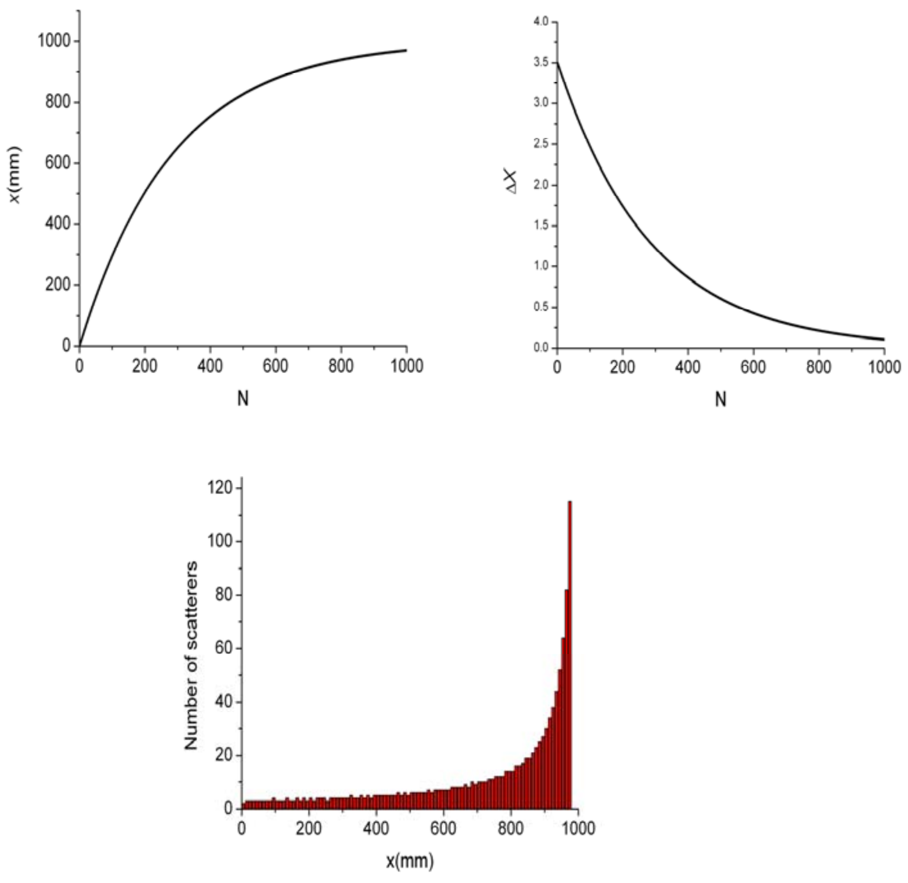


Figure 32: Upper panels: the coordinate *x*(N) (left) and Δ*x*(N) (right) as a function of the scatterer's order number N. Lower panel: the density of scatterers.

Another problem of interest is the behavior of the emitted power density for the case when the scatterer's configuration is realized according to the expression (6) assuming a certain *k* which is different from the real one k_0. the reason for investigating this problem is threefold: i) by comparison with the simulations and experimental results one can validate the model; ii) if the mold to be embossed has a different thickness than the one of the final waveguide then their corresponding outcoupling coefficients are different such that the design and the optimization process have to be done according to a corrected expression which will be written below; iii) it provides a method to measure the real outcoupling coefficient.

Assuming that one places the scatterers according to the equations (5) where *k* is a given outcoupling constant not necessarily equal to the real outcoupling constant k_0 . The differential equation describing the propagation in the waveguide is :

$$-\frac{dI}{dx} = \gamma \frac{1}{L-x} I \qquad \text{where } \gamma = k_0/k \tag{8}$$

With the solutions for the intensity in the waveguide and the irradiance given by the following expressions.

$$I(x) = I_0 \left(1 - \frac{x}{L}\right)^{\gamma} \tag{9a}$$

$$Q(x) = \frac{\gamma I_0}{L} \left(1 - \frac{x}{L}\right)^{\gamma - 1} \tag{9b}$$

It can be seen that for $k<k_0$ the ratio is greater than 1 and the irradiance goes to zero at the end of the waveguide. For the case $k>k_0$ the ratio is less than 1 and the irradiance tends to infinity at the end of the waveguide.

By measuring the irradiance of a waveguide embossed with scatterers possessing an unknown k_0 and distributed according to the relation (5) where *k* has a predefined value, and plotting ln(*Q*) versus ln(1-*x/L*) one has to obtain a straight line whose slope is k_0/k -1. Knowing the value k one can determine the real value of the outcoupling coefficient.

Mould Making and Mass replication

One of the new and innovative consequences of the FlexPAET process is that the embossing tool is used to make a master that is replicated – this means that the price and time needed to make this master, is not so important since it is replicated over and over again. It is extremely important however, is that the process chain used to replicate the master is not corrupting the fine structures or adding to the low surface roughness.

Using a transparent polymer material for embossing the master plate, it is possible to use the on-line metrology system of the embossing machine to constantly measure the quality and optical output of the master. Partly as a result of this, it is an advantage if the substrate is made of the same material as the final product - and among the possible transparent thermoplastic materials, such as PMMA, COC, PC, PS or PET, cyclic olefin co-polymer (COC) was chosen as substrate for this investigation. The substrate was then embossed using an adaptive step and repeat process. The overall size of the master was 130 x 122 mm with a thickness of 6.35 mm. The COC materials was TOPAS 6013 kindly supplied by To-pas-US.com. The stamp used for the step and repeat embossing process, was a simple lens structure as roughly illustrated in Figure 34. After filling the substrate with identical lenses (excluding the edges), the surface was subjected to metrology. The surface scan was recorded as Step 1 (see Figure 34 and Figure 33). Only the 6 lenses in the upper left hand corner were scanned.

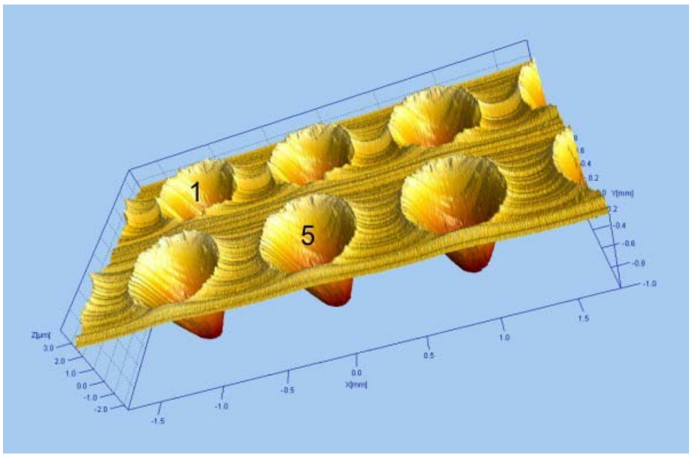


Figure 33: Metrology scan of the 6 lenses in the upper left hand corner of the lens array, with indication of lens number 1 and 5. Please note that the scale for X and Y are in mm, while the scale for the Z axis is in µm.

