Injection Moulding Production Technology for Multi-functional Nano-structured Plastic Components enabled by NanoImprint Lithography

Reporting

Project Information

PLAST4FUTURE

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Executive Summary:
Plast4Future (Injection Moulding Production Technology for Multi-functional Nano-structured Components enabled by NanoImprint Lithography) is a FP7 NMP FoF Integrated project aiming to upgrade existing injection moulding production technology for manufacture of plastic components by enhancing the lateral resolution on free-form surfaces down to micro- and nanometer length scales. The Plast4Future consortium counts 14 partners with a total project volume of 9.7 M€ of which the EC grant contribution covers 6 M€. The three year project started in January 2013 and finishes in December 2015.
The main objective of PLAST4FUTURE is to create a manufacturing chain, which responds to the cross-sectoral needs for multifunctional surfaces on plastic products. The PLAST4FUTURE manufacturing chain comprises four main components: (1) A library of multifunctional micro and nanometer topography defined plastic surfaces. Functionality and manufacturability modelled. Lab-scale prototypes demonstrated. (2) Process flow for cost-efficient production of nano-structured injection moulding tool inserts, achieved through the development of a complete nanoimprint lithography solution for structuring the free-form surface of injection moulding tools and tool inserts (3) New steel tool materials and tool fabrication processes enabling tool surfaces suitable for nanostructuring. (4) Life Cycle Assessment for Cradle-to-Cradle production philosophy.

Plast4Future has developed and analysed the value chain and Road Map for production of injection moulded, free-form plastic components with nano-texture enabled surface functionalities. The project had focus on target markets: automotive and toy industry, and the nano-texture enabled surface functionalities: easy-to-paint, anti-fog, and color. The Plast4Future Road Map is consistent with the NANOfutures Integrated Research and Innovation Road-map (2013-2025), and can be included in the VC3 Nano-enabled value chain for structured surfaces.

The Plast4Future value chain includes:
• A library of multifunctional micro and nanometer topography defined plastic surfaces: Easy-to-paint, anti-fog, anti-reflective, and color.
• Process flow for cost-efficient production of nano-structured, free-form injection moulding tool inserts: Master origination, polishing of steel tool, nanoimprint lithography on steel tools, pattern transfer by etching.
• New steel tool materials and tool fabrication processes enabling tool surfaces suitable for nanostructuring.
• Injection moulding processes.
• Life Cycle Assessment for Cradle-to-Cradle production philosophy

Project Context and Objectives:

WP2:
WP2 concerns the scientific development prior to industrial implementation. In particular, a new color technology is developed based on metal-coated nano-structured polymer surfaces. Angle-insensitive scratch-resistant structural colors are demonstrated. The method holds potential for large-scale implementation of structural colors in plastic products for daily use.

WP3:
The manufacturing chain for nanostructuring injection moulding inserts was developed in WP3. The objective was to develop nanoimprint lithography and pattern transfer solutions for making durable nanostructures on free-form surfaces on injection moulding steel tools. Steel inserts with functional nanopatterns for color effects, increased hydrophobicity and easy-to-paint were fabricated and delivered to the end-users for injection moulding.

WP4:
The nano-structuring technology calls for specific characteristics from the tool steel. Due to the specific
The nano-structuring technology calls for specific characteristics from the tool steel. Due to the specific requirements, it was necessary, not only to develop a new steel type, but also to focus on the whole process, from raw material to the finished steel insert ready for nano-structuring. Therefore, milling, polishing and etching processes were optimized to be able to accomplish the nano-structuring.

WP5:
A Life Cycle Assessment was carried out to evaluate the environmental impacts of Plast4Future products in their whole life cycle (from cradle to cradle). The goals of the work package were to establish knowledge through a Life Cycle Assessment analysis regarding the environmental benefits of the Plast4Future technology and develop new solutions based on this technology to reduce the environmental impacts. A comparative Life Cycle Assessment analysis of two different production systems based on injection moulding to produce colourful plastic parts was made:

a) Reference system based on the traditional injection molding scheme applied that uses pigment in the raw material to create a base color and subsequently painting steps for decoration.

b) Plast4Future system based on structural coloring, where different nano-scale surface topographies define colors without the use of pigments.

The analysis shows that the recycling phase makes the Plast4Future system more environmentally friendly compared to the reference system. Further analysis, after the Plast4Future system is fully developed on mass-production scale, must be performed to get more accurate results.

Significant opportunities lay open to implement surface structure as a way to embed information into the surface of plastic objects. In order to allow Plast4Future technology to become competitive as a solution provider within the value chain, the cost requirement target will be a determining factor. The time available for commercialization will be a determining factor to grab the potential application of Plast4future technology, which results from upcoming recycling challenges.

WP6:
WP6 will provide the assessment of the up-scaling of the P4F technologies for the production of multifunctional surfaces for the selected applications as automotive (exterior surfaces and lighting) and toy sectors. The main targets are the manufacturing of large area final demonstrators to validate the coloured surfaces as well as the easy-to-clean and anti-fog optics on 2D and 3D shapes. The specific WP6 achievements are the manufacturing of the specific nanostructured 2D-3D injection moulding tools to be used for application demonstrators development, the simulation and optimization of injection moulding parameters to guarantee the fidelity replication of nanostructures, the production by injection moulding of test samples, the optimization of hard coating technology (spray coating) polymer films for durable nanostructures, the feasibility studies of new nano-replication manufacturing equipment in industrial environment and finally the morphological, optical and wettability characterization and cost analysis for the new products.

