Lasers in Manufacturing Conference 2023

Investigation of laser-based biofouling cleaning underwater and the influence of water flow on removal behavior

Stanislav Zimbelmann[a,*], Benjamin Emde[a], Markus Baumann[b], Tim Heusinger von Waldegge[c], Dorothea Stübing[c], Jörg Hermsdorf[a]

[a]*Laser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hannover, Germany*
[b]*Laserline GmbH, Fraunhofer Straße 5, 56218 Mülheim-Kärlich, Germany*
[c]*Fraunhofer-Institut für Fertigungstechnik und Angewandte Materialforschung IFAM, Wiener Straße 12, 28359 Bremen, Germany*

Abstract

The settlement of marine organisms on a ship's hull can significantly affect its operational costs. The growth of these fouling organisms leads to the spread of invasive species, an increased drag caused by water friction, higher fuel consumption and a corresponding increase in greenhouse gas emissions. Hence, it is crucial to either prevent or remove biofouling. Traditional cleaning methods which are performed in situ underwater have some ecological and regulatory drawbacks.
These negative consequences of fouling form the framework for the development of a laser-based underwater ship cleaning system, whose interaction between laser radiation and its lethal effect on biofouling is investigated in this work. Biofouling samples from the North Sea were irradiated underwater in a functional demonstrator. The post-treatment detachment behaviour of the biofouling was investigated for different coating systems at laboratory scale using a hydrodynamic flow cell, which simulates ship movement at speeds of up to 9.3 knots.

Keywords: blue Laser, under water, shipp hull, cleaning, Biofouling, water flow

1. Introduction

Biofouling refers to the unwanted formation of biological layers on technically relevant surfaces under water. If a surface is exposed to natural conditions in seawater, a biofilm forms after a short time. This leads to considerable problems, especially in shipping. The contamination of the ship's hull increases the overall weight of the vessel, and the roughness leads to an increase in water resistance. This lengthens transport times and increases energy consumption [1–4]. For this reason, antifouling coatings are often used in shipbuilding, which offer limited protection against fouling. Therefore, additional mechanical cleaning procedures are used periodically [5].

Traditionally, fouling removal on larger vessels is achieved by using brushes that make direct contact with the surface of the hull. Additional methods include the utilization of rotating blades, which generate a lifting shear force above the hull surface without direct contact, as well as high-pressure water jets and cavitation water jets. These techniques aim to mitigate the negative impacts of abrasion on antifouling coatings, extending their lifespan and reducing the release of biocides into the water environment. Due to the frequent removal of coating material during the cleaning process, it is necessary to collect the process water and the removed biomaterial in order to prevent environmental pollution. [6]. A more expensive alternative to in-situ cleaning of the ship's hull underwater is the cleaning in dry dock. This method is performed when the ship undergoes a comprehensive examination in dry dock, typically occurring approximately every five years after delivery. Restricting the ability to conduct in-water cleaning can impose a substantial financial burden on the shipping industry, resulting in heightened fuel and personnel costs, expensive dry-docking expenses, as well as income loss during relocation and docking periods [7].

Various studies have already demonstrated the damaging effects of laser radiation on biofilms and cells in a water environment. These investigations focused on the sublethal/lethal influence of different laser radiation types, including ultraviolet (UV) radiation [8], visible radiation (VIS) [9–18], and near-infrared radiation [19]. Pulsed laser radiation with long exposure durations was frequently used, primarily to examine the fundamental impact of the radiation on organisms. Previous approaches addressed the fundamental harm caused to organisms in a aquatic environment but did not consider the combination of high-power lasers' efficacy and the preservation of existing material protection coatings, which is crucial for industrial applications.

