Vilniaus universiteto

Fizikos fakulteto

Lazerinių tyrimų centras

Ignas Bitinaitis

DIELEKTRINIŲ DANGŲ NUSĖDANČIŲ ANT JONAPLUOŠČIO DULKINIMO ĮRENGINYJE NAUDOJAMŲ GARDELIŲ ŠALINIMO LAZERINĖS ABLIACIJOS METODU EKSPERIMENTINIS TYRIMAS

Magistrantūros studijų baigiamasis darbas

Lazerinės technologijos

studijų programa

Studentas	Ignas Bitinaitis
Leista ginti	2021-05-21
Darbo vadovas	Dr. Alexandr Belosludtsev
Konsultantas	Prof. Habil. Dr. Valdas Sirutkaitis
Recenzentas	Dr. Nerijus Slavinskis
LTC vadovas	Prof. Dr. Aidas Matijošius

Vilnius 2021

Vilnius University
Faculty of Physics
Laser Research Center

Ignas Bitinaitis

INVESTIGATION OF THE LASER CLEANING PROCESS FOR IBS GRIDS IN OPTICAL COATING TECHNOLOGY

Master's degree final dissertation

Laser technology
study field

Student	Ignas Bitinaitis
Allowed to defend	2021-05-21
Supervisor	Dr. Alexandr Belosludtsev
Consultant	Prof. Habil. Dr. Valdas Sirutkaitis
Reviewer	Dr. Nerijus Slavinskis
VU LRC director	Doc. Dr. Aidas Matijošius

Vilnius 2021

Table of contents:

1. Introduction

As technology advances, there is a growing need for new cleaning methods that offer unique benefits. The laser cleaning procedure is one of the most important technologies in areas where precision, efficiency and accuracy are highly critical [1]. In ablative laser cleaning, a short laser pulse is applied to the surface of materials to remove the top layer of a controlled thickness. Flexible delivery of laser radiation to the processed sample is carried out through free space or via optical fiber. The temporal and spatial characteristics of the laser radiation are controlled by acousto-optical or electro-optical modulators and focusing optics. Laser cleaning is known for its fast and easy operation without the use of chemicals or abrasives and it might be used to complex surfaces [2]. The selection of the appropriate cleaning parameters avoids the negative impact on the metal surface [3]. The short interaction time of nanosecond laser pulses with the surface to be cleaned reduces the thermal or chemical influence on the underlying substrate. In addition, this cleaning technique is environmentally friendly [4].

It has been reported that laser cleaning has advantages over traditional wiping and scrubbing, which are often limited due to possible mechanical damage to the substrate. It has been demonstrated that laser radiation is capable of removing 1 μm copper particles from silicon wafers [5] or airborne particles above the gold-coated glass [6]. It has also been reported on successful use of laser cleaning in electronics [5], artworks [7–9], automotive [10] and other fields of technology [3, 11–14]. The scientific and practical importance of laser cleaning increases every day and finds new applications. For example, laser cleaning was used for rhodium films deposited by a pulsed laser for fusion diagnostic mirrors [15], diagnostic mirrors from tokamak-like carbon contamination [16,17], silicon wafers [18], granite [2], marble [9], aluminum [10], aluminum alloy [13], chrome-plated die [19], black sulphur [20], gold [6], steel [21,22] and brass [23]. Theoretical and experimental studies on the cleaning of molybdenum and stainless-steel mirrors were carried out using a laser with a high repetition rate [24].

As technology advances, the demand for precision optics with specially designed coatings increases. Ion beam sputtering (IBS) and magnetron sputtering (MS) are one of the widely used physical vapor deposition (PVD) techniques for the fabrication of high-precision optics [25]. The IBS method uses a broad-beam ion source for sputtering the material [26] and surface treatment [27]. The set of grids constitutes the core of this source, consisting of at least two, but usually three or even four grids. The grid design has precise geometry and this part is relatively expensive. During the generation of ions, some grids are grounded, and at least one is at a negative potential. As the coatings grow inside the IBS chamber, some of the material is also deposited on the grid surface. Over time, a dielectric coating applied to the grid surface might completely cover the work surface and render it non-conductive. Contamination of the grid surface causes problems with process stability and ion generation. Therefore, as part of maintenance work, the grid is periodically cleaned.

Aim of this work is to demonstrate the advantages of the IBS grid and magnetron shutter cleaning procedure using a nanosecond pulsewidth laser. In order to reach the aim, several tasks must be done: 1) investigate the influence of laser parameters on IBS grid cleaning procedure; 2) compare laser cleaning with widely used manual cleaning or sandblasting; 3) investigate the laser parameters on MS shutter cleaning procedure.

1.1 Laser parameters in laser cleaning systems

Fundamental laser parameters such as pulse fluence, repetition rate, pulse duration and wavelength determine laser cleaning system efficiency for specific application. Laser fluence describes damage threshold for material ablation. For laser cleaning systems it is essential to provide pulse fluence higher than required for damage threshold to ablate or vaporize contaminated layer [30].

Laser repetition rate plays major role determining maximal laser system cleaning speed. In order to ensure surface cleanness after single scanning pass laser pulses must overlap in the focal plane. Laser systems equipped with high scanning speed galvanic scanners require laser source providing high repetition rate pulses for pulse overlap. In certain applications such as zinc coating removal high repetition rate induced heat accumulation allows to increase material removal rate [31]. On the other hand, high level pulse overlap induces formation of stochastic microstructures [32] which are undesirable in applications requiring minimal surface impact.

Long pulse durations, especially in hundreds of nanosecond scale as mostly found in industrial laser cleaning systems causes heat accumulation and material thermal heating. Study demonstrates that increase in laser pulse duration increases ablation threshold of the material [33]. Ultrashort, femtosecond duration pulse laser processing offers many advantages over short pulse laser machining, for example, reduced trace of melting or molten material and debris contamination [36 - 38].

1.2 Factors influencing laser cleaning efficiency

Angle-dependent absorption is commonly observed in metals [34]. Therefore, to obtain efficient cleaning speed of flat surfaces, angle of focused beam with respect to the sample surface should be considered. Often materials achieve higher absorption at a lower angle of incidence into the plane of the sample compared to the perpendicular incidence. Additionally, low angle of incidence reduces the amount of reflections returning back to the laser system from the sample surface.

Working with temperature sensitive materials or in pollution sensitive areas water-assisted laser cleaning is commonly practiced. Besides material cooling effect, steam assisted laser cleaning requires lower laser fluence to reach damage threshold for material removal compared to dry laser cleaning [35, 36]. Water assisted technique such as laser shock processing is practiced in applications where no base material melting or removal is allowed.

1.3 Laser cleaning applications in industry

Due to low cost, compactness, efficiency and reliability, fiber laser cleaning systems are widely used in various industries - tire casting, metal construction, automotive, artwork or building restoration. This technology makes it possible to speed up many processes that require precision, accuracy and alternatively are performed mechanically, such as the restoration of painted frescoes, the cleaning of molds, and other.

1.3.1 Restoration

Among the first to notice and widely apply laser cleaning technology in practice were artwork restorers. Technology made it possible to simplify restoration tasks such as probing paint layers, removing soot or dust deposits after a fire or improper storage of exhibits. Significant improvement in work quality and speed is observed in frescoes and altar restoration [40].