WP7:
The Plast4Future consortium developed a Roadmap with the exploitable results related to the technology and products developed at the end of the project. The roadmap highlights the European position in the toy and automotive industry and offers recommendations to the industrial implementation and commercialization of the Plast4Future technology. Plast4Future Roadmap (2014-2021) identifies actions to overcome the technological barriers. The
Plast4Future Roadmap (2014-2024) identifies actions to overcome the technological barriers. The consortium has analysed the maturity level of the technology developed in the project and its future application in the industrial mass production. The roadmap is industry oriented and the contribution of the plastic industry has been taken into account in the workshops organized. Centro Ricerche Fiat and LEGO hosted two training workshops for different target groups: automotive and toy industry.

- 11 November 2015, CRF – Centro Ricerche Fiat, Italy
- 25 November 2015, Lego Headquarters, Denmark

Technical aspects such as nanotechnology, structure in general, milling, surface measuring, structuring of the steel, etching, moulding, and usage of the technology in applications were presented in the workshops for discussion amongst industrial attendees (industrial stakeholders).

The outcome of the Roadmap shows that the project results are quite promising and that the partners have the potential capacity to overcome the limitations. The Plast4Future technology faces the following challenges:

- Plast4Future technology was developed to a point where demonstration of its use in specific applications is needed to convince automotive and toy industry in their applicability towards high throughput, large areas, etc.
- Plast4Future technology needs the integration into the standard manufacturing chain.

Finally, all partners contributed to the communication and dissemination efforts and ensured the successful future industrial adoption of the project results. Several communication materials were drafted (banners, posters, website, video, etc.). These materials were used for the communication with the plastic industry and academia. Conferences, workshops and exhibitions where the Plast4future project was presented can be found in the PUDF, where a list of the exploitable results also is shown. The last dissemination activity was a video about the project technology and applications, which is uploaded on YouTube and the website of the European Commission/ Research & Innovation/ Key Enabling Technologies.

Project Results:
WP2:
WP2 concerns the definition of functional surface structures, industrial requirements, and protocols for validation converted into scientific and technical acts as a guide for the development of tools/equipment and processes. In addition to this core task, a substantial compilation of academic works were published in relation to the project, which describes the scientific and technological results suitable for publication.

Firstly, imprinted and injection-molded nano-structured optical surfaces is investigated by Christiansen et al. (2013), Proceedings of SPIE, 8818(881803), 1–12, doi:10.1117/12.2025133. Inspired by nature, nano-textured surfaces have attracted much attention as a method to realize optical surface functionality. The moth-eye antireflective structure and the structural colors of Morpho butterflies are well-known examples used for inspiration for such biomimetic research. In this paper, nanostructured polymer surfaces suitable for up-scalable polymer replication methods, such as imprinting/embossing and injection-molding, are discussed. The limiting case of injection-moulding compatible designs is investigated. Anti-reflective polymer surfaces are realized by replication of Black Silicon (BSi) random nanostructure surfaces. The optical transmission at normal incidence is measured for wavelengths from 400 nm to 900 nm. For
Optical transmission at normal incidence is measured for wavelengths from 400 nm to 900 nm. For samples with optimized nanostructures, the reflectance is reduced by 50% compared to samples with planar surfaces. The specular and diffusive reflection of light from polymer surfaces and their implication for creating structural colors is discussed. In the case of injection-moulding compatible designs, the maximum reflection of nano-scale textured surfaces cannot exceed the Fresnel reflection of a corresponding flat polymer surface, which is approx. 4% for normal incidence. Diffraction gratings provide strong color reflection defined by the diffraction orders. However, the appearance varies strongly with viewing angles. Three different methods to address the strong angular-dependence of diffraction grating based structural color are discussed.

Secondly, single-spot e-beam lithography are discussed for defining large arrays of nano-holes by Højlund-Nielsen et al. (2014), Microelectronic Engineering, 121, 104–107, doi:10.1016/j.mee.2014.03.025. Efficient nanoscale patterning of large areas is required for sub-wavelength optics. A single-spot exposure strategy is used, where electron beam lithography (EBL) with a focused Gaussian beam is used to define shapes directly. The serial technique is optimized on the JEOL JBX-9500FS 100 keV prototype EBL system for speed and pattern fidelity to a minimum writing time of around 30 min/cm² for 200 nm periods in 2D lattices, which allows large scale pattern definition. The machine time and feasibility of the method are assessed in terms of the trade-off between high current and large writing field.

Thirdly, angle-independent structural colors of silicon are investigated as model system for plastics by Højlund-Nielsen et al. (2014), Journal of Nanophotonics, 8(1), 083988, doi:10.1117/1.JNP.8.083988. Structural colors are optical phenomena of physical origin, where microscale and nanoscale structures determine the reflected spectrum of light. Artificial structural colors have been realized within recent years. However, multilayer structures require substantial fabrication. Instead, one-layer surface textures of silicon are considered. Four patterns of square structures is investigated in a square lattice with periods of 500, 400, 300, and 200 nm. The reflectivity and daylight-colors are measured and compared with simulations based on rigorously coupled-wave analysis with excellent agreement. Based on the 200-nm periodic pattern, it is found that angle-independent specular colors up to 60 deg of incidence may be provided. The underlying mechanisms include (1) the suppression of diffraction and (2) a strong coupling of light to localized surface states. The strong coupling yields absorption anomalies in the visual spectrum, causing robust colors to be defined for a large angular interval. The result is a manifestation of a uniformly defined color, similar to pigment-based colors. These mechanisms hold potential for color engineering and can be used to explain and predict the structural-color appearance of silicon-based textures for a wide range of structural parameters.

Furthermore, injection moulding antireflective nanostructures is investigated by Christiansen et al (2014), Microelectronic Engineering, 121, 47–50, doi:10.1016/j.mee.2014.03.027. A method for injection moulding antireflective nanostructures on large areas is presented that allow for high volume production. Nanostructured black silicon masters are fabricated by mask-less reactive ion etching, and electroplated with nickel. The nickel shim is antistiction coated and used in an injection moulding process to fabricate the antireflective surfaces. The cycle-time is 35 s. The injection moulded structures has a height of 125 nm, and the visible spectrum reflectance of injection moulded black polypropylene surfaces was reduced from 4.5% to 2.5%. The gradient of the refractive index of the nanostructured surfaces is estimated from atomic force micrographs and the theoretical reflectance is calculated using the transfer matrix method.
atomic force micrographs and the theoretical reflectance is calculated using the transfer matrix method and effective medium theory. The measured reflectance shows good agreement with the theory of graded index antireflective nanostructures.