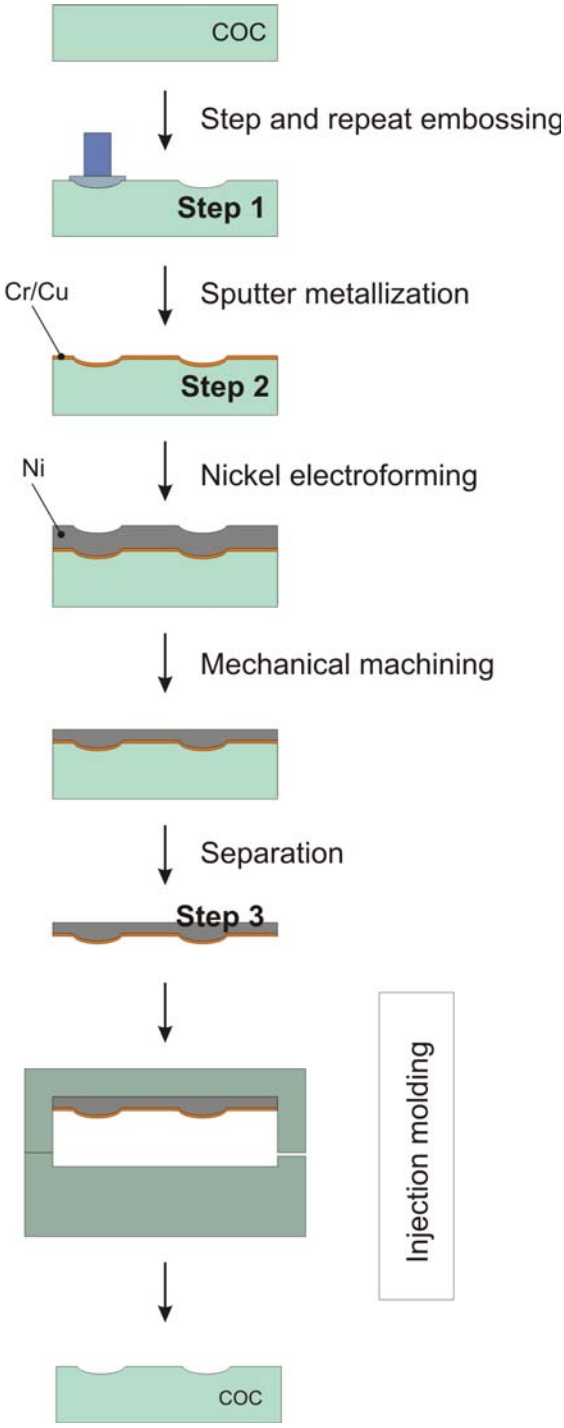


Figure 34: Simplified drawing of the process chain used in this study, which is one of several chains utilized in the FlexPAET project. Steps 1 through 3 correspond to the metrology scans performed on a small portion of the lens array.

Metalisation of thermoplastic master

Several metal layers are deposited on the transparent polymer substrate after embossing. The main challenge is to deposit a thin coherent layer, sufficient for providing the electrical conductivity required for the subsequent galvanic processes. On the other hand the metallization layer must not alter the optical features of the polymer master by thermal decomposition or uneven material distribution.

The best results have been obtained using magnetron sputtering of chromium and copper. Chromium provides adhesion to the polymer substrate and copper provides conductivity for the electroforming (galvanic) step. For this investigation 60 nm of chromium and 200 nm of copper was sputtered onto the surface of the COC master. Prior to magnetron sputtering the COC master was plasma cleaned in a mixture of argon and residual gas in the chamber at 70·10-3 mbar. The magnetron sputtering was conducted in argon plasma at 10·10-3 mbar. After metallization the same lenses were measured again, and recorded as Step 2.

Galvanic deposition

The first galvanic layer will, when the mold is completed, become the surface of the injection molding tool (ignoring the metallization layer since it is extremely thin and might be removed during the separation step). For this reason the galvanic layer must be wear resistant and hard enough to with-stand the high pressure of injection molding.
At first the galvanic process must progress relatively slowly since the electrical conductivity of the master is low due to the thin metallization layer. Later on the current density can be increased, in order to reach the desired thickness in a reasonable time.
To avoid thermal stress, induced by the large difference in thermal expansion coefficient for the various materials (polymer, metallization layers and galvanic layer), the process temperature should be as low as possible – preferably close to room temperature. So far the best results have been obtained using sulphamate nickel electrolytes. The FlexPAET consortium have established three different electrolytes operating at either 32, 40 or 50 °C and with plating rates from very slow (15 µm/hour) to very fast (200 µm/hour).
Due to the relatively poor adhesion between the metallization layers (Cr/Cu) and the substrate (COC), it is of the out-most importance to keep the internal stress in the electroplated nickel as close to zero as possible. Any deviation from a close-to-zero stress behavior will result in de-lamination of the outer areas of the nickel deposit (particularly in corners and edges), and defoliation in the middle area of the part. This is effect is created by the fact that the internal stress in sulphamate nickel deposits (however small they may be), will depend on the local current density – so that a low level of tensile stress will exist at the perimeter of the part (corners and edges) while a low level of compressive stress is found in the middle of the part.
For this investigation approximately 1000 µm of nickel was deposited on top of the metallization layers, using a relatively low current density of 1.38 A/dm2 – corresponding to a nickel deposition rate of 15 µm/hour.

Separation of mould and master

The most gentle and least damaging way to separate master and mold is to dissolve the master polymer in a solvent that does not – in any way – attack the surface of the mold. However, the easiest way is to separate the nickel and master mechanically. In this investigation the mechanical method was used, and immediately after the separation both the nickel replica (the scan called Step 3) and the COC master (this scan is called Step 1a) was measured using the profilometer.
So far investigations have demonstrated that mechanical separation is possible, at least with the relatively simple lens structures utilized in this investigation. Structures having sharper edges or almost vertical sidewalls (Fresnel lenses, pyramidal shapes, etc.) are expected to make mechanical separation much more difficult.

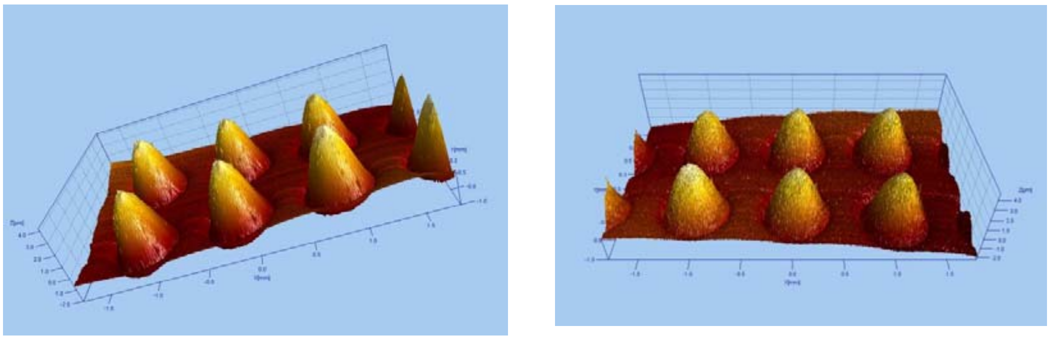


Figure 35: Comparison of surface scans after mechanical removal of the COC substrate. The top image shows the nickel surface with the Cr/Cu metallization, the lower image (rotated) shows the same surface after the Cr/Cu layers has been dissolved

