



## PROJECT FINAL REPORT

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**Project acronym: POLIMATIC**

**Project title: Automated Polishing for the European Tooling Industry**

**Funding Scheme: SME-targeted collaborative project**

**Period covered: from 01.06.2010 to 31.05.2013**

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<sup>1</sup> Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement .

<sup>2</sup> The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: [http://europa.eu/abc/symbols/emblem/index\\_en.htm](http://europa.eu/abc/symbols/emblem/index_en.htm) logo of the 7th FP: [http://ec.europa.eu/research/fp7/index\\_en.cfm?pg=logos](http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos)). The area of activity of the project should also be mentioned.

# 1. Final publishable summary report

## 1.1. Executive summary

For the manufacturing of tools 12 to 15 % of the manufacturing costs and 30 to 50 % of the manufacturing time are allocated to polishing. As current automated polishing techniques are almost not applicable on parts with freeform surfaces and function relevant edges like 95% of the tools, the polishing is predominantly done manually.

Therefore the overall objective of poliMATIC was to strengthen the competitiveness of the European Tooling Industry by overcoming the current drawbacks of die and mould finishing by realizing automation in laser polishing and force controlled robot finishing. Both processes already achieve low roughness values on flat surfaces. But the critical step to bring these demanding processes into production is the polishing of freeform surfaces and cavities. To achieve this, the following significant technological innovations are needed:

- Process development to achieve a roughness of  $Ra=0,05\text{ }\mu\text{m}$  (Laser Polishing) /  $Ra=0,005\text{ }\mu\text{m}$  (Robot Finishing) on freeform surfaces and cavities
- The development of a knowledge-based CAM-NC data chain to make the new technologies usable for end-users
- The development of a new surface metrology framework for polished surfaces. Current measures are insufficient to express e.g. the visual impression of a finished surface

The fundamentals of laser polishing have been investigated on predominantly flat surfaces. The treatment of first demonstrators with rotational symmetric and freeform surfaces affirmed in general that laser polishing offers the potential of overcoming the current drawbacks in surface finishing but also revealed the need for research and development. In poliMATIC laser polishing were further developed to a reliable manufacturing process.

The activities in poliMATIC with respect to robot finishing and based on preliminary investigations encapsulate the knowledge, skill and experience of the human worker within an automated solution. The approach consists of a force-controlled finishing spindle and a fully automated CAD/CAM-based task planning and enables the user to process freeform surfaces by a step-wise automated robot fine machining in the same way milling tasks are performed.

poliMATIC developed and evaluated contemporaneously the use of metrology as an enabler to support the automation of the polishing process by introducing a knowledge- and hardware-based metrology system. Novel parametric descriptions of the features in the polished surface enable the technical process control and communication between designers and production engineers, the polishers and machine.

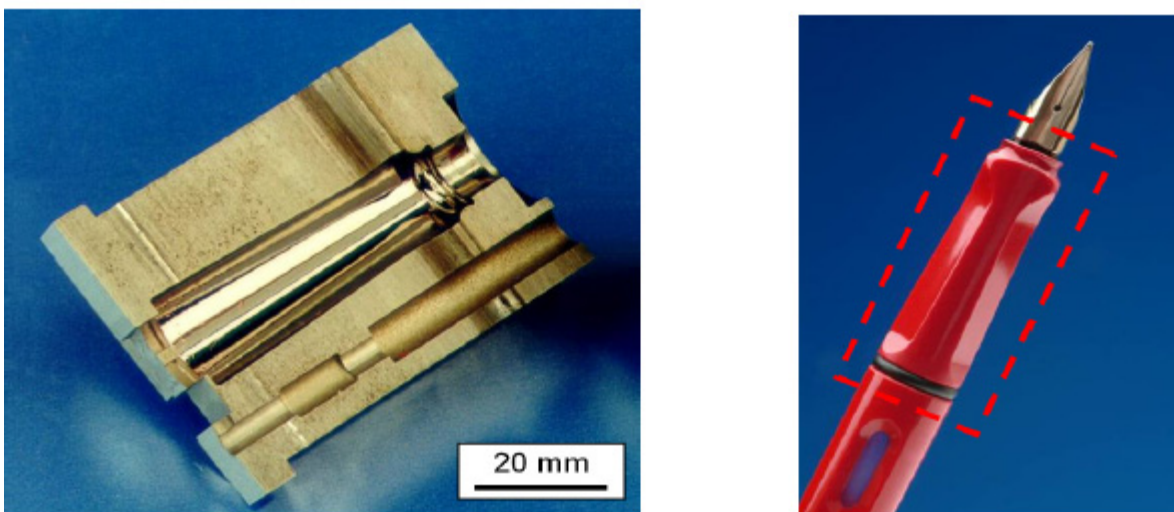
## 1.2. Summary description of the project context and objectives

### Concept and project objectives, problems and needs

The predominantly small and medium sized companies in the European Tooling Industry are currently facing a low-cost competition situation with Asia. This new competitive situation resulting from globalization menaces the European Tooling Industry due to lower cost of the resources (especially labour), poor working conditions and environmental disrespect in the Asian countries. Common goal in the tooling industry and the MANUFUTURE Platform is to strengthen the European competitiveness in a globalized tooling market by reducing costs and delivery times, by increasing the features and qualities of the tools and by respecting ecological aspects. The Tooling Industry (moulds, dies and special tools) in Europe represents an average annual turnover of 13 billion € and comprises more than 7.000 companies, 95% of them being SMEs, representing more than 100 000 workers directly in the sector. For the manufacturing of injection and die casting moulds 12 to 15 % of the manufacturing costs and 30 to 50 % of the manufacturing time are allocated to polishing.

Current automated polishing techniques, e.g. electro polishing, electro-chemical polishing or slide grinding are based on large-area ablation. These polishing technologies lead to problems in edge rounding and unprocessed areas because deeper shafts are not processed. Therefore the current automated techniques are almost not applicable on parts with freeform surfaces and function relevant edges like most tools. Due to the lack of available automated polishing technologies for freeform surfaces, the finishing in the tooling industry is predominantly done by manual polishing. The quality of manual polishing strongly depends on the worker's skill and experience. As manual polishing is a very demanding but monotone work, skilled workers are a scarce resource and companies all over Europe have great problems to recruit suitable employees. Due to the low processing speed (typically in the range of 10 to 30 min/cm<sup>2</sup>) and the sequential workflow, production of moulds and dies with manual polishing is time-consuming and cost-intensive.

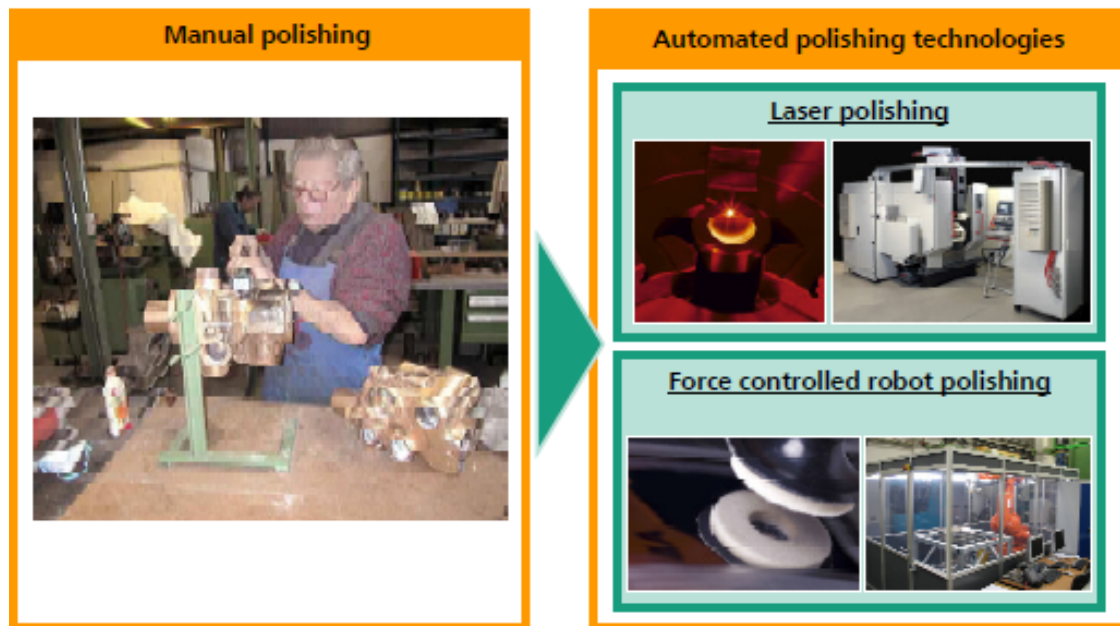
***Therefore the overall objective of the poliMATIC project is to strengthen the competitiveness of the European Tooling Industry by overcoming the current drawbacks of die and mould finishing by developing automated polishing techniques.***



**Figure 1:** Injection mould for fountain pen making, time for manual polishing: 9 h (»30 min/cm<sup>2</sup>)

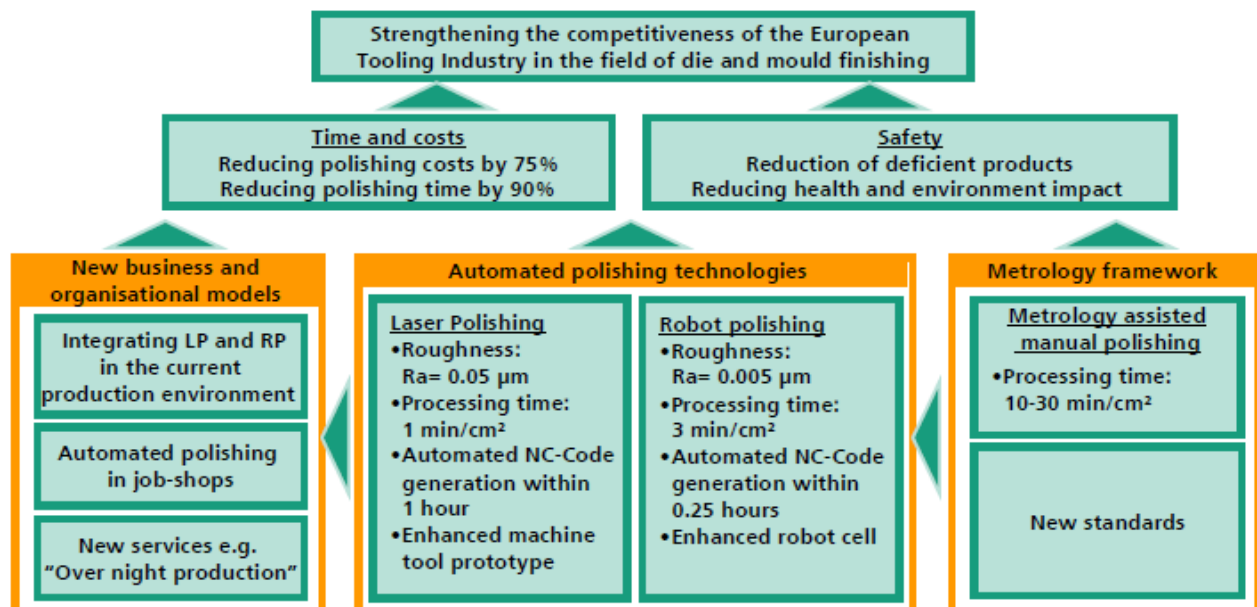
A typical task for a manual polisher is shown in Figure 1. Even for a skilled labourer it takes more than one working day to polish this injection mould for fountain pen making.

Automated manufacturing processes have already been introduced in virtually every manufacturing stage but not in polishing. Arising from the work shop “Steel polishing” in October 2008 the poliMATIC consortium therefore identified the two most promising automated polishing technologies and committed itself to bring laser polishing (LP) and force controlled robot polishing (RP) into market (Figure 2).



**Figure 2:** Concept of the poliMATIC project

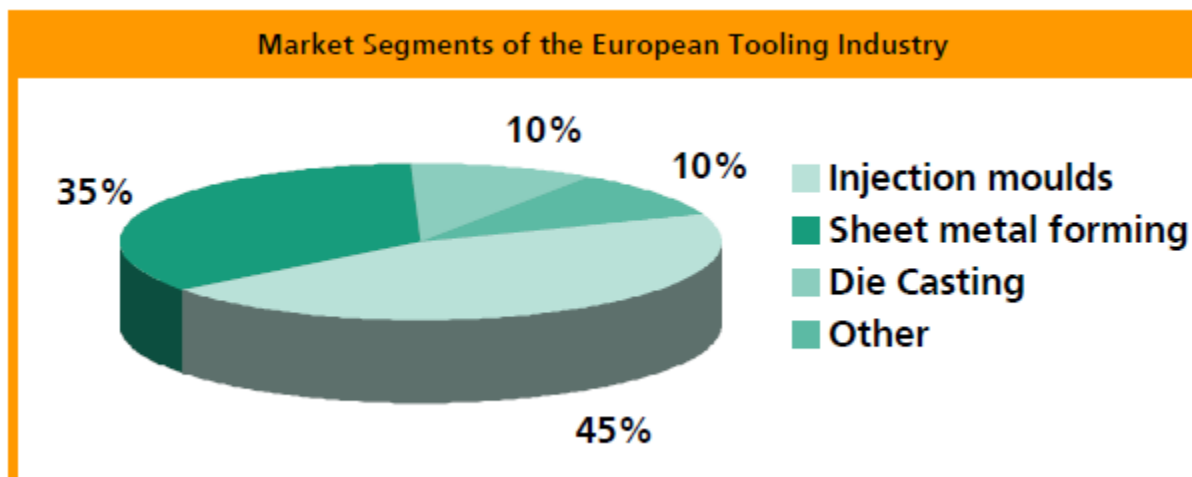
The poliMATIC consortium identified two contributions to the strengthening effect of automated polishing technologies for the European Tooling Industry (Figure 3).



**Figure 3:** Hierarchy of objectives of the poliMATIC project

Firstly automated polishing will generate significant savings in time and costs and secondly the quality and safety will be increased in terms of higher reproducibility, higher robustness, higher flexibility regarding tool geometries and reduced hazardous impacts on the worker and the environment. Consequently the objectives for these contributions have been determined and broken down into technical sub-objectives shown in Figure 3.