Fig. 1. Uncovering the gilded surface of a painted altar using laser cleaning technology. Exposure of this layer using alternative technologies without damaging the gilded paint layer would be complicated task.

1.3.2 Shipbuilding

Shipbuilding and ship restoration works require efficient large surface area cleaning in accordance with global ISO surface preparation standards. Main requirements for surface preparation are surface roughness achievable after the cleaning process (denoted Ra) and the surface cleanliness standard (denoted SA). By achieving a controlled surface roughness up to $Ra = 80$ μm study demonstrates that surface roughness for paint adhesion requirements in shipping industry can be met using laser cleaning technology and laser-cleaned surfaces complies with the ISO 8501 (SA 2.5) surface cleanliness standard [41]. Compared to abrasive cleaning technology, laser cleaning yet does not reach cleaning speeds required by the industry, but is a suitable technology for minor repairs, which due to the compactness of laser cleaning systems can be performed inside the ship during expeditions, avoiding unwanted dust in work environment. Controlled surface roughness opens possibility to clean parts of sensitive surfaces such as engine parts during the expedition.

1.3.3 Aviation

Thin duralumin sheets are one of the most commonly used materials in aviation for aircraft exterior. Since aircraft outer surfaces are coated with a layer of paint to prevent oxidation, aircraft maintenance works often require exposing precise area of sheet rivets for fracture inspection. Laser cleaning, in contrast to dry cleaning, makes it possible to remove precise paint layer area without damaging the adjacent coating and as opposed to abrasive cleaning technology, does not damage or bend thin duralumin sheets. For this reason, use of laser cleaning can improve the quality of work, avoiding additional costs caused by damaged surfaces or lack of accuracy in aviation maintenance works.

1.3.4 Automotive

In the automotive industry, laser cleaning technique offers numerous advantages and is commonly used for surface preparation before the welding process, for weld cleaning after the welding process and for coating removal [42]. Compared to abrasive cleaning technology, laser cleaning does not damage or bend thin metal sheets, nor it pollutes work environment by producing additional dust in workplace by abrasive particles.

Fig. 2. Engine part with convex and uneven surfaces, covered in grease and soot deposits after laser cleaning procedure.

1.3.5 Molds

Laser cleaning technology is widely used for cleaning molds for rubber and bulk products. Compared to alternative technologies such as chemical deposition, abrasive cleaning or mechanical cleaning, laser cleaning does not severely damage the mold structure, resulting in a significant extension of mold life, thus ensuring product quality and increasing production efficiency [43].

1.3.6 Food industry

Laser cleaning is used in the food industry to remove residues from baking forms, to degrease surfaces, disinfect baking tins and thin steelsheets pinholes cleaning [44]. The technology is also suitable for cleaning ovens from flammable or unwanted layers, restoring baking tins affected by corrosion or cracking of the Teflon layer. When using alternative methods such as dry cleaning, the residues of frequently used chemicals or abrasives that are not completely removed from the surfaces can lead to poor quality of baked goods.

2. Experimental details

The layout of the portable laser cleaning apparatus Optola S-50 used in the work is shown in Fig. 3. It consists of a galvanic scanner, optical fiber and a laser control unit. The laser control unit with dimensions 390×180×485 mm^3 weighs 18 kg. The laser source operates at a repetition rate of 25 – 500 kHz, providing a maximum energy of up to 2 mJ at a wavelength of 1064 nm. The span of the scanning line can be controlled from 0.1 mm to 80 mm by software installed in laser control unit.

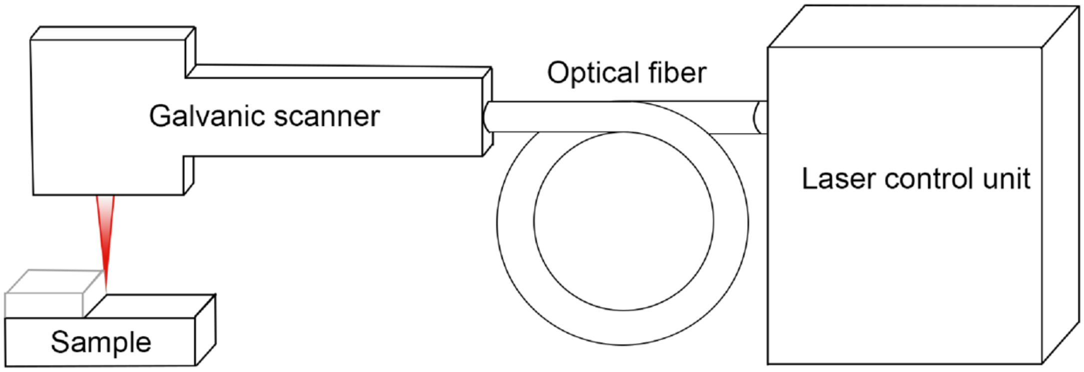

Fig. 3. Layout of the Optola S-50 portable laser cleaning system.

The scanning mirrors of the galvanometer allow the laser beam to move in a raster mode (Fig. 4). The laser beam was focused on the surface to be cleaned through an F-Theta lens with a fixed focal length of 160 mm. During the experiment, the maximum pulse energy reached 0.3 mJ and the pulsewidth was 120 ns at a repetition rate of 100 kHz.

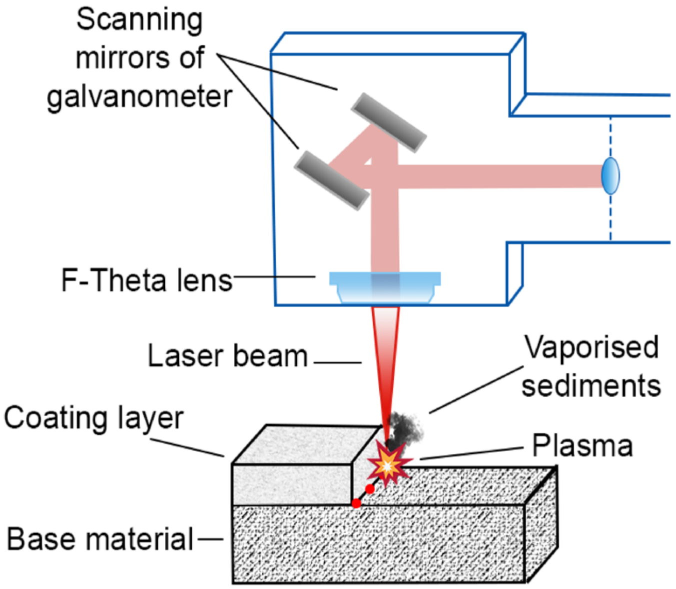

Fig. 4. Layout of the galvanometer and surface cleaning procedure.

The transverse profile of the laser beam on the sample was close to Gaussian with a diameter of 100 µm (at 1/e^2 level), and the scanning speed in the focal plane was 8 m/s. The scanning path of the laser beam (Fig. 5.) provides effective surface cleaning in single path.

