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Structuring of injection molding tools with ultrashort laser pulses for surface functionalization after casting

Sebastian Wächter[a], Daniel Conrad[a], Sabine Sändig[a], Stefan Wiedemeier[b] and Felix Dreisow[a,c*]

[a]ifw - Günter-Köhler-Institut für Fügetechnik und Werkstoffprüfung, Otto-Schott-Straße 13, 07745 Jena
[b]Institut für Bioprozess- und Analysenmesstechnik e.V. – IBA, Rosenhof, 37308 Heilbad Heiligenstadt
[c]Friedrich Schiller Universität Jena, Institute of Applied Physics, Abbe School of Photonics, Max Wien Platz 1, 07743 Jena

Abstract

We structured injection molding tools and subsequently imprint the micro-structured surface onto the work piece during the molding. We studied the influence of the laser parameters for the fabrication of micro- and nanostructures. They are characterized using laser scanning microscopy and scanning electron microscopy. Finally, the tools are applied for two different purposes. We achieved vanishing adherence to blood in small capillaries of microfluidic devices. In a second example, we show that the forces to remove the tool from the workpiece after casting are reduced.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Laser material ablation with ultrashort lasers is not a material removal process, solely. Additionally, on the surface of the sample an underlying nanostructure evolves [Bir65]. Choosing appropriate sets of laser parameters yields a periodic structure a so-called LIPSS (laser induced periodic surface structure). Such LIPSS are created in a self-organizing process during the laser treatment. Here, the incident light field interferes with surface plasma waves yielding a periodic structure in the order of the wavelength and below. The grating structure is oriented perpendicularly with respect to the polarization direction of the light and can be strongly suppressed, e.g., by using circularly polarized light [Grä15].

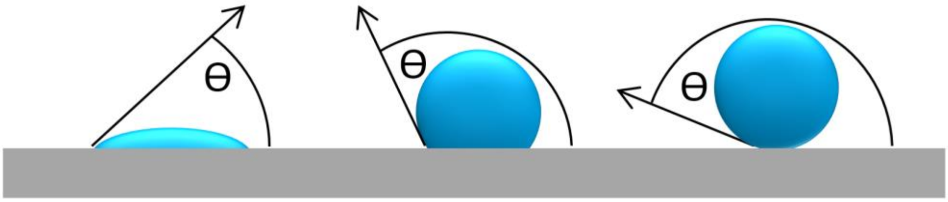
* Corresponding author. Tel.: +49-3641-204-245; fax: +49-3641-204-110.
E-mail address: f.dreisow@uni-jena.de – fdreisow@ifw-jena.de

Today, such LIPSS offer vast potential for manifold surface modifications. Particularly, equipping surfaces with new functionality is a specific aim in recent and current research. Surface functionalization with lasers is well-known on semiconductor surfaces, particularly on silicon. First observed on semiconductor materials with pulsed lasers in the early 1960s [Bir65], today with ultrashort laser pulses LIPSS formation has been achieved on a large variety of materials [Vor07]. Particularly, transferring this technique to metals, dielectrics and polymers makes laser induced surface functionality relevant for daily life.

Due to the imprinted nanostructure, hydrophobicity, a property describing that water is repelled from a surface, is one of the most prominent examples for surface functionalization.

In Table 1 the property of hydrophobicity is defined. A surface is called hydrophilic, when the contact angle Θ is smaller than 90°, which is the property of everyday surfaces. A hydrophobic surface has a contact angle larger than 90° and water starts to repel from the surface. Some surfaces, such as the lotus leaf, show superhyrdrophobic behavior, where the contact angle is large (Θ>160°). Here, a water droplet is only with a few percent of its surface in contact with the substrate. Even more, such a surface has a self-cleaning effect, where water drops can dust and dirt from the surface.