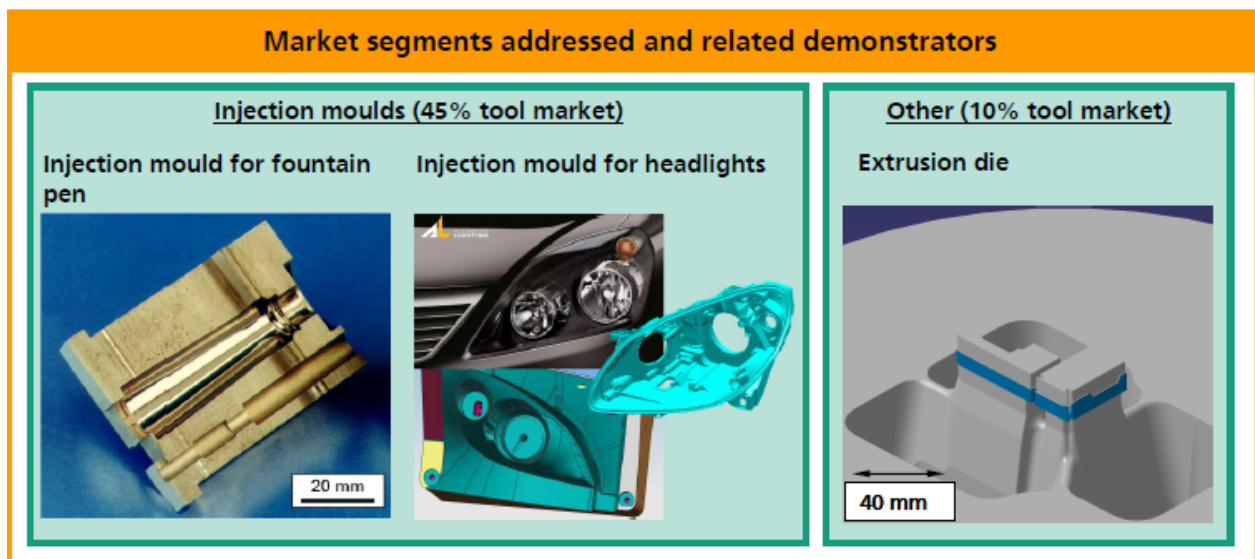
The development of the two automated polishing technologies will be supported by a new surface metrology framework. In order to assess the automated polishing technologies in comparison to manual polishing, new measurable criteria for the evaluation of the surface quality have to be investigated. Current figures are insufficient to express the characteristics of polished surfaces e.g. the visual impression to a viewer. This development can be the basis for a new European standard for polished surfaces. To ensure the success of poliMATIC the results will be demonstrated by the automated polishing of moulds and dies with geometries highly relevant for industrial manufacturing. Polishing is the finishing manufacturing stage in virtually every segment of the tooling industry. The proportion of the polishing costs depends on the segment of the tooling industry. As mentioned before an average of 12-15 % of the manufacturing costs are allocated to polishing in the tooling industry. In the manufacturing of injection moulds, which is in addition the largest market segment (Figure 4), this proportion increases to 30% as in this market segment smaller and more complex parts with better surface qualities are needed.



**Figure 4:** Market segments with turn over shares of the European Tooling Industry

Based on this market analysis the poliMATIC consortium decided to firstly address the injection moulding industry and selected two demonstrators which represent the variety of moulds and dies in this sector (Figure 5 left and middle).

Although laser polishing and robot polishing have been approved particularly capable by industrial partners and prospective end-users, both automated polishing technologies have not been applied on complex shaped freeform surfaces in the tooling industry yet. Despite the differences in the working principle, the current drawbacks of the technologies are comparable. To apply the automated polishing technologies in an industrial environment both technologies need significant research by industry and research institutes in the field of machine technology, process technology, a suitable CAM-NC data chain for a predominantly automatic NC-code generation and intensive tests of polished tools under service conditions.



**Figure 5:** Market segments directly addressed by poliMATIC with their respective examples

### Main innovations of poliMATIC

At present the drawbacks in automated polishing technologies prevent an industrial implementation. As poliMATIC will overcome these drawbacks the project will represent a real breakthrough for automated polishing. The main innovations of the poliMATIC project are:

- Processing strategies for laser and robot polishing of tools and dies with freeform surfaces
- New measurable criteria for a quantitative assessment of polished surfaces
- End-to-end CAM-NC data chain for laser polishing and CAx framework for robot polishing
- Enhanced machine technology for laser and robot polishing
- Tests of automated polished tools under service conditions

Although some first steps for the development of laser and robot polishing have been accomplished, significant research is needed to bring these technologies into market.

This hurdle is also identified by the MANUFUTURE platform as a weakness of the European manufacturing industry:

- “Capitalise on its (European Tooling Industry) enabling technologies to increase the already high level of factory automation and productivity, thereby overcoming the labour cost disadvantage”

The poliMATIC consortium fully supports the appraisal of these current weaknesses and committed itself to accomplish the significant research needed to bring automated polishing technologies into market.

### Transferability of the project results

The potential impact of automated polishing technologies is not limited to the tooling industry. Automated polishing technologies can be transferred to other industrial sectors in which polishing is widely used. Examples are:

- medical implants,
- medical devices,
- turbine components,
- engine parts,
- interior parts (metal),
- mechatronical components and
- valve units.



### 1.3. Description of the main S&T results

In this chapter, the achievement of each work package, regarding the main S&T results/foregrounds of the poliMATIC project is reported. Next to a summary of the technical results, attention is paid to the Gantt chart of the work package (WP) and the singular invested Person-month (PM) for each WP and involved participant of the project (Annex 1, DOW).

#### 1.3.1. Work package 1 – Requirements specification and organisational models

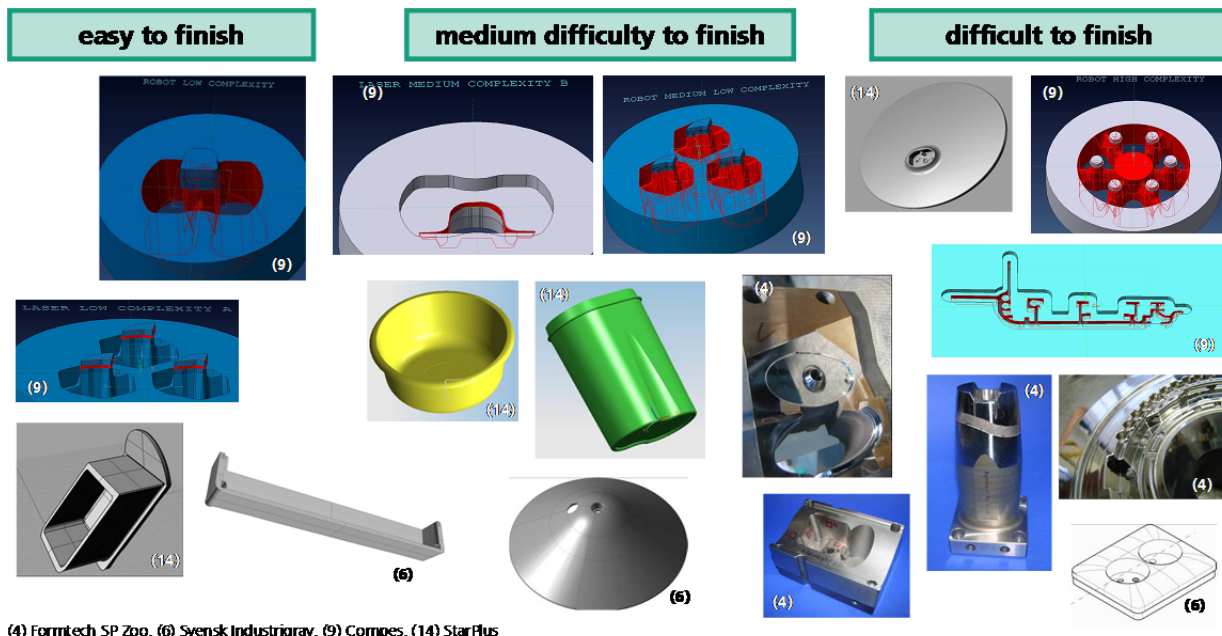
##### Main Objectives:

To define the relevant specifications and project targets resulting from the requirements of the selected parts and components in order to start the planned investigation and developments in the following work packages.

##### Work package 1 – Main results

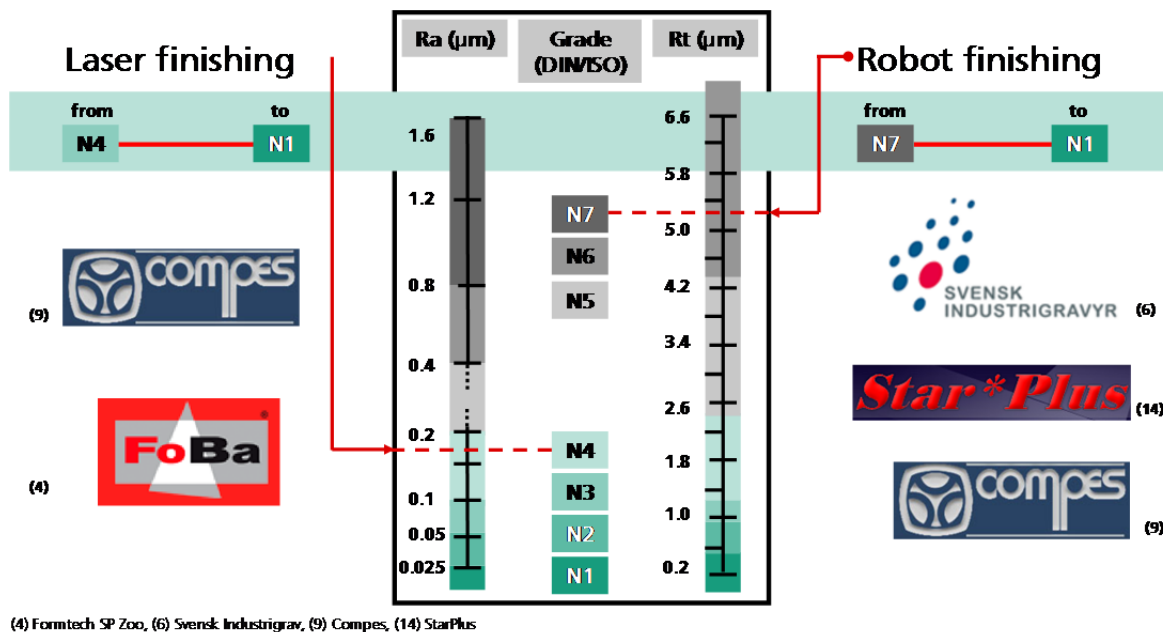
- **Definition of detailed requirement specification regarding all partners**

Due to the great variety of moulds and tools presented by the end-users of the consortium, the primarily objective on this WP of the project was to identify the possible similarities of the moulds regarding their respective geometry features and material (Figure WP1.1). The identification of similarities could facilitate the development for both laser and robot polishing process and to the surface qualities characterizations, avoiding specific mould characteristics that would affect the finishing process.



**Figure WP1.1:** Moulds and dies presented by the end-users of the consortium

Foreseeing the capabilities of each system being developed (laser & robot polishing) to furthermore automated the finishing process of complexes components, two requirement of surface qualities were defined to each approach.



**Figure WP1.2:** Expected surface quality after Laser & Robot polishing

Figure WP1.2 shows the both required surface qualities expected to be reached by the both automated approaches. The grades from N7 to N1 are described as surface qualities by DIN/ISO regarding the typically applied abrasive tool to generate the surface and the respective reached roughness (Ra and Rt).

### • Formulation of an Organizational model regarding the project

In general an organisational/business model is a conceptual tool that contains a set of elements and their relationships and allows expressing the business logic of a specific firm. It is a description of the value a company offers to one or several segments of customers and of the architecture of the firm and its network of partners for creating, marketing, and delivering this value and relationship capital, to generate profitable and sustainable revenue streams. In general organisational/business models can best be described through nine basic building blocks that show the logic of how a company intends to acquire profit. The nine blocks cover the four main areas of a business: product, customer interface, infrastructure and financial aspects.

Every SME of the poliMATIC project developed at least one organisational/business model based on automated polishing (laser polishing or/and robot finishing) (see deliverable D1.2).

## 1.3.2. Work package 2 – Technology specific CAM-NC data chain for laser polishing

### Main Objectives:

Enabling end-users to generate their own NC-code ready to be used on 3D laser polishing machines Liberating the end-user from the need of detailed process knowledge by integrating the knowledge developed in WP3 in the Technology Module for laser polishing Supporting the industrial strength of the automated polishing by developing user friendly NC-code functionalities.



### Developed tasks:

Task T 2.1 Analysis of requirements (Task leader: ILT)

Task T 2.2 Layout of the data chain and the Technology Module (Task leader: SFS)

Task T 2.3 NC functionalities (Task leader: SFS)

Task T 2.4 Implementation and integration of the Technology Module (Task leader: FHG-ILT)

Task T 2.5 Beta testing of the whole data chain (Task leader: FHG-ILT)

### List of deliverables:

D2.1 Software requirements specification for

D2.2 Software prototype “Technology Module” for LP:

D2.3 NC functionalities:

## **Work package 2 – Main results**

### Software “Technology Module”

- **Import of CAM path data**

The starting point of the aspired CAM-NC process chain for laser polishing is a 3D CAD model of the treated work piece. The Technology Module is able to load in an apt-file generated by CAM software (e.g. Siemens NX or Delcam PowerMill) and imports a complete track including its geometrical data.

- **Parameter database**

The “Technology Module” comprises an application database which enables the storage and handling of necessary process parameters and strategies. This includes a different beam diameter, scanning velocity, shielding gas concentration etc. for each stage. These parameters are determined on flat parts before.