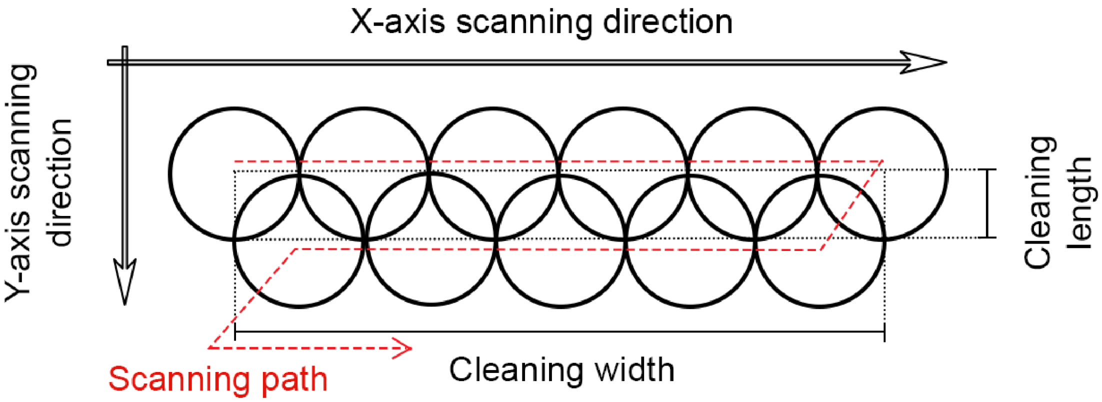

Fig. 5. Scanning path during the laser cleaning procedure.

In this study, a primary source grid from IBS coating system (Cutting Edge Coatings GmbH) was used to clean from a set of 3 grids in the primary plasma source. During research, the same grid and the same side of this grid was used. Also, it was used stainless steel substrate shutter from KJ Lesker magnetron sputtering machine. Prior to cleaning, the details were used in the deposition of typical dielectric multilayer coatings used in laser optics. The cleaning procedure was carried out in air at room temperature and normal humidity. The pulse energy and repetition rate effect were investigated. To investigate the cleaning efficiency, a Nikon Eclipse LV100 optical microscope, a Dektak 150 profilometer, and a Keithley Fluke 77 multimeter were used.

3. Results and discussion

3.1. Laser cleaning process

Effective laser cleaning of multiple grid surfaces in one continuous process is shown in Fig. 6. Thus, the ability of laser cleaning for complex surfaces demonstrates the first advantage. In addition, the tilt of the incident laser beam makes it possible to clean even the inner surfaces in the holes on the third 3D surface (Fig. 6d).

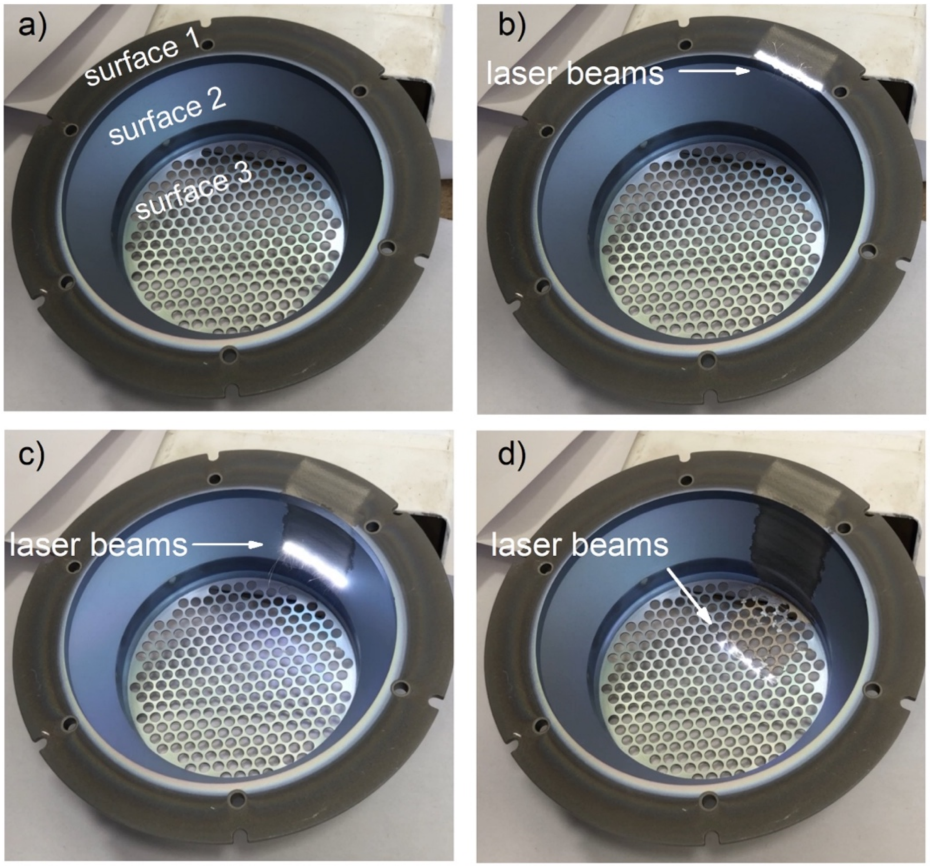

Fig. 6. Laser cleaning procedure: a) untreated coated surface, b) cleaning the first surface, c) cleaning the second surface, and d) cleaning the third surface.

After laser cleaning, all surfaces became conductive again, which indicates the successful removal of the deposited dielectric layers. Restoration of conductivity is very important for the operation of the IBS grid.

3.2 Investigation of the cleaned surface

In Fig. 7 are shown photographs of untreated and cleaned by various methods grid surface. The examined part of the grid was not new and was manually cleaned several times prior to this investigation. The coated surface repeats the scratched texture of a hand-cleaned metal surface (Fig. 7a). After additional manual cleaning of the coating (Fig. 7b), scratches on the metal surface become more pronounced. After sandblasting, scratches from manual cleaning disappear (Fig. 7c). After laser cleaning (Fig. 7d), the largest scratches on the metal surface are still visible because the laser effectively removes the coating with minimal impact on the metal substrate. All cleaned surfaces were tested and indicate conductivity. Details on the material removal rate will be given below.