The author's research has already shown that by determining the destruction thresholds of conventionally used antifouling coatings, no damage is caused to the coating by laser treatment [20]. Furthermore, it has already been proven that both microorganisms in the water [21] and biofouling on coating samples can be lethally damaged by laser irradiation, resulting in a cleaning effect [22]. Current studies from other research-groups deal with laser-induced ablation of surface layers under water [23, 24]. However, the actual research goal differs significantly, as the results indicate that a complete removal of all layers down to the bare metal takes place. In this paper, the main objective is to consider the influence of water flow under dynamic conditions, in addition to the proven lethal damage to the fouling and the resulting time-delayed cleaning effect, and to derive initial conclusions from this.

2. Experimental setup

First, the experimental setup is described in which the biofouling samples were irradiated under water with a blue laser. Figure 1 shows a schematic illustration of the setup on the left-hand side. The samples were moved with a sample holder inside the water tank in z- and x-direction. The blue diode laser source from Laserline emits radiation at a wavelength of 448 nm with a maximum power of 1.5 kW. To couple the laser beam from the air into the water, a processing head with a protection window were used. The processing optics form a line-shaped focus with adjustable line widths to create different power densities. The working distance between the processing head and the sample surface correspond to the distance the laser passes through the water. This value of 50 mm was the same for all experiments. The right side of the figure shows the process in lateral view, with the laser radiation in an on and off state.

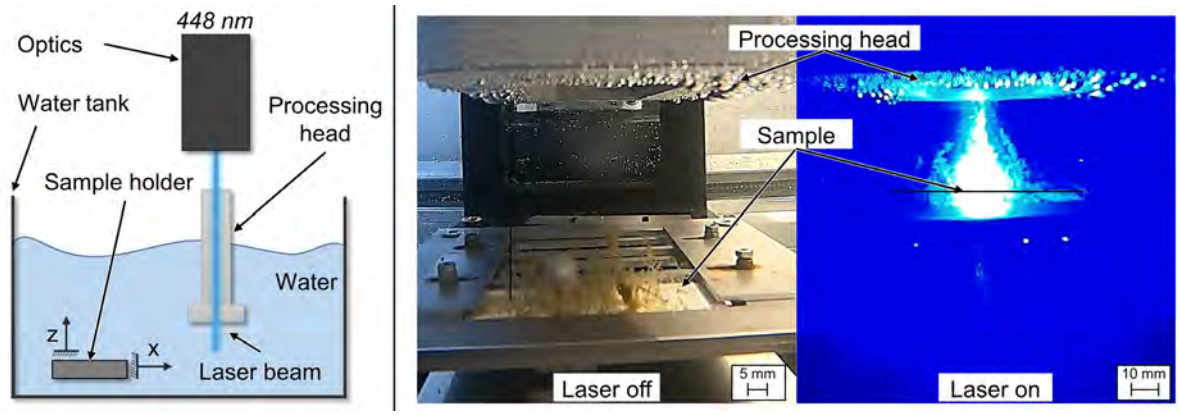

Fig. 1. Left - Schematic experimental setup. Right - Side view during the process with the laser radiation switched off and on. The coating sample with biofouling on the surface is clearly visible.

The preparation of the fouling samples plays a crucial role in the investigations. To achieve this, glass slides measuring 76 mm x 26 mm were coated with a red fouling-release coating. These coated slides were then placed in seawater under natural conditions, allowing biofouling to grow on their surfaces. The accompanying figure 2 depicts a floating pontoon, which features a central opening where the biofouling samples can be suspended in the water. Over the course of several weeks to months, the samples become covered with biofouling, as illustrated in the right-side sample frame in figure 2.

Fig. 2. Left - Swimming pontoon in the North Sea with a hole inside where sample racks can be stored underwater. Right - biofouling samples in the sample frame after an immersion period of several weeks.

In a future application, the biofouling, which has been lethally damaged by the laser irradiation, is to be sheared off in the water as a result of the sailing resistance. To simulate the motion of a ship and the resulting water flow on a laboratory scale, a flow cell was designed and constructed by the Fraunhofer IFAM. The frequently cited flow cell by Schulz *et al.* from 2000 served as a reference for the concept [25]. The structure of the flow cell is shown in figure 3. To ensure the targeted flow rates, the water is fed into the channel using a centrifugal pump. Control of the water flow is enabled by valves and flow meters. A settling chamber is used

to remove potential solid particles. Up to 6 samples can be placed in the test section and held in place by negative pressure while exposed to the water flow.