- **Calculation and process strategies**

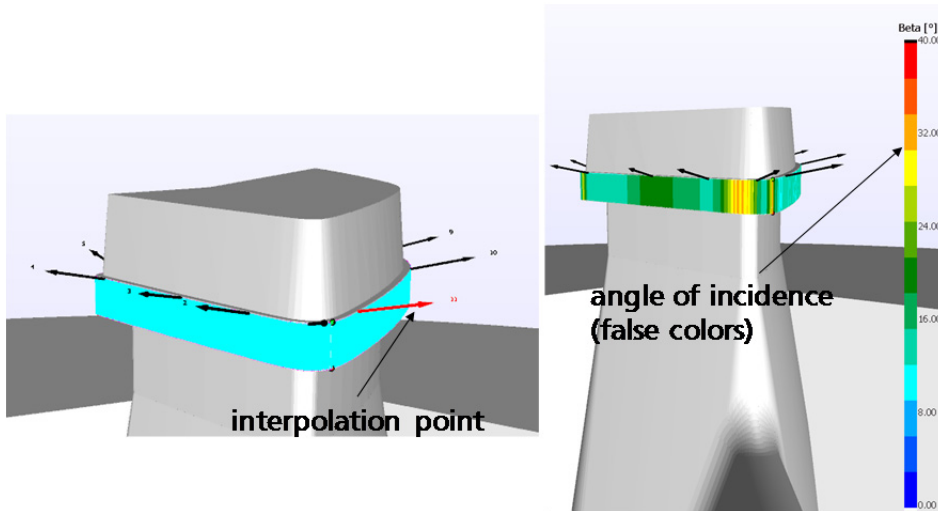
Main task of the developed software prototype “Technology Module” is the transformation of the geometrical raw data of the milling tracks into a machine specific NC code regarding the material dependent process parameter. The laser scanner and the mechanical axes have to be addressed separately. Therefore the software transforms the whole trajectory of the path into both coordinate systems. The software is also able to calculate the laser power depending on the angle of incidence, the laser power near turns and the alternating track offset on tilted surfaces.

- **Generation of NC programs**

The “Technology Module” generates two programs: One which is running on the NC of the machine (Siemens 840D) and another program with commands for the laser scanner, which is running on a Scanlab Scanner-Control-Card. The NC program includes the NC commands introduced on the machine in T2.3.

- **Beta testing**

The complete process chain has been tested with a work piece from COMPES (s. Figure WP2.1). This guarantees the process chain to be complete and fluently including fully functional software (Technology Module).



**Figure WP2.1** Calculation result of a workpiece from COMPES during the beta testing of the process chain

### NC functionalities

- **Server software**

The server software controls scanner, gas control and has an integrated tool management system. A user interface enables the user to execute all functionalities manually.

- **Tool management system**

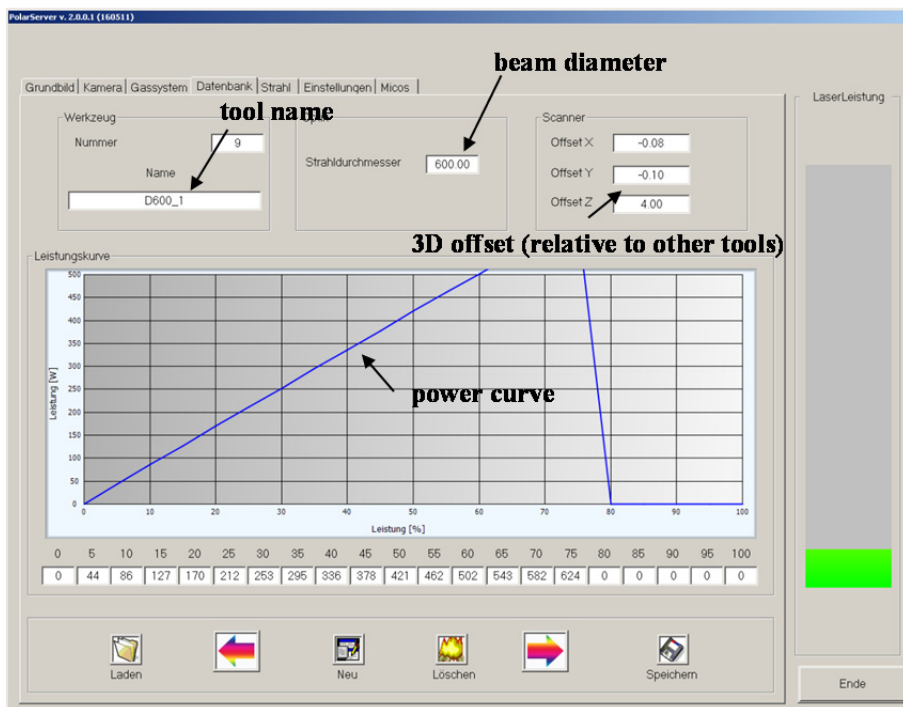
The tool management system has a user interface (GUI, see Figure WP2.2) and allows the user to create new tool which can be selected by a NC command during the process. The data for each tool includes the beam diameter, a power curve (to calculate the laser power from watts to a control voltage) and a 3D position offset.

- **New NC commands**

New NC commands are implemented on the machine to get the process automated. All components of the machine like gas control or beam diameter can be directly controlled by NC commands.

- **Synchronisation**

Fast IOs between NC and scanner enables the scanner to work synchronized to the mechanical system.



**Figure WP2.2:** Screenshot of the tool management system

- **Scanner controlled by own NC program**

The 3D laser scanner is controlled by separated programs (one for each subarea) containing all the points of the trajectory (including laser power) and commands for the synchronization. These programs are called by the main NC program on the control.

### 1.3.3. Work package 3 – Knowledge-based CAx framework for robot polishing

#### Main Objectives:

Development and implementation of CAx framework. This work package also includes the development of suitable polishing algorithms, implementation of necessary software for the CAx framework as well as beta testing of the software.

#### Developed Tasks:

Task T 3.1 Analysis of requirements (Task leader: MOD)

Task T 3.2 Design of algorithms and software architecture (Task leader: MOD)

Task T 3.3 Implementation and Integration of CAx framework (Task leader: FHG-IPT)

Task T 3.4 Development of local force and surface based computation model for uniformly distributed abrasion (Task leader: EVO)

Task T 3.5 Beta testing and verification of CAx framework (Task leader: FHG-IPT)

#### List of deliverables:

D3.1) Software requirements specification for RP

D3.2) Software requirements specification for RP (final version)

D3.3) Software prototype suitable for RP

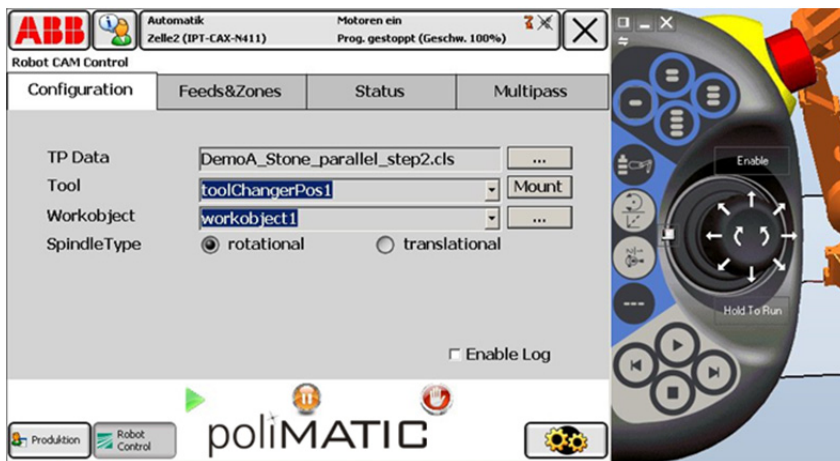
## Work package 3 – Main results

- **CAM modules**

During the project PoliMATIC a CAM module with a distinctive set of algorithms was developed providing standard tool path strategies as well as custom strategies with emphasis on seemingly arbitrary movement resulting in a patternless surface finish. The developed algorithms are based on the movement patterns of a manual worker overlaying existing strategies with a certain noise. To cover a broad variety of movement patterns the original tool path strategies are combined resulting in different finishing tool paths with different coverage and path density. Additionally those tool paths can be simulation using a tool kinematic simulation allowing the user to verify computed tool paths before transferring them to the robot control. To allow an execution of APT code directly on the robot control a sophisticated postprocessor was implemented on the robot control. The postprocessor is able to read APT code as well as custom designed commands for tool change or metrology operations.

- **Graphical user interface on robot control**

To simplify the tool path generation process a set of graphical input masks was implemented allowing to configure most of the process parameters directly on the robot control, this omits tedious changes inside the CAM module in case a process step should be repeated with minor changes to orientation or offset. Those GUIs also easily allow to prepare for the execution of finishing steps by providing functions for referencing the workpiece inside of the robot cell or just for automatically switching tools. Those GUI are directly executed on the robot control and use the robots native libraries for visualising data directly on the robot control respectively on the FlexPendant handheld. Figure WP3.1 shows the main view on the robot control allowing the modification of the used tool, the tool path data as well as the work object reference.



**Figure WP3.1:** Screenshot of the graphical user interface running on the robot control

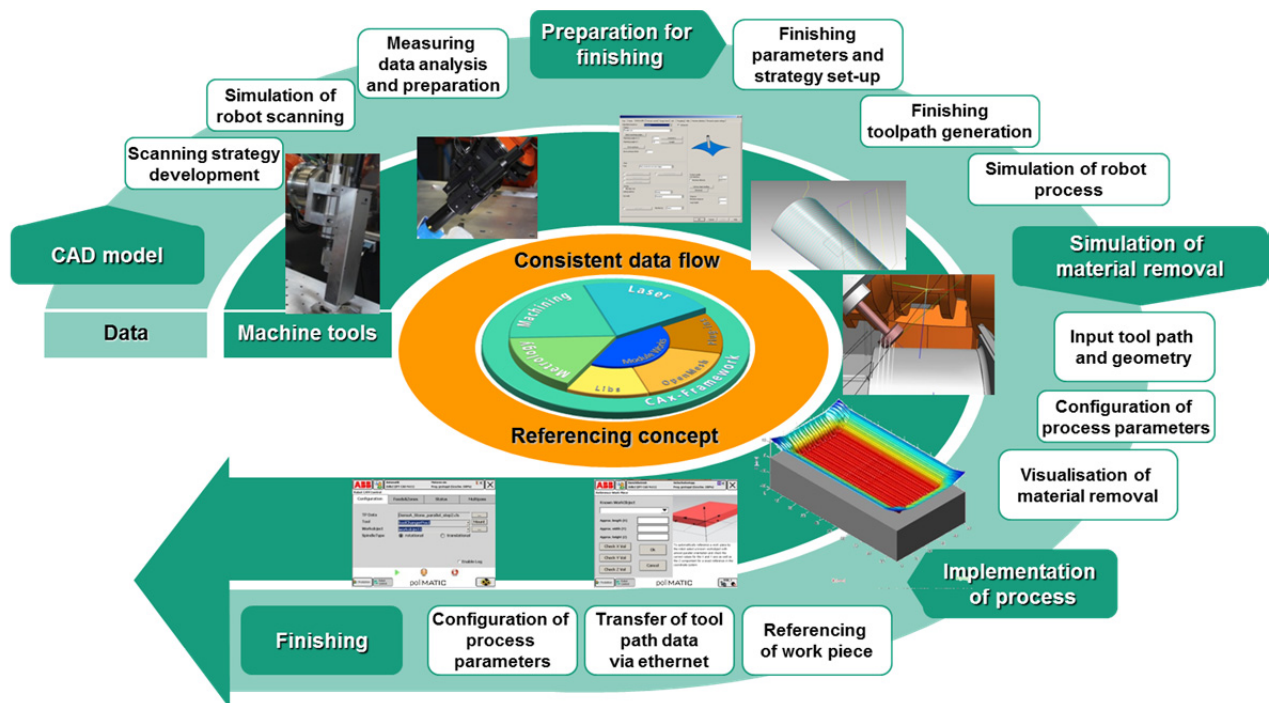
- **Integrated peripherals**

To obtain a holistic solution approach several additional device were integrated into the robot cell allowing automated qualification of finished parts. In detail two metrology systems for surface inspection were integrated into the robot control now allowing a tool path guided usage of the metrology systems from Altimet and Halmstad. Those systems internally communicate via DeviceNET in the sense of a deterministic state machine. This means that every involved component is aware of the state of its neighbouring systems.

To allow an automatic usage of all connected systems an tool changer was implemented handling all metrology devices and tools. The robot hereby is responsible for his own tool management and is able to switch depending on the type of the process steps to the corresponding tool. This completes the virtual process chain, allowing the definition and configuration of a whole finishing process consisting of several process steps in a single configuration step and then start with process execution.

- **Material removal simulation**

For finishing processes where beside the movement of the tool other parameters like pressure, surface curvature and tool shape play a role an additional simulation is necessary predicting the material removal on a certain surface based on the used tool path and process parameters. Such an material removal simulation was implemented and used for verification of the CAM modules. Experiments have validated the results of the simulation with actual results from finishing tests.



**Figure WP3.2:** Holistic process chain for finishing tasks with integrated surface inspection

As shown in figure WP3.2 the presented main results cover the complete virtual process chain and provide functions and methods to plan and configure the finishing of an arbitrary work piece. Doing that the developed software components provide auxiliary functions which help the user to automate all involved tasks like work piece referencing, selection of tools or metrology data evaluation.

### 1.3.4. Work package 4 – Laser polishing

#### Main Objectives:

Developing the necessary process knowledge for laser polishing freeform surfaces. Enhancement of the current machine technology for laser polishing to improve the industrial strength.

#### Developed Tasks:

Task T 4.1 Laser polishing with a non-perpendicular angle of incidence (Task leader: FHG-ILT)

Task T 4.2 Consecutive laser polishing of sub areas (Task leader: FHG-ILT)

Task T 4.3 Laser polishing near the edge of the work piece (Task leader: FHG-ILT)

Task T 4.4 Optimal tool path geometries (Task leader: FHG-ILT)

Task T 4.5 Shielding gas chamber (Task leader: ARN)

Task T 4.6 Optical system (Task leader: ARN)

Task T 4.7 Process combination laser polishing and manual polishing (Task leader: FOR)

#### List of deliverables:

D4.1) LP with non-perpendicular angle of incidence

D4.2) LP near the edge of a work piece

D4.3) LP at the boundaries of subareas

D4.4) Optimal tool path geometry LP

D4.5) Shielding gas chamber:

D4.6) Optical system

D4.7) Process combination

### **Work package 4 – Main results**

#### Laser polishing with a non-perpendicular angle of incidence

- **Angle of incidence**

Due to the projection of the circular laser focus on a tilted surface, the interaction zone becomes elliptical. Therefore the intensity in the focus decreases and as result the remelted zone thickness decreases. An increased roughness for angles of incidence  $0^\circ < \vartheta < 65^\circ$  is the result. With adapting the laser power in dependence of the angle  $\vartheta$  this effect can be compensated very efficiently. But for  $\vartheta = 65^\circ$  the roughness increases about 50%. This limits the laser polishing process of freeform surfaces to an aspect ratio of 2:1 (height:width).