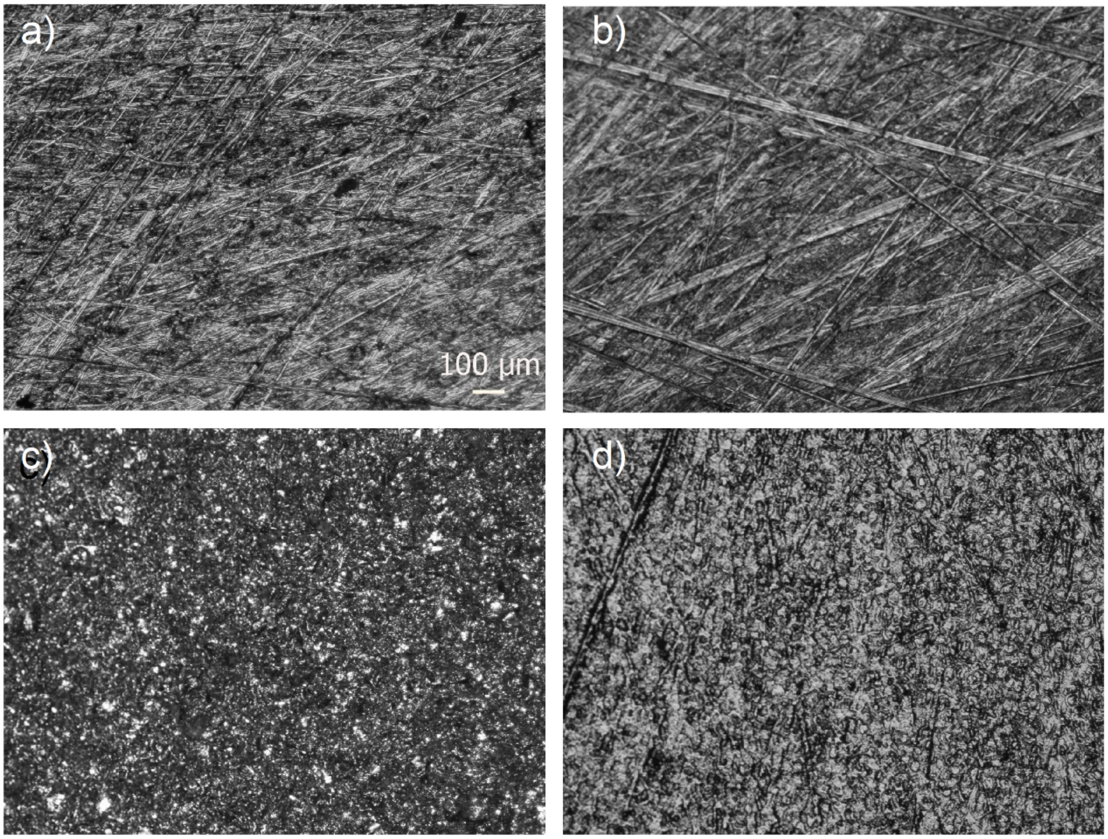

Fig. 7. Comparison of surface morphology: a) untreated coated surface, b) manually cleaned, c) sandblasted, and d) laser cleaned. All figures are in the same scale.

For a more detailed investigation, all cleaning procedures were analyzed with a high magnification (Fig. 8). In Figs. 8a and 8b, scratches from manual cleaning are clearly visible on the surface, and after coating, the deposited material repeats the surface roughness. Sandblasting results in a larger surface roughness (Fig. 8c), although at this magnification, some areas appear blurry because they are out of focus. After laser cleaning (Fig. 8d), melted spots appear on the surface, overlapping along the scanning path (Fig. 5). Similar molybdenum surface melting by the 1064 nm nanosecond laser was observed in Ref. [28]. It should be noted that laser interaction with the surface material is affected by roughness, which leads to enhanced scattering of laser light. The mass movement occurs along the temperature gradient, hence the round signs remain.

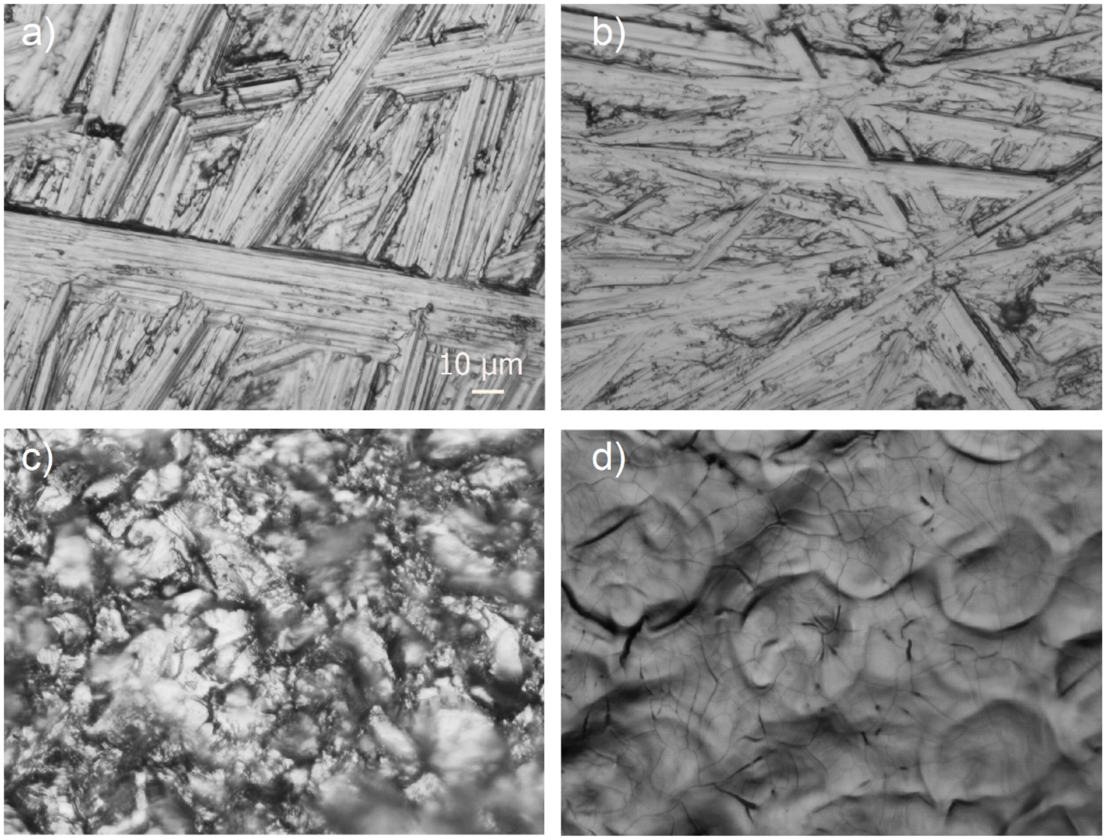

Fig. 8. Comparison of surface morphology: a) untreated coated surface, b) manually cleaned, c) sandblasted and d) laser cleaned. All figures are in the same scale.

The effect of the cleaning procedure on the surface roughness of the grid was compared in Fig. 9. It is clearly seen that, in accordance with Fig. 8 sandblasting has the greatest impact. Such aggressive removal of the metal surface is highly undesirable as it significantly reduces the lifetime of the grid.

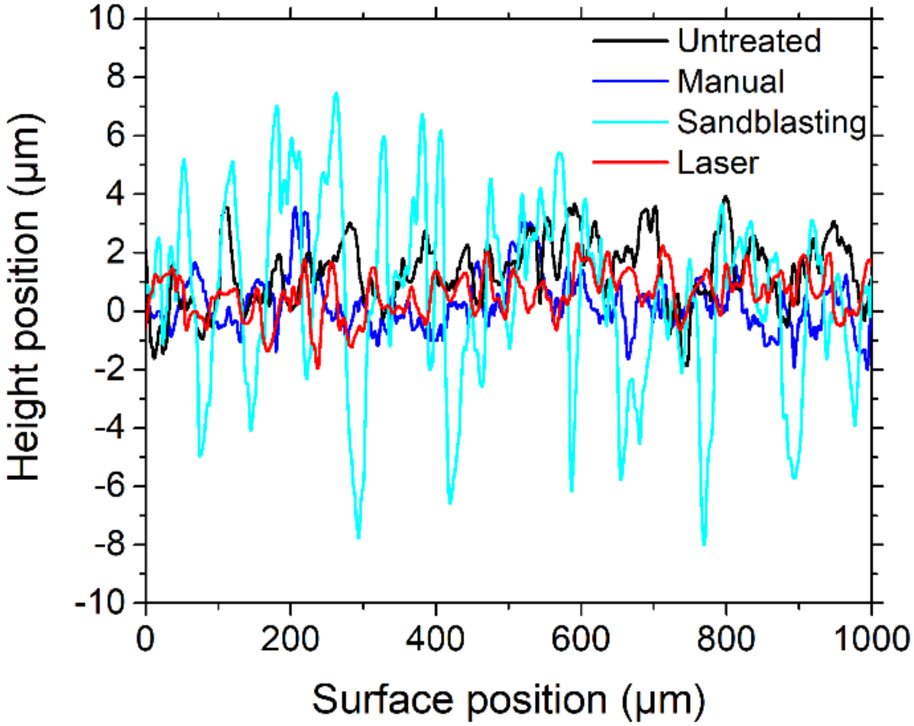

Fig. 9. Comparison of the profiles of the untreated and cleaned by various methods grid surface.