As a core part of the Plast4Future project, plasmonic metasurfaces for coloration of plastic consumer products are investigated by Clausen et al. (2014), Nano Letters, 14(8), 4499–4504, doi:10.1021/nl5014986. Reflective plasmonic colors are presented based on the concept of localized surface plasmon resonances (LSPR) for plastic consumer products. In particular, the widely existing technological gap between clean-room fabricated plasmonic metasurfaces and the practical call for large-area structurally colored plastic surfaces robust to daily life handling are bridged. The hybridization between LSPR modes in aluminum nanodisks and nanoholes is used to design and fabricate bright angle-insensitive colors that may be tuned across the entire visible spectrum.

In addition, black metal thin films are investigated via deposition on dielectric antireflective moth-eye nanostructures by Christiansen et al (2015), Scientific Reports, 5, April, 10563, doi:10.1038/srep10563. Although metals are commonly shiny and highly reflective, it is shown that thin metal films appear black when deposited on a dielectric with antireflective moth-eye nanostructures. The nanostructures are tapered and close-packed with heights in the range 300-600 nm, and a lateral spatial frequency in the range inverse micron range. A reflectance in the visible spectrum as low as 6% and an absorbance of 90% is observed for an Al film of 100 nm thickness. Corresponding experiments on a planar film yield 80% reflectance and 20% absorbance. The observed absorbance enhancement is attributed to a gradient effect causing the metal film to be antireflective, analogous to the mechanism in dielectrics and semiconductors. The investigated nanostructures have too large spatial frequency to facilitate efficient coupling to the otherwise non-radiating surface plasmons. Applications include decoration and displays.

A high-impact result of the project is plasmonic colour laser printing, described by Zhu et al. (2015), Nature Nanotechnology, December, 1–6. doi:10.1038/nnano.2015.285. Colour generation by plasmonic nanostructures and metasurfaces has several advantages over dye technology: reduced pixel area, sub-wavelength resolution and the production of bright and non-fading colours. However, plasmonic colour patterns need to be pre-designed and printed either by e-beam lithography (EBL) or focused ion beam (FIB), both expensive and not scalable processes that are not suitable for post-processing customization. Here, a method of colour printing on nanoimprinted plasmonic metasurfaces using laser post-writing is developed. Laser pulses induce transient local heat generation that leads to melting and reshaping of the imprinted nanostructures. Depending on the laser pulse energy density, different surface morphologies that support different plasmonic resonances leading to different colour appearances can be created. Using this technique, all primary colours can be printed with a speed of 1 ns per pixel, resolution up to 127,000 dots per inch (DPI) and power consumption down to 0.3 nJ per pixel.

Polarization-dependent aluminum metasurface is demonstrated operating at 450 nm by Højlund-Nielsen et al (2015), Optics Express, 23(22), 28829. doi:10.1364/OE.23.028829. A polarization-dependent plasmonic aluminum-based high-density metasurface operating at blue wavelengths is developed. The fabricated sub-wavelength structures, tailored in size and geometry, possess strong, localized, plasmonic resonances able to control linear polarization. Best performance is achieved by rotating an elongated rectangular structure of length 180 nm and width 110 nm inside a square lattice of period 250 nm. In the case of 45 degrees rotation of the structure with respect to the lattice, the normal incidence reflectance
In the case of 45 degrees rotation of the structure with respect to the lattice, the normal-incidence reflectance drops around the resonance wavelength of 457 nm from about 60 percent to below 2 percent. The developed platform is mass-producible and constitutes an important step towards application of polarization-dependent metasurfaces.

In terms of smart plastic functionalization by nanoimprint and injection molding, this is described by Zalkovskij et al. (2015), Proceedings of SPIE 94230T, doi:10.1117/12.2085766. A route for making smart functionalized plastic parts by injection molding with sub-micrometer surface structures is developed. The method is based on combining planar processes well known and established within silicon micro and sub-micro fabrication with proven high resolution and high fidelity with truly freeform injection molding inserts. The link between the planar processes and the freeform shaped injection molding inserts is enabled by the use of nanoimprint with flexible molds for the pattern definition combined with unidirectional sputter etching for transferring the pattern. With this approach, transfer of down to 140 nm wide holes on large areas is demonstrated with good structure fidelity on an injection molding steel insert. The durability of the sub-micrometer structures on the inserts is investigated by running two production series of 102,000 and 73,000 injection molded parts, respectively, on two different inserts and inspecting the inserts before and after the production series and the molded parts during the production series.

Finally, wetting properties are also investigated. The influence of structure heights and opening angles of micro- and nanocones on the macroscopic surface wetting properties is described by Schneider et al. (2016), Scientific Reports, 6, February, 21400, doi:10.1038/srep21400. The influence of surface structure, namely the height and opening angles of nano- and microcones on the surface wettability is discussed. Experimental evidence shows that the opening angle of the cones is the critical parameter on sample superhydrophobicity, namely static contact angles and roll-off angles. The textured surfaces are fabricated on silicon wafers by using a simple one-step method of reactive ion etching at different processing time and gas flow rates. By using hydrophobic coating or hydrophilic surface treatment, the surface wettability is switched from superhydrophilic to superhydrophobic without altering surface structures. In addition, examples of polymer replicas (polypropylene and poly(methyl methacrylate) are showed with different wettability, fabricated by injection moulding using templates of the silicon cone-structures.

In conclusion, Plast4Future has enabled results with global academic and industrial impact, in particular the plasmonic colours and the enablement of laser printing and the enhancement of wetting properties.

WP3:
In WP3, the manufacturing chain for nano-structuring injection moulding inserts was developed. The objective of the work package was to develop nanoimprint lithography and pattern transfer solutions for making durable nanostructures on free-form surfaces on injection moulding steel tools.

- Development and supply of resist that are suitable for spray-coating onto tool steel and durable in the pattern transfer process
- Development of a spray-coating process for resist deposition on free-form injection moulding tool surfaces
- Development and installation of lithography equipment for patterning of injection moulding tools by nanoimprint lithography
- Development and supply of flexible and stretchable polymeric stamps with micro and nano patterns for nanoimprint lithography
**Nanoimprint Lithography**

- Development and supply of Ni plating processes for intermediate coating layers and pattern transfer
- Development and supply of controlled steel tool etching of micro and nano patterns
- Development and supply of steel tool coating process suitable for nanostructuration
- Development of step and repeat hot embossing for large nanostructured surfaces
- Development of model for stamp deformation

Figure 1 summarizes the manufacturing chain developed in WP3.

The process starts with the fabrication of a nanostructured silicon master, which is made by semiconductor processing techniques (1). A flexible polymeric stamp is fabricated by replication from the silicon master (2). The flexible stamp allows for imprinting on free form surfaces. A thin polymeric resist layer is applied on the surface of the steel tool (3), and the flexible nanostructured stamp is imprinted into the resist. The silicon master, the flexible stamp and the imprinting is done by NIL Technology (NILT). The polymeric imprint resist is developed by MicroResist Technology (MRT).

The steel tool is a polished injection moulding insert, which can be coated with an industrial protective hard coating or an intermediate Ni layer. The steel is developed by Uddeholm (UAB), the inserts and polishing process by TOOL partners (TOOL), the hard-coating by Cemecon Scandinavia (CSA) and the intermediate layer by Karlsruhe Institute of Technology (KIT).

The patent protected nanoimprint process defines a pattern in the resist (4), which is subsequently used as a mask layer in the pattern transfer process (5).

The pattern transfer is done either by etching into the hard coating or by electroplating (“up-plating”) of metallic structures on top of the intermediate layer of the tool. Etching is done at CSA and electroplating at KIT. In a final step, the resist layer is removed, and after quality inspection, the tool is ready for moulding (6-7). By this unique technology, free-form moulding tools can be processed to have surface structures that allow for production of smart functionalised plastic products and more efficient production.

In WP3, focus was on functional nanopatterns for colour effects from diffraction gratings and plasmonic structures, increased hydrophobicity and easy-to-paint. The etching pattern transfer process was used for the color effects and the up-plating transfer process for the easy-to-paint and hydrophobic effects. The main insert format for the development work was 20x20 mm² steel inserts, see Figure 2.

During the project, the nanoimprint method for pattern definition on free form inserts was established. The imprint process is compatible with both up-plating and etching of nanostructures and the reproducibility is high. Spin-coating is the standard process for applying resist on wafer scale formats but to allow for resist deposition on free form inserts, a spray-coating process was developed. Spray-coating is more complicated than spin-coating since there are a lot more parameters to optimize.

As a result of the R&D work done by MRT, a significant progress in material development for spray-coating and imprinting on free form substrates can be stated. Starting from well-established spin-coatable resist materials for thermal and UV-based nanoimprint lithography, new formulations and dilutions of known materials were defined for spray-coating and eventually applied in the fabrication process for the technical demonstrators.
For imprinting on free form steel tools, NILT developed a nanoimprint lithography tool named “Blow-NIL” (prototype). The Blow-NIL tool can be used for injection moulding tools and inserts with a diameter up to 200 mm and with a thickness/height of 30 mm. The tool performs both thermal and UV nanoimprint lithography. The largest injection moulding tool inserts that have been imprinted are triangular shape inserts with a length of 150 mm.

CSA demonstrated nanostructures etched both in hard-coatings, such as CrN, on the steel surface and directly into the steel surface of the tool insert. Nanostructures etched directly into the steel surface were demonstrated using a new type of steel developed for the project by UAB. Etching of nanostructures for plasmonic colours with a diameter down to Ø100 nm was demonstrated, see Figure 3. Optimized and controlled etching of diffraction gratings with a half-pitch grating of 700-1400 nm was well established.

Full implementation of the whole galvanic wet-chemical process chain for steel substrates was developed at KIT. Diverse wet-chemical pretreatment solutions and galvanic electrolytes were used for deposition of Ni(P) intermediate layers over the complete surface of the steel inserts.

Up-plating of Ni nanostructures (up to 600 nm height) for increase hydrophobicity was successfully demonstrated, see Figure 3.

Thus, the full manufacturing chain for functional free form inserts was demonstrated. Several insert with nanostructures for colour effects, superhydrophobicity and easy-to-paint effect were delivered to the end-users.

An alternative method for imprinting on free-formed surfaces was developed by ICN. The method is based on reverse imprinting. The novel micro/nano manufacturing techniques was developed and utilized to generate hierarchical two level patterned surfaces. In particular super-hydrophobic (166 oC) and easy to clean surfaces were realized in commercial resist material, see Figure 4.

To enable nanopatterns on large areas, Fraunhofer IPT optimized a step & repeat process for nanopatterned shims and foils. This process is crucial for up-scaling to inserts larger than Ø150 mm. Successful embossing processes were developed and carried out with good replication quality results on a larger scale.

Another objective of WP3 was to develop a model, which can predict the deformation of the flexible stamp used for the nanoimprinting process. This is essential, as the nanostructures will be stretched during imprint on a curved surface, and this stretch has to be taken into account in the design of the planar silicon master. Experiments showed that the model is able to predict the final wavelengths of the nanostructure giving the colour effect with an error of only around 0.5 %. This work was done by DTU-Mechanical Engineering.

WP4:
Production of injection moulds often requires tool steel with unique and demanding characteristics. The requirements are even higher for tool steel used for nano structuring where the properties of the steel...
Requirements are even higher for tool steel used for nano-structuring where the properties of the steel needs to be very specific.

Six different tool steels, which already were existing commercial products at Uddeholm, and commonly used for plastic moulding, were studied regarding microstructure and suitability for nano-structuring. Machinability tests of the existing steels were performed by TOOL. However, none of the steels directly met the demands for steel suitable for nano-structuring.

Four different approaches were tested to improve the steel microstructure and properties:
1. Change the heat treatment parameters of the existing steels
2. Use a surface treatment of the steel such as laser welding or laser remelting
3. Develop a new steel with an optimized chemical composition and heat treatment recommendations
4. Investigate a super bainite steel developed in Cambridge university

Initial investigations showed that only development of a new steel would be sufficient for nano-structuring and to fulfill the demanded property profile.

After several simulations, small test melts were produced. One of the melts fulfilled the demand profile and from this chemical composition, material was produced in small scale. The new Plast4Future steel is a molybdenum-, chromium-, vanadium- and nickel-alloyed tool steel of hot work type.

Milling tests performed at TOOL also showed good machinability of the new Plast4Future steel. After the requirements were reached, seven 50 kg melts was produced to get enough material for the demonstrators. The ingots were forged to bars with a suitable dimension and sent to TOOL for production of tools for the demonstrators. A patent application was submitted on the material.

To further fulfill the requirements of high cleanliness, i.e. low inclusion content, and to lower the segregations, a full 60 ton heat was melted, ESR-ingots were cast and the material went through UAB’s remelting process. This material was forged and rough machined to dimensions 254x102 mm and 254x90 mm, which will cover the needs for further trials and for commercialization of the nano-structuring technique.

The milling process has been through a considerable development. A lot of work was put into refining the strategies to achieve optimal results. This is primarily done to minimize the time and effort for traditional polishing by hand. If a 3D freeform surface is polished too much, there is a risk of deforming the surface, especially on the edges and corners.

The developments in the milling processes and machining of inserts for moulds in Plast4Future resulted in milled samples that can be compared to polished samples, see Table 1.

In addition to the milling, a system to control and validate the milled surfaces was implemented. The validation is done using an Optosurf OS500 device, and takes place in the CNC milling machine while the milled part is still in the machine.

The OptoSurf device measures surface roughness based on scattered light method, and provides an average Aq value for the measured area.
This is completely new and unique solution for the tool industry. And this setup has opened up a new segment in the line of producing high-end solutions for the plastic injection moulding industry, not least due to the fact that this equipment can withstand an industrial workshop environment, and can easily be implemented in a production line.

Robot aided polishing. The fine machining process, or in other words “polishing”, is a sequence of process steps starting from grinding over lapping to polishing and finally to buffing. Each step is performed in various levels of fineness. The abrasive liquid or slurry needs to be renewed in constant interval. When switching to the next finer level, cleaning is mandatory to avoid pollution of the upcoming process. If the geometry of the polished area changes its curvature, then tool shapes need to be adopted accordingly.

To achieve an automatic fine machining process, a database was developed organising the polishing steps from the first grinding step to the final buffing run. The structure as it is presented in the graphic user interface is illustrated in Figure 7. The overall process is built from a sequence of sub steps, which are customised to the requirements by the choice of process parameters i.e. process force, tool speed, abrasives and repetitions (orange box). In addition to that, tool types are to be chosen (green box). Tool types are enrolled in a database where their properties (blue box) such as TCP-dimensions and affiliation to suitable kinematic modules (yellow box) are stored, and so forth. Once fully defined, a process is stored in the control and is available for future cases, when similar tasks need to be completed. This means that the fine machining process is only dependent on manual work for the cleaning process.

WP5:
The comparative Life Cycle Assessment (LCA) of two different production systems based on injection moulding had as main objective to determine which one of the analysed systems was more environmentally friendly. The LCA study is in accordance with the ISO 14040 and 14044 standards and includes: A goal and scope definition, an inventory analysis (LCI) and an impact assessment (LCIA). The results have been analysed, interpreted and evaluated with completeness, uncertainty and sensitivity checks.

The data was collected from reliable sources, or estimated. In the Life Cycle Inventory phase (LCI), the data was grouped into the different processes within the system boundaries of the study, avoiding identical processes in order to provide a clear focus on the difference between the systems.

For the Life Cycle Impact Assessment phase, the two systems were modelled using GaBi software and IMPACT 2002+ methodology. Based on the findings in the LCIA, and within the limitations of this study, the most environmentally friendly system is found to be the Plast4Future system, which had the lowest scores in the overall assessment. However, this system is not fully developed, and the level of uncertainty is higher than the reference system.

The main process in the LCIA was found to be disposal; this was the most different stage between both systems. On the other hand, for the Plast4Future system, the LCIA revealed that the total impact scores for this system across most of the categories are lower.
Based on the LCIA, a sensitivity analysis was conducted to further investigate the influence of recycling with respect to the environmental impact of the Plast4Future technology. The results suggest that the most important advantage of the Plast4Future system, with respect to the reference system, is the possibility of large scale recycling of plastic waste.

Finally, this LCA study suffers from technical limitations regarding data collection and a high degree of assumptions, which causes a high uncertainty of the results. Therefore, it is recommended that further analysis should be made after the Plast4Future system is fully implemented on a mass-production scale. A future LCA study will benefit from having more accurate information.

In order to make the Plast4Future technology competitive and decrease the environmental impacts even more, it can be developed and implemented a solution based on the project outcome. Plast4future can also contribute to increase the recyclability of products by providing a solution for plastics traceability.

A QR-code can be design with Plast4future technology to codify injection moulded parts. The code embedded in the surface potentially allows for a solution that meets other criteria:
- Codify precise identification information of composition, origin, use, additive systems, etc.
- Collect high amounts of data.
- Use existing sorting infrastructure (optical detection systems) to read the Plast4Future QR-code and distinguish plastic types.
- Destruction of the QR code after the recycling process.

Another advantage of this surface topography codification is that the QR-code can be customized to gather standardized information and linked to a database. Such a database system could be effectively implemented since there is push from the legislators to provide an increasing amount of data to value chain stakeholders and customers and since there is a trend to intensify collaboration within the industrial value chain to further improve recycling.

WP6:
WP6 provided the assessment of the up-scaling of the Plast4Future technologies for the production of multifunctional surfaces for the selected applications as automotive (exterior surfaces and lighting) and toy sectors. The technical milestones are the fabrication of the large format of the inserts starting from small flat area test samples. Table 2 presents an overview of the three final demonstrators as targets of Plast4Future.

The three demonstrators are:
- Cover of external mirror cup of FIAT BRAVO 2010 – MAIER and CRF
- Outer lens of automotive rear lamp - CRP
- Lego brick - LEGO

There are several processes in the automotive industry in manufacturing a vehicle such as: Stamping process, body assembly process, painting process, and trims and final quality assessment. Within the automotive sector, the Plast4Future project studied the management of surface properties in terms of wettability to improve painting of plastic components as well as to manage the fog issues within the
wettability to improve painting of plastic components as well as to manage the fog issues within the headlamp and taillight components. In order to demonstrate those benefits of the developed materials with respect to materials currently present on the market, two different demonstrators have been defined as mirror cup based on PP (Polypropylene) material and taillight lens based on PMMA (Polymethylmetacrylate) material.

Test and optimization of the injection moulding process including the fabrication of nanostructured insert tools for injection moulding have been carried out within the WP6 in the last period of the project. The preliminary steps were the optimization of the process and the further assessment for flat samples in terms of area (20x20 mm) and process (Ni shim based samples). Both test cases have been performed to investigate the final wettability achieved onto the plastic replicated surface and the durability of the insert after injection cycles.

Cover of external mirror cup (MAIER and CRF)
PLAST4FUTURE nanostructured surfaces have been studied for easy-to-paint applications in external plastic part of existing vehicle. The increase of intrinsic exterior wettability allows a best spreading of the paint onto the surface and the improvement of the adhesion of the resin to the surface. For such reason we selected the PP materials that is a well-known challenging plastic for the paint process. Even if the injection moulding trials of TM5 (headlamps reported in D6.3) show some benefits in the use of the variotherm injection process, for the TM6 we used the standard industrial injection process parameters to be scaled up at industrial scale. The mirror cup is following reported.

The nanostructured large area insert is not the overall mould but it is a part within the 3D curvature area. After a cleaning phase, the enclosure in to the mirror cup mould have been carried out.

Even if the quality of the nanostructured surface of the insert is not perfect (leopard effects are evident by visual inspection) we performed wettability analysis and painting. The coating has been expected only for the mirror cup (external plastic components of FIAT car) but we performed onto PMMA lens for taillight to investigate potential benefits of the P4F structuring of the plastic surfaces. We used standard process parameters applying the paint with a manual painting procedure directly onto the cleaned surface of the injected parts.

The validation procedure has been carried out according with the harmonized standard between Chrysler-FIAT named 9.55842. This manages the chemical/physical/aging resistance of plastic resins onto plastic parts for exterior and interior as well. However, we paid attention to cross cut adhesion because the real target of Plast4Future project. The other tests are considered not fundamental because we used the standard paint resins. The following pictures report the final plastic exterior mirror cups with the nanostructured insert after painting and after cross cut test.

Even if the leopard effects still exist limiting the homogeneity before and after the painting of the surface, we can conclude that the developed formulation has OK adhesion without primer. This is a great improvement in terms of cost of manufacturing time and materials (primer) usage. Summarizing the adhesion is OK / Not Good depending on the formulation of the paint but increase of wettability contributes to increase the surface quality before the painting.
Outer lens of automotive rear lamp (CRP)

PLAST4FUTURE nanostructured surfaces have been studied for anti-fog application in a rear lamp application. The nanostructured surface has not given an anti-fog intrinsic functionality to the lens. However, the increasing of the coating distribution uniformity and the painting defects prevention confer an EASY TO PAINT behaviour. To achieve precise replication of the cavity and traverse long flow paths during injection moulding, the so-called vario-therm process is commonly employed. This involves heating the mould’s surface prior to injection of the plastic, followed by cooling the mould as quickly as possible after the cavity has been filled.

The material used for the production of the outer lens is PMMA Plexiglas 7N (Evonik), transparent colorless. PMMA 7N resulted in a better filling behavior and surface replica to respect the materials (PC Makrolon Al2447, PMMA Evonik 8N, PMMI and PMMA/PLA blend) tested, by standard injection molding process, during the preliminary trial phase. Picture of the moulded outer lens are shown in Figure 11.

Iridescent effects due to nanostructured surface are clearly visible on the moulded components. Moreover, on part of the surface it is possible to detect a spotted area, the same imperfections are visible on the metal insert. This means that there is a good replica of the nanostructured surface on plastic parts. The rear lamp prototype is reported in the following picture.

We performed all the antifog tests expected for automotive sector but no improvement of the function has been achieved. This means that there is a good replica of the nanostructured surface on plastic parts, but a fog layer on the surface is clearly visible after condensation. After that to test the improvement in Easy-to-paint effect, a number of outer lenses were painted with the anti-fog coating usually utilized in Automotive lighting plant (GAF209; thickness: 1 – 5 μm). An in-line automatic painting process was used. The analysis, the comparison between nanostructured and polished areas, shows high improvement in the quality of the lens. The coating quality in the nanostructured area is much better than the coating quality in the polished area, thus confirming the improvement in easy-to-paint effect of the nanostructured surface.

WP7:

The Plast4Future Road Map is based on “NANOfutures Integrated Research and Innovation Road-map (2013-2025)”, which was developed in 2013 by 11 European Technology Platforms from different industry sectors, stakeholders from the nanotechnology field and with support from the European Commission. To be consistent with the NANOfutures Roadmap, the assessment of the Plast4Future analysis was developed according to a value chain approach. Plast4Future can be included in the VC3 Nano-enabled value chain for structured surfaces. The Plast4future scope is focused on the target markets (automotive and toy industry) and the nano-enabled properties defined for the project (easy to paint, anti-fog and colour).

Potential Impact:

WP2:

The human eye can distinguish close to 10 million colors. It forms the basis of the faculty of sight, from which human beings arguably glean the most important information about their surroundings. In general, vision is considered one of the key developments in animal evolution and for human beings colors play a critical role, for example as indicators of putrid food. Besides being important for survival, the colors of nature have also been of great fascination and inspiration. This is reflected throughout history as artworks from ancient paintings of sunsets and animals to modern art forms of geometry and contrast. In many
from ancient paintings of sunsets and animals to modern art forms of geometry and contrast. In many ways, one might say, humans perceive in color. The importance of color calls for scientific study and indicates the care taken in controlling the appearance of consumer products, such as toys for children or cars for adults.

The color of an object is the result of a complex interaction of the light incident on the object, the optical characteristics of the object, and human perception. In many products, especially plastic products, the base color is given by bulk properties. Added surface decoration provides additional cost-effective color effects, for example logos, text decoration or line art to enhance aesthetic value. WP2 has developed the utilization of color metasurfaces in a plastic production perspective, where colors and materials play an important role. Colorants, such as pigments or dyes, are used to color plastic-based consumer products, either as base for solid colored bulk polymer or in inks for surface decoration.

Plastics materials are a key enabler of the modern mass consumption society through cost efficient and durable consumables. As an example, the European plastics industry directly employs more than 1.4 million people, according to Plastics Europe. Since 1950, the global production of plastic has seen exponential growth. In 2014, plastic production was 311 million tonnes globally and 59 million tonnes in Europe. The total registered waste generation of post-consumer plastics in Europe was 25.8 million tonnes, where 30.8 % ended as landfill, 39.5 % was burned and only 29.7 % of the generated waste was recycled, according to Plastics Europe. Today most plastic products are burned after use or end in landfills. Less than one third of the generated waste in Europe is recycled.

Plastic originates from crude oil with a mass conversion-rate of about 1:2 and the conversion contributes with about 0.5 % of the global warming. The time frame of the decline of oil production, as more and more resources dry out, may be discussed. The estimates of global population growth rate and increase in global living standard may also be discussed. Inevitably, the oil production will come to a halt due to a lack of resources in the earth's crust. From this point on, the world consumption must rely on synthetic oil products. Therefore, recycling and life-cycle assessment supporting a circular economy will become increasingly important, also for materials today considered of low value. In this context, the use of coloration makes recycling difficult because the powerful pigments tend to be mixed in the recycling stage. After usage, the products must be mechanically sorted by color before recycling, limiting any large-scale efficient recycling effort.

As an alternative to chemistry-based coloring, nano-scale structural coloring has been proposed by scholars to reduce the number of materials needed and to increase pattern resolution. Here colors are created by structural based light-matter interactions in the surface. Thereby, the sorting by color can be avoided in the recycling stage as destruction of the nano-scale texture removes any color perception, leaving a (semi)-transparent bulk polymer ready for re-processing.

WP2 has developed and supported utilization of color metasurfaces in an industrial perspective, where nano-scale textures and contingent post processing replace inks, dyes and pigments in plastic production. The concept of color by structure arguably reduces the number of raw materials and eliminates mechanical color sorting in the recycling stage providing new perspectives for the sustainability of plastic products. The high recyclability leads to reduced environmental impact compared to conventional plastic production. In summary, a promising future is anticipated for plasmonic colors as a decoration element for...
production. In summary, a promising future is anticipated for plasmonic colors as a decoration element for everyday use based on the Plast4Future project.

In terms of dissemination activities and the exploitation of results, the results of Plast4Future has been communicated at several academic conferences and workshops, including TechConnect 2015 in Washington, where the talk initiated response from American industrial players, and a talk at SPP7 in Jerusalem 2015, which was reported in Nature Photonics in August 2015.

WP3: The European plastics industry needs to be more innovative and to advance the injection moulding technology in order to find new cost-effective and safe ways to add value to everyday plastic products. Direct decoration and labelling of plastics without use of additional processing, reduction of food waste due to smart functionalized packaging materials, and easy to paint plastic surfaces are just a few examples of where the Plast4Future technology will have significant impact and will advance European injection moulding industry to be more competitive and ‘green’ in the future. Our patented technology allows for manufacturing of plastic products with functionalized surfaces directly in the injection moulding process thereby eliminating existing post-production surface treatments.

The entry barrier for the technology is low since the functional nanostructures can be integrated directly into the existing value chain of injection moulding tools.

The inspiration comes from nature i.e. butterfly (colour), the lotus flower (self-cleaning), moth’s eye (anti-reflection) and sharkskin (drag reduction) and the technology can be extended to many other functionalities that are known from nature.

The technology has been under development for more than four years, and we are now ready to commercialize the technology. NILT, TOOL and CSA started to commercially promote the technology a year ago and the first press release came in February 2015 (www.nil.com/lbs). The feedback from potential customers has been significant. In the beginning of 2015, the first industrial test sample was delivered.

Some of the main dissemination events were the two Plast4Future Workshops that took place at Fiat in Turin and Lego in Billund in 2015. Talks were given by UAB, TOOL, ICN and NILT. Plast4Future was awarded the Best Ongoing EU NMP project in April 2014 at the Industrial Technologies conference in Athens, and in addition to this Plast4Future was also awarded the Best Exhibitor Award at the same conference.

The technology has also been presented at the Euro Nano Forum in Riga 2015. The WP3 partners NILT, KIT, TOOL and ICN had an exhibition booth, an invited talk was given by NILT, and KIT presented a poster.

ICN and KIT presented the technology at the NIL Industrial Day in Berlin in 2015, which was hosted by MRT.

In October 2015, the global innovation platform Launch Nordic chose NIL Technology as one of the top ten innovators due to the Plast4Future technology. The technology was presented to Launch council members from NASA, IKEA, NIKE, the Danish Ministry of the Environment and several business advisors and investors.

Finally, a number of presentations were held at other scientific conferences and industrial workshops as
Finally, a number of presentations were held at other scientific conferences and industrial workshops as well as some papers were published in scientific journals.

WP4:
The new steel developed for this project is of great interest for Uddeholm AB as it correlates well into our portfolio of tool steels for the plastic mould industry. As the steel is electro slag remelted material it matches in our plan to grow in this segment. As this project deals with future technologies it also fulfils our image to be a steel company within the technology forefront. One of the focus areas for this project is the automotive industry, therefore it has been important for Uddeholm AB to participate, as plastic moulding tools for this industry segment is a major part of our business. It will probably take some years before the technology is fully commercialized, but at that point Uddeholm will be ready to deliver material with the needed properties, and it is our expectation that it will be of great economical value.

Although manufacturing of inserts are “business as usual” the new cutting methods developed in this project give a huge advantage compared to the rest of the industry. Milling of parts and inserts with very low surface roughness combined with the measuring of the roughness in the machine.

The main disseminations activities have been participation with a booth on the Medica fair in November 2014. Participation with a booth at the Euronano forum in Riga. And also the two workshops, where the whole project was presented to invited people from the industry. The workshops took place at LEGO in Billund, DK and at FIAT in Torino, IT.

WP5:
As a result of the work done in WP5, the importance of recycling was highlighted in relation to the competitiveness of the Plast4Future technology. The Plast4future technology does not add any substances to the plastic parts to achieve the desired surface properties, i.e. benefitting the recycling potential. This is believed to give a high socio-economic impact in the European society such as creation of jobs by the construction of new recycling facilities, manufacturing of equipment for recycling, maintenance and repair of recycling facilities and equipment, as well as administrative and management positions.

WP6:
In WP6, pilot implementation in real industrial settings (automotive components and toys) has been carried out. Collaboration among the partners was successful in achieving the targets and exploitation toward potential customers. Likewise, novel business alliances have been carried out. Especially injection moulding, technology transfer, materials development, painting process for lighting- toys- automotive exterior painted parts have been achieved.

The results about the mould durability have been carried out. The mould does not show any modification or damage after 3,000/5,000 cycles. However, a cleaning procedure will be needed because residual plastics onto the nanostructured metal surface reduce the quality of the replicas at the injection moulding phase, increasing the final scraps. This could be an issue in the technology transfer toward customers. However, we demonstrated at least two main benefits in the automotive sector:
- Reduction of number of painted layers for exterior painted parts (primer less)
- Improvement of the quality and consequently reduction of the scarps for antifog coating process conventionally used in headlamps and taillights
The values of these final achievements clearly show the potential economic advantage of the Plast4Future technology for the PP painted parts. For instance, within automotive painting process, the total costs of the plastic parts injected by P/E-T20 and painted in a conventional way (standard paint formulation and a layer of primer as adhesion promoter) are approximately 6% higher than the similar parts made of ABS. On the other hand, parts made of the same P/E-T20 but injected from a nanotextured mould, as the Plast4Future TM6 demonstrator, do not need the use of adhesion promoters, so the estimated costs are significantly lower (reduction of 8%) than the standard version and even lower (2%) than the ABS painted version. This is the real achievement transferred as exploitable result.

WP7:
Apart from the PUDF, in WP7 two activities contributed to the visibility of the project and established the framework for future improvements to be achieved.

Plast4future Roadmap

A list of common gaps and actions towards the development of Plast4Future technologies and products in the value chain was identified. The Plast4Future consortium and other stakeholders contributed addressing the technological gaps for the technology and products developed in the project.

According to the Plast4Future partners, the technology faces the following challenges:

- The Plast4Future technology was developed to a point where demonstration of its use in specific applications is needed to convince the automotive and toy industry in their applicability towards high throughput, large areas, etc.
- Plast4Future technology needs the integration into standard manufacturing chain.

The types of needed actions to overcome these barriers are:

- Collaborative research actions, including pilot lines should be proposed. The action should cover: upscaling of the technology, metrology issues and prototypes fabrication.
- Research for the benefit of the SME projects could warrant integration.

Workshops

Two workshops were organized at the end of the project:

- Workshop at CRF – Centro Ricerche Fiat in Turin, Italy
  The workshop took place in the CEA auditorium and was hosted by Luca Belforte from CRF and moderated by Alicia Johansson from NIL Technology. In total, 32 participants from five countries attended the event (Italy, 22; Spain, 1; Germany, 1; Sweden, 1; Denmark, 7).

- Workshop - LEGO Headquarters in Billund, Denmark
  The workshop took place in a meeting room at the Lego Headquarters, hosted by Per Hoevsgaard from Lego and moderated by Alicia Johansson from NIL Technology. The Plast4Future partners welcomed around 52 participants from seven countries (Italy (5), Spain (2), Greece (3), Germany (3), Sweden (1), Netherlands (1) and Denmark (37)).

List of Websites:

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