- **Melt pool drift**

The elliptical interaction area for non-perpendicular angles of incidence in combine with a diagonal scanning direction to the major axis of the elliptical focus leads to a an alternating track offset. This phenomenon leads to an increased roughness, which can be compensated by a beforehand correction of the generated tool path.

#### Consecutive laser polishing of sub areas

Due to the limited accessibility and the limited working volume based on the optical system the area to be polished has to be divided in subareas. Every subarea has to be processed sequentially. Without an adapted process strategy this results in a visible curb at adjacent surfaces. Via adapting the laser power near the turning points of the laser the formation of



these bulges can be reduced. Another efficient strategy is to avoid the segmentation into subareas with a continuous 8-axis-processing of the whole area.

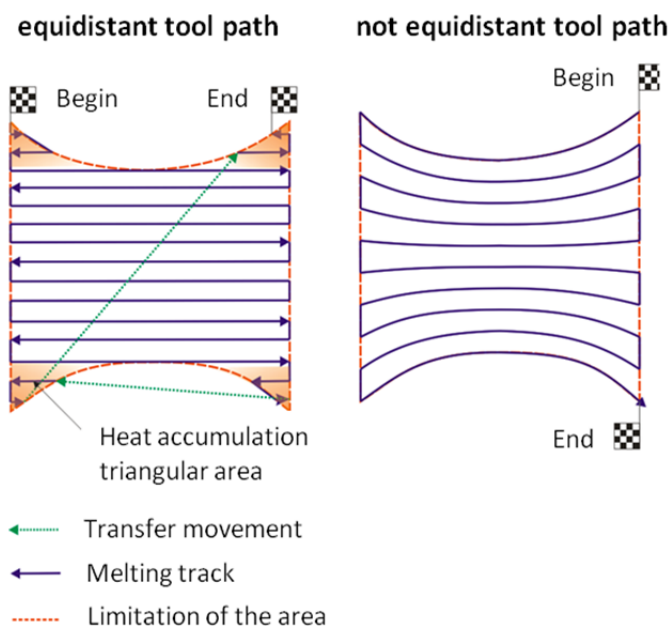
#### Laser polishing near the edge of the work piece

Laser polishing without any adaptation strategies leads to rounded edges. A limitation of the polishing area in combination with an adaptation of the laser power leads to sharp edges. However due to the limitation of the polishing area a small stripe around the edge of a diameter of about 100 µm isn't polished.

#### Optimal tool path geometries

Short scan vectors leads to a heat accumulation in local areas of the freeform. This will result into a higher roughness. Another criterion for an optimal tool path is an equidistant track offset over the whole area. This is why the geometry of the scanning trajectory is important for the result.

It doesn't exist one optimal solution for generating tool paths for all 3D geometries, but a path can be optimised. The strategy depends on the geometry itself. Optimal results in respect to get a low roughness can be achieved by continuous and equidistant (onto the surface) tool paths. For example a slight change of the track offset could significantly reduce the accumulation of heat (see Figure WP4.1). CAM path generation algorithms like "flowline fishing" are an efficient tool for generating sufficient paths.



**Figure WP4.1:** Heat accumulation near the turning points of the laser

#### Shielding gas chamber

The shielding gas chamber has been overworked to enhance the accessibility and the ability to polish bigger work pieces with freeform optics. The new process chamber encloses the whole swivelling rotary table. Furthermore the 4 windows for laser beam entrance are replaced by one big window on the top of the process chamber. This only window supports the full accessibility and allows the processing of significant bigger work pieces up to 300x300x200 mm<sup>3</sup>. Furthermore the control of the process gas system was integrated in the process control.

### Optical system

The state of affairs at the beginning of the PoliMATIC project was an optical system of the laser polishing machine designed for a 150 W slab laser. For polishing work pieces with a relatively high initial surface roughness, a higher laser power is needed and the beam diameter has to be adapted at the initial surface quality. Therefore a new laser source (750 W disc laser) was bought and the optical system was adapted. The new optical system allows the selection of the beam diameter in the range of 150  $\mu\text{m}$  to 800  $\mu\text{m}$ . Furthermore the selection of the beam diameter was integrated in the process control to automate the selection.

### Process combination of manual polishing and laser polishing

Laser pre-polishing leads to an economical advantage for the polishing of EDM processed initial surfaces. The total processing time is reduced by a laser pre-polishing step. For milled initial surfaces, on which the initial roughness is usually smaller than on EDM processed initial surfaces, laser pre-polishing doesn't lead to an economical advantage.

## **1.3.5. Work package 5 – Robot polishing**

### Main Objectives:

Development of an automated robot-assisted fine machining (grinding, lapping and polishing) by the means of a force controlled polishing spindle and CAD/CAM-based process strategies in order to support the manual worker up to 80% with a brush, glossy or mirror finish of freeform steel moulds and dies.

### Developed Tasks:

Task 5.1 Development of the force-control module (Task leader: SNT)

Task 5.2 Development of the module for translational tool movement (Task leader: SNT)

Task 5.3 Adaption of fine machining tools for rotational and translational movement (Task leader: FHG-IPT)

Task 5.4 Evaluation of force, infeed and contact areas for different tools and parameters (Task leader: FHG-IPT)

Task 5.5 Preliminary parameter study for rotational and translational fine machining tools (Task leader: FHG-IPT)

Task 5.6 Influence of steel grade, hardness and quality (ESR, VAR, PM) (Task leader: SMK)

Task 5.7 Evaluation of tool wear and influence on surface quality and shape accuracy (Task leader: FHG-IPT)

Task 5.8 Preliminary tests of path planning and CAM-based programming for rotational and translational tools (Task leader: MOD)

### List of deliverables:

D5.1) Polishing spindle

D5.5) Tool wear and tool lifetime

D5.2) Module for translational movements

D5.6) Integrated CAD/CAM module

D5.3) Fine machining tools

D5.7) Process strategies for different tool steels

D5.4) Process parameters

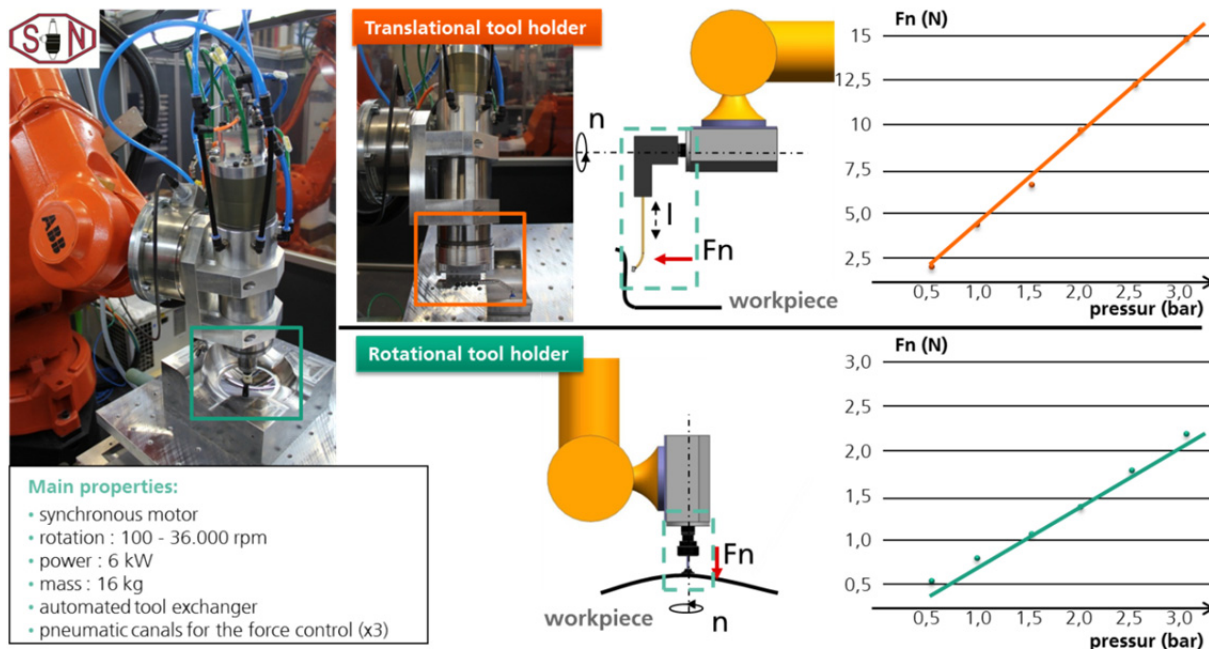
D5.8) Process strategies for different geometrical features

D5.9) Polished demonstrators with different processing strategies

## Work package 5 – Main results

### • Finishing spindle and rotational/translational tool holders

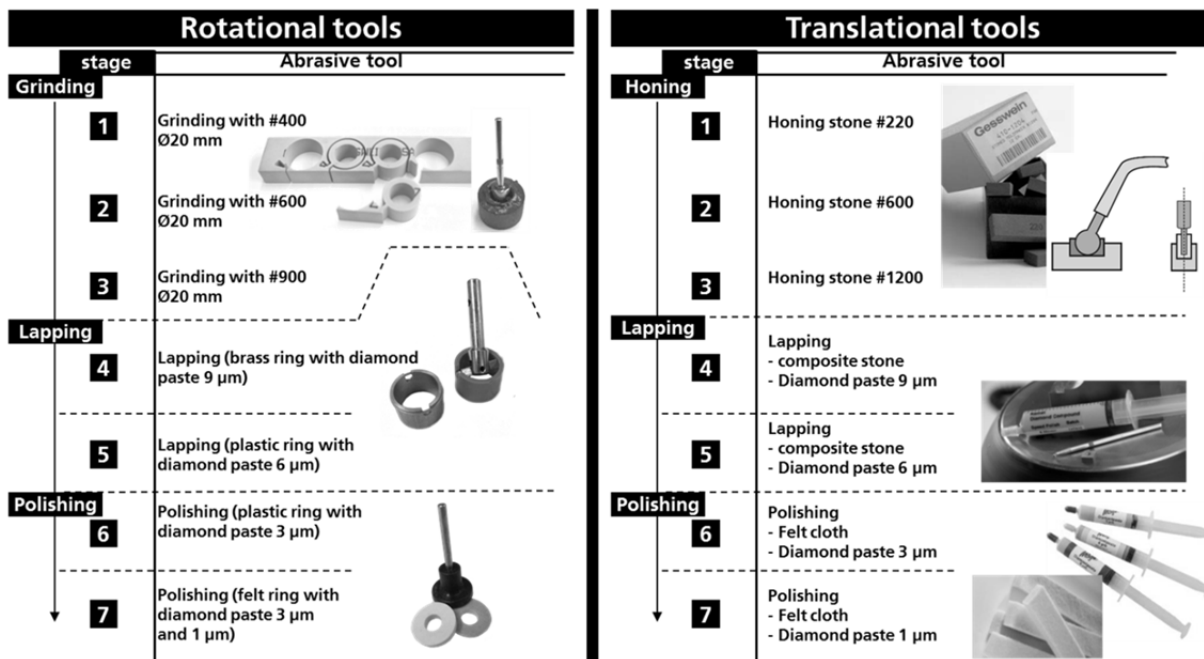
In order to elaborate robust and reproducible finishing strategies a force-controlled spindle was developed during the project (SN-Spindeltechnik, Fraunhofer IPT) and integrated to the available robot at Fraunhofer IPT (ABB IRB 4445). The developed synchronous spindle (see Figure WP5.1) presented the unique features combination (e.g. high rotation speed, low mass, compact, automatic tool changer) and the capability to control a wide range of process force by the means of an inexpensive electric-pneumatic system. The spindle works with the application of compliance tools holders (for rotational and translational tools) which actuated with necessary variable forces against the finished workpiece in dependency of the pressure programmed by the CAM program.



**Figure WP5.1:** Finishing spindle capable to regulate a wide process force spectrum and to enable rotational and translations finishing kinematics

### • Finishing process strategy and parameters

The classical finishing procedure of steel moulds is a multistage process where different machining procedures are taken in use. Regarding the material removal rate and the desired surface quality, machining procedures as grinding, honing, lapping and polishing are adopted. This sequence of fine machining procedures follow a tendency to present decreasing material removal capacity but simultaneously to increase surface qualities from the grinding/honing up to the polishing process. The Figure WP5.2 presents the developed and adopted multistage process strategy to finish typical milled surfaces up to a glossy surface quality.



**Figure WP5.2:** Multistage process strategy for rotational and translational tools

This process strategy was selected from experimental trials during the project development and from an intense information exchange between the SMEs participating on the project. Johansson Susan Svensk Industrigrav and Formtech SP ZOO provided their knowledge and strategy to finish milled surfaces and this information was transferred and adapted to the integration with the automated approach with the robot at Fraunhofer IPT. Besides the selection of the tools, the definition of the main process parameters to each process step and tool was carefully analysed.

- **Further developments**

Aside the planned activities and expected outcomes of the project poliMATIC regarding the WP5, further results were achieved due to the development of aid systems to the automated robotic approach. Once, the development of a material removal simulation program, based on scientific material removal models. Further, the development of an automated abrasive paste dispenser, increasing the automation level degree of the robotic cell. The fully integration of the surface quality measurements devices from WP6 into the robotic cell. Integration and application of a second spindle to rotational tools with radial compliance capabilities, allowing the finishing process of geometries like from the SME COMPES (see WP7).

### 1.3.6. Work package 6 – Surface metrology

#### Main Objectives:

The surface metrology activities of the project will enable the assessment of the quality of the polished surfaces in an objective manner. Formulation and verification of a metrology framework (parameters, method, selection of hardware, result representation) will be done to ensure the control by the "correct" variables and to ease the communication of polishing result between customer and polisher.

### Developed Tasks:

Task 6.1 Establish a metrology framework for in-machine control of laser- and robot polishing (Task leader: ALT)

Task 6.2 Develop a novel general characterisation system for polished surface structures (Task leader: HAL)

Task 6.3 Develop a metrology framework for Metrology Assisted Manual Polishing – MAMP (Task leader: SVE)

### List of deliverables:

D6.1) In-machine metrology framework

D6.3) MAMP

D6.2) Metrology framework

### **Work package 6 – Main results**

A revised “Steadman” diagram was designed to select proper ranges and resolutions of technologies to be developed.