The approximate calculations took into account the time from the dismantling of the part from the IBS apparatus to its installation back. In the case of manual cleaning, the removal efficiency is very low due to the relatively high hardness of the coating materials. Moreover, for manual cleaning, a variety of tools must be used to clean all surfaces (Fig. 6a). Sandblasting is a faster technique, nevertheless, it has a strong effect on the surface, as discussed earlier. In addition, hard coated surfaces require sufficient cleaning particle flow and power. Sandblasting might not be applied to the inner surfaces of the grid, as it causes deformation. Any changes to the grid geometry might adversely affect the IBS deposition process. Even small changes in geometry, caused by manual cleaning require additional calibrations of IBS coating system. This leads to increased production costs. Low-impact laser cleaning completely solves these problems. Finally, sandblasting requires a separate equipped room with adequate noise and dust insulation. For manual and laser cleaning, all that is required is a work table and a suitable hood.

Table 1. Comparison of time required for different cleaning methods of IBS grids.

Cleaning method	Time (hours)
Manual cleaning	<16
Sandblasting	<4
Laser cleaning	<2

3.3 Long-term laser processing

One of the most significant advantages of laser cleaning is the very limited influence, so that it becomes possible to successfully remove small microparticles without damaging the substrate [5, 29]. The damage threshold is higher at longer wavelength since the beam reflectivity at the metal surface increases with increasing wavelength [5], making the 1064 nm wavelength effective for laser cleaning. Since in our laser cleaning single pass was sufficient to completely remove the coating from the grid surface, it was impossible to establish the rate of removal of the substrate metal. Therefore, a long (1200 cycles) laser processing was carried out for the substrate material. For this, an area of the back side of the IBS grid was selected that had not been previously manually cleaned.

Usually the IBS grid is made of molybdenum. Damage thresholds for a molybdenum mirror irradiated by a pulsed ytterbium-fiber laser with a pulse width of 120 ns and repetition rate of 20 kHz were $F_{sp} = 6.46$ J/cm^2 and $F_{mp} = 3.1$ J/ cm^2 for a single pulse and multiple pulses, respectively [24]. In this work, we used the energy density of up to 3.82 J/cm^2, leading in the removal of ~20 µm uncoated molybdenum after 1200 passes (Fig. 11). Hence, the molybdenum removal rate of less than 20 nm in a single pass can be estimated.

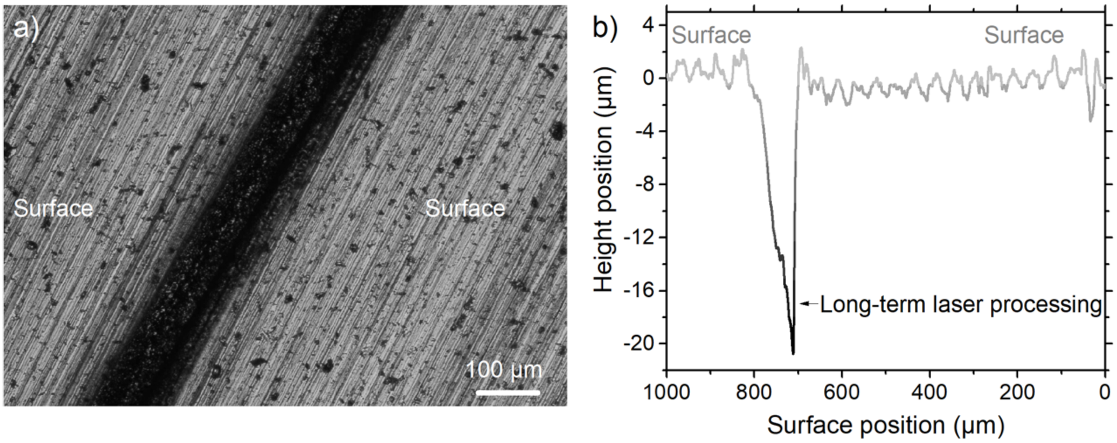

Fig. 10. A groove after long (1200 cycles) laser processing of an uncoated IBS grid surface under a) an optical microscope and b) profilometer.

3.4 Investigation of pulse power and repetition rate effect to the cleaning surface

Investigation of various laser parameters (pulsed power and repetition rate) was done on magnetron sputtering (MS) coated substrate shutter. The shutter is made from stainless steel. The photo before and after cleaning is shown in Fig. 11.

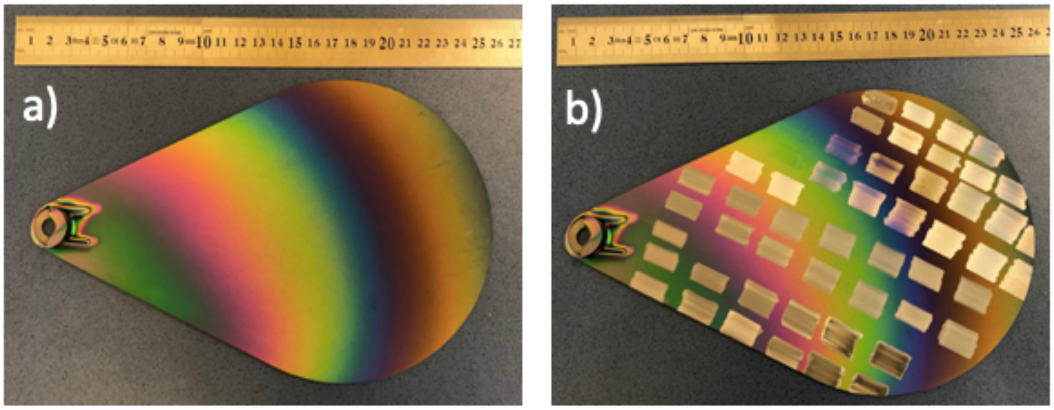

Fig. 11. Substrate holder shutter a) before and b) after laser cleaning with various parameters.

For a more detailed investigation, test areas were analyzed by optical microscope with a high magnification (Fig. 12). In this case, the sample was processed using fixed laser repetition rate of 100 kHz, scanning speed of 8 m/s, varying laser pulse power from 0.005 mJ to 2 mJ with a step of 0.025 mJ. Two scanning passes were done for each test area. Pulse energy of 0.005 mJ was sufficient to remove coating from the shutter. Pulse energy higher than 1.1 mJ resulted in thermal damage to shutter base material.

