NEWSLETTER

N° 3 | October 2018

This is the third newsletter, containing the latest news and results from the LASER4FUN project.

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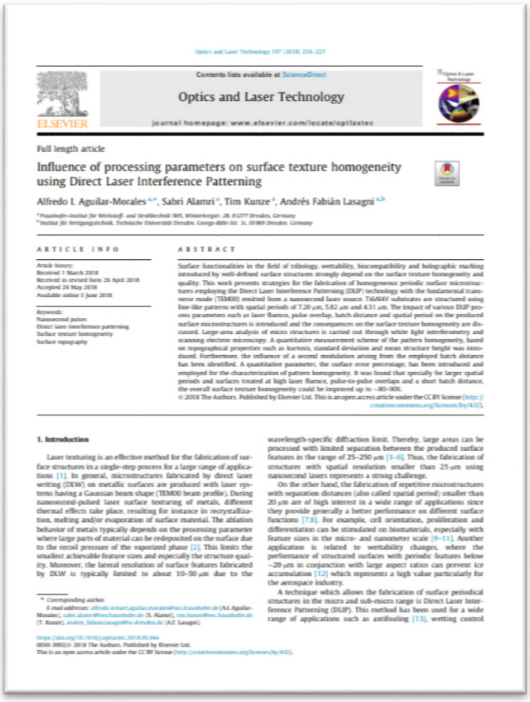
The project

The LASER4FUN project is a research programme, as well as training network, funded by the European Committee. In this innovative project European universities, RTD institutes and industry collaborate in order to develop new methods for surface structuring & patterning methods by exploiting emerging (ultra) short pulsed laser sources. New surface functionalities in the field of tribology, aesthetics and wettability are being developed. Our innovative training programme trains a new generation of creative, entrepreneurial and innovative early stage researchers (ESRs) focused on laser surface engineering. The project started in 2015. We are happy to announce that, since then, the project runs very well and many interesting results and achievements have spawned from it. This newsletter reports some of these interesting results. For an extensive and complete overview of all our results, please point your web browser to http://www.laser4fun.eu

The Early Stage Researchers (ESRs) and their supervisors at the annual progress meeting in Bari, Italy (2018) (October 1-5, 2018).

Publications

Scientific and Industrial publications of the Laser4Fun project are Open Access. That means that our publications are distributed online and can be downloaded and read free of cost. For an overview of all publications, point your web browser to:
https://www.laser4fun.eu/publications/



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Full length article

Influence of processing parameters on surface texture homogeneity using Direct Laser Interference Patterning

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ABSTRACT

Surface functionalities in the field of tribology, wettability, biocompatibility and holographic marking introduced by well-defined surface structures strongly depend on the surface texture homogeneity and quality. This work presents strategies for the fabrication of homogeneous periodic surface microstructures employing the Direct Laser Interference Patterning (DLIP) technology with the fundamental transverse mode (TEM00) emitted from a nanosecond laser source. Ti6Al4V substrates are structured using line-like patterns with spatial periods of 7.20 μm, 5.82 μm and 4.31 μm. The impact of various DLIP process parameters such as laser fluence, pulse overlap, hatch distance and spatial period on the produced surface microstructures is introduced and the consequences on the surface texture homogeneity are discussed. Large-area analysis of micro structures is carried out through white light interferometry and scanning electron microscopy. A quantitative measurement scheme of the pattern homogeneity, based on topographical properties such as kurtosis, standard deviation and mean structure height was introduced. Furthermore, the influence of a second modulation arising from the employed hatch distance has been identified. A quantitative parameter, the surface error percentage, has been introduced and employed for the characterization of pattern homogeneity. It was found that specially for larger spatial periods and surfaces treated at high laser fluence, pulse-to-pulse overlaps and a short hatch distance, the overall surface texture homogeneity could be improved up to ~80–90%.
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1. Introduction

Laser texturing is an effective method for the fabrication of surface structures in a single-step process for a large range of applications [1]. In general, microstructures fabricated by direct laser writing (DLW) on metallic surfaces are produced with laser systems having a Gaussian beam shape (TEM00 beam profile). During nanosecond-pulsed laser surface texturing of metals, different thermal effects take place, resulting for instance in recrystallization, melting and/or evaporation of surface material. The ablation behavior of metals typically depends on the processing parameter where large parts of material can be redeposited on the surface due to the recoil pressure of the vaporized phase [2]. This limits the smallest achievable feature sizes and especially the structure quality. Moreover, the lateral resolution of surface features fabricated by DLW is typically limited to about 10–50 μm due to the wavelength-specific diffraction limit. Thereby, large areas can be processed with limited separation between the produced surface features in the range of 25–250 μm [3–6]. Thus, the fabrication of structures with spatial resolution smaller than 25 μm using nanosecond lasers represents a strong challenge.

On the other hand, the fabrication of repetitive microstructures with separation distances (also called spatial period) smaller than 20 μm are of high interest in a wide range of applications since they provide generally a better performance on different surface functions [7,8]. For example, cell orientation, proliferation and differentiation can be stimulated on biomaterials, especially with feature sizes in the micro- and nanometer scale [9–11]. Another application is related to wettability changes, where the performance of structured surfaces with periodic features below ~20 μm in conjunction with large aspect ratios can prevent ice accumulation [12] which represents a high value particularly for the aerospace industry.

A technique which allows the fabrication of surface periodical structures in the micro and sub-micro range is Direct Laser Interference Patterning (DLIP). This method has been used for a wide range of applications such as antifouling [13], wetting control

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Laser4Fun at LPM2018 conference

The 19th International Symposium on Laser Precision Microfabrication (LPM2018) took place from June 25th to 28th, 2018 in Edinburgh, Scotland, UK. This symposium is the world's number one meeting of the laser user community where the most advanced developments and recent trends in laser application for fine and precise fabrication of diverse materials are discussed between industry, research and academia.
On Tuesday June 26th, a whole session was dedicated to presentations by near all our ESRs, disseminating results from the Laser4Fun project.