The AFM, Interferometer-, Confocal-and Stylus type systems all in general are able to measure laser and robot polished surface structures. Optical objectives, CCD array size and mechanical stylus size and sampling distance are necessary to specify.

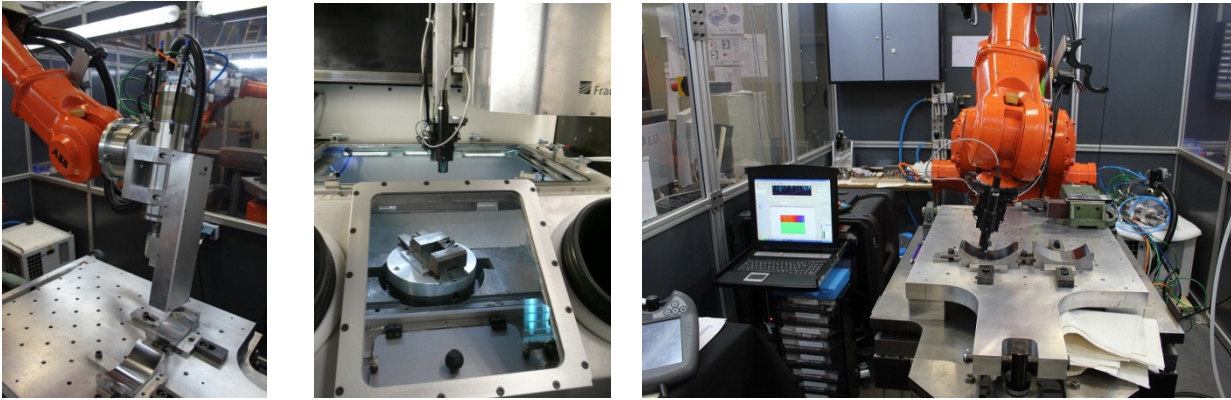
- Verification throughout the work was made by using reference plates to establish the In-machine metrology frame work.
- A laser marking technique to enable relocated and comparable measurements was established.
- A replica technique suitable for the measurement of highly polished surfaces was developed

Characteristics of the poliMatic laser- and robot process surfaces were compiled:

- Laser polishing requires complete mapping of laser waves on the whole polished surface to detect wavelengths between 300-2000  $\mu\text{m}$  with a lateral resolution of 100  $\mu\text{m}$  and vertical resolution approximately 200 nm.
- Robot polishing requires firstly to identify the roughest area over the polished surface and then measure it in order to aid the polishing process needed for e following polishing step, e.g. to set the polishing variables grain size, paste type, polishing time and force.
- Robot polishing roughness requires to measure for the initial process steps is in the range of  $R_a = 1 - 100\mu, \text{nm}$  range  $R_a$  measurements are only required at the finishing steps.

Point- and line scanning confocal light sensors were introduced for in-line metrology measurements for both the laser- and the robot polishing process.

A scattering instrument was developed to measure statistical surface structures over a larger area. The philosophy of the scattering instrument is to be as simple as possible to make it robust and useful in harsh industrial conditions (Figure WP6.1).



**Figure WP6.1:** The scattermeter on the robot at IPT (left); the confocal sensor mount on the laser head at FHG-ILT (middle) and the robot at FHG-IPT (right)

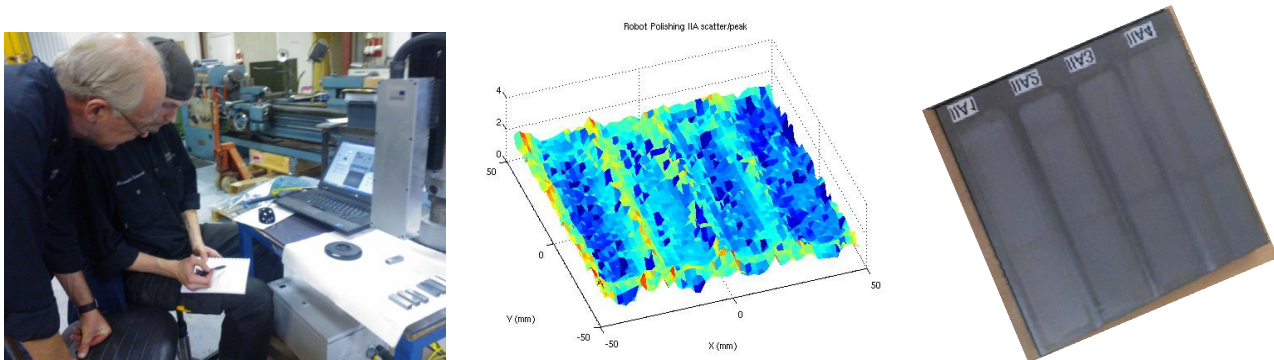
The functionality of the new instruments were shown and tested on-line in industrial conditions. The scattermeter is especially useful for quality statistical measurements over large areas. It is estimated to be both fast and robust.

The metrology framework has been developed to supply the confocal light sensors and the in-line laser scattering metrology device with suitable parameter sets to distinguish surface defects, texture patterns and average roughness.

Acceptance levels / parameter	Sq [nm]	Str	Sk [nm] (step 1)	MHoI out [nm]	MHoI in [nm]	MSoI out [ $\mu\text{m}^2$ ]
Good surface quality	< 12	$\geq 0,4$	< 25	< 5	< 5	< 30
Accepted surface quality	12-20	$\geq 0,4$	25-35	5-15	5-15	30-200
Non-accepted surface quality	> 20	< 0,4	> 35	> 15	> 15	> 200
Type of defect structure:	to get an overview of the surface roughness	to detect anisotropic structures (e.g. Scratches)	to detect orange peel	to detect outwardly features	to detect inwardly features	to detect relief structures

**Figure WP6.2:** Defect characterisation

ISO 25178 parameters Sq, Sk, and Str along with image analysis parameters MHol in, MHolout and MSolin, defect class characterization from the Uddeholm chart, are suitable for defect characterisation (Figure WP6.2). Scattering light related parameters are highly correlated to ISO parameters Sq and Str but faster to use for the in-line measurements over larger areas and insensitive to vibrations.



**Figure WP6.3:** Left: Picture showing the scatter instrument. The measured surface is placed under the instrument. The instrument is started with a single key. Middle: Measurements of Sq made with the scattermeter. Right: image of the surface.



The scattermeter instrument was developed for specific use on the workshop floor in real working conditions. The tests (Figure WP6.3) were made at Svensk Industrigravvyr AB in Hylte, Sweden.

The Metrology Assisted Manual Polishing – MAMP – is meant to replace or complete previously qualitative surface inspection for manual polishing operations with quantitative and objective characterization.

A scattering instrument based on previous results together with the new developed software interface with minimum control parameters, gives the manual polisher an objective tool to measure and document the process of the manual polishing. A set of parameters were deducted from the data to supply the manual polisher with sufficient input for continuing polishing while sustaining a robust and easy-to-use and fast instrument for work-shop conditions.

The measured values correspond very closely with surface parameter values. The developed technique and instrument was shown to measure surface parameters for polishing quickly and accurately on the work shop floor, without taking the surface piece into a laboratory area.

### **1.3.7. Work package 7 – Demonstration and Evaluation**

#### Main Objectives:

Demonstration of the projects results. Verification and evaluation of the developed technologies in terms of economical and quality issues.

#### Developed Tasks:

Task 7.1 Manufacturing of real parts (Task leader: FHG-ILT)

Task 7.2 Evaluation of the new metrology framework (Task leader: HAL)

Task 7.3 Comparison of technologies and investigation of possible process combination (Task leader: FHG-IPT)

Task 7.4 Test of polished tools under service conditions (Task leader: SMK)

Task 7.5 Economical evaluation and project review (Task leader: COM)

#### List of deliverables:

D7.1) Polished dies and moulds

D7.2) Characterization of automated polished tools

D7.3) Test of automated polished tools

D7.4) Process combination LP & RP

D7.5) Calculation of economics

### **Work package 7 – Main results**

#### Polished dies and moulds – Laser polishing

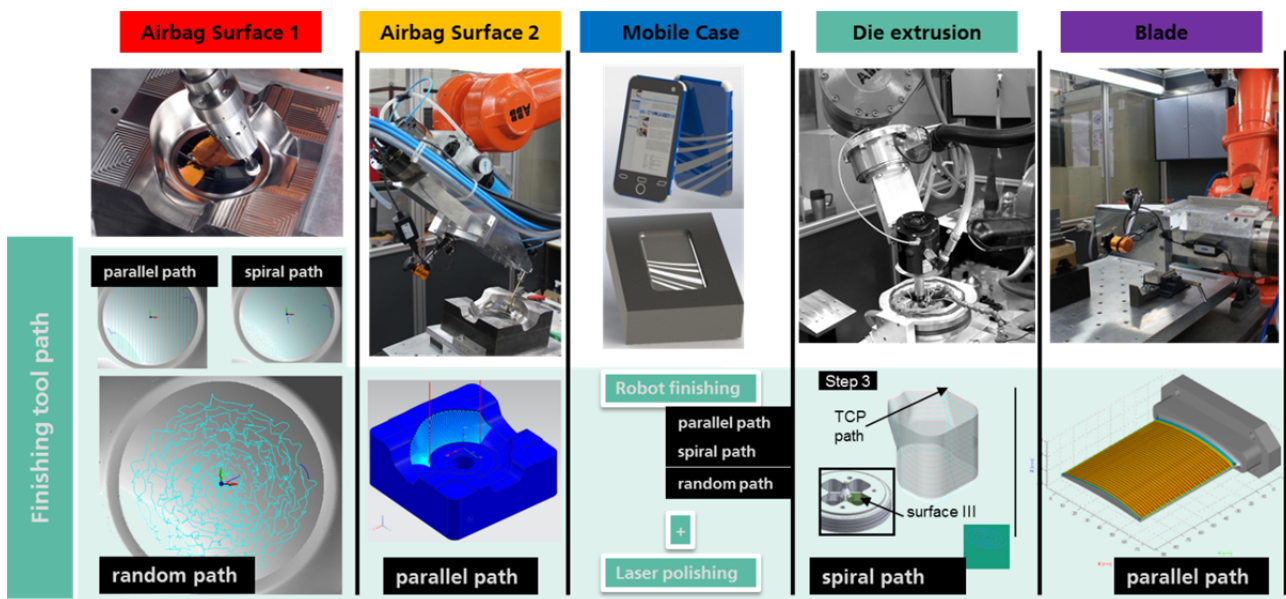
For the manufacturing of real parts COMPES and Star\*Plus provided different moulds to be laser polished. During the polishing of these parts the whole process chain could be tested successfully. While the first part from COMPES could not be processed correctly due to heat accumulation and limited accessibility, the other parts could be polished completely (Figure WP7.1). The second part from COMPES as well as the part from Star\*Plus were processed continuously (one subarea) to prevent the formation of bulges.



**Figure WP7.1:** Polished mould from COMPES (left) and Star\*Plus (right)

- **Polished dies and moulds – Robot polishing**

Figure WP7.2 depict the selected Demonstrators to prove the capability of the automated finishing process adopted with the robot approach. The geometry of the demonstrators was selected regarding common geometry features present in the typical mould cases from the SMEs (SMK, COM, FOR, SVE) from the project.



**Figure WP7.2:** Finished dies and moulds – Robot finishing

The first case, Airbag Surface 1 depicts the rotational finishing process result of a single surface in a mould polished until qualities N1 (according to DIN/ISO 1302) were achieved. The second example, Airbag surface 2 present the remaining surfaces of the mould that required an individual finishing strategy than the one adopted in the first example, due to tool accessibility restrictions. Therefore a translational tool is applied to this surface finishing.

The third example is a generic mobile phone case geometry that was finished with translational and rotational tools with surface qualities up to N1 class.

The fourth example present an overview of the adopted strategy to finish a die, differing completely from all other cases, where the fundamental restrictions were the accessibility

of the tool and the reduction of the process time (approx. 60 min.), requiring a high finishing rate process rather than a high surface quality (N3).

The last demonstrator, the blade, was finished through similar strategy as the Airbag surface 2 and planned strategy to the mobile phone case. However, the decision to adopt the similar strategy was necessary due to surface qualities requirements (surface structuring in the fluid flow direction) and not due to tool accessibility difficulties.

- **Process combination LP & RP.**

Regarding the initial assumed hypotheses to explore the advantages of the laser polishing and robot finishing approach in a process combination, the following could be concluded:

1. Reduction of the process time due to the substitution of initial process steps in the robot finishing approach by the fast laser finishing. A real process time reduction of at least 2.5 min/cm<sup>2</sup> could be achieved with the combination of the both process, due to the direct substitution of the initial abrasive finishing steps (robot finishing) by a much faster laser polishing process.
2. Enhancement of the final surface quality due to the elimination of the material defects (material vacancies) by the laser polishing step. No clear advantage in the quality of the surface analysing the surface roughness values was detected.
3. Improvement of the material finishability for the robot finishing process due to the possible increment of the surface hardness by the laser polishing process. The material did not react differently to the abrasive finishing process (robot finishing) with the variation of the hardness of the workpiece material by a previous laser polishing process. The previous laser polishing therefore did not present any advantage to a following robot finishing operation.

#### Test of automated laser polished tools

- **Laser polished injection mold from Star\*Plus**

Star\*Plus tested a freeform injection mold which has been laser polished by Fraunhofer ILT. Star\*Plus manufactured 10000 (regarding 2% of the predicted die life-time) plastic parts with both a laser polished and a manually polished mold. As a testing material a Polypropylene type Sabic PHC27 (unfilled) was chosen, with 2% masterbatch added for colouring. The parts of the manually polished mold are more matt, but the shine is overall good and acceptable for this product (s. Figure WP7.3).



**Figure WP7.3:** Plastic Parts (front: manufactured from the laser polished mold, back: manufactured from the manually polished mold)

- **Laser polished extrusion die from COMPES**

The die from COMPES is composed of two pieces, used to extrude a hollow section: a die-cap and a mandrel. The material of the mould is 1.2343 and the hardness 46-49 HRC. Profilgruppen AB (a customer from COMPES) tested and compared two dies - one laser polished and one manual polished (using aluminium alloy 6082). Analysing data provided by Profilgruppen AB shows that the starting extrusion pressure is lower for the laser polished sample (LP: 160 bar, non LP: 200 bar). Less pressure, especially at the beginning of the process, means that the die is less solicited. It means a longer die life (less probability of cracks on the mould due to overload or fatigue). Due to the lower extrusion pressure throughput could be increased by 20% (LP: 8.5 m/min, non LP: 7 m/min). Furthermore the surface of the extruded part was visibly better. It was brighter and without significant defect.