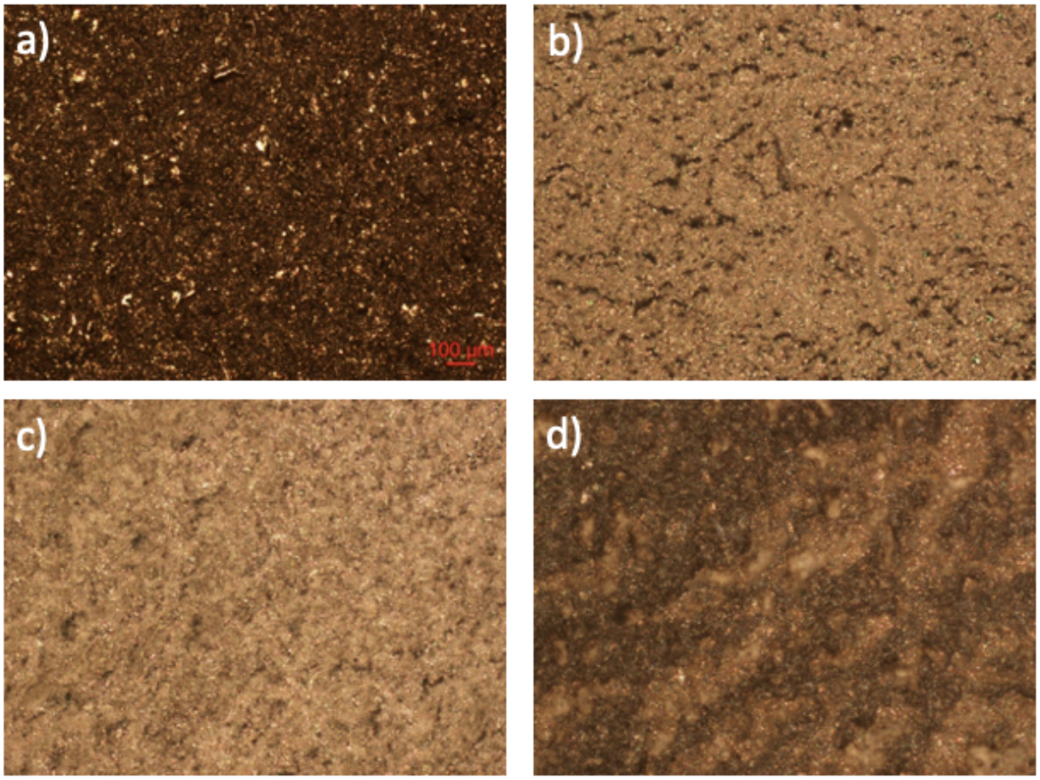

Fig. 12. Comparison of using different pulse power: a) untreated coated surface, b) after cleaning with pulse power of 0.005 mJ, c) after cleaning with pulse power of 0.7 mJ, d) after cleaning with pulse power of 1.1 mJ. All figures are in the same scale (5x magnification).

Investigation of laser clearing of MS coated substrate shutter using variously repetition rate was compared in Fig. 13. In this case, the sample was processed using fixed laser pulse energy of 0.6 mJ, scanning speed of 8 m/s, varying laser repetition rate from 25 kHz to 220 kHz with a step of 15 kHz. Two scanning passes were done for each test area. As seen in Fig. 13, repetition rate has minor influence in surface cleaning quality.

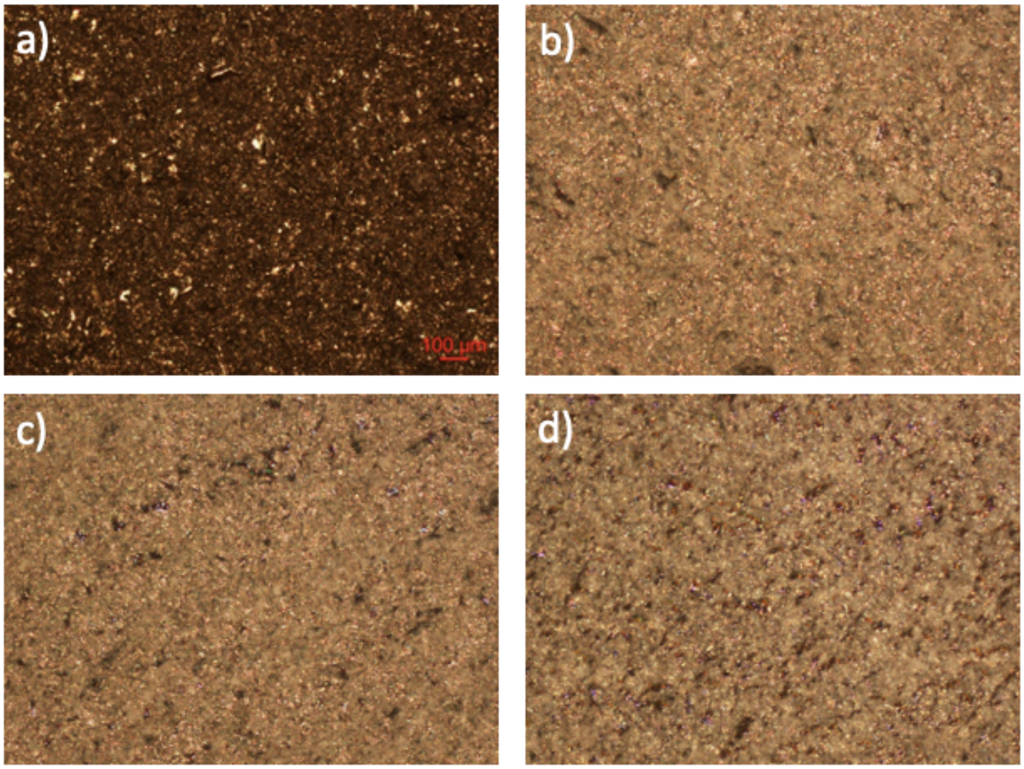

Fig. 13. Comparison of using different laser repetition rate: a) untreated coated surface, b) after cleaning with repetition rate of 25 kHz, c) after cleaning with repetition rate of 100 kHz, d) after cleaning with repetition rate of 220 kHz. All figures are in the same scale.

4. Main results and conclusions

Efficient cleaning of the IBS grid and MS substrate shutter surface using a nanosecond fiber laser is demonstrated. This technique ensures a significant reduction of 2 to 8 times in cleaning time compared to traditional methods such as manual cleaning and sandblasting. During MS shutter cleaning it was found that the repetition rate in range of 25-220 kHz has minor influence in cleaning quality. The time and efficiency should be tuned by the laser power. The effect of laser cleaning on the surface of the metal substrate is minimized, providing extended lifetime for expensive IBS grids. In addition, maintaining the precise geometry of the metal parts eliminates the need to recalibrate the coating system. Thus, laser cleaning can be successfully applied to quickly and safely remove deposits in optical coating technology.

Acknowledgment

I would like to thank Optical Coating Laboratory and Solid State Laser Laboratory at the Center for Physical Sciences and Technology (Vilnius, Lithuania). Main results were published in paper: Belosludtsev A., Bitinaitis I., Baltrušaitis K., Rodin A. M. *Investigation of the laser cleaning process for IBS grids in optical coating technology*. Int J Adv Manuf Technol (2021) doi.org/10.1007/s00170-021-07035-0

References

[1] J.R. Lawrence, Advances in laser materials processing: technology, research and applications, Woodhead Publishing, 2017.

[2] A.J. López, J. Lamas, J.S. Pozo-Antonio, T. Rivas, A. Ramil, Development of processing strategies for 3D controlled laser ablation: Application to the cleaning of stonework surfaces, Opt. Lasers Eng. 126 (2020) 105897, https://doi.org/10.1016/j.optlaseng.2019.105897.

[3] Y. Lu, L. Yang, M. Wang, Y. Wang, Improved thermal stress model and its application in ultraviolet nanosecond laser cleaning of paint, Appl. Opt. 59 (2020) 7652–7659, https://doi.org/10.1364/ao.398101.

[4] E. Büchter, A Green Way to Clean—Laser Cleaning: Compact laser systems for industrial cleaning, coating removal and surface preparation, Laser Tech. J. 9 (2012) 36–38, https://doi.org/10.1002/latj.201290068.

[5] J.M. Lee, C. Curran, K.G. Watkins, Laser removal of copper particles from silicon wafers using UV, visible and IR radiation, Appl. Phys. A. 73 (2001) 219–224, https://doi.org/10.1007/s003390100685.

[6] Y. Ye, X. Yuan, X. Xiang, W. Dai, M. Chen, X. Miao, H. Lv, H. Wang, W. Zheng, Laser plasma shockwave cleaning of SiO2 particles on gold film, Opt. Lasers Eng. 49 (2011) 536–541, https://doi.org/10.1016/j.optlaseng.2010.12.006.

[7] J. Marczak, A. Koss, P. Targowski, M. Góra, M. Strzelec, A. Sarzyński, W. Skrzeczanowski, R. Ostrowski, A. Rycyk, Characterization of laser cleaning of artworks, Sensors. 8 (2008) 6507–6548, https://doi.org/10.3390/s8106507.

[8] M. Cooper, Laser cleaning in conservation: an introduction, Butterworth-Heinemann Oxford, 1998.

[9] P. Mazzinghi, F. Margheri, A short pulse, free running, Nd: YAG laser for the cleaning of stone cultural heritage, Opt. Lasers Eng. 39 (2003) 191–202, https://doi.org/10.1016/S0143-8166(01)00133-6.

[10] T. Shi, C. Wang, G. Mi, F. Yan, A study of microstructure and mechanical properties of aluminum alloy using laser cleaning, J. Manuf. Process. 42 (2019) 60–66, https://doi.org/10.1016/j.jmapro.2019.04.015.

[11] B. Lukiyanchuk, Laser Cleaning: Optical Physics, Applied Physics and Materials Science, World Scientific, 2002.

[12] D.M. Kane, Laser cleaning II, World Scientific, 2006.

[13] C. Zhou, H. Li, G. Chen, G. Wang, Z. Shan, Effect of single pulsed picosecond and 100 nanosecond laser cleaning on surface morphology and welding quality of aluminium alloy, Opt. Laser Technol. 127 (2020) 106197, https://doi.org/10.1016/j.optlastec.2020.106197.

[14] V. Veiko, A. Samohvalov, E. Ageev, Laser cleaning of engraved rolls coupled with spectroscopic control, Opt. Laser Technol. 54 (2013) 170–175, https://doi.org/10.1016/j.optlastec.2013.05.015.

[15] A. Uccello, A. Maffini, D. Dellasega, M. Passoni, Laser cleaning of pulsed laser deposited rhodium films for fusion diagnostic mirrors, Fusion Eng. Des. 88 (2013) 1347–1351, https://doi.org/10.1016/j.fusengdes.2013.01.036.

[16] A. Maffini, A. Uccello, D. Dellasega, V. Russo, S. Perissinotto, M. Passoni, Laser cleaning of diagnostic mirrors from tokamak-like carbon contaminants, J. Nucl. Mater. 463 (2015) 944–947, https://doi.org/10.1016/j.jnucmat.2014.10.016.

[17] Y. Zhou, L. Zheng, Y.G. Li, L.C. Li, C.Z. Li, Y.M. Jiao, Z.C. Deng, G. Zhao, H. Gao, Q.W. Yang, Development of carbon deposits cleaning technique for metallic mirrors in HL-2A, J. Nucl. Mater. 415 (2011) S1206–S1209, https://doi.org/10.1016/j.jnucmat.2010.12.009.

[18] M. Mosbacher, V. Dobler, M. Bertsch, H.-J. Münzer, J. Boneberg, P. Leiderer, Laser cleaning of silicon wafers: prospects and problems, in: Kash L. Mittal (Eds.), Surface Contamination and Cleaning, CRC Press, 2003.

[19] X. Jia, Y. Zhang, Y. Chen, H. Wang, G. Zhu, X. Zhu, Laser cleaning of slots of chrome-plated die, Opt. Laser Technol. 119 (2019) 105659, https://doi.org/10.1016/j.optlastec.2019.105659.

[20] M.S. Raza, S.S. Das, P. Tudu, P. Saha, Excimer laser cleaning of black sulphur encrustation from silver surface, Opt. Laser Technol. 113 (2019) 95–103, https://doi.org/10.1016/j.optlastec.2018.12.012.

[21] G.X. Chen, T.J. Kwee, K.P. Tan, Y.S. Choo, M.H. Hong, Laser cleaning of steel for paint removal, Appl. Phys. A. 101 (2010) 249–253, https://doi.org/10.1007/s00339-010-5811-0.

[22] Y. V Kravchenko, S.M. Klimentov, S.I. Derzhavin, D.N. Mamonov, N. V Karpov, A.N. Mayorov, Optimization of laser cleaning conditions using multimode short-pulse radiation, Opt. Quant. Electron. 52 (2020) 280, https://doi.org/10.1007/s11082-020-02399-1.

[23] M.P. Mateo, T. Ctvrtnickova, E. Fernandez, J.A. Ramos, A. Yanez, G. Nicolas, Laser cleaning of varnishes and contaminants on brass, Appl. Surf. Sci. 255 (2009) 5579–5583, https://doi.org/10.1016/j.apsusc.2008.08.034.

[24] A. Leontyev, A. Semerok, D. Farcage, P.-Y. Thro, C. Grisolia, A. Widdowson, P. Coad, M. Rubel, J.-E. contributors, Theoretical and experimental studies on molybdenum and stainless steel mirrors cleaning by high repetition rate laser beam, Fusion Eng. Des. 86 (2011) 1728–1731, https://doi.org/10.1016/j.fusengdes.2010.12.068.

[25] C. Bundesmann, H. Neumann, Tutorial: The systematics of ion beam sputtering for deposition of thin films with tailored properties, J. Appl. Phys. 124 (2018) 231102, https://doi.org/10.1063/1.5054046.

[26] H.R. Kaufman, J.J. Cuomo, J.M.E. Harper, Technology and applications of broad-beam ion sources used in sputtering. Part I. Ion source technology, J. Vac. Sci. Technol. 21 (1982) 725–736, https://doi.org/10.1116/1.571820.

[27] M. Becker, M. Gies, A. Polity, S. Chatterjee, P.J. Klar, Materials processing using radio-frequency ion-sources: Ion-beam sputter-deposition and surface treatment, Rev. Sci. Instrum. 90 (2019) 23901, https://doi.org/10.1063/1.5063976.

[28] I. Zagoranskiy, P. Lorenz, M. Ehrhardt, K. Zimmer, Guided self-organization of nanodroplets induced by nanosecond IR laser radiation of molybdenum films on sapphire, Opt. Lasers Eng. 113 (2019) 55–61, https://doi.org/10.1016/j.optlaseng.2018.10.005.

[29] C. Seo, H. Shin, D. Kim, Laser removal of particles from surfaces, in: K.L. Mittal Wei-Sheng Lei (Eds.), Laser Technology: Applications in Adhesion and Related Areas, Scrivener Publishing LLC, 2018, pp. 379–415.

[30] Brikas, M. (2011). Silicio ir metalų mikroapdirbimas didelio impulsų pasikartojimo dažnio pikosekundiniais lazeriais: daktaro disertacija. Vilniaus universitetas. Nacionalinė Lietuvos akademinė elektroninė biblioteka.

[31] H. Mustafa, D.T.A. Matthews, G.R.B.E. Römer, The role of pulse repetition rate on picosecond pulsed laser processing of Zn and Zn-coated steel,
in: Optics & Laser Technology, Volume 131 (2020) 106408, https://doi.org/10.1016/j.optlastec.2020.106408
[32] Schnell, G., Duenow, U. and Seitz, H., 2020. Effect of laser pulse overlap and scanning line overlap on femtosecond laser-structured Ti6Al4V surfaces. *Materials*, *13*(4), p.969.

[33] M Hashida, A.F Semerok, O Gobert, G Petite, Y Izawa, J.F- Wagner, Ablation threshold dependence on pulse duration for copper, Applied Surface Science, Volumes 197–198 (2002), Pages 862-867, https://doi.org/10.1016/S0169-4332(02)00463-4.

[34] Hipp, Dominik & Mahrle, Achim & Beyer, Eckhard. (2019). Beyond Fresnel: Absorption of fibre laser radiation on rough stainless steel surfaces. Journal of Physics D Applied Physics. 52. 355302. 10.1088/1361-6463/ab2415.

[35] Arvi Kruusing, Underwater and water-assisted laser processing: Part 1—general features, steam cleaning and shock processing, Optics and Lasers in Engineering, Volume 41, Issue 2 (2004), Pages 307-327, https://doi.org/10.1016/S0143-8166(02)00142-2.

[36] M.She, D.Kim, C.P.Grigoropoulos: J. Appl. Phys. 86(11), 6519 (1999), https://doi.org/10.1063/1.371617

[37] A.Y. Vorobyev, Chunlei Guo, Femtosecond laser structuring of titanium implants, Applied Surface Science, Volume 253, Issue 17, (2007), Pages 7272-7280, https://doi.org/10.1016/j.apsusc.2007.03.006.

[38] Chichkov, B.N., Momma, C., Nolte, S. *et al.* Femtosecond, picosecond and nanosecond laser ablation of solids. Appl. Phys. A 63**,** 109–115 (1996). https://doi.org/10.1007/BF0156763
[39] Le Harzic, R.; Huot, N.; Audouard, E.; Jonin, C.; Laporte, P.; Valette, S.; Fraczkiewicz, A.; Fortunier, R. Comparison of heat-affected zones due to nanosecond and femtosecond laser pulses

using transmission electronic microscopy. Appl. Phys. Lett. 80 (2002), 3886–3888. https://doi.org/10.1063/1.1481195

[40] S. Siano, J. Agresti, I. Cacciari, D. Ciofini, M. Mascalchi, I. Osticioli, A.A. Mencaglia, Laser cleaning in conservation of stone, metal, and painted artifacts: state of the art and new insights on the use of the Nd:YAG lasers, Applied Physics A (2012) 106:419–446

[41] G. X. Chen, T. J. Kwee, K. P. Tan, Y. S. Choo, M. H. Hong, High-Power Fibre Laser Cleaning for Green Shipbuilding, JLMN-Journal of Laser Micro/Nanoengineering Vol. 7, No. 3, 2012

[42] Razab, Mohammad Khairul Azhar Abdul, et al. "Influence of elemental compositions in laser cleaning for automotive coating systems." Journal of Russian Laser Research 37.2 (2016): 197-206.

[43] Ye, Y., Jia, B., Chen, J., Jiang, Y., Tang, H., Wang, H., Luan, X., Liao, W., Zhang, C. and Yao, C., 2017. Laser cleaning of the contaminations on the surface of tire mould. International Journal of Modern Physics B, 31(16-19), p.1744100. https://doi.org/10.1142/S0217979217441008

[44] Veiko, V. P., et al. "Laser cleaning of metal surfaces: physical processes and applications." Fundamentals of laser assisted micro-and nanotechnologies. Vol. 6985. International Society for Optics and Photonics, 2008.

Investigation of the laser cleaning process for IBS grids in optical coating technology

Abstract: This work describes the process of laser cleaning of an Ion-Beam Sputtering (IBS) grid and magnetron sputtering (MS) substrates shutter as an alternative to manual cleaning and sandblasting in terms of the surface morphology, roughness and speed. It has been demonstrated that processing with a nanosecond fiber laser might be applied for the controlled cleaning of complex grid surfaces at high speed and low surface impact that is important for longer lifetime of expensive parts. Thus, laser cleaning can be successfully applied to quickly and safely remove deposits in optical coating technology. Under optimal processing conditions in a single pass, the scanning speed in the focal plane was 8 m/s at a laser pulse energy of 0,3 mJ, a pulsewidth of 120 ns at a repetition rate of 100 kHz.

Dielektrinių dangų nusėdančių ant jonapluoščio dulkinimo įrenginyje naudojamų gardelių šalinimo lazerinės abliacijos metodu eksperimentinis tyrimas

Santrauka: Šiame tyrime buvo ištirtas efektyvus dielektrinių dangų šalinimo metodas nuo jonapluoščio dulkinimo įrenginiuose (IBS) naudojamų gardelių bei nuo magnetroninio dulkinimo (MS) įrenginyje naudojamų sklendžių, naudojant nanosekundinių impulsų skaidulinę lazerinio valymo sistemą. Ši technologija leidžia pasiekti ženkliai didesnį gardelių valymo greitį lyginant su tradiciniais metodais kaip rankinis poliravimas ar abrazyvinis valymas. Daugkartinio proceso atžvilgiu lazerinio valymo technologija leidžia sumažinti gardelės paviršiaus pažaidą išsaugant jos erdvinę struktūrą, taip prailginant brangių gardelių naudojimo resursą. Gardelių erdvinės struktūros išsaugojimas taip pat sumažina IBS optinių dangų dengimo sistemos kalibracijos poreikį po gardelių valymo proceso, užtikrina stabilesnį įrangos darbą. Lazerinis valymas yra tinkama technologija greitam ir kokybiškam dielektrinių dangų pašalinimui nuo įvairių formų gardelių lazerinei sistemai tenkinant 0,3 mJ impulso energijos, 120 ns impulso trukmės, 100 kHz pasikartojimo dažnio bei 8 m/s skenavimo greičio židinio plokštumoje parametrus.