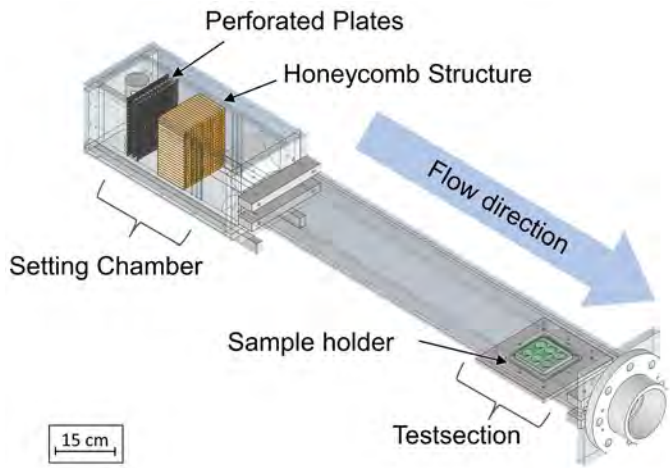

Fig. 3. Setup of the flow cell ©IFAM

The results obtained in the study [22] showed that the cleaning effect of the laser irradiation occurs with a time delay. For this reason, different sample stages are compared with each other and evaluated. To illustrate the stages, a schematic overview of the documentation process is shown in figure 4. State ① shows the biofouling after storage in the North Sea. The duration of this storage varies from two weeks to several months, depending on the degree of fouling to be investigated. After the irradiation of the fouling samples, the condition ② is recorded to document the state of biofouling immediately after the laser irradiation in the experimental setup shown in figure 1. The irradiated sample is then stored back in the North Sea and taken again after an interval of two weeks. This condition represents the actual time-delayed stationary cleaning success ③. In some test series, the samples are additionally flushed with water in the flow cell to simulate the movement of the ship and the resulting water flow. The final dynamic cleaning effect is then documented ④.

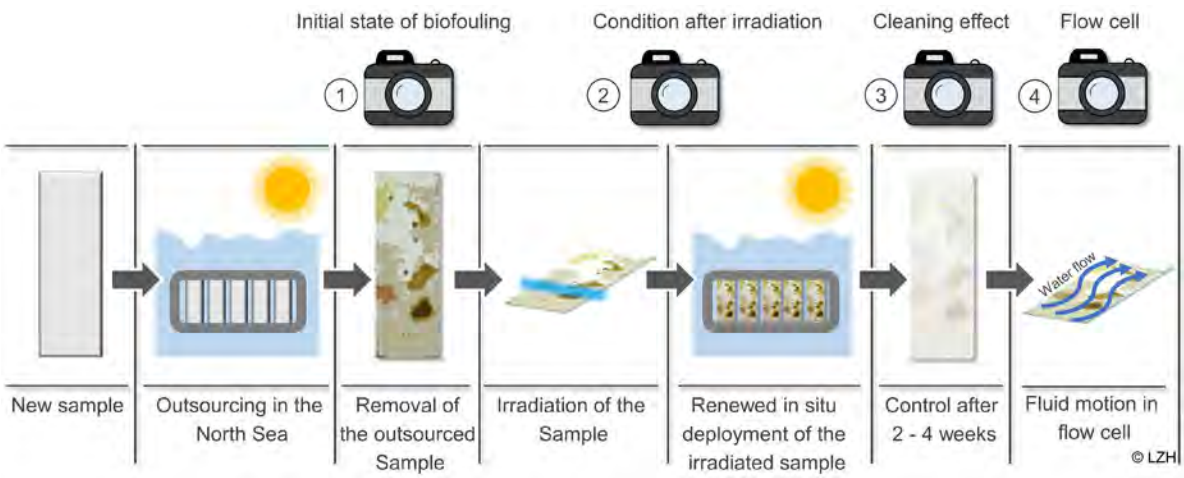

Fig. 4. Schematic illustration of the experimental procedure and the four different stages of documentation.