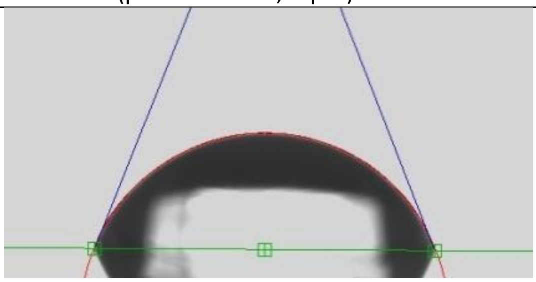
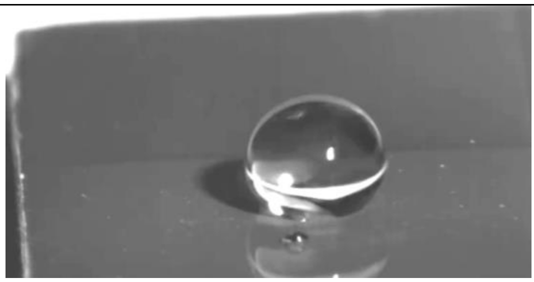
Table 1: Definition of hydrophobicity



hydrophilic	hydrophobic	superhydrophobic
Θ<90°	Θ>90°	Θ>160°

Table 2 demonstrates that a laser treatment can provide surface functionality. Table 2 (left column) depicts a water droplet on a polished stainless steel plate. The contact angle is well below 90°. The same test is conducted with a laser treated sample. Here, the contact angle is around 120° and the water droplet is repelled from the surface.

Table 2: Water on stainless steel, (left) on polished surface, (right) on laser treated surface

Reference (polished Ra=0,01µm)	laser treated surface
	
water @ 20 °C (Θ=69°)	water @ 20 °C (Θ=122°)

However, ultrashort laser material processing is still very expensive and therefore in cost sensitive markets, such as, micro fluidics, we aim on the combination of ultrashort laser manufacturing in combination with mass fabrication, e.g., injection molding. Here, a recent publication states that the preparation of casting tools improve the molding process [Con14]. In this work, we will continue elaboration in this field, and we show how micro and nano structured surfaces can improve the casting process further. Additionally, we provide insights on how the structure can be casted to realize cost effective replicas of the microstructure including the functionalization.

2. Laser treatment

For utilizing laser treatment in casting applications, we aimed on implementing a microstructure with dimensions in the order of 10 µm. The microstructure reduces the contact between the liquid polymer and the casting tool. Depending on the width, the casting compound can enter the microstructures. If the width of the gap is smaller than a critical size (approximately 15 µm), under certain injection molding conditions the compound does not creep into hole and hence the contact surface is reduced by the opening area of the form.