The overall process chain, seems to function in the sense that it is possible to obtain a tool insert with an acceptable quality. This insert can then be used for injection molding of accurate copies of the original master, although unfortunately it was not possible to include measurements of injection molded parts in this investigation. The sputter metallization layers provides the necessary “controlled poor adhesion” over the entire surface of the master and makes the surface electrically conducting for the following galvanic deposition of nickel.
The biggest reduction in quality – or the biggest deviation from the surface of the master – occurs during the sputter metallization of the embossed COC substrate. This is relatively clear when comparing Fig. 3 and Fig. 4, but looking at the Sa-values in table 2 there is a significant increase in roughness moving from Step 1 (the COC master) to Step 2 (the metalized master). Nickel was deposited in a virtually stress-free mode, at a low temperature (32 °C), making sure that stresses originating from thermal expansion mismatch does not become critical. Using relatively flat and smooth optical structures, such as an array of lenses, it is possible to separate the nickel insert from the COC master in a non-damaging way. This opens the possibility of reusing the master. However, from table 1 it appears that something remains in the lenses after the mechanical separation of the COC master and the metallic replica, since the depth of the all the lenses for Step 1 are larger than for Step 1a. The roughness however, seems not to be changed significantly (see table 2).
Finally, it can also be concluded that the best tool inset is obtained if the metallization layers (chromium and copper) are not removed from the underlying nickel. However, since the wear resistance of copper is not very high – and the me-tallization layers will become the outermost surface in the injection molding tool – it would be better to find a combination of metallization layers with a higher wear resistance. This way it would also not be necessary to remove the layers (leading to Step 3a), and roughness values and heights would be as Step 3 in tables 1 and 2 – which are clearly closest to the COC master (Step 1).

Mould making and Production of demonstrators

Finally, the demonstrators has been embossed and the mould has been produced. Figure 36 shows the mould for the light-guide demonstrator. For attaching the mould in the injection moulding system, a special injection moulding tool has been produced. The tool is able to clamp thin nickel moulds by means of vacuum.

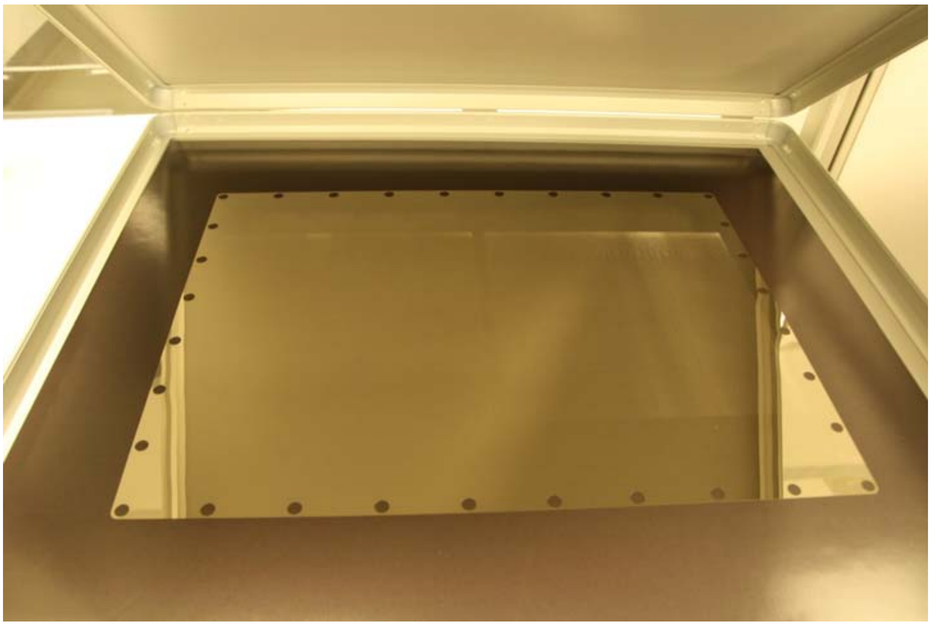


Figure 36: Mould for production of demonstrators

Mass Replication

For mass production the injection moulding process was optimised in order to replicate the fine optical structures. Figure 37 depicts the entire process, starting with the single optical structures on a micro tool, the nickel replica of the embossed master substrate and the polymer replica.

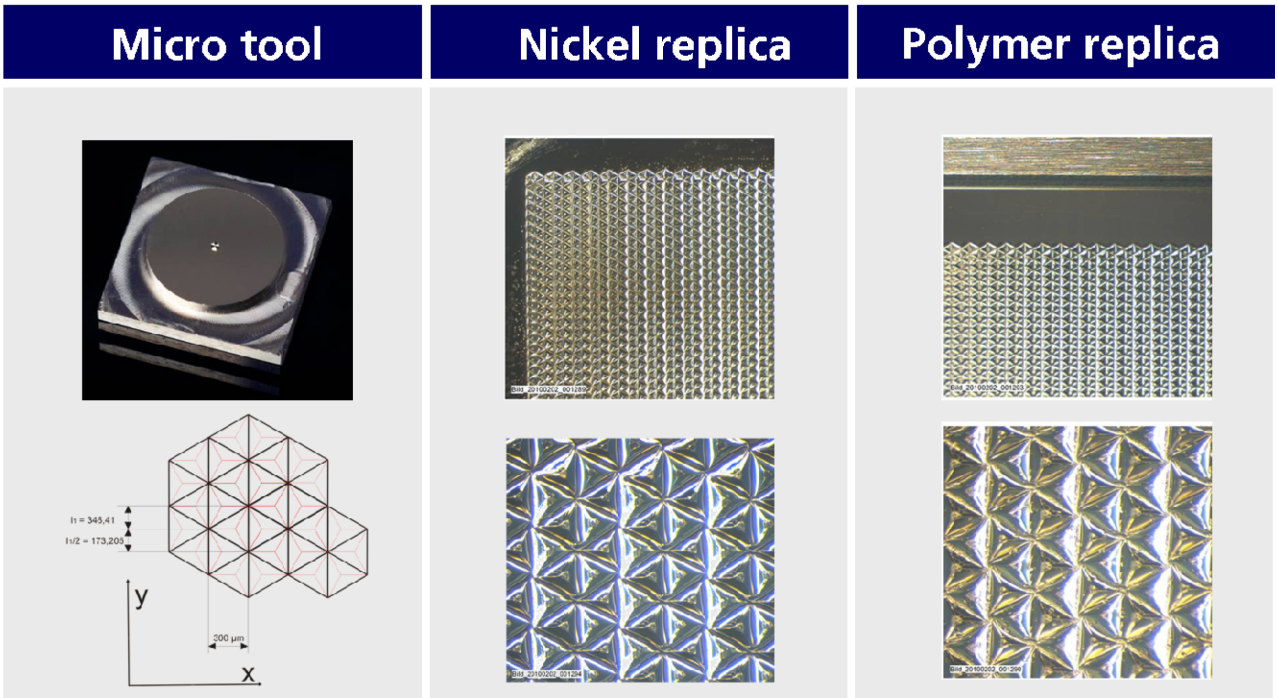


Figure 37: Replication results

Potential socio-economic impact of FlexPAET

Strengthening European nano- and μ-manufacturing industry

FlexPAET outlined three targets to contribute to the strategic objective of establishing a European nano- and micro-manufacturing industry:

1) serving a global, high volume, growth market
2) improving competitiveness for European manufacturers, and
3) integrating and supporting high tech SMEs

By reaching the main project result (establishing a manufacturing process of large-area micro structured surfaces in thermoplastic substrates on an industrial scale), a first step toward the strengthening of the European nano- and micro-manufacturing industry could be made.