3. Results

3.1. Cleaning effect under static immersion conditions

The cleaning performance under static immersion conditions, state ③, is illustrated below using a series of tests and illustrated in figure 5. Different feed rates at maximum power density were used as parameters. In the initial state ①, the coating samples show clear growth of biofouling. The composition of the different species varies depending on the sample. In addition to a variety of sea squirts, sponges, hydrozoans and a general biofouling film are also detected. These species are assigned to the soft fouling group in biology. Hard fouling organisms such as barnacles can occasionally be observed. Hard fouling poses a significant problem in shipping because these organisms have a strong adhesive force and are difficult to remove with conventional cleaning methods.

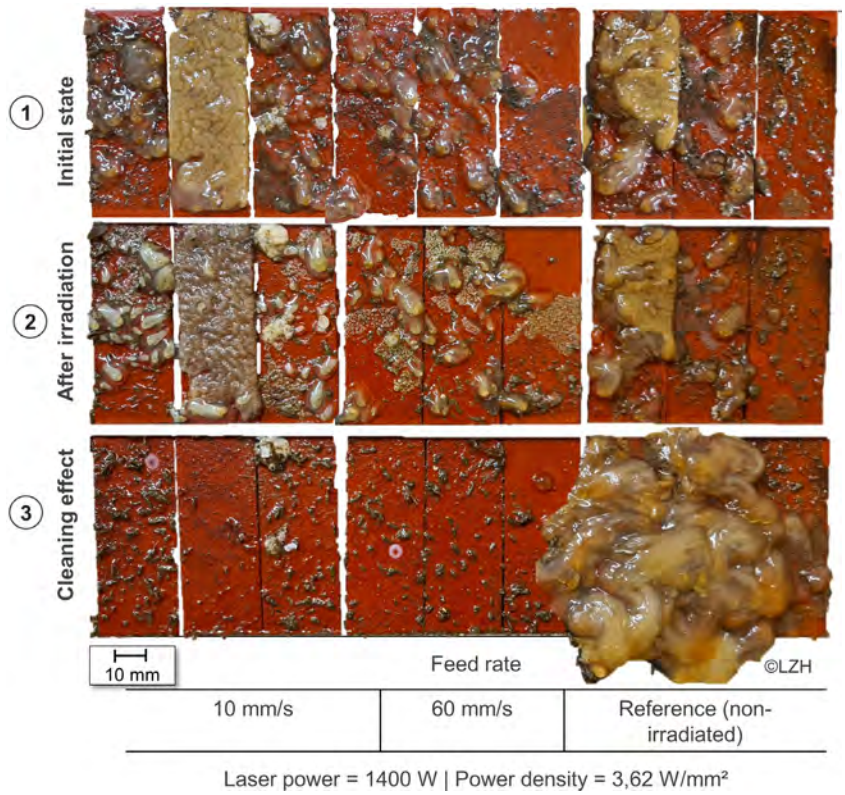

Fig. 5. Test series with fouling-release coating (FRC) at maximum power density with different feed rates for the blue laser source. The circled numbers indicate the documentation status, which was defined in figure 4.

Directly after irradiation with blue laser radiation ②, a clear change in the soft fouling organisms can be perceived. In general, a colour change can be detected, which has a bleaching effect. This means that brown and green tones become significantly lighter and partly take on a white shade. In addition, transparent and milky structures lose their transparency and also take on a white hue. The hard fouling organisms do not show any external changes. However, the general degree of biofouling remains identical directly after irradiation.

The results of a renewed storage in the North Sea of two weeks of the irradiated samples and the non-irradiated reference, state③, are shown in figure 5. Soft fouling as well as hard fouling in the form of barnacles are lethally damaