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Automated Polishing for the European Tooling Industry

Informe

Información del proyecto

POLIMATIC

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Sitio web del proyecto

Proyecto cerrado

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Este proyecto figura en...

Final Report Summary - POLIMATIC (Automated Polishing for the European Tooling Industry)

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 fnishing. 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 µm (Laser Polishing) / Ra=0,005 µm (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.

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^2) 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.

A typical task for a manual polisher is shown in Figure 1 (see attachment). 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 (see attachment Figure 2).

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

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 character-istics 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 (see attachment Figure 4), this proportion increases to 30% as in this market segment smaller and more complex parts with better surface qualities are needed.

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 (see attachment 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 pre-dominantly automatic NC-code generation and intensive tests of polished tools under service conditions.

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

Project Results:
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.

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. 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.
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.

• 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).

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

Sotware “Techonoly 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. Therefor 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. This guarantees the process chain to be complete and fluently including fully functional software (Technology Module).

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 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.

• 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 to 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 steps 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.
• 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.

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°• 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. CAM path generation algorithms like "flowline fishing" are an efficient tool for generating sufficient paths.

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^3. 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 µm to 800 µm. 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
D5.2) Module for translational movements
D5.3) Fine machining tools
D5.4) Process parameters
D5.5) Tool wear and tool lifetime
D5.6) Integrated CAD/CAM module
D5.7) Process strategies for different tool steels
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 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.

• 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. 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 scientifical 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
D6.2) Metrology framework

D6.3) MAMP

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 µm with a lateral resolution of 100 µm 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 Ra = 1 - 100µ, nm range Ra 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.

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.

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.

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.

• Polished dies and moulds – Robot polishing
During the project development Demonstrators were selected 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.
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^2 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 .

• 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.

• 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 form 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 and colloquia.

• 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).

• Exploitation.
(see chapter 2.2 Section B of attachment)

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
D9.2 6-month reporting notes
D9.4 Periodic report
D9.8 Final report
Potential Impact:
The exploitation and dissemination strategy was already described in the early stages of the project and the expected impact from the outcomes of the project poliMATIC were kept the same.
According to the list below 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 “Qasar Interferometer Systems AB” for further developments and commercialization of the Scattermeter prototype, which was developed in the poliMATIC project (HAL, TOP)

Participant:
1A FHG-ILT
Potential impact:
Fraunhofer ILT will generate new knowledge on laser polishing. Due to this knowledge ILT will be able to carry out feasibility studies and new projects about automated laser polishing in other parts of the tooling industry and beyond. Due to the expected economic impacts ILT expects a significant increase in demand for RTD. As laser polishing has been predominantly developed at FHG-ILT it can be assumed that FHG-ILT will be the number one contact for industrial RTD projects in this sector.
Economical impact and Exploitation strategy:
1 year after project termination: 150,000 €/a (equates to 1 new job)
5 years after project termination: 750,000 €/a (equates to 5 new jobs)

Participant:
1B FHG-IPT
Potential impact:
Fraunhofer IPT will generate process knowledge in the field of robot polishing and spindle development. Due to this knowledge, they will organise workshops (continue with the industrial reference group), participate at fairs, to acquire new projects in the field of automated polishing, and publish in high impact journals to demonstrate scientific excellence in this field.
Economical impact and Exploitation strategy:
Concerning the impacts, Fraunhofer IPT expects a significant increase for R&D activities. Furthermore Fraunhofer IPT will strengthen their good reputation as contact number one for industrial R&D projects in the field of polishing/ automated polishing 1 year after project termination: 150 000 €/a (equates to 1 new job)
5 years after project termination: 750 000 €/a (equates to 5 new jobs)

Participant:
2 HAL
Potential impact:
Halmstad University will generate process knowledge in the field of manual polishing and metrology.
With the participation at fairs and publication in high impact journals to demonstrate scientific excellence in this field, the university will be able to enlarge their R&D activities with new research projects. Furthermore they will strengthen their good reputation as contact number one in the field of surface metrology for industrial R&D projects in this sector.
Economical impact and Exploitation strategy:
1 year after project termination: 50 000 € (equates to 1 new job)
5 years after project termination: 250 000 € (equates to 5 new jobs)

Participant:
3 ARN
Potential impact:
The prototype developed by ARN an SFS will be the basis for a machine tool for laser polishing with industrial strength. A machine tool for laser polishing will cost about 250,000€. ARN's part of the value added chain covers 150,000€. In the launch phase, one year after project termination ARN will be able to

sell 2 machine tools for industrial application per year. After 5 years ARN will sell approximately 20 machine tools per year.
Economical impact and Exploitation strategy:
1 year after project termination: 500,000 €/a (equates to 2-4 new jobs)
5 years after project termination: 5,000,000 €/a (equates to 25-40 new jobs)

Participant:
4 FOR
Potential impact:
As a participant in the poliMATIC project FORMTECH SP ZOO. will be one of the first companies which implement automated polishing in their production environment. Formtech will benefit directly from the project results in terms of time to market, quality and prizes.
Economical impact and Exploitation strategy:
5 years after project termination: 500,000 €/a (equates to 6-10 new jobs)

Participant:
5 MOD
Potential impact:
Module Works S.R.L. aims on the development and programming of appropriate CAD/CAM software tools for the automated polishing of freeform surfaces. The price for the software cannot be determined yet, but similar software products developed for optics manufacturing are currently sold for 100,000 €. Even though for the tool and die branch much lower prices have to be reached, a realistic price in the range of 20,000 € can be assumed.
Economical impact and Exploitation strategy:
1 year after project termination: 100,000 €/a (equates to 1-2 new jobs)
5 years after project termination: 1,000,000 € (equates to 10-20 new jobs)

Participant:
6 SFS
Potential impact:
In close cooperation with ARN, SFS will develop and distribute the software for the laser polishing machine tools. SFS’s part of the machine tool can be estimated at 30,000 €/machine.
Economical impact and Exploitation strategy:
1 year after project termination: 60,000 €/a (equates to 1 new job)
5 years after project termination: 600,000 €/a (equates to 10-15 new jobs)

Participant:
7 SVE
Potential impact:
Johansson Susan Svensk Industrigrav aims on the more efficient finishing of moulds and dies due to the substitution of labour intensive and little reproducible manual work. Thus, the skilled workers can focus - after a successful termination of poliMATIC - on special challenging tasks where automated solutions are not applicable (e.g. steep and narrow geometrical features).
Economical impact and Exploitation strategy:

5 years after project termination: 250,000 € (equates to 3-5 new jobs)

Participant:
9 COM
Potential impact:
CO.M.P.ES. S.p.A. aims at an automated finishing of their extrusion dies. Due to the expected reduction in manufacturing time and deficient products a significant cost reduction is expected. The cost reduction will enable lower costs per part which will result in a significant increase of market share and therefore in a turnover increase.
Economical impact and Exploitation strategy:
1 year after project termination:100,000 €/a (equates to 1-2 new jobs)
5 years after project termination:500,000 €/a (equates to 6-10 new jobs)

Participant:
10 TOP
Potential impact:
Toponova AB aims for solving surface engineering problems in industry. With poliMATIC and the development of an "objective metrology" they will have a wider knowledge in this field than any other comparable company and can expand their area of consultancy.
Economical impact and Exploitation strategy:
5 years after project termination: 200,000 €/a (equates 2-4 new jobs)

Participant:
11 ALT
Potential impact:
ALTIMET SAS is a specialist in surface metrology especially for instrument development (e.g. AltiSurf⍰) and aims for an objective surface qualification, which is also part of poliMATIC. With this new "objective metrology", the communication and tasks between polisher, tool maker and end user will be better defined and will lead to fewer misunderstandings. With the development of the metrology frame-work and a new or enhanced metrology instrument including software and hardware, ALT will bring new products into market.
Economical impact and Exploitation strategy:
1 year after project termination: 200,000 €/a (equates 2-4 new jobs)
5 years after project termination: 2,000,000 €/a (equates 25-40 new jobs)

Participant:
12 SNT
Potential impact:
With the development of a force-controlled spindle for the polishing robot, SN-Spindeltechnik can enlarge their portfolio and thus their turnover with the sale of the spindle, resp. maintenance and service.
Economical impact and Exploitation strategy:
5 years after project termination: 300,000 €/a (equates 3-6 new jobs)

Participant:
13 EVO

Potential impact:
Evolute GmbH aims on the development and programming of a local abrasion model. The price for this core component cannot be determined yet as similar products aren't available on the market. A preliminary estimation of the component as a part of the MOD software ranges in the area of 10,000 €.
Economical impact and Exploitation strategy:
1 year after project termination: 50,000 €/a (equates to 1 new job)

Participant:
14 SMK
Potential impact:
Star*Plus Müanyagipari Kft. aims on the more efficient fabrication and especially finishing of injection dies. Due to the expected reduction of manufacturing time by applying automated finishing operations, a higher throughput and thus an increase in competitiveness is expected.
Economical impact and Exploitation strategy:
1 year after project termination:100,000 €/a (equates to 1-2 new jobs)
5 years after project termination: 500,000 €/a (equates to 6-10 new jobs)
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