Serving a global, high volume, growth market

All optical industries have been considered in assessing the economic impact of the new Flexible Pattering Technology. The corresponding markets can be segmented into nine different fields of application, which are all individually influenced by this new technology to create complex, functional surface structures (see Figure 38).

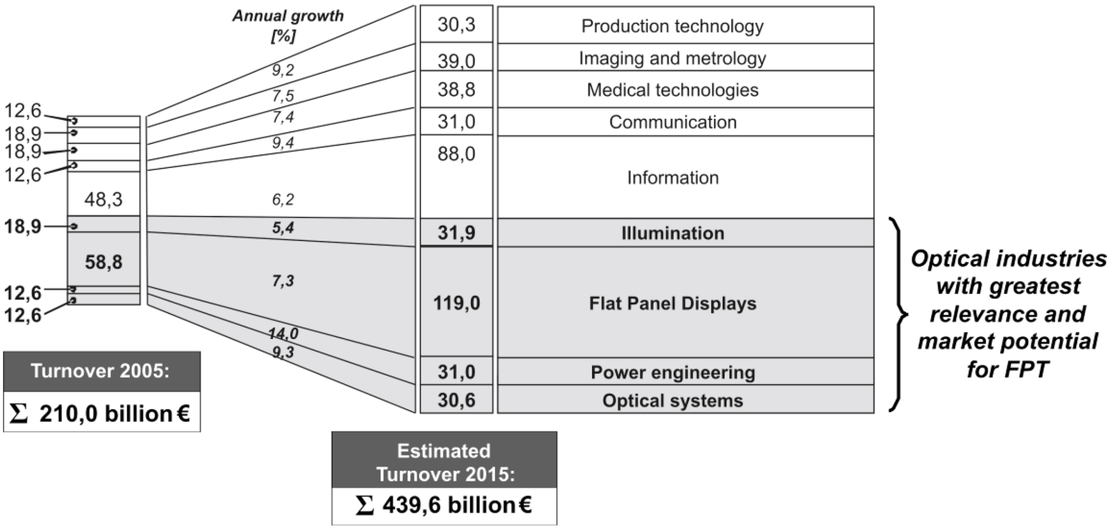


Figure 38: Global market segmentation, volume and growth forecasts for optical technologies (OPTECH 2007)

Both in terms of volume and growth rate, the overview illustrates highly attractive markets with significant potential for the diffusion of the technological developments of FlexPAET, as each product segment represents an area of application for relevant components. As indicated in Figure 39, four of these nine segments show the most significant demand for advanced optical elements and thereby represent the four most relevant markets for FlexPAET. In Figure 39, the market impact expected in the year 2015 is quantified for each of these markets and examples of according products and systems are given.

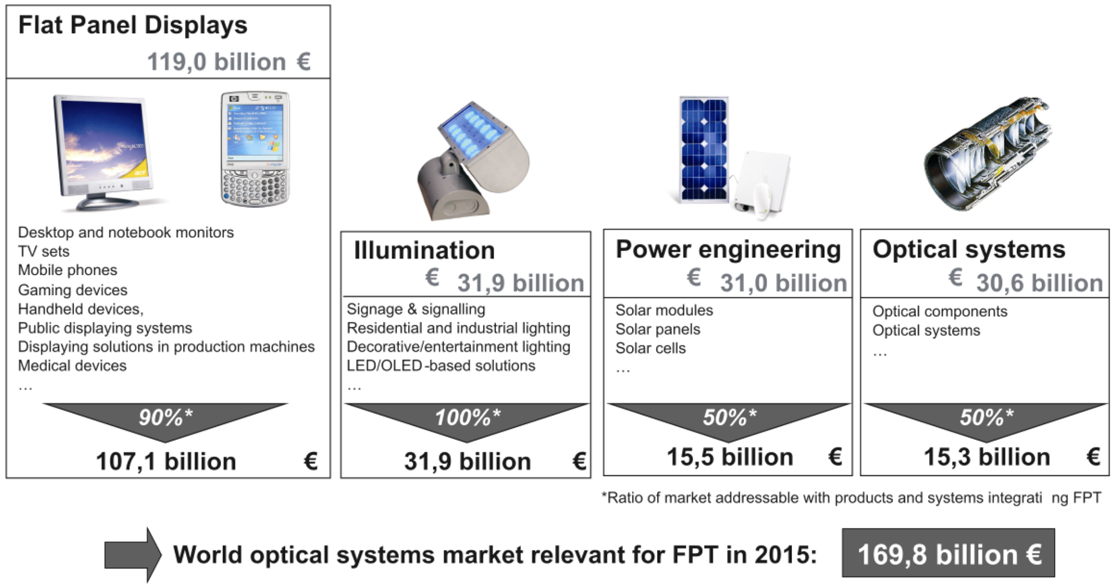


Figure 39: World market estimation based on most relevant optical industries

To address these potential markets, within the FlexPAET project first business contacts on the level of conducting feasibility studies or manufacturing of prototypes were established during the course of the project.
Particularly, in the area of flat panel displays a world leading manufacturer of consumer electronics conduct a feasibility study for a diffractive optical light guide in a TV application. In the market of illumination, four different companies could be provided with a prototype of a light guide. The considered application range from general lighting within buildings including display lighting (emergency exits displays) as well as high resource intensive greenhouse lighting. One of those companies also provide circular and linear concentrating single lenses and lens arrays on large scale-area for solar energy systems. The adoption of FlexPAET for these application is considered. Two supplier of LED components and optical systems contacted the project. Components of this supplier are suited for lighting and imaging applications for use in optical metrology and image processing as well as in optical sensor systems, laser applications and image beamers. Beside the direct addressed markets the FlexPAET project could established contacts to four major automotive light supplier serving the world automotive market. Several prototypes were produced for outside and inside automotive lighting applications with low energy consumption. Thus FlexPAET could also contribute to the target of enabling electro mobility as reducing the energy consumption for auxiliary electric consumers is crucial for electro mobility. An other positive potential environmental impact of FlexPAET occurred as a company of street lighting systems ask for a prototype of an optical element for using LED technology in street lighting products.

All business contacts occurred in the latter phase of the project, were considerable results could be shown. The established business contacts are still ongoing. **To explore the results of FlexPAET and to serve the potential markets a spin-off of FlexPAET was founded under the name of polyscale GmbH.** It is expected for the future to bring the FlexPAET technology, optical elements and optical tools to market.

2) Improved Competitiveness for European Manufacturers

Low-cost countries achieve significant competitive advantages in global competition based mainly on low labour costs and the exploitation of economies of scale. High-wage countries, on the other hand, have gradually lost market shares in many consumer markets and invested mainly in highly complex, know-how-intensive, specialised products manufactured in small volumes. As the profits achievable in high-volume (consumer) markets in general exceed those achievable in niche markets by economies of scope, this development has resulted in a rather one-sided global value chain that benefits emerging economies in Asia and other areas of the world and is especially dominant in optical technologies. Consequently, research activities in the field of production technology must strive to develop advanced technologies which help to sustain Europe's technological and knowledge-based leadership and at the same time, provide flexibility in a way that economies of scale and scope can simultaneously be achieved, and cost-efficiency realised. FlexPAET embodies this principle in a unique way, as it combines:

- flexibility in terms of quick reaction to rapidly changing customer requirements, and
- large lot sizes based on established mass replication technologies.

Both attributes represent fundamental requirements for a sustainable increase of the value contributed by European manufacturers within these highly dynamic and profitable markets for optical components. By providing high value added, key components with significantly superior characteristics in terms of cost, quality and functionality to those produced with any competing technology, FlexPAET represents an enabler to access new markets and thereby dominate component supply and serve numerous global markets. The European manufacturing industry benefits on all steps of the supply chain, see Figure 40.

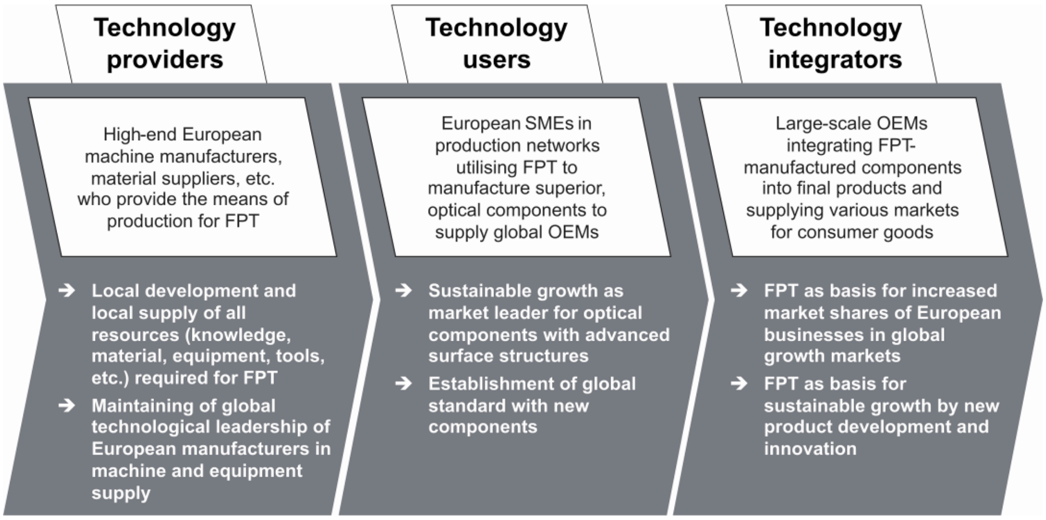


Figure 40: Benefits achieved along the entire FlexPAET supply chain

Concerning the technology providers in the FlexPAET supply chain the competitive position could be improved. Considering that the FlexPAET embossing system is one of the largest micro machines in the world and has never been built in that scale before, the development or enhancing of machine components in terms of quality or accuracy was crucial. However, as the FlexPAET project was succeeded the gained knowledge and developed components can be used by the technology provider in their established markets. Successful developed components are for example high accuracy air bearings, high accuracy of large scale structural machine components, the application of fast-tool system for high dynamic stamping applications as well as an optical high accuracy and dynamic online metrology system. Beside machine components used for the embossing system, the technology providers also improved their process knowledge. For example adhering of different materials in galvanic processing was tested and solutions for large scale injection moulding were developed. Also scientific partners found in FlexPAET a platform to develop mathematic models as an industrial application.

An side effect of FlexPAET results in the establishment of an European business network not limited to the FlexPAET supply chain: the close cooperation between the technology providers necessary for developing the FlexPAET technology was an positive experience. Further co-operations are planed, so spill-over effects of FlexPAET for the European nano- and micro-manufacturing industry are likely in the future.

The established business contacts during the FlexPAET project show the high market demand on European micro optical technology on the side of technology user. FlexPAET address these markets and provide an production network close to the European technology users. Geographical closeness enables cooperative development and specific product improvement that is likely to result in superior product performance in the future.

The superior performance will also have direct effect to the technology integrators. By establishing FlexPAET technology, European OEMs will have direct access to nearby suppliers witch is likely to enables the adoption of LED based technologies. Furthermore, the technology is well suited to factor cost levels in Europe due to the highly automated production. FlexPAET thereby supports local value creation and prevents further cost-driven relocations to low-cost countries in Asia and other regions of the world. Simultaneously, by local presence, new customer needs can be stimulated in Europe. European businesses will be integrated into the global value chain and global market structures will be rebalanced, see Figure 41. Its intelligent, self-optimisation capacity characterises FlexPAET as an advanced technology, suited not only to maintain and enhance the technological leadership of European manufacturers, but also to provide the basis for a sustainable, research and knowledge-based society.

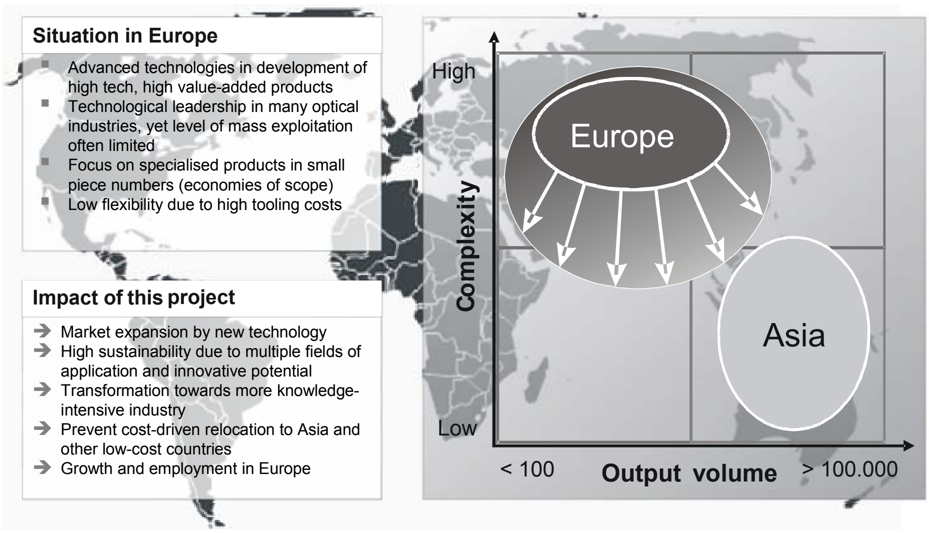


Figure 41: Estimated impact on European industry

3) Integration and support of high tech SMEs - FlexPAET production networks

As described before, advanced expertise in a variety of different fields was required in order to established FlexPAET process chain. Furthermore, new developments and technological advances within the respective fields could be implemented. These developments towards technological excellence and concurrent flexibility was served by high technology SMEs, participating in a production network as is shown in Figure 42. Thus, Flexible Patterning Technology relied on the adaptation and integration of high tech SMEs. Figure 42 shows the transfer of materials and products as well as information and know-how within an FlexPAET production network and the interaction of the network with the respective markets of the participating SMEs. As can be seen, SMEs participated in the FlexPAET production networks benefit first and foremost from their entry into the advanced optical element market. At the same time, they also benefit substantially from the network inherent knowledge and information transfer. Beyond the scope of optical element production, technological advances based on FlexPAET participation is been utilised and exploited in other applications and markets. Thus, the development of FlexPAET within the project supported the adaptation and integration of high tech SMEs to the new needs of the supply chains for micro structured surfaces.

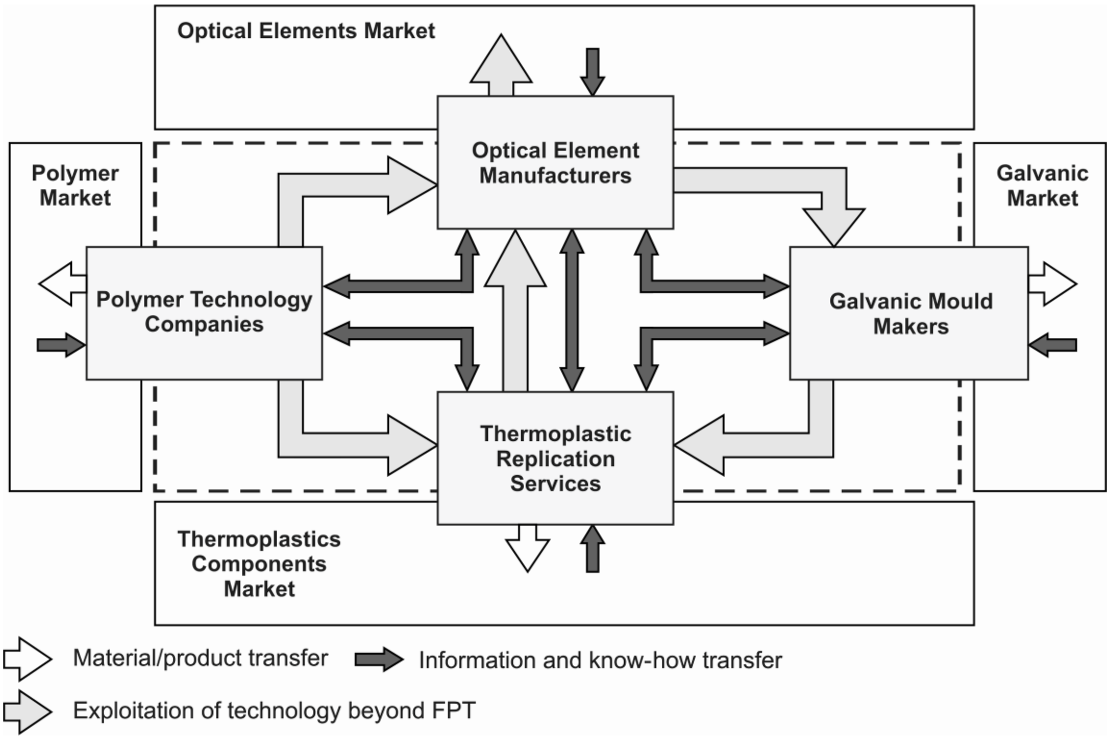


Figure 42: Networked production model for Flexible Patterning Technology

Effects on cost and resource consumption

The technological impacts of FlexPAET to enhance competiveness can be characterised by four basic enablers:

- Savings of up to 60% in material costs for many products, enabled by “smarter” functional structures: PMMA is a costly material but forms the most important material for light guide plates. By means of the FlexPAET structuring method, the thickness of light guide plates can be reduced from typically 8 mm for large light guide plates to around 3 mm, and for smaller plates to a thickness of 500µm.
- New product functionalities and innovation based on increased complexity and functionality of generated structures: The complex microstructures provide not only diffuse outcoupling of light but also directed outcoupling. Luminance of light guide plates can be enhanced without using any brightness enhancement films.
- Shorter time-to-market by self-optimisation capacity in manufacturing of master: The selfoptimising process avoids the iterative production sequence of many steel injection moulding inserts and reduces the time to market dramatically.
- Significantly reduced tooling costs as key to competitive pricing of products in the global market: Flexible changes of micropatterns inside the injection moulding tool by changing only nickel shims inside the tool reduces the costs for a changed optical design by the factor 10.

New features – Innovation for existing products

Some of the most significant impacts of Flexible Patterning Technology can be foreseen in the area of diffractive optics elements for LED-based display and lighting systems, used in a variety of applications, such as those shown in Figure 43. Display and image quality as well as manufacturing cost and power consumption of these products are directly connected to the quality of the diffractive optics elements. Utilising FlexPAET capabilities, product improvements can be achieved with respect to:

- reduced power consumption,
- lower manufacturing costs,
- enhanced system performance.

Thus, through enabling such considerable improvements to the product quality, FlexPAET is directly contribute to ensuring continuous and sustainable growth in many well-established markets.

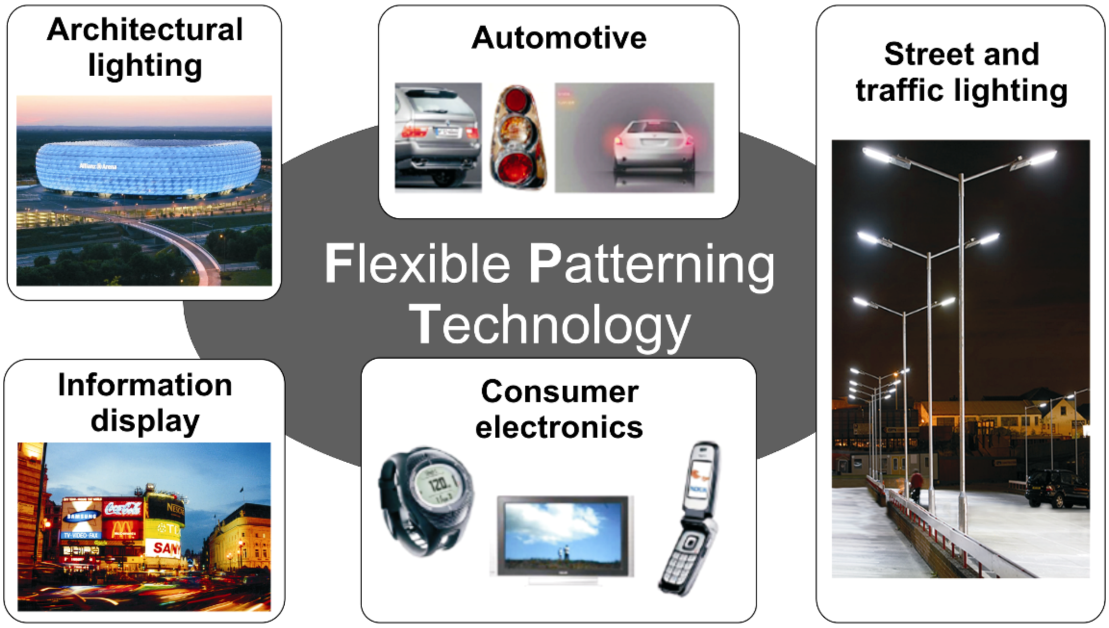


Figure 43: LED-based display and lighting solutions

<u>Example 1: Consumer electronics – LCD display technology</u>

As an example, the potential FlexPAET-related improvements for LCD displays utilising LED backlighting elements are shown in Figure 44. LED backlighting solutions are already available and highly praised for their enhanced picture quality, including:

- a brighter, evenly lit screen,
- a much wider gamut of colours,
- better contrast,
- a mercury-free system.

However, they are at present far too cost-intensive for the consumer products market. Together with the business contact out of the consumer electronic market, the impact of FlexPAET were discussed. It seems to be likely, that due to the much higher efficiency of a DO-structured backlighting element manufactured by FlexPAET, much fewer light sources are needed, reducing both the manufacturing costs for the display as well as the power consumption during operation. Additionally, through the use of Adaptive Embossing featuring self optimisation, Flexible Patterning Technology significantly reduces the production cost for the backlighting element tool master and simultaneously increases the quality and performance of the elements. Furthermore, the shell based tool concept of FlexPAET, derivation several parent tools reduce the tooling cost. Additionally, the thickness of the backlighting element can be reduced, leading to potential raw material savings of up to 60%. As shown in Figure 44, the total savings in material and manufacturing costs for a 40" LCD TV unit through the use of Flexible Patterning Technology was estimated at roughly € 620 in front of the project. This figure was proved within the expert discussion.

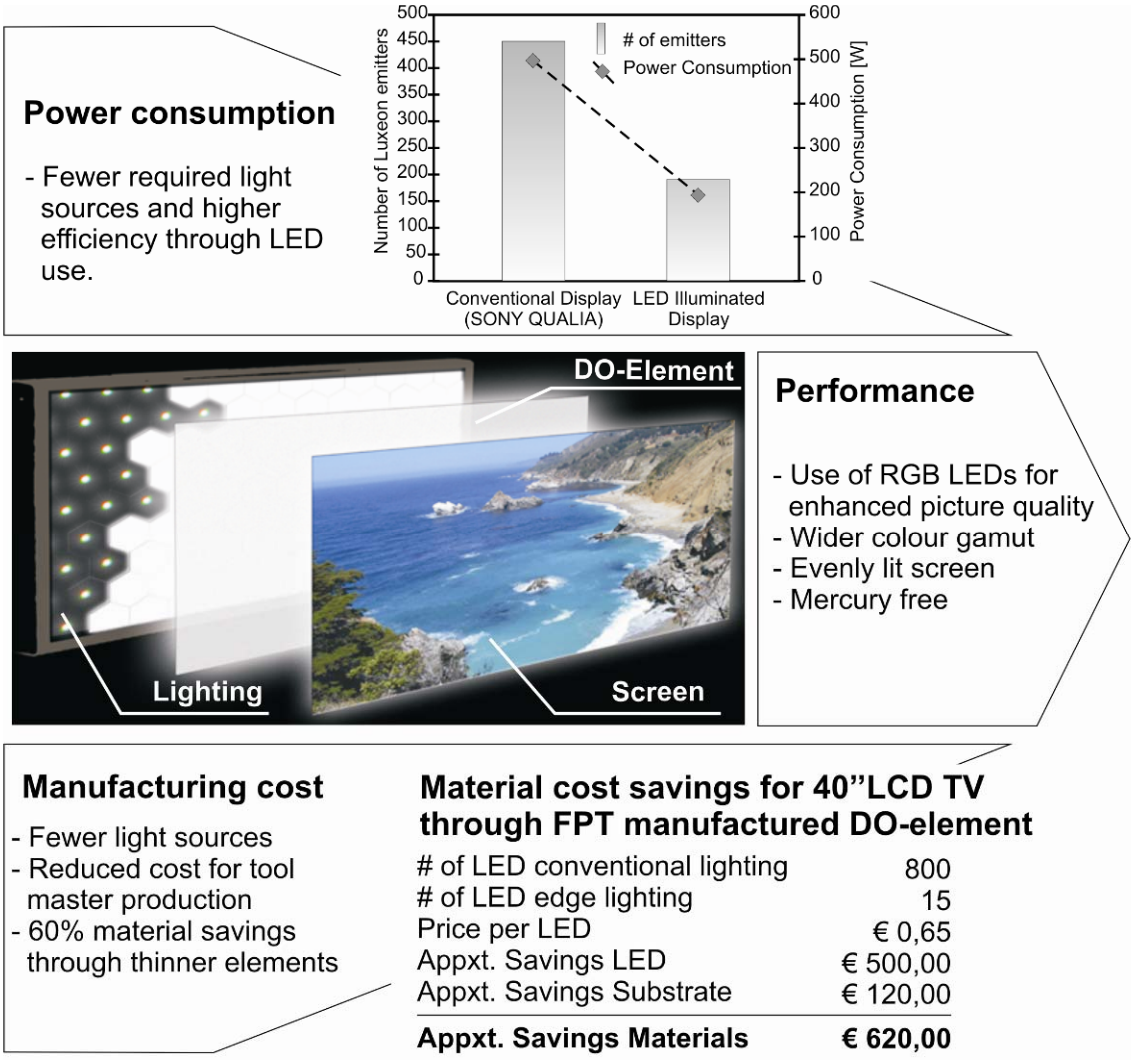


Figure 44: New features - FlexPAET related product improvements for LCD displays

Thus, FlexPAET is providing European industry with a method to economically produce highly advanced backlighting elements for distribution and sale in the global market place.

<u>Example 2: Street lighting</u>
Beyond the scope of consumer electronics, the economically viable production of complex optically functionalised elements is contributing to the transformation of the LED into a valid light source for illumination, creating significant energy saving potential regarding power consumption as well as reduced production and maintenance efforts and costs. According to a study for Lumistrator Technology in Denmark, the total annual energy consumption for lighting in Europe amounts to nearly 200 000 GWh. The Consortium for Energy Efficiency (CEE) estimates that LED traffic lighting uses 80-90% less energy than comparable incandescent lamps.[1] This means that up to 180

[1] www.CEE1.org

000 GWh of electrical power can be saved per year, which currently equals about €9 billion in energy production cost or 72 million tons in CO_2 emissions. According to information from Osram, a leading European manufacturer of lighting solutions and equipment, major required factors for the enhanced usage of LED street lighting are:

- increase of the luminous efficacy
- prevention of glare
- significant reduction of component costs.

LEDs in combination with optically functionalised elements provide a viable solution to these issues. Furthermore, the highly directional light from an LED source with an optically functionalised element will significantly lower the level of light pollution, thus reducing the disruption of ecosystems by over-illumination and sky glow as well as negative influences on human health and psychology, and interferences with astronomical observatories. The product can furthermore support various light management application such as in tunnels, thus enhancing safety and avoiding accidents caused by excess lighting. Keeping this into mind, the FlexPAET project contact a supplier established in the street lighting industry. Feasibility test and prototyping production are currently undergoing together with the spin-off polyscale GmbH.

Main dissemination activities

The dissemination activities in course of the FlexPAET project can be distinct in scientific and commercial activities:

Scientific dissemination activities

Partners involved into FlexPAET project attend various scientific conferences. Thereby, the partner focused on micro manufacturing conference and optical conferences. Namly FlexPAET was present on the conferences out of the JOSA A (USA), the EOSAM (France), EOS (Germany), the 4M conference series (France), the 2nd Aachen Precision Days (Germany), International conferences in automotive plastics (Spain), ICOMM (Tokyo) and EUSPEN (Spain). In addition FlexPAET was presented the scientific community of semiconductors during the CAS conference (Romania). All scientific conferences were accompanied by scientific papers and/ or by oral presentation about different topics of FlexPAET.

Commercial dissemination activities

As FlexPAET clearly focussing on the commercialisation of the research results, commercial dissemination activities obtain importance. Target of the commercial dissemination activities was to get the project itself as well as the objective well known in the relevant markets. To achieve this target, FlexPAET created a homepage (www.flexpaet.eu) and different project flyer of FlexPAET as advertising material. In addition all partners mention the involvement of FlexPAET on their own homepage. As a result, 12.000 findings of FlexPAET appear in a google search, ranking the project homepage as first result. Furthermore, FlexPAET was present at different trade fares. For example, the HANNOVER MESSE (Germany), MMLive – Exhibition (United Kingdom), Symbol- and Ambient Lighting (Germany), the OPTATEC (Germany), and the LASER (Germany). In addition to the attendance of the trade fares, non-scientific papers and press releases were published.

Exploitation of results

The main exploitation result of the FlexPAET project is the founding of a spin-off called polyscale GmbH. The objective of the spin-off is the commercialisation of FlexPAET results concerning the hot embossing process. Within the FlexPAET project it was possible to develop a production network beside the development and manufacturing of the micro embossing system. The network of production will strongly cooperate on a daily business base with the spin-off to provide, light guides, tools and special processes.

In addition to the commercialisation of micro structured related products the involved project partners have the aim to use developed components or know-how in their core businesses. As an example for foreground not directly related to micro embossing products following exploitation activities are named:

Scanning system for luminance measurement system

Development of a scanning system for luminance measurements is planned. Two project partner will cooperate for exploiting the luminance scanning system. Ramp of is planned for 2012. Within the project a prototype was built. Research activities for reducing the production costs will be performed after the project in order to enhance profit when for selling the system.

New machine controller for highly dynamic applications

New concept for machine controller for highly dynamic application will be exploit by selling the architecture of the new controller setup for embossing systems. The system is also suitable for other comparable applications like Fast-Tool-Systems.

Compositional analysis of electrodeposited metals

When nickel or other metals are deposited by electroforming, and particularly when the metals are used in applications where they are heated, it is important that there are no impurities co-deposited with the nickel (or other metal). Typically impurities such as carbon or sulphur will diffuse to the grain boundary upon heating and thus create a brittle and less durable metal. Therefore, using glow discharge optical emission spectroscopy (GD-OES) it is possible to slowly remove a material layer by layer, and at the same time measure the composition of the removed material very accurately. Such as compositional profile will reveal any impurities inside the material, and also whether the impurities are evenly distributed or mainly present at the surface. A little more testing of electroformed materials from other suppliers would helpful to gain more experience, but the principles have been demonstrated and will be exploit as an industrial service.

Inert anode system for nickel bath maintenance

During electroforming a small amount of the current is used in a side reaction and hydrogen gas is developed. This leads to a slow increase of the pH value in the plating tank, which particularly for large parts will lead to bath instability. During FlexPAET a method has been developed, using a special inert anode set-up, allowing compensating for the side reaction that creates hydrogen gas. On the surface of the inert anode water is split, oxygen gas is formed and hydrogen ions can then pass through a membrane and into the plating tank. This way the pH value can be maintained at a constant level indefinitely. It is expected to use the new knowledge to enhance the quality of nickel plating capabilities as well as using it for consultancy work externally.

Step by step optimization algorithm based on on-line measurements

Development of a procedure for finding the optimal distribution of scatterers in an edge-lit light guide plate (LGP) presenting intrinsic absorption losses for rendering a controlled distribution of the outcoupled light. A partner will provide solutions for customers who need to optimize the project of master for an LGP with a specific function. The solutions will be developed in cooperation with the customers.

Low-cost conoscopy measurement camera

The conoscopic measurement of light emitting systems is normally performed using very expensive instrumentation. The new lowcost conoscopy camera developed in FlexPAET is providing a good approach to perform conoscopic characterization of lighting devices. The system is able to measure angular radiation of devices like TV flat screens or mobile screens through the developed software. The new system will be exploited by a partner, which is a company selling optical instruments for quality control having a worldwide network of sales offices. IPR protection of this component will be performed. It is expected to reach a market share of 15% in 4 years. Additionally, it is expect to increase sales of other instruments of quality control for the same kind of customers.

Optical Micro-structures quality control automatic vision system

The optical micro-structures quality control system using machine vision will provide the necessary information on the quality of the manufactured diffractive structures for flat optical components for TV screens, computers. Mobile phones and lighting products. The system will be capable of automatically detect defects of the micro-structures of 5-10 microns. The system will be integrated in 2D positioning robots or machines to perform a full scan of the flat optical panel. A relevant component of the new instrument is the software. IPR protection of this component will be performed. It is expect to reach a market share of 20% in 4 years.

High accuracy components for embossing and flycutting machines

Development of a multi-axis machine for hot embossing, flycutting and inspection of plastic substrates. The machine base provides exceptional accuracy, repeatability and dynamics over a large working area. By the time the process for creating large elements with uniform light distribution comes to market, there will be the need for several similar embossing machines. Furthermore, a partner manufactures high-accuracy cross tables and multi-axis positioning systems for a wide range of applications, including chip inspection, hologram manufacturing, solar industry or pickand-place. While previous systems were designed for a comparably small working area, the bridge-type concept of the new machine extends the working area to more than 1x2 meters. Besides the mentioned applications, this allows opening new markets, for example the manufacturing of high-accuracy/high-speed milling and drilling machines.

The achievements during the development of the machine comprise miscellaneous advances and experience in various fields, for example manufacturing, mounting and adjustment techniques for large air bearings, thermally decoupled and still stiff linear motor mounting, advanced guideway configurations, the use of new materials for high-speed slides, experience with FEAs of mechanical, thermal and magnetic effects, the integration of preload magnets directly into the air bearings, and so on. Thus there is no single novelty for which patenting would be feasible. Instead the gained knowledge will help in developing and manufacturing a wide range of future products.

Fabrication of conductive non transparent polymers

Research has been leaded within FlexPAET to produce conductive polymers made with addition of CNT’s within a polymer matrix. Results are not sufficient to make use of this result for FlexPAET process (electrical conductivity much too low). Nevertheless this new polymer could find exploitation for new markets such as coloured black polymers or polymers with a small electrical conductivity. The results will be exploit by one partner in cooperation of a nonofiller provider not part of the project.

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