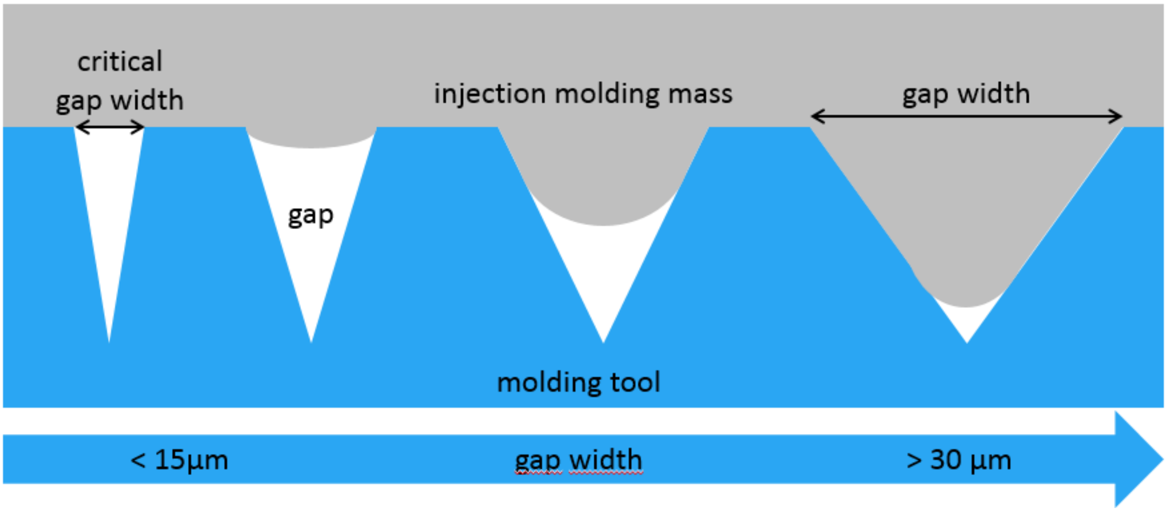
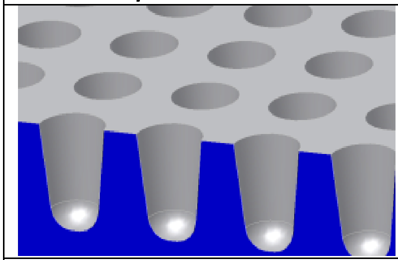
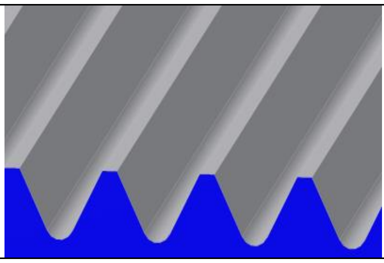
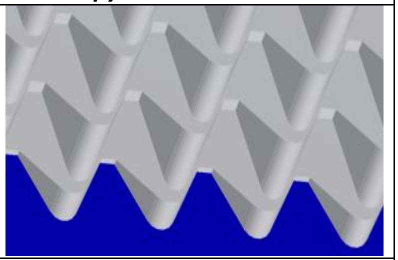
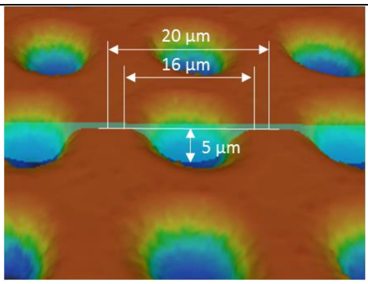
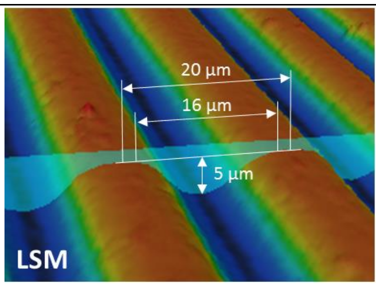
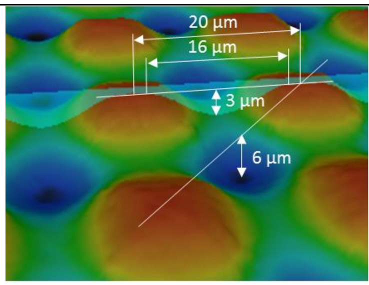
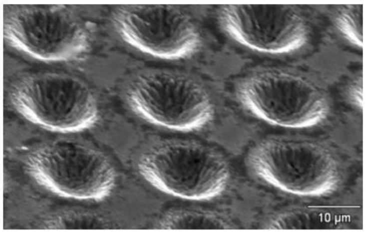
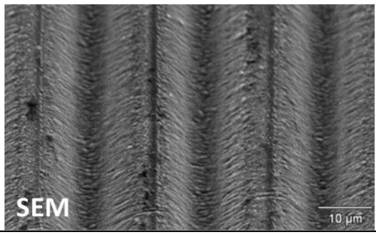
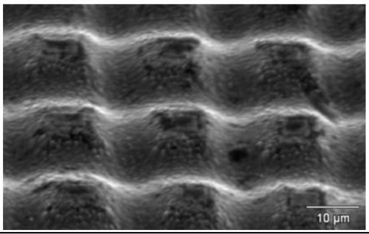


Figure 1: Effect of a microstructure on liquid polymer

We investigated three different types of microstructures for casting applications, the pit structure, line structure and pyramid structure (Table 3). For the fabrication of the microstructure an ultrashort pulse laser (Lumera Hyperrapid, 355 nm, 8 ps) was used. The fluence was 0.4 J/cm² and the laser operates at a repetition rate of 1 MHz. The pits were drilled with 40 laser pulses on each spot, whereas the line and pyramid structure was scanned 25 times with a scan speed of 1000 mm/s. During the laser processing the LIPSS structure is imprinted onto the microstructure simultaneously. This allows for an additional repelling effect of the molding compound. Additionally, a flat surface was laser treated to investigate the effect of the LIPSS structure, only.

Table 3: Different types of microstructures for casting tools.

pit structure	*line structure*	*pyramid structure*
		
• square lattice of drilled holes • contact area: 50-70 %	• parallel structured grooves • contact area: 20-40 %	• parallele structured grooves in orthogonal directions • contact area: 5-15 %
		
		
contact area between molding compound and tool surface gets smaller →		

3. Ejection Forces

In the next step, we evaluated the structure by means of the ejection forces after the casting process. Therefore, the forces, which are required for ejecting the molded parts from the tools, were measured (see Figure 2). For comparison, we used a state-of-the-art tool with an eroded surface as reference. The force for ejecting this reference part was 2.7 kN. All the three tests, where the tools were equipped with a microstructure showed higher ejection forces even though increased water contact angles were observed on the surface. The highest contact angle was obtained for the line structure (Θ=122°). An explanation could be that the structure size is still too large and the laser ablated structure is cast on the molding part. The contact area is decreased but a higher friction is obtained due to the higher waviness of the surface. If one uses the ripple structure (LIPSS) only on a flat surface the ejection force can be reduced by 20 % to 2.2 kN on the same tool, which allows for applying such tools in injection molding applications.

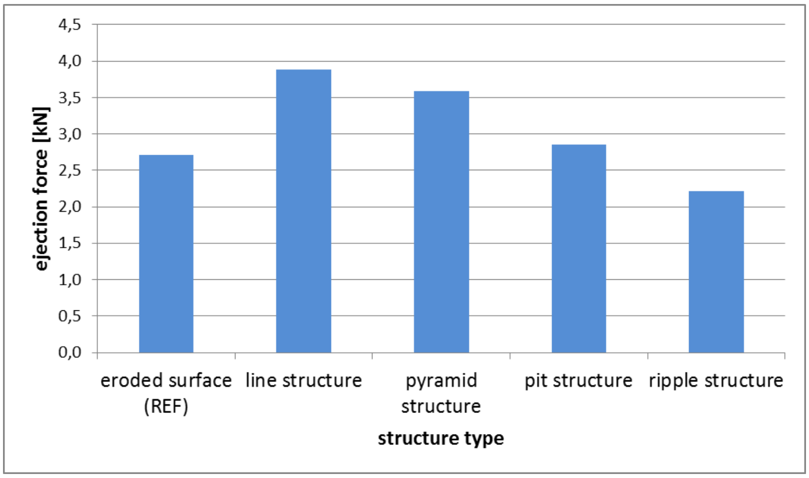


Figure 2: Ejection forces of the structured tools

4. Casting of the microstructure

Laser treatment with ultrashort laser pulses is in general a very expensive process. Even though excellent properties and functionalization can be achieved, the expenses and therefore the inhibition threshold to establish a serial production with ultrashort lasers is too high. Additionally, the material removal rates are very low and magnify the costs problem even more. Therefore, it was our aim to subject the casting tools to

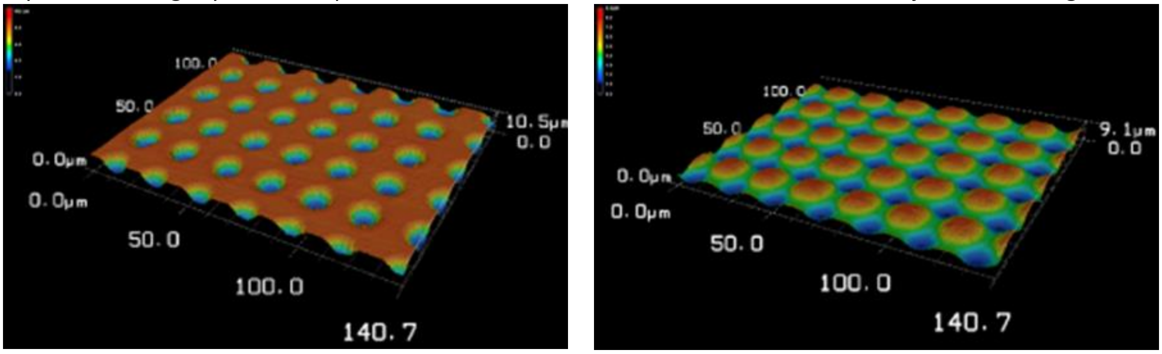


Figure 3: Laser scanning microscope images of laser treated samples. (left) pit structure, (right) cross lines.

a laser treatment instead of directly laser ablate the surface of the respective workpiece. This technique allows for replicating the laser-fabricated structure with a cheap and repeatable process. Particularly, in microfluidic systems, where single use elements are produced in large amounts, injection molding is a state-of-the-art technique.

In a first step, we developed this method on flat surfaces. We fabricated pit and cross line structures on stainless steel plates (c.f. Table 1), which are subsequently used in the polymer casting process. The best results have been achieved with the pit structure. The N15/15 structure (Figure 4) showed the best results to increase the hydrophobicity. The pit size was 15 µm in diameter and 15 µm in depth. The realized surface geometry strongly correlates in topography and size with that of a lotus leaf. The contact angle of a water drop on the polymer substrate was measured to 135°.

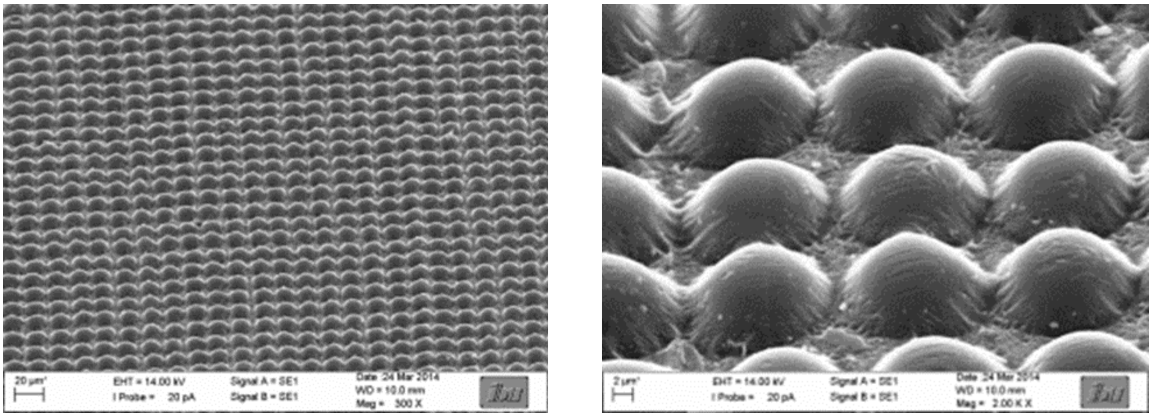


Figure 4: SEM image of a cast surface for the pit structure: (left) 300x magnification, (right) 2000x magnification

Additionally, it proves that process parameters for injection molding strongly influence a successful casting of the lasered structure to the polymer part. The 3D SEM images in Figure 5 demonstrate that a sufficient pressure (1600 bar) is required and the temperature of the polymer needs to be as high as 150 °C. The polymers used were the standard polymer PC2805, PC2400 with lower viscosity and COC6017. The best results delivered the low viscous PC2400.

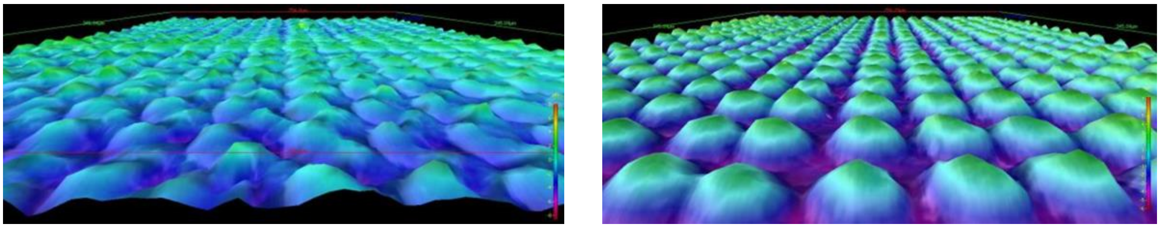


Figure 5: Dependence on the injection molding parameters: (left) dwell pressure 800 bar, injection temperature 110 °C, (right) dwell pressure 1600 bar, injection temperature 150 °C,

In a second step, we optimized the pit structure to increase the packaging density of the pits. We changed the arrangement from square to hexagonal lattice and thus increased the density from 70 % to 90 %.

We applied this technique for manufacturing a micro fluidic micro pipe device. The device contains two crossing channels, a larger main channel and smaller utility channel. The diameters at the ends for the entry of the pipes are large to allow for coupling to external peripherals. In the application, the smaller crossing channel is used to admix an additional fluid, which enables separation of the main stream into single droplets.

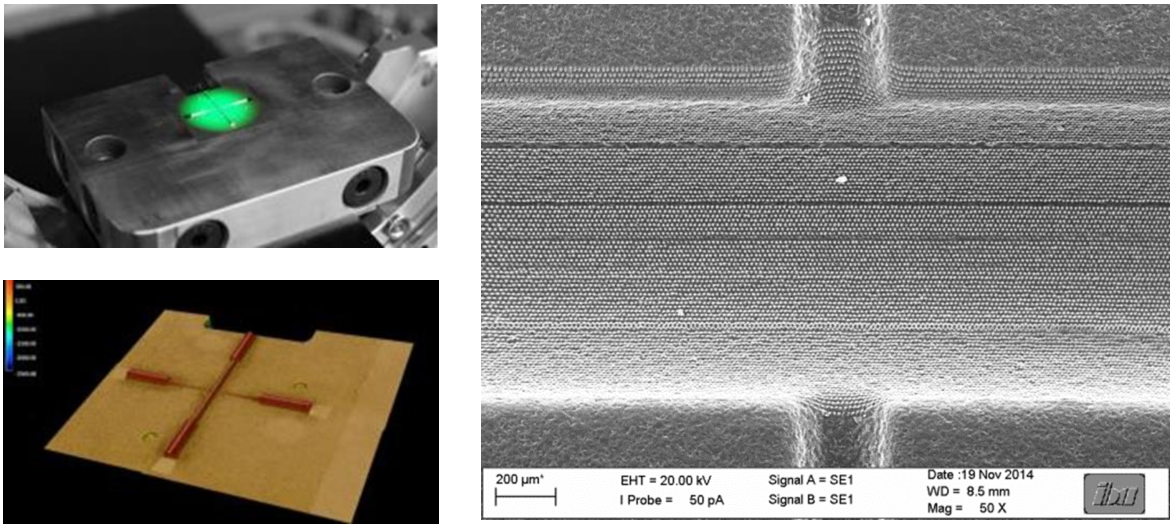


Figure 6: The casting tool: (left) photograph of the casting tool in the laser machine, and microscope image, (right) SEM image with 50x magnification

As the shape of the casting tool is three dimensional, a conventional 2D scanning is improper for fabrication. Therefore, we used a goniometer stage to mount the casting tool. However, on this axis the microfluidic channel cannot be placed exactly in pivotal point, which means that a continuous rotation cannot be performed. We chose the alternative way to manufacture the tool in several steps. We split the manufacturing in five steps, whereas for each step we set the angle of goniometer axis to a fixed value. Then, we aligned the laser to the respective area and fabricated the hexagonal pit structure on an angle range ±22.5° on the half cylinder. The casting was performed with the optimized parameters determined in the previous step on the flat surface. The SEM image of the polymer part is shown in Figure 6. Note here, that there are slight stitching errors between the goniometer steps. However, this does not affect the functionality of the micro fluidic device.

The functionality of the device is finally demonstrated by means of a component for micro drop generation. For the application in biological relevant media due to protein molecules such a device would clog when the flow is interrupted for drop generation. The hydrophobic property inside the channel will prevent such a clogging. The fabricated device is depicted in operation in Figure 7. The liquid flows in the functionalized main channel from left to right. The medium to be segmented is Dulbecco's Modified Eagle Medium (DMEM) admixed with veal serum and phenol red. For separation, perfluordecalin is injected via the utility channels from the top and bottom. We see a continuously running process, where small droplets exit the device.

Figure 7: Demonstrator device. The fluid is continuously injected from the left (pink). From the top and bottom channels a separation liquid is injected into the main stream.

Acknowledgements

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References

[Bir65] M. Birnbaum, Semiconductor surface damage produced by ruby lasers, J. Appl. Phys. **36** (1965) 3688–3689

[Con14] Daniel Conrad, Lars Richter, "Ultra-short Pulse Laser Structuring of Molding Tools", Physics Procedia **56**, (2014), 1041–1046

[Grä15] Stefan Gräf and Frank A. Müller "Polarisation-dependent generation of fs-laser induced periodic surface structures," Applied Surface Science **331** (2015) 150

[Vor07] A. Y. Vorobyev, V. S. Makin and Chunlei Guo "Periodic ordering of random surface nanostructures induced by femtosecond laser pulses on metals", J. Appl. Phys. 101, 034903 (2007)