#### Test of automated robot polished tools

Due to the fact that the applied abrasive tools in the robotic approach are the same ones in use in the established manual finishing process, the automation does not generated any variation in the material property of the mould nor unusual defect as by the laser polishing.

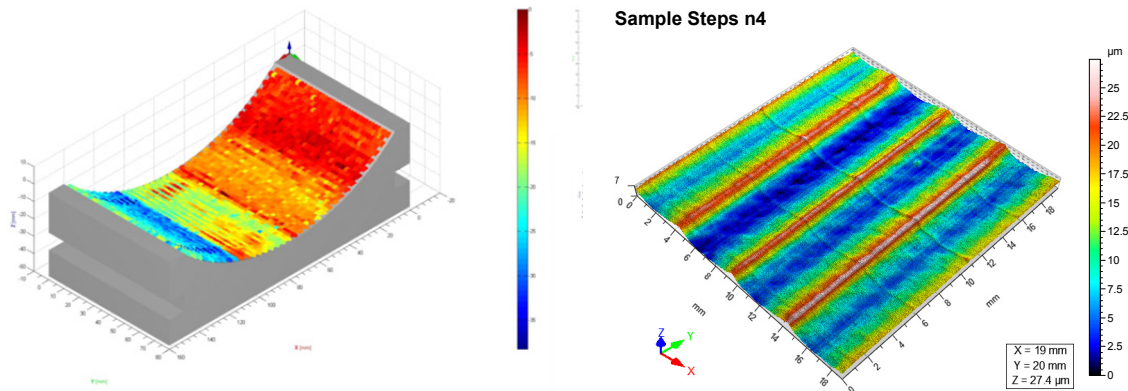
Therefore specific tests oriented in the life time and abrasion inspection of the moulds automated finished by the robot are not required. The conventional examination of the moulds and dies surfaces automated finished by the robot using tactile and optical measurement devices are adequate and enough.

- **Evaluation of new technology**

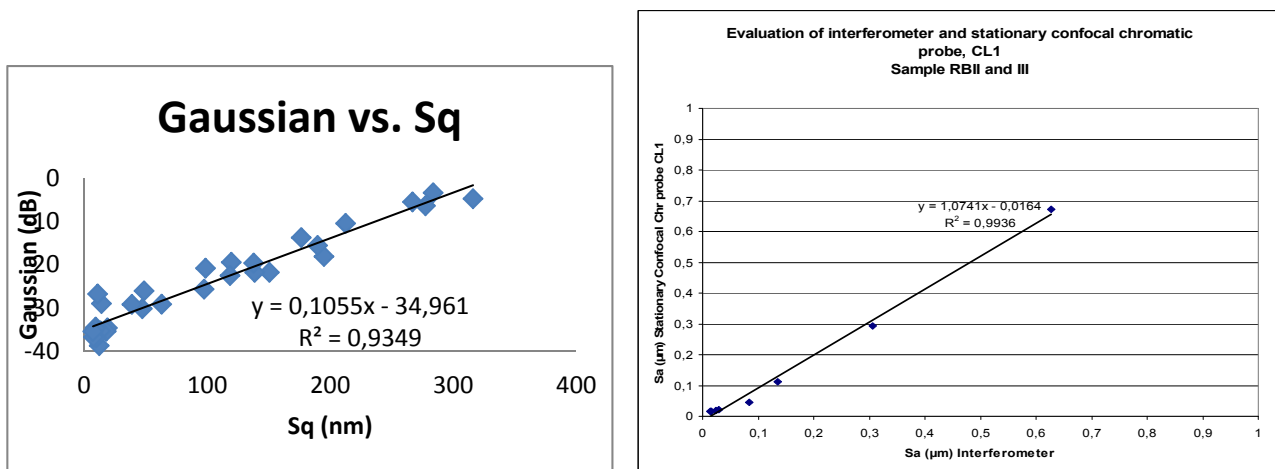
In connection to the automated technologies, metrology frame work for in-machining control for the laser as well as for the robot polishing system has been developed in WP6. Two complimentary methods were developed to allow fast process feed-back as well as final quality assurance. The integrated metrology systems allow in-line uniform quantification for describing e.g. scratches, pull-outs or waviness on a surface and as consequence support the automated execution of the polishing process with topographical feed-back information (Figure WP7.4).

- Qualitative statistic measurements – laser coherent scattering is used for fast characterization of the whole polished part with information of the specular and diffuse reflected laser light statistically related, e.g. Sq (rms surface amplitude) and Str (Symmetry of structure), to the polished topography and lay directions.

- Quantitative detailed measurements – the non-contact confocal chromatic probe point scanning of the polished surfaces allow a feedback of traditional known profile topography like Ra (average amplitude) and novel areal parameters characterizing the surface features like scratches, peaks and defects in detail.



**Figure WP7.4:** Qualitative, blue is finer surface, statistic measurements (Sq) of curved robot polished surface (left) and quantitative measurement (height) of flat laser polished surface (right)



**Figure 7.5:** Left: Gaussian (peak) vs. Sq with scattermeter (measured with white light interferometer.); Right: Sa measured with Confocal instrument vs. white light interferometer.

The scattering instrument was evaluated against a statistical sample of known polished surfaces. Figure WP7.5 shows the correlation with co-efficient of 93%. The new confocal instrument shows a correlation of 99%.

- **Economical evaluation**

#### Economical evaluation – Laser polishing

The evaluation of economics showed during the project that neither for the moulds and dies from Star\*Plus nor for COMPES laser polishing is profitable. This is due to the low labor costs and the individuality of each part.

However chances of profitability are more likely to be found in high-wage countries or in companies producing many parts with identical geometry.

As outlook the economic aspects of laser polishing could be enhanced with reducing the costs of the whole machine. For specific geometries (symmetrical etc.) the whole kinematical system could be simplified. For special materials and geometries also the price for the laser could be reduced (laser system with less power). Also producing the machine with a larger quantity could reduce the costs for each machine.

### Economical evaluation – Robot finishing

The evaluation of economics shows that based on the actual achieved technological results, the worldwide first finishing robotic cell prototype, capable to finish rough milled surfaces up to high glossy surfaces from complexes free form mould and dies of steel, is rather not economic suitable to any of the end-user partners from the project poliMATIC.

However, as a prototype concept, the robotic cell still presents specific technical flaws that can be corrected in further developments. Aside of the restrictions to the process generated from the robot, the finishing process still present a high potential of optimization of quality assurance and reduction of time.

Another important aspect of the present calculations is that all values are regarded as costs during normal work hours or days. During the project poliMATIC, demonstrators were partially or entirely finished during over-night operations and during weekends and holidays without any supervision of an operator. Adopting this approach, the robotic cell would be already profitable, although more accurate system self-reliance for industrial applications has to be previously guaranteed.

### **Work package 8 – Dissemination, Training, Standardisation and Exploitation**

#### Main Objectives:

Ensure the exploitation of the project results through the participants and by the whole European Tooling Industry. Ensure the transfer of knowledge from RTD to SME. Increase the skill of scientists and engineers. Educate and training people (students and professionals).

#### Developed Tasks:

Task 8.1 Dissemination (Task leader: FHG)

Task 8.3 Standardisation (Task leader: HAL)

Task 8.4 Exploitation (Task leader: ARN)

#### List of deliverables:

D8.1) Web-page

D8.2) Exhibitions and trade fairs

D8.3) Training materials for students

D8.4) Training materials for professionals

D8.5) List of future products and poliMATIC implementation plan

### **Work package 8 – Main results**

#### **• Dissemination**

Regarding the dissemination of the project, the poliMATIC project was presented in diversified ways to the scientific field and industrial market. The project was mainly presented to the scientific field by means of the publication of papers, participation at conferences and presentation of the project development internally to the involved universities and research institutes (Halmstad University, RWTH University, Fraunhofer IPT and ILT). The public from the industry was essentially contacted by means of the project home-page, publications of articles in magazines and a strong presence in fairs (see Figure WP8.1) and colloquia.

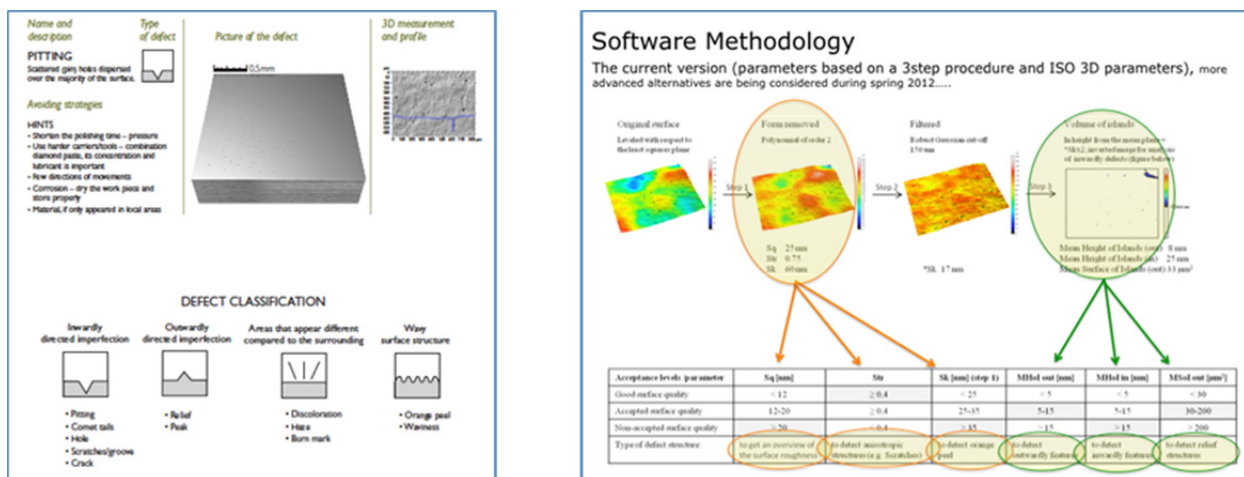




**Figure WP8.1:** Presentation of partial results of the project poliMATIC during the fair Hannover 2013

- **Standardisation and Training materials.**

The project engaged in the further development of standards to a clear characterization of surfaces topographies measured by optical measurement devices and the specific description of typical surface defects generated during the finishing process. Therefore the researcher partner Halmstad University in cooperation with the SME Toponova worked specifically in contact with the ISO TC213 group, focusing in the development of an international standard with the title elucidate – Surface Texture: Surface defects on material measures (Figure WP8.2).



**Figure WP8.2:** Standardisation of surface defects on surface measures

- **Exploitation.**

(see chapter 2.2, Section B)

### 1.3.8. Work package 9 – Management

#### Main Objectives:

The overall goal of the project management is to make sure that all defined objectives within the work packages are realised within the conditions of time, budget control, effectiveness and quality of output. Specific objectives:

- Setting up of project administration and S&T integration procedures
- Organisation of project meetings
- Preparation of progress reports and cost statements for timely submission to the EC
- Monitoring project finances and subsequent reporting to the related Management Group

#### Developed Tasks:

Task T 9.1 Preparation of plans and project management procedures (Task leader: FHG-ILT)

Task T 9.2 Administrative follow-up and monitoring of activities and costs (Task leader: FHG-ILT)

Task T 9.3 Reporting (Task leader: FHG-IPT)

#### List of deliverables:

D9.1 – 3, D9.5 – 7 reporting notes

D9.4 Periodic report

D9.2 6-month reporting notes

D9.8 Final report

## **2. Use and dissemination of foreground**

In sequence a plan for use and dissemination of foreground (including socio-economic impact and target groups for the results of the research) was established at the end of the project.

### **2.1. Section A**

This section describes the dissemination measures, including scientific publications relating to foreground.

- Table A1: List of all scientific (peer reviewed) publications relating to the foreground of the project.
- Table A2: List of all dissemination activities (publications, conferences, workshops, web sites/applications, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters).

<b>Table A1 : LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES</b>										
<b>NO.</b>	<b>Title</b>	<b>Main author</b>	<b>Title of the periodical or the series</b>	<b>Number, date or frequency</b>	<b>Publisher</b>	<b>Place of publication</b>	<b>Year of publication</b>	<b>Relevant pages</b>	<b>Permanent identifiers<sup>13</sup> (if available)</b>	<b>Is/Will open access<sup>14</sup> provided to this publication</b>
1	Robot assisted manufacturing system for high gloss finishing	Wilbert, A.	Intelligent Robotics and Applications	Lecture Notes in Computer Science Volume 7506	Springer Berlin Heidelberg	Berlin, Germany and Montreal, Canada	2012	pp 673-685	ISBN 978-3-642-33508-2	no
2	Automated Finishing Process - an Extrusion Die Case Study	Wilbert, A.	CIRP Journal of Manufacturing Science and Technology	7th International Conference and Exhibition on Design and Production of Machines and Dies/Molds, 2013	ELSEVIER, CIRP, The International Academy for Production Eng.	Antalya-Turkey	2013			no
3	Towards new interferometer technology for surface metrology	Baath, L.B.	EUSPEN conference proceedings	12 <sup>th</sup> international conference	EUSPEN	Bedford, UK	2012	158-161	ISBN 13:978-0-9566790-0-0.	no
4	Laserpolieren von Freiformflächen	Ostholt	Dissertation		Shaker Verlag	Aachen, Germany	2012		ISBN: 978-3-8440-0696-4	
5	Laser polishing of metallic freeform surfaces	Ostholt	Congress Proceedings; LIA 613, Vol.103	29th International Congress on Applications of Lasers & Electro-Optics		Anaheim, California USA	2010		ISBN: 978-0-912035-61-1	
	Laserpolieren metallischer Oberflächen	Willenborg	Congress Proceedings	8. Jenaer Lasertage		Jena, Germany	2012			

<sup>13</sup> A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view or to the final manuscript accepted for publication (link to article in repository).