Prof. Lasagni presenting the Laser4Fun project at the LPM2018 conference, see http://www.lpm2018.org

Awards

Our achievements valued and recognized internationally, in terms of prizes awarded to our Early Stage Researchers and/or their supervisors. For example, during the EUROMAT2017 conference in Greece, prof. Andrés Fabián Lasagni was awarded the *Materials Science and Technology Prize 2017* by the Federation of European Materials Societies (FEMS). Vittorio Vercillo, ESR, was awarded the *Enzo Ferroni Award 2017* during the European Colloid and Interface Society (ECIS) conference in Madrid. Vittorio was also runner-up of the *Best Speaker Award*, during the Airbus PhD Day 2018.

Vittorio Vercillo (left).

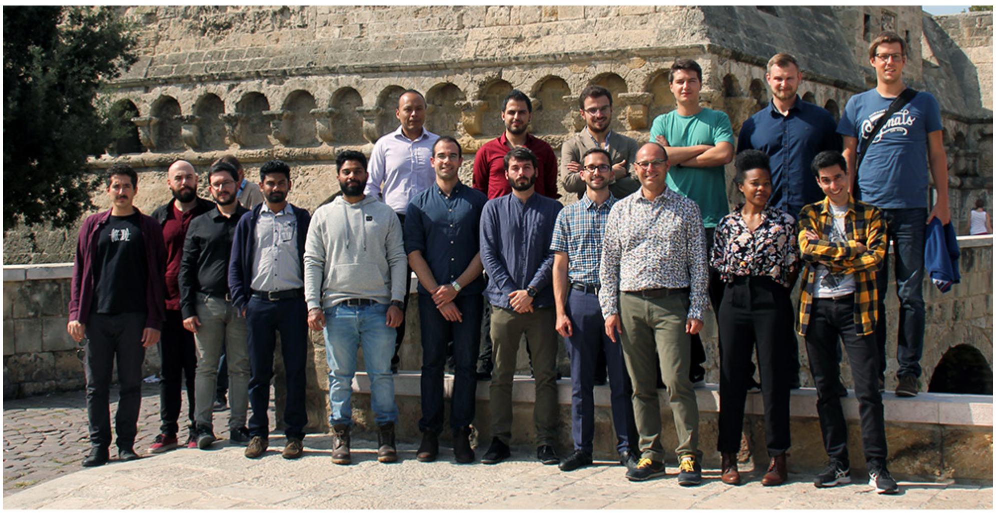
Jean-Michel Romano, an ESR, received an *Honorable Mention Paper Award* at the 2018 World Congress on Micro and Nano Manufacturing in Portoroz, Slovenia. Last, but not least, Melissa Sikosana, and ESR, won 3rd place for "breaking the wall of bacteria related deaths" at the Falling Walls Lab Marie Sklodowska-Curie Actions Event 2018.

Melissa Sikosana (center).

Summer School 2018 in Bari, Italy

The 3rd Laser4Fun international Summer School took place from October 1st to 5th and was hosted by prof. Antonio Ancona of the IFN-CNR, *Istituto di Fotonica e Nanotecnologie* in Bari, Italy. The participants of the summer school were "fully-immersed" into the world of Laser Micro/Nanostructuring and Surface Tribology. Lectures and presentations by academic experts and of the participants alternated, with ample time for discussions. Topics included, but were not limited to:

- Contact mechanics of elastic bodies, by dr. Ing. Carmine Putignano (Politecnico di Bari, Department of Mechanics, Mathematics and Management),
- Universal lab-on-a-chip platform for complex, perfused 3D tissues generated by 3D printing – opportunities and perspectives for laser technology, by dr. Ing. Udo Klotzbach (Fraunhofer-Institut Material and Beam Technology IWS Dresden, Business Unit Manager Microtechnology),
- Management of innovative project at Bosch: LST case study, by ing. Antonio Grimaldi and Ing. Renato Giannoccaro (Robert Bosch Group – Centro Studi Componenti per Veicoli s.p.a)
- Cross Cultural Competences through cooperation and autonomy. Learning organization: higher education management and research administration, by dr. ssa Mariapia Circella (Physics Department, University of Bari),
- Femtosecond laser micro-fabrication of polymeric lab-on-chip for advanced and mini-invasive diagnostics, by Udith K. Vadakkum Vadukkal (University of Bari, Italy),
- Femtosecond laser bursts induced micro and nanostructuring on steel surface, by


The Early Stage Researchers (ESRs) at the 3rd Annual LASER4FUN Summer School in Bari, Italy (October 1-5, 2018).

Giuseppe Giannuzzi (Università di Bari, Italy).
- Contact mechanics of viscoelastic bodies, by prof. Ing. Giuseppe Carbone (PoliBa-Department of Mechanics, Mathematics and Management),
- University of 21st century: threats and opportunities. Organizational chart: practical experiences, by dr.ssa Mariapia Circella (Physics Department, University of Bari).

Improved wetting properties using DLIP

By Alfredo Ismael Aguilar Morales, Andrés F. Lasagni (Fraunhofer IWS, Germany)

The combination of micro and nano structures on surfaces is a key factor for inducing water repellency on natural surfaces [1]. Tailored surface structures can nowadays be produced using laser based fabrication methods such as Direct Laser Interference Patterning (DLIP).

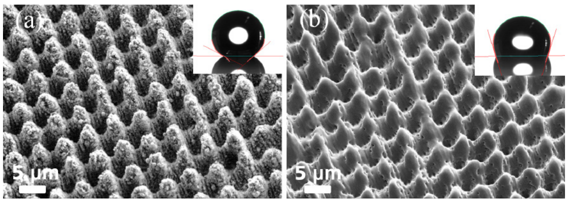


Figure 1: (a) Pillar-like structures on stainless steel fabricated by DLIP with a spatial period of 5.5 µm using a 10 ps laser source. The interaction of ps pulses with the materials surface leads to the development of LIPSS. (b) Pillar-like DLIP structures after irradiation with nanosecond laser pulses in order to erase the LIPSS features. The insets show a visual representation of the water contact angles on the textured surfaces.

DLIP has shown to be an effective method to fabricate periodical patterns on many materials such as metals with feature sizes down to the sub-micrometer range. This is possible by a well-controlled overlapping of two or more coherent laser beams on the materials surface. By using a two-beam DLIP configuration in conjunction with a pico-second laser source, pillar-like DLIP surface structures can be fabricated on stainless steel. The well-defined DLIP textures can show additionally Laser Induced Periodic Surface Structures (LIPSS) with characteristic feature sizes down to 180 nm.A representative pillar-like DLIP pattern with additional LIPSS is shown in Figure **1**(a). The DLIP structures are fabricated with a spatial period of 5.5 µm, which mimics the leaf morphology of the plant Nelumbo Nucifera (lotus flower). This combination of topographic features with different length scales (DLIP+LIPSS) leads to hydrophobic surfaces with contact angles up to 140° [2]. The contribution of the individual surface textures to the hydrophobic behavior was further investigated using a post-processing of the surface topography shown in Figure 1 (a). By using a nanosecond pulsed laser source, the nano-sized LIPSS features were melted and thus erased from the materials surface (see Figure **1**(b)). As a result, the water contact angle decreased to 110°. Note that the contact angles were measured after 50 days, thus allowing carbon decomposition, which promotes non-polar surfaces further enhancing the water contact angle [3].

[1] Y.Y. Yan, N. Gao, W. Barthlott. "Mimicking natural superhydrophobic surfaces and grasping the wetting process: A review on recent progress in preparing superhydrophobic surfaces", Adv. Coll. Int. Sci.169:80–105, 2011.
[2] A.I. Aguilar-Morales, S. Alamri, A.F. Lasagni, "Micro-fabrication of high aspect ratio periodic structures on stainless steel by picosecond direct laser interference patterning". J Mater. Process. Technol. 252:313–21, 2018.
[3] A.M. Kietzig, S.G. Hatzikiriakos, P. Englezos, "Patterned Superhydrophobic Metallic Surfaces", Langmuir. 25(8), 4821-4827, 2009.

Microstructures to mimic snakes' skin

By Sabri Alamri, Andrés F. Lasagni (Fraunhofer IWS, Germany)

In nature it is easy to find examples of surfaces with excellent properties in terms of water repellency, antibacterial properties

and frictional behavior. An excellent example of how peculiar structures help developing a function is the snake skins, whose microstructures on the ventral part have a lower friction coefficient in the direction of movement of this reptile. This effect results from the morphological anisotropy of the skin microstructures which consists on lamellas (or line-like structures) which are inclined in the direction perpendicular to the movement direction.
Therefore, replicating this kind of structures could help mimicking their functionality, which means producing an anisotropic friction coefficient. However, fabricating this type of microstructures with an inclination or an undercut is nowadays only possible using lithographic processes, which are applicable only on photosensitive materials. In order to overcome this limit, we developed a new laser based method that enables the production of inclined structures using the interference of two laser beams on every kind of material which is capable to absorb the laser light. The technique, properly called Direct Laser Interference Patterning (DLIP), has been employed tilting the sample to be irradiated at a specific angle and thus producing the inclined line-like structures.

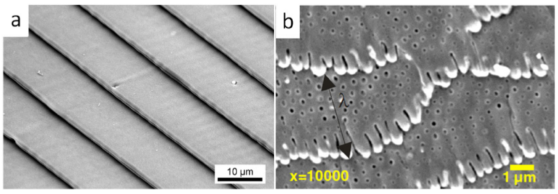


Figure 2: (a) Micrograph of inclined microstructures on polyimide and (b) micrograph of the Python Regius ventral skin.

In our experiments, polyimide foils were used. This polymer material is ablated following a photochemical ablation mechanism, when treated with nanosecond pulses at an irradiation wavelength of 266 nm. By titling the sample up to 75°, the structuring mechanism for defining regular ablation profiles have been investigated, allowing to produce anisotropic patterns with a inclined line-like structure and thus showing an undercut (see Figure **2**(a)). This geometry is similar to the ones present on the ventral skin of the Python Regius (see Figure **2**(b)) [2]. Through the inclined DLIP method, it was possible to fabricate well-defined microstructures with a variable lateral distance (period), depth and inclination by controlling the processing parameters. Further investigations of the tribological behavior of the produced patterns as well as their wettability response will be investigated in the short future.

[1] Abdel-Aal and M. El Mansouri., Tribological analysis of the ventral scale structure in a Python regius in relation to laser textured surfaces, Surf. Topogr. Metrol. Prop., 1, 2013

Laser-Material interaction in sapphire

By Luigi Capuano, Daniël De Zeeuw, Gert-Willem Römer (University of Twente, Netherlands)

Crystalline sapphire shows unique physical and chemical properties, which make this material a potential choice for a series of applications, for example in the fields of semiconductor technology and micro-fluidics. Ultrashort pulsed laser processing is an effective and flexible way of machining this material. When applying IR laser wavelengths, sapphire can be laser-processed inside the bulk (sub-surface) to produce 3D structures.

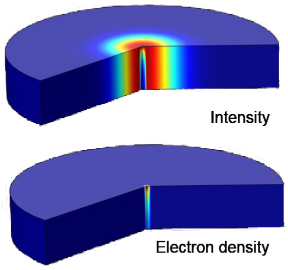


Figure 3: An example of the calculated (simulated) laser intensity and electron density in the bulk of a cilindric sapphire sample. Simulation conditions: laser wavelength 1030 nm, pulse energy Ep=0.45 µJ (collimated beam) and pulse duration of 3 ps (FWHM).

The physical phenomena that contribute in the laser processing of sapphire are not fully understood and despite the existence of models covering only parts of the physics, there is none available allowing the simulation of all the processes occurring during and after the laser pulse. The morphology of the single laser-induced modifications in sapphire depends on several phenomena which are influenced by the material properties and the laser processsing conditions. At the University of Twente, we developed a numerical model that allows the simulation of the laser-material interaction during short-pulsed processing of sapphire. The model describes the laser intensity distribution, electron densities, electron temperatures and lattice temperature during and directly after the pulse where the laser beam is assumed as collimated. Governing equations, describing the relevant phenomena were established and implemented in COMSOL Multiphysics®. This numerical model was validated, and results for various laser processing conditions were obtained. The simulation results (Fig. 3) show that absorption phenomena in sapphire are highly nonlinear, which is in line with recent publications. The model is ready to be further extended such that it can take into account beam propagation through focusing optics. This will allow a complete study of the influence of process conditions on the laser-material interaction and the resulting morphology of the induced subsurface modifications.

Bio-inspired structures on aluminium

By José Cardoso (Universidad Politécnica de Madrid, Spain)

Machining a metal's surface at a micro and nano scale via laser irradiation constitutes an effective way to fabricate hydrophobic surfaces with robust features.

By adapting laser machining techniques and using pulsed laser irradiation it was proved that it is possible to alter several material's properties and shape the surface at both nano- and micro-scale for numerous different materials with distinct structures.

Following the Laser4Fun internal exchange program, this work aimed to achieve an unique combination of short- and ultra-short pulsed laser machining in order to fabricate hierarchical surface structures that are able to improve the wettability properties of a standard aerospace aluminium alloy (Al2024). During the procedure, two distinct laser sources and techniques were considered in order to shape the material's surface. First, an UV nanosecond laser source was used to perform Direct Laser Writing (DLW), this step allowed the fabrication of close packed square cells on the surface. Using Direct Laser Interference Patterning (DLIP) with an IR picosecond laser source, one was able to obtain hierarchical structures by creating pillar like structures on top of the previous patterns (see Figure 4).

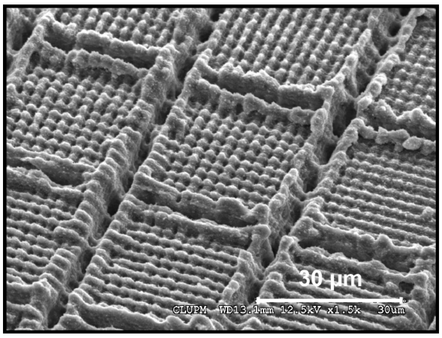


Figure 4: SEM image of the fabricated hierarchical structures.

Created structures demonstrated a highly hydrophobic behavior and were able to completely repel water droplets that were dispensed on the surface. Therefore, by varying and combining distinct laser micro machining techniques, one was able to reproduce structure topographies that are naturally present in plants like the lotus leaves or in rose petals. Finally, bio-inspired hierarchical surfaces also demonstrated several improvements on bacteria repellency and corrosion resistance. A thorough characterization of the ability to improve these features with hierarchical structures is currently being developed.

2D Laser Induced nanostructures

By Fotis Fraggelakis (ALPhANOV, France)

Laser surface processing accounts numerous examples of producing functional surfaces. Lab developed structures often follow the paradigm of textures found in nature. Generally, a systematic link is observed between the structure morphology and the macroscopic surface property. Depending on the structure's size, symmetry and hierarchical length scale formation, anti friction, bactericidal and anti-reflective surfaces could be produced. One of the most wanted are antireflective surfaces. These can be obtained with 2D structures in the submicron regime. Examples in nature can be found in wings of insects like in cicada or dragonfly wing. Nevertheless, it is difficult to produce structures at that length scale by laser since the size is smaller than the laser wavelength and ranges below the light diffraction limit.

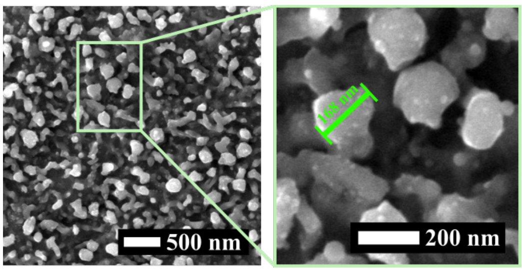


Figure 5: SEM of 2D biomimetic structures fabricated on stainless steel surface.

In our work we employed the innovative approach of the double pulse irradiation. Utilizing this approach, it was possible to fabricate 2D structures in the nanoscale on stainless steel surface. An example is shown in Figure 5. This particular morphology is similar to the one found in dragonfly wing which combines bactericidal, anti-reflective and hydrophobic properties. Moreover, by utilizing an industrial femtosecond laser system and processing large areas we pushed this technology a step forward the application into an industrial environment.

Wear resistance of hydrophobic surfaces

By Antonio García Girón (University of Birmingham, England)

In previous publications we demonstrated the possibility to produce hydrophobic surfaces on hardened stainless steel plates by combining surface alloying and laser surface texturing (see Figure **6**(a)). This process combination could be useful in a wide range of applications, for example, the manufacturing of home appliances with self-cleaning properties. However, the behaviour of the functionalized surfaces in real working conditions remained unknown.
In order to mimic the cleaning process of a surface, a system incorporating a counter pad fixed to a mechanical arm driven by an electric motor was used. In particular, reciprocating cycles with the pad holding an aluminium oxide fibre cloth with a 1750 g load were performed on the surfaces and thus to imitate the exercised force and movements of a human hand while cleaning a surface, for example, an oven after cooking (See Figure 6 b).

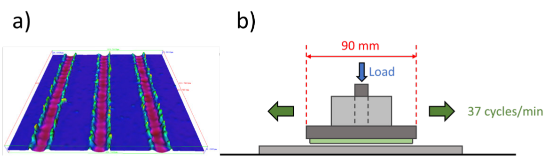


Figure 6: (a) Topography of the produced structures. (b) Sketch of the setup used to mimic the cleaning of the surfaces.

After hundreds of cleaning cycles on both, stainless steel and hardened stainless steel plates, the surfaces were analysed and it was concluded that the functional patterns on the

plasma treated surfaces retained for longer time their topography and respective wetting properties, due to their higher hardness. However, the functionality deteriorated progressively with the increase of the number of cycles. Further investigations have shown that the surface chemistry plays an important role in obtaining and then maintaining the desired hydrophobic properties, due to the presence of non-polar molecules that combined with the topographies are water repellent.
Thus, laser patterned surfaces are not suitable alone to create self-cleaning surfaces in one-step process. However, as the topographies can remain for longer time after the wear tests, it is possible to retain the desired surface response by combining laser patterning with chemical coating. In this way, the patterns will act as a protection against wear, while the coating will repel water drops, making the combined processing suitable for industrial applications.

Hydrophobicity surfaces and their properties

By Daniel Huerta (Universidad Politécnica de Madrid, Spain)

Hydrophobicity is a term used to describe the property to repel or diminish in some manner the contact and/or adhesion of water droplets on the surface of a material. A natural example of a hydrophobic surface can be observe on the leaves of the lotus plant. When observed at a microscopic level, it has been discovered that the surface topography of the lotus leaves displays dual-scale features (micro and nano-length), and it has been proved that this unique roughness configuration is strongly related to the hydrophobicity of the lotus leaves. Based on this kind of natural surfaces, several methods of production have been propose and proven to re-create the hydrophobic effect of the lotus leaves in several kinds of materials, from polymers to metals. Among these methods, laser manufacturing has receiving a lot of attention in recent years due to several advantages when comparing with other fabrication methods, like no chemical contamination or fast and precise control of the micro-features creation.

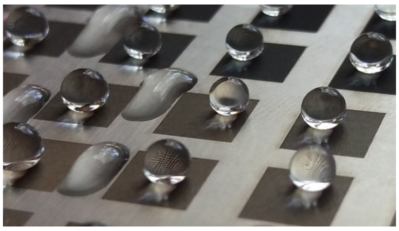


Figure 7: Water droplets deposit on laser manufactured Ti-6Al-4V samples showing excellent hydrophobic behavior.

Nevertheless, recent scientific research in the Laser4Fun project has given an insight that additionally to the requirement of a dual-scale surface roughness, it is also necessary that the chemical composition of the surface undergo a change in order to achieve a good hydrophobic behavior. Specifically, for the case of Ti-6Al-4V alloy manufactured with a nanosecond pulsed laser using a 355 nm wavelength, it has been found that the absence or presence of polar and non-polar molecules is somehow related to the hydrophobicity of the laser processed sample. Polar and non-polar molecules refers to the property of molecules to either have or not, a natural polarity (electrical charge), this means that, polar molecules will have a positive charged end and a negative charged; water molecules is an example of polar molecules. It has been show that for nanosecond laser manufactured surfaces; the absence of polar molecules on the chemical composition of the surface is related to a good hydrophobic behavior of the sample, demonstrating that the hydrophobic behavior of the surface material depends on both the surface roughness topography and its chemical composition.

LIPSS on Polymers with Picosecond Pulses

By Marek Mezera (University of Twente, Netherlands)

Laser-induced periodic surface structures (LIPSS) are widely researched on metals and on semiconductors. For polymers on the other side, only a couple of dozen papers are published, at which polymers are produced when applying laser sources operating either in the ultraviolet wavelength and nanosecond pulse duration, or radiation of wavelengths ranging from 265nm to 1045nm and pulse durations in the femtosecond regime. LIPSS were not reported when using pico-second laser sources, see Figure 8. At the University of Twente, two polymers were irradiated with two wavelengths (343nm and 515nm), using a laser source with a pulse duration in the picosecond regime.

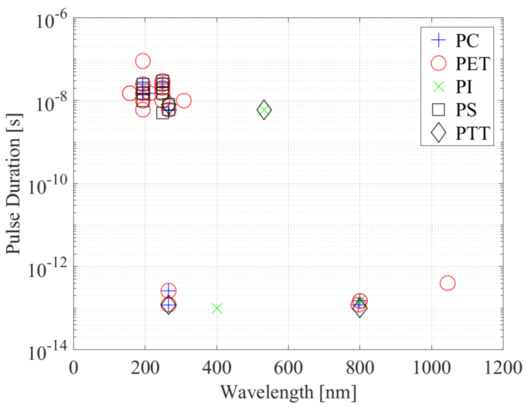


Figure 8: LIPSS (categorized by laser parameters pulse duration and laser wavelength) on the five polymers on which have been reported the most in literature.

It was found that Low Spatial Frequency LIPSS (LSFL) and High Spatial Frequency LIPSS (HSFL) do form on Polycarbonate and Polystyrene at a wavelength of 343nm. Using the latter wavelength, homogeneous areas of LSFL with a periodicity of about 200nm were produced on polycarbonate, see Figure 9. At a wavelength of 515nm, LSFL and HSFL do form on PC, but the processed surface does become porous when applying that wavelength. LIPSS were not found on PS at the latter wavelength. Hence, picosecond laser sources have a broader wavelength spectra, at which LIPSS processing is possible, than ns laser sources but do not reach the wavelength spectra of fs laser pulses for allowed LIPSS development.

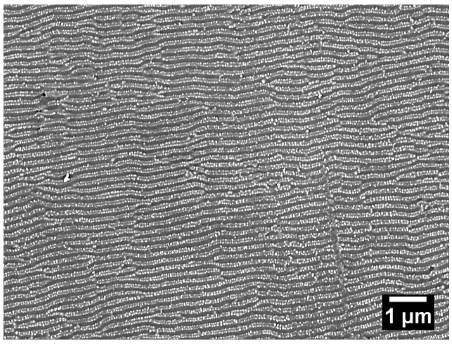


Figure 9: Homogeneous area of LSFL processed on Polycarbonate with a 343nm wavelength picosecond laser source.

Durability of micromoulded functional surfaces

By Jean-Michel Romano (University of Birmingham, England)

Various plant leaves and animal skins have shown functional properties, such as water repellency and inhibit bacteria colonization, that are partially due to their complex surface topographies. Until now, the production costs associated with such surfaces was prohibitive and so they were rarely utilised in industrial applications. Therefore, the mass “imprinting” of such surfaces on plastic parts by using industrial replication processes is of great interest. To respond to this industrial interest, a process chain was specially designed that employs laser texturing for producing replication masters.

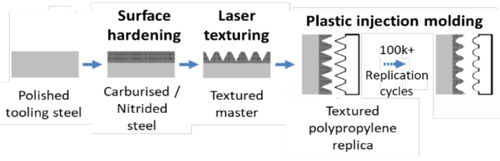


Figure 10: Laser processing combined with mass replication in a process chain.

In particular, laser processing was used to generate surface patterns on metallic inserts that were then used for injection moulding. In this study, different laser-based surface treatments were considered, i.e. Direct Laser Writing (DLW), microlens-assisted Photonic Jets (PJ) and Laser Induced Periodic Self Structures (LIPSS). In addition, to slow down the mechanical wear when using tooling steel inserts for serial production, low temperature plasma carburising was used to enhance their wear resistance properties.

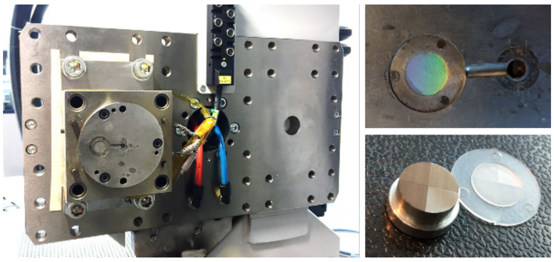


Figure 11: Images of micromoulding system; integration of a laser-textured insert; the insert together with a polypropylene replica.

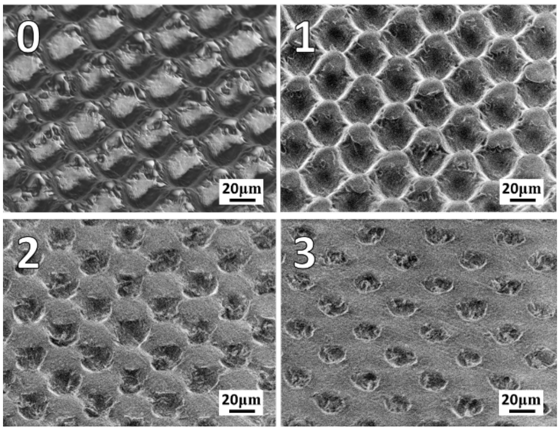


Figure 12: Progressive mechanical cleaning of a microtextured plastic part.

Another major factor limiting the use of microtextured functional surfaces is their potential wear and associated with this degradation of their properties when deployed in industrial applications. A standardised cleaning procedure was used to study the durability of the textured surfaces on plastic replicas. Mechanical abrasion alters the surface topography and thus their functionality. The evolution of microtextured surfaces' wetting properties was studied after undergoing different cleaning cycles in order to propose wear-resistant textures that could remain water repellent for longer.

Laser textures: from industry to your home

By Melissa Sikosana (Leibniz IPF, Germany)

Clean water is a basic human need. By 2014, 80% of villages in Nepal had access to improved water systems, however, at the same time, there was a peak in bacterial infections. On average 90% of household water containers were re-contaminated with faecal matter! Globally, 2 million people die per annum from drinking contaminated water, yet the uptake of household treatment units remains slow - it is not a priority. Let's face it, how often do you clean your own drinking bottle? - considering there are 30'000 times more bacteria colonies in your water than on a toilet seat, you should be concerned! But, what if you did not have to worry at all and water containers cleaned themselves?

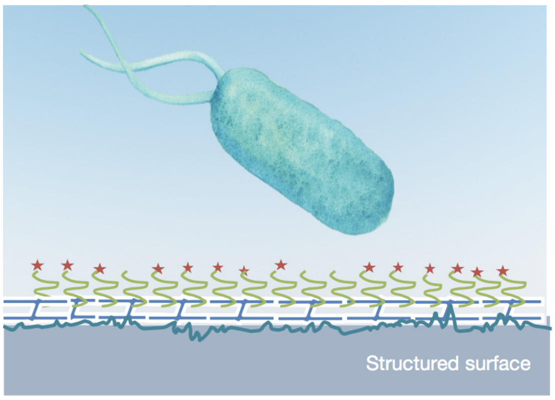


Figure 13: Representation of bacteria interacting with a structured surface.

This is the grand challenge that researchers at the IPF are tackling, to meet 1 of the Sustainable Development Goals. Self-cleaning surfaces are not new. Biomedical and food-packing applications are vast, but current designs loosely administer drugs and can even promote resistance. An IPF team is using a systems approach to translate lessons learnt from 4 billion years of nature's R&D, into a model for a 'Superior Surface', that uses a combination of physical and responsive-chemical defences to prevent and kill bacteria for prolonged periods. This model comprises a bacteria-triggered coating tethered to an antifouling laser-structured surface, to passively yet precisely maintain drinking water quality. Surface micro-roughness increases hydrophobicity and surface area for the active chemical coating; the nano-roughness additionally prevents bacteria colonisation; whilst the overall hierarchical structure contributes to the surface superhydrophobicity, but more importantly, to wear resistance. In addition strategic patterning in comb-like arrays further maintains structural integrity. To date, the responsive chemical component kills 80% of bacteria tested under realistic conditions, is stable in wash cycles of running water and has been successfully coupled to an FDA approved antiseptic. This coating can be anchored to PS and PE - common materials found in water distribution systems.

In the search for the ideal surface structuring, various antifouling capabilities of laser processed surfaces that incorporate differing bio-inspired elements have been investigated.

- honeycomb arrays with 1-µm periodicity fabricated using Photonic Nanojets on ferric treated stainless steel (SS)
- hierarchical structures created by picosecond DLIP processing on SS (LSFL Λ ≈ 800 nm and HSFL Λ ≈ 200 nm) with periodicities (1.2 µm – 5.5 µm)

These were incubated in two types of bacteria solutions: Fresh (typical lab culture) and long-term conditioned Escherichia coli (more realistic culture).

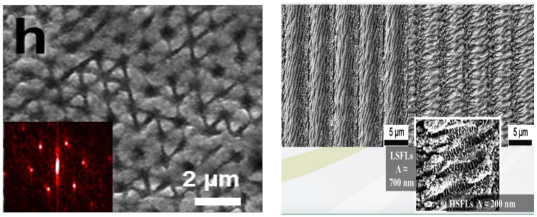


Figure 14: (A) Honey-comb array with PN. (B) Hierarchical structures using DLIP.

In regards to the PN honeycomb array, abrasion resistance is the main motivation.
Periodicities close to the cells size, similar to the 1 µm period of the PN-structures, typically support bacterial surface colonization. However, no such trend was observed. Hierarchically structured samples on stainless steel showed a decrease in bacterial colonisation, with a decrease in micro-roughness; with the highest adhesion achieved at 5.5µm and lowest at 2µm/ 1.2 µm, close to the size of E.coli. To further understand the effects of hierarchical structures on adhesion, the nano-roughness was varied instead. Hierarchical structures for 600nm + 5µm and 825nm + 5µm showed an advantage over single structures. Our team will continue to work closely with our collaborators to find the 'sweet spot' for compatible laser-structured surfaces that are both anti-adhesive and wear resistant, whilst increasing surface exposure and protection for the active chemical coating - A superior surface, that like nature sustainably prevents and kills bacteria, all at once.

Laser-texturing for tribological applications

By Tobias Stark (Robert Bosch GmbH, Germany)

The lifetime of many Bosch products is limited due to wear and friction. One objective in product development therefore is to reduce wear and friction. A key factor to influence these parameters is lubrication. Lubrication inside the tribocontact is essential to avoid contacting asperities. However, due to heat formation and dynamical effects starvation of lubricant inside the tribocontact occurs. Therefore, active transport of lubricant towards the tribocontact is necessary. To this end, different laser structured surfaces are created. Their effects on the active transport phenomena (e.g. capillary forces) are investigated. The investigation is twofold. Firstly, the transport towards the tribocontact and secondly, the transition out of the surface structures into the tribocontact are investigated. The main result of the study is that the structures in the transition area are important. These structures are responsible for delivering oil into the tribocontact. For this, also the meniscus of the wetting process plays an important role. This behavior will be tested in the coming months in order to understand the role which the active lubricant transport plays for the tribological performance of laser structures surfaces.

Friction Tailoring through Laser Texturing

By Gagandeep Singh Joshi (CNR, Italy)

Over the recent years, the laser technology and its potentials have been exciting laser manufacturers as well as researchers and industrial users. Lasers with their excellent beam quality promised noticeable advantages and improvements in high precision and material processing at the microscale. Surface texturing in terms of topographical modification has shown significant promise over the past decades as one of the surface engineering methods to modify friction performance. In order to control the friction, it is important to understand the mechanism which occur during the reciprocating or sliding contact between textured and un-textured surfaces in dry or lubricated conditions [1,2]. Studies on the wettability and the spreading behavior of the lubricant on a laser textured surface help to understand more about its tribological performance. The aim is to control the friction and increase the life time of the mechanical components [3]. The tribological behavior of different textured surfaces has been studied using mineral oil as lubricant.

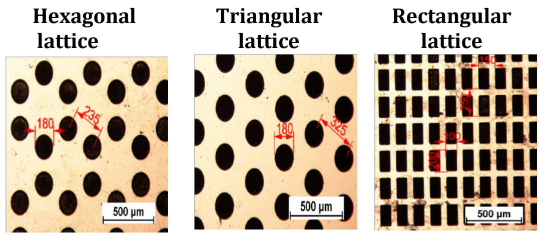


Figure 15: Micro-textured geometrical pattern. LST samples with different texture geometries (Triangular geometry: dimples with diameters d=183µm, depth h~6.7µm, areal density A [%] =0.29; Hexagonal geometry: dimples d=183µm, h~6.6µm, A [%] =0.27; Rectangular geometry: dimples: major axis L=200µm, minor axis W=100µm depth h~7.3µm, areal density A[%]=0.53) compared to the stainless steel polished surface].

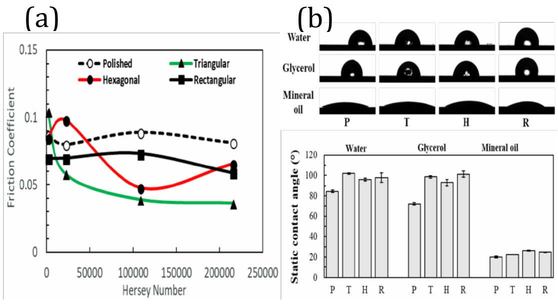


Figure 16: (a): Friction coefficient vs Hersey number for different texture geometries (b): Image and measurement of static contact angles of the textured and different textured surfaces, using mineral oil polished (P), triangular (T), hexagonal (H), and rectangular as a lubricant. (R) textured surfaces, using comparatively water, glycerol and mineral oil as probe liquid.

Experiments have been carried out on a plint-off tribometer, where a steel ball slides against the surface of the samples. Results show that textured surfaces have friction reduction under different lubrication regimes as compared to un-textured surfaces. Furthermore, static contact angle and spreading were evaluated with water, mineral oil and pure glycerol. All considered textures showed a slight reduction of contact angle for the 3 liquids, compared with the polished surface (see Figure 16). Mineral oil exhibited a more persistent spreading over the un-textured and textured surfaces, and more consistency in friction reduction. We highlight that mineral oil is relevant for low and high dynamic velocities in the case of textured and un-textured samples, whereas, glycerol is beneficial at specific velocities. Therefore, we propose a novel approach for the design of tribological systems depending on surface texturing, lubricant, working temperature and sliding velocity. Ultimately, the outcomes from these experiment enhance the lifetime and reduce the friction in different mechanical equipment's like e.g. in automotive engines. This will improve the efficiency of vehicles' engines thus reducing fuel consumptionand exhaust emissions for the benefit of the environment.

[1] Effects of the micro surface texturing in lubricated non-conformal point contacts, G.S. Joshi,
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[2] Femtosecond laser full and partial texturing of steel surfaces to reduce friction in lubricated contact ; Antonio Ancona*, Giuseppe Carbone, Michele De Filippis, Annalisa Volpe and Pietro Mario Lugarà, Advanced Optical Technologies Vol. 3(5-6), pp. 539-547 (2014).
[3] Non-Uniform Laser Surface Texturing of an Un-Tapered Square Pad for Tribological Applications, Antonio Ancona, G. S. Joshi, Annalisa Volpe, Michele Scaraggi, Pietro Mario Lugarà and Giuseppe Carbone, Lubricants 2017, 5, 41; doi:10.3390/lubricants5040041

Superhydrophobicity by fs-laser texturing

By Vittorio Vercillo (Airbus Group Innovations, Germany)

Today, surface technologies and functional coatings are the key to enable more cost-efficient air transport by helping to reduce emissions and optimize fuel consumption. One aim of the Laser4Fun project is to achieve benefits for airlines and passengers through short and ultra-short pulsed laser technologies. Nanostructures are fabricated on the selected metal surfaces of aircraft (e.g. Ti, Al, NiCo, Steel, ...) in order to generate superhydrophobic properties, to repel water, insects, dirt, ice and in general any unwanted contamination. Thanks to the nano- and micro-structures on the metal, supercooled water droplets and insects no longer wet the surface or stick to it, thus giving the surface anti-contamination/self-cleaning and icephobic functionalities. Such structures mimic a lotus leaf's topography

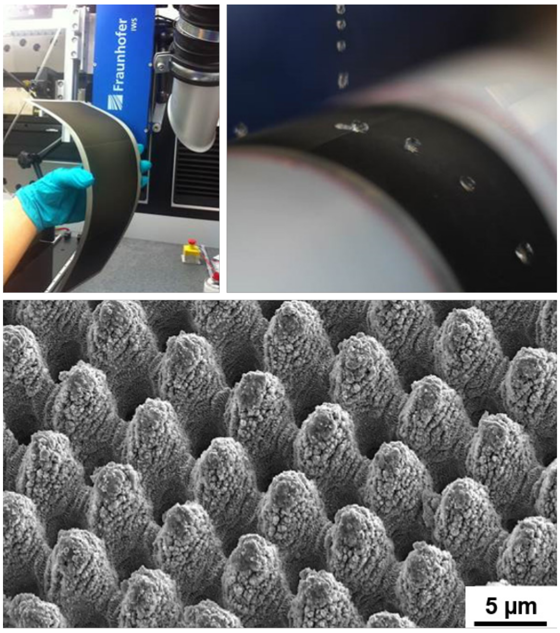

Figure 17: Lotus-like micro-/nano-structure manufactured on Ti6Al4V at Fraunhofer IWS [1].

and the well-known "lotus effect," where droplets do not wet the surface but instead collect and carry contaminants as they roll away (see Figure 17). To test the durability in an operational environment, a laser-structured and functionalized titanium metal sheet has been installed by Airbus CRT Materials X department on a A350 test aircraft's. The flight tests started in May and the sample has already flown for more than 100 hours in different places around the world. Data

[1] A. I. Aguilar-Morales, S. Alamri, and A. F. Lasagni, "Micro-fabrication of high aspect ratio periodic structures on stainless steel by picosecond direct laser interference patterning," J. Mater. Process. Tech., vol. 252, pp. 313–321, 2018.

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