<sup>14</sup> Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

Table A2 : LIST OF DISSEMINATION ACTIVITIES								
NO.	Type of activities <sup>15</sup>	Main leader	Title	Date	Place	Type of audience <sup>16</sup>	Size of audience	Countries addressed
1	Colloquium	FhG-IPT	10th International Colloquium “Tool and Die Making for the Future”	26 February 2010	Aachen, Germany	Industry, Scientific Community	More than 800 visitors	International (Global)
	Conference	FHG-ILT	Icaleo, 29th International Congress on Applications of Lasers & Electro-Optics	30 Sept. 2010	Anaheim, USA	Scientific, Industry	Approx. 400 visitors	International (Global)
	Conference	FHG-ILT	38 <sup>ème</sup> Séminaire INFOMAT, Nouvelles techniques de polissage	12 Nov. 2010	Neuchâtel, Schweiz	Scientific, Industry	Approx. 100 visitors	International (Global)
2	Fair	FhG-IPT, FhG-ILT, SNT	EuroMold Fair	01-04 Dec. 2010	Frankfurt, Germany	Industry, Scientific Community	Approx. 50.000 visitors	International (Global)
4	Colloquium	FhG-IPT	AWK 2011 - Aachen Machine Tool Colloquium, "Integrative Production Technology for High-Wage Countries"	26-27 May 2011	Aachen, Germany	Industry, Scientific Community	Approx. 1.000 visitors	International (Global)
5	Fair	FhG-IPT, FhG-ILT, SNT, ARN	EuroMold Fair	27-30 Nov. 2011	Frankfurt, Germany	Industry, Scientific Community	Approx. 50.000 visitors	International (Global)
6	Educational Program	FhG-IPT, FhG-ILT,	Girl’s Day 2011	14 Apr 2011	Aachen, Germany	Civil Society	20 visitors	Germany
7	Workshop	FhG-IPT, FhG-ILT, HAL	2nd Workshop “Steel Polishing”	9 – 10 Nov 2010	Aachen, Germany	Industry, Scientific Community	Approx. 50 visitors	International (Europe)
8	Workshop	FhG-IPT, HAL	3rd Workshop “Steel Polishing”	19 – 20 Nov 2012	Aachen, Germany	Industry, Scientific Community	Approx. 50 visitors	International (Europe)
9	Conference	HAL	12th international conference of the	04-08 Jun 2012	Stockholm, Sweden	Scientific Community	-----	International (Europe)

			European Society for precision engineering and nanotechnology					
10	Conference	FhG-IPT	International Conference on Intelligent Robotics and Applications (ICIRA 2012)	3 – 5 Oct 2012	Montreal, Canada	Scientific Community	Approx. 300 visitors	International (Global)
11	Conference	FhG-ILT	8. Jenaer Lasertage	22 – 23 Nov 2012	Jena, Germany	Industry, Scientific Community	120	Germany
12	Fair	FhG-IPT, FhG-ILT, SNT, ARN	EuroMold Fair	27-30 Nov. 2012	Frankfurt, Germany	Industry, Scientific Community	Approx. 50.000 visitors	International (Global)
13	Symposium	FhG-ILT	EuroMold	28-29 Nov. 2012	Frankfurt, Germany	Industry, Scientific Community	Approx. 50.000 visitors	International (Global)
14	Fair	FhG-IPT, SNT	intec - 14. trade fair for manufacturing, tool and special purpose machine construction	26.02 – 01.03 2013	Leipzig, Germany	Industry	Approx. 10.000 visitors	International (Global)
15	Fair	FhG-IPT, SNT, HAL, TOP, ALT	Hannover Fair	08-12 May 2013	Hannover, Germany	Industry, Scientific Community	Approx. 70.000 visitors	International (Global)
16	Fair	FHG-ILT	Laser	13-16 May 2013	München, Germany	Industry, Scientific Community	Approx. 27000 visitors	International (Global)

<sup>15</sup> A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

<sup>16</sup> A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias ('multiple choices' is possible)



## 2.2. Section B

The overall objective and strategic impact of the poliMATIC project is to strengthen the competitiveness of the European Tooling Industry by overcoming the current drawbacks of die and mould finishing by developing two automated polishing techniques - laser polishing and force controlled robot finishing, including measuring technologies to ensure the polishing quality. The European polishing market for surface finishing of dies and moulds is currently organized in two pillars. On one hand the polishing is done within a department of the tool manufacturer, mostly manually. In the poliMATIC project this group is represented by CO.M.P.ES. S.p.A. (COM) and Star\*Plus Műanyagipari Kft. (SMK). On the other hand - and this is the main part - this work is done by several job shop companies specialized on manual polishing of tools. Representatives for this group are Johansson Svensk Industrigravyr (SVE) and FORMTECH SP ZOO. (FOR).

Within the poliMATIC project new organisational and business models have been developed to integrate automated polishing in the European Tooling Industry. Furthermore poliMATIC established new business models in technology based markets for machine manufacturers (for example Maschinenfabrik Arnold) and software vendors (for example S&F Systemtechnik, Module Works).

### Part B1

LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC						
Type of IP Rights <sup>18</sup> :	Confidential I Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant(s) (as on the application)	Place of publication
Patent application	YES	03/11/2013	SE 1330009-0	Quantitative measurement method and apparatus for surface polishing	Baath, Lars B.	PRV Stockholm, Sweden
QSO Interferometer Systems AB	NO	01/01/2013		Spin-off Comapny	Baath, L.B., Rosen, B.G., Rosen, S.	Halmstad, Sweden

<sup>18</sup> A drop down list allows choosing the type of IP rights: Patents, Trademarks, Registered designs, Utility models, Others.

## Part B2

Type of Exploitable Foreground	Description of Exploitable Foreground	Confidential Click on YES/NO	Foreseen embargo date	Exploitable product(s) or measure(s)	Sector(s) of application <sup>20</sup>	Timetable, commercial or any other use	Patents or other IPR exploitation	Owner & Other Beneficiary(s) involved
R&D results	CAM technology module –	NO		Product: Technology Module for automated laser polishing (software). Adaptation of technology module for other polishing applications and laser processing methods like laser marking, specific software solutions		After 2013		1A FHG-ILT (owner)
General advancement of knowledge	Process Know How “Laser Polishing of 3D metal parts” (process strategies)	NO		New projects about automated laser polishing and feasibility studies	tooling industry, aerospace and medical industry	After 2013		1A FHG-ILT (owner),
General advancement of knowledge	Process Know How “Laser Polishing of 3D metal parts” (process strategies)	NO		Consulting services for customers who bought a laser polishing machine from Maschinenfabrik Arnold	tooling industry, aerospace and medical industry	After 2013		1A FHG-ILT (owner), Maschinenfabrik Arnold
R&D results	Parameter data base	NO		Use of parameter data base for new feasibility studies	tooling industry, aerospace and medical industry	After 2013		1A FHG-ILT (owner)
R&D results	Optical system	NO		Robust optical system for high power laser sources, esp. for laser polishing developed during the the project can be explored separately	Machine manufactures	After 2013		1A FHG-ILT (owner)
General advancement of knowledge	Test of laser polished tools under service	NO		The positive test results lead to a higher acceptance of other potential end-users	tooling industry, aerospace and medical industry	After 2013		1A FHG-ILT (owner)

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General advancement of knowledge	Industrial Robotics - Programming	NO		Consulting service regarding existing robot programming solutions to companies already applying (e.g. existing Path program optimization) or intending to apply robots in the manufacturing line	all manufacturing sectors (e.g. automotive, aeronautical, naval, Medical and valve industry)	Starting in 2013		1B FHG-IPT (owner)
General advancement of knowledge	Industrial Robotics - CAM	NO		Consulting service and specific software solution development to tailored applications	all manufacturing sectors	2014		1B FHG-IPT (owner)
General advancement of knowledge	Industrial Robotics – Functionality	NO		Consulting service regarding robot functionality to companies already applying or intending to apply robots in the manufacturing line (processing, manipulation of parts or sensors, etc.)	all manufacturing sectors	Starting in 2013		1B FHG-IPT (owner)
R&D results	Industrial Robotics – End-effectors and further peripheral devices	NO		Consulting service, design, manufacture and test of end-effectors and further peripheral devices added with force control capabilities to companies already applying or intending to apply robots in the manufacturing line spindle development.	all manufacturing sectors	Starting in 2013		1B FHG-IPT (owner), SNT
General advancement of knowledge	Industrial Robotics – Machining	NO		Consulting service, design and prototype assembly to the specific development of machining processes (Milling, Deburring, and Finishing) to companies already applying or intending to apply robots in the manufacturing line	all manufacturing sectors	Starting in 2013		1B FHG-IPT (owner)

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R&D results	Surface quality and material properties modification related to manufacturing process	NO		Consulting service, regarding the generated surfaces qualities and work piece material modification according to the manufacturing process strategies	all manufacturing sectors	Starting in 2013		1B FHG-IPT (owner)
General advancement of knowledge	Abrasive tools	NO		Consulting service, regarding the required machining tools (milling, deburring, finishing) to robotics applications	Abrasive tools manufacture, all other manufac. sectors	Starting in 2013		1B FHG-IPT (owner)
R&D results	Industrial Robotics & Automated Finishing	NO		Basis for further R&D on the present topics: Process strategy, Abrasive tools for automated processes <ul style="list-style-type: none"> <li>- Robot end-effectors (Spindle, sensors, tool holders, etc)</li> <li>- Deterministic finishing process modeling and forecast</li> <li>- Robot programming, automated CAM generation</li> </ul>	all manufacturing sectors	Starting in 2013		1B FHG-IPT (owner)
R&D results	New measure.technology Scattermeter	YES	03/11/2013	Product: Scattermeter	Polishing industries	End of 2013	YES, initiated registration	2 HAL
R&D results	Prototype Scattermeter	YES	03/11/2013	Founding of a spin-off company to bring Scattermeter to market	All manufacture sectors that require a surface inspection	2013	YES	2 HAL

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R&D results	Prototype Scattermeter	YES	03/11/2013	Adaptation of Scattermeter product regarding client requirements	All manufacture sectors that require a surface inspection	>2013	NO	2 HAL
General advancement of knowledge	New contacts to companies in branches where ARN did not have contacts before	NO		Use of the new network for future developments and business	Manufacturing industry	Direct after the project		3 ARN
R&D results	LASER POLISHING Machine technology for laser polishing developed by ARN, SFS and ILT	NO		Job shop laser polishing of tools: <ul style="list-style-type: none"> <li>- Acquisition of customers for laser polishing</li> <li>- Buying of a laser polishing machine, as soon as enough customers show interest</li> <li>- Job shop polishing of tools</li> <li>- 24h fast polishing service if the appropriate database, is available – directly readable data or high precision scanner</li> </ul>	Producer of polished surfaces (finalizing)	1-3 years after the project - Provided that all general technological preconditions are given		4 FOR, SFS, FHG-ILT
R&D results	ROBOT POLISHING Robot polishing equipment developed by IPT, SNT and MOD	NO		Job shop robot polishing of tools: <ul style="list-style-type: none"> <li>- Acquisition of customers for robot polishing</li> <li>- Buying of a robot polishing cell, as soon as enough customers show interest</li> <li>- Job shop polishing of tools</li> <li>- 24h fast polishing service</li> </ul>	Producer of polished surfaces (finalizing)	1-3 years after the project - Provided that all general technological preconditions are given		4 FOR

Type of Exploitable Foreground	Description of Exploitable Foreground	Confidential Click on YES/NO	Foreseen embargo date	Exploitable product(s) or measure(s)	Sector(s) of application <sup>20</sup>	Timetable, commercial or any other use	Patents or other IPR exploitation	Owner & Other Beneficiary(s) involved
General advancement of knowledge	Broadening knowledge and technological expertise w.r.t. the requirements for fine machining processes to further software development.	NO		Module Works S.R.L. aims on the commercialization of the developed algorithms integrated into their core product. To provide a solution which is suitable for commercial use ModuleWorks is planning to further develop the solution approach until reaching commercial maturity. ModuleWorks is able to provide a set of new tool paths strategies suitable for fine machining tasks.	Various niche markets of specialized manufacturers and industrial processors dealing with complex geometry and finemachining tasks	2014		5 MOD, IPT
General advancement of knowledge	Know-how in the polishing process as well as in building control systems for polishing machines	NO		The partner ARN has built up a machine tool prototype for laser polishing. For this machine SFS developed a couple of software modules based on the results of poliMATIC and has set up the control devices. SFS offers the implementation of the software modules as well as the set-up of the machine tools. For both of these a revenue of 30.000 € per machine is detached	Machine Building; Automated Polishing	2014		6 SFS, ARN (owner), FHG-ILT
R&D results	Knowledge in integrating special components into the Siemens SINUMERIK control	NO		In 2013 the SFS will announce the capability of implementing the mentioned components into the control. So SFS estimates first activities in 2014	Machine Building, Laser Polishing and Other Laser Applications	2014		6 SFS, ARN (owner), FHG-ILT

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R&D results	Control of multiple laser sources			Within this project a laser-switch-box was set-up as by-product of the control unit. This box enables the n:m usage of different laser sources (or even light ways) for different machines. It is planned to bring this system to market in 2014/2015 and to sell the system. The revenue is roundabout €15.000		2014:		6 SFS, ARN (owner), ILT
R&D results	Laser pre-polishing in combination with manual polishing.	NO		Acc. to report sent April 5 <sup>th</sup> -2011: Here we see a big potential when it comes to laser pre-polishing of EDM surfaces, especially with complex geometry. Time savings are substantial, and quality of overall dimension accuracy is drastically improved.	Mould surfaces formed with EDM where dimensional accuracy is of importance.	Immediate, given that suitable laser equipment is available.		SVE, ILT
R&D results	LASER POLISHING The first extrusion tests with the laser polished dies have shown a possible improvement in the life-time of the die due to minor stress on the die.	NO		Tests regarding the die life-time will be proceeded beyond the end of the project. The die has to be extruded several times in the next months before coming to a final conclusion for die life-time. If all tests are completed satisfactorily, Compes will integrate the automated polishing techniques in their production of extrusion dies.	extrusion dies	From 2014 or 2015 of		COM, ILT



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R&D results	ROBOT POLISHING: A superior surface quality of the finished die was achieved. However, a mature industrial solution still required	NO		Two options are expected to allow the transfer of the process knowledge developed in the project to the industrial application by COMPES. Increase the robot precision through the integration of position sensors in the robot cell and doing that reducing the finishing time. OR Integrating the finishing concept applied to the robot directly to the milling machine available at COMPES.	extrusion dies	From 2014 or 2015		COM, IPT
R&D results	Metrology framework	NO		Trainings for professionals (consulting character) and students (educational character)	Manufacture and end-users of polished surfaces. University Students.	2013		TOP
R&D results	Scattermeter developed in cooperation with HAL	YES	03/11/2013	New company, QISAB - QSO interferometer Systems AB, have been started officially in April 2013, together with Prof. Lars Bååth and Prof. Bengt Göran Rosén for development and commercialization of the Scattermeter prototype. First commercial product leaflets were handed out on Hannover Fair in April 2013.	Manufacture and end-users of polished surfaces.	2013		TOP, QISAB - QSO interferometer Systems AB
R&D results	Developed replica measurement technique	NO		Surface texture consultancy projects and service for customers	Manufacture and end-users of polished surfaces.	2013		ALT

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R&D results	Stedman diagrams	NO		Consultant services tool when selecting measurement instruments and defining the system resolution for functional characterization	Manufacture and end-users of polished surfaces.	2013		ALT
General advancement of knowledge	Knowledge of polishing process, manual, robot & laser	NO		Commercial offer of polishing process support & consulting with experts	Watch industry for watchcase and steel/gold/platinum parts. Lapping industry of metal or sapphire parts. Semiconductor wafer polishing	Already ongoing, 2013		ALT
General advancement of knowledge	Environmental criteria for acquisition chain capability in process metrology	NO		Module embedded in robot cell Robot communication (new item in Phoenix S/W)	All process industries for which on-line control of the polishing steps is relevant	Already available and applied in some watchmaking industry, 2013		ALT
R&D results	Scattermeter developed by HAL and TOP	YES	03/11/2013	Distribution of the Scattermeter in France and Southern Europe.	Manufacturing industry	Direct after the project, 2013		ALT, TOP, QSO
R&D results	Development of a robot integrated spindle	NO		Robotic Spindle for milling, grinding, polishing applications Integration of the developed spindle in CNC Machines	Diversified manufacturing sectors	2013		SNT, IPT
R&D results	Interpretation of a spindle system for translational and rotational finishing	NO		Force regulated spindle for finishing applications, integrated in: Robots & CNC Machines	Engineering, Die and Mold Industry	2014		SNT, IPT

Type of Exploitable Foreground	Description of Exploitable Foreground	Confidential Click on YES/NO	Foreseen embargo date	Exploitable product(s) or measure(s)	Sector(s) of application <sup>20</sup>	Timetable, commercial or any other use	Patents or other IPR exploitation	Owner & Other Beneficiary(s) involved
R&D results	Knowledge on milling, polishing, and automated manufacturing applications in general.	NO		Evolute plans to sell the geometry software package developed for the poliMATIC project to assess and control the geometric surface quality using scan data and surface reconstruction through consulting services and possibly as a standalone software product.	specialized manufacturers and industrial processors dealing with complex geometry milling, polishing	2014		EVO, IPT, MOD
General advancement of knowledge	LASER POLISHING: Application in the manufacturing chain	NO		Integration of laser polishing in production chain of injection moulds, more competitive by winning short-lead time projects	Injection moulds (Household, engineering parts for the electrical and machine-making industry)	1-1,5 years for the first project, 2015		SMK, ILT, ARN
General advancement of knowledge	ROBOT POLISHING: best practice knowledge of finishing	NO		Investment in the developing of a robotic cell for the automated finishing of the existing moulds and dies at SMK, if costs requirements and qualities results could be guarantee in an industry mature automated robotic cell.	Injection moulds (Household, engineering parts for the electrical and machine-making industry)	4 years after project conclusion, 2017		SMK, IPT, SNT, MOD

<sup>19</sup> A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

<sup>20</sup> A drop down list allows choosing the type sector (NACE nomenclature): [http://ec.europa.eu/competition/mergers/cases/index/nace\\_all.html](http://ec.europa.eu/competition/mergers/cases/index/nace_all.html)

According to the table above and the results achieved during the project the partners have defined the exploitable knowledge and products. The main exploitable knowledge and products for the 3 main fields of investigations are:

- Laser polishing: The CAM-NC-data chain (SFS, FHG-IPT), the developed optical system (ARN), process gas chamber (ARN), NC functionalities (SFS) and process knowledge (FHG-ILT) from poliMATIC are basis for a laser polishing machine tool prototype.
- Robot finishing: The CAM-Tool path planning (MOD, EVO, FHG-IPT), the rotational and translational tools and the spindle (SNT) and the process knowledge (FHG-IPT) form a complete robot-polishing-framework

- Metrology: Founding of a Spin-Off “QISAB - QSO interferometer Systems AB” for further developments and commercialization of the Scattermeter prototype, which was developed in the poliMATIC project (HAL, TOP)

### **3. Project Flyer**

poliMATIC



## AUTOMATED POLISHING FOR THE EUROPEAN TOOLING INDUSTRY



# poliMATIC – Strengthening the competitiveness of the European Tooling Industry by automating the polishing process

## Concept and Objectives

For the manufacturing of tools 12 to 15 % of the manufacturing costs and 30 to 50 % of the manufacturing time are allocated to polishing. As current automated polishing techniques are almost not applicable on parts with freeform surfaces and function relevant edges like 95 % of the tools, the polishing is predominantly done manually. Therefore the overall objective of poliMATIC is to strengthen the competitiveness of the European Tooling Industry by overcoming the current drawbacks of die and mould finishing by realising automation in laser polishing and force controlled robot polishing.

To ensure relevance to targeted markets and practical use of the results, the project is strongly driven by end users and machine tool manufacturers from different markets. Laser and robot polishing offer potential to strengthen the European Tooling Industry by a significant decrease of polishing costs (75 %) and time (90 %). In 5 to 7 years this will result in expected annual savings of manufacturing costs for tools of 150 Mio. Euros and in reductions of the time-to-customer by 27 to 45 %. The shorter time-to-customer will stimulate new demands. In conjunction with the decreased costs this will lead to a regain of world market shares and therefore relocation of labor back to Europe. poliMATIC will contribute to the transformation of the resource intensive tooling industry into a knowledge-based one.

The potential impact of automated polishing technologies is not limited to the tooling industry. The polishing technologies can be transferred to other industrial sectors in which polishing is widely used, for example:

- implants
- medical devices
- turbine components
- automotive parts
- mechatronical components
- valve units

## Laser Polishing

Polishing with laser radiation is based on remelting a thin surface layer of the workpiece and smoothing of the surface roughness due to the surface tension. The innovation of laser polishing results from the fundamentally different active principle (remelting) compared to conventional grinding and polishing (abrasion). For metals usually diode pumped solid state lasers are used. A new developed CAM-NC data chain enables the polishing of complex shaped free form surfaces.

- Workpiece material: Well suited for laser polishing: 1.2343, 1.2344, 1.2379, 1.3207, 1.3244, 2.4668, 3.7164, among other metals
- Workpiece geometry: Automated processing of 3D surfaces; suitable also for complex shaped parts and small workpieces
- Surface quality: N5 to N3 according to DIN/ISO 1302 depending on the material and its homogeneity; polishing results independent of the workers skills
- Process time: 1 min/cm<sup>2</sup> (cw) to 0,1 min/cm<sup>2</sup> (pulsed); polishing time nearly independent of the geometry
- Highlights: No pollutive impact from grinding and polishing wastes; avoidance of contaminations of the material with abrasives; selective polishing of limited areas is possible.



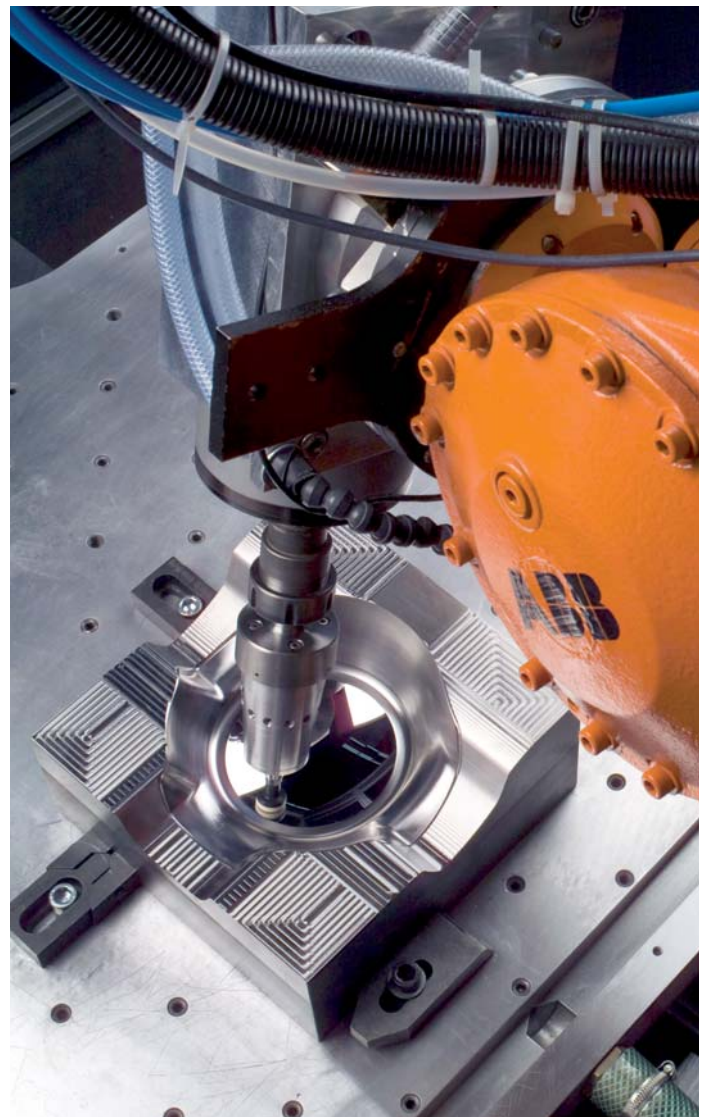




## Robot Polishing

The established abrasive finishing (e.g. grinding, lapping and polishing) process applied manually in the die and mould industry is aimed to be automated through the employment of a force controlled robot. Finishing with a robot leads to an encapsulation of the knowledge, skill and experience of the human worker within an automated solution. The approach consists of a force-controlled finishing spindle and a fully automated CAD/CAM-based task planning and enables the user to process freeform surfaces by a step-wise automated robot finishing.

- Workpiece material: The project focuses on the finishing of steels applied in the mould and die industry (e.g. 1.2334 ESR, 1.2083 ESR), Nonetheless the technology is applicable to other materials (metals, ceramics, plastics, wood)
- Workpiece geometry: The solution is appropriate for medium-large workpiece surfaces (injection moulds from 50 to 1000 kg)
- Surface quality: Independent from previous machining, a wide range of surface qualities and textures are feasible from brush finishing up to glossy surfaces (N12 to N1 according DIN EN ISO 1302)
- Process time: Up to 10 times shorter than a manual polisher, offering a finishing process rate in dependence of the geometry and surface quality between 1 to 30 min/cm<sup>2</sup>
- Highlights: An industrial robot can imitate human kinematic attributes – with the advantage that it can perform the craftsman actions far more frequently and precisely. The hourly rate is equal or even less than the hourly rate of a manual polisher.



## Metrology

In connection to the automated technologies, metrology framework for in-machining control for the laser as well as for the robot polishing system has been developed. Two complimentary methods have been developed to allow fast process feedback as well as final quality assurance. The integrated metrology systems will in the future allow an in-line uniform quantification for describing e.g. scratches, pull-outs or waviness on a surface and as consequence support the automated execution of the polishing process with topographical feed-back information.

### – Measurement principles

- Qualitative statistic measurements: Laser coherent scattering is used for fast process feedback.
- Quantitative detailed measurements: Confocal chromatic probe is used for mapping of surface features.

### – Standards for characterization

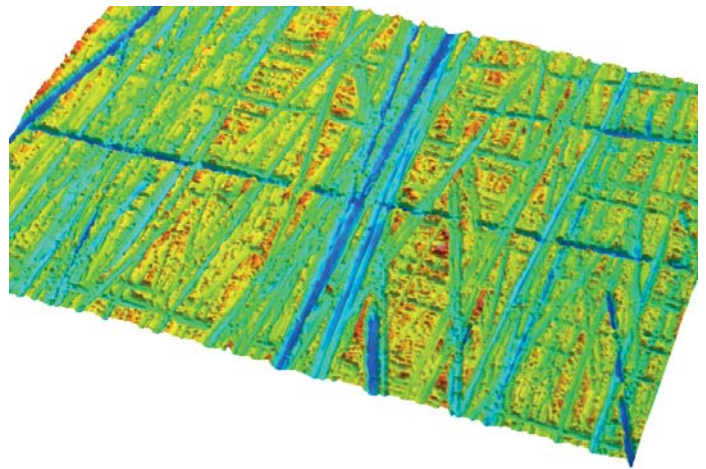
- Qualitative statistic measurements: Characterization works towards the technical norm "VDA 2009 Geometrische Produktspezifikation" for a fast qualitative feedback loop to the process.
- Quantitative detailed measurements: Characterization uses ISO 4287:1997 profile parameters and ISO 25178-2:2011 areal parameters, as well as 25178-602:2007 (probe type) for the hardware.

### – Measuring time

- Qualitative statistic: 100 mm<sup>2</sup>/s measuring spot (scannable over large areas)
- Quantitative detailed: 10 to 50 mm/s traversing speed in a volume of 25 x 25 x 25 mm<sup>3</sup>. Sensor vertical range (and resolutions) are 100 µm (5 nm) and 400 µm (15 nm).

### – Highlights

- Qualitative statistic measurements: Enable fast characterization of the whole polished part with information of the specular and diffuse reflected laser light statistically related, e.g. Sq (rms surface amplitude) and Str (Symmetry of structure), to the polished topography and lay directions.
- Quantitative detailed measurements: The non-contact confocal chromatic probe point scanning of the polished surfaces allow a feedback of traditional known profile topography like Ra (average amplitude) and novel areal parameters characterizing the surface features like scratches, peaks and defects in detail.



# poliMATIC

Automated Polishing for the European Tooling Industry

Project Reference: 246001

Programme Acronym: FP7-NMP

Subprogramme Area: Innovative and knowledge-based tooling industry

[www.automated-polishing.eu](http://www.automated-polishing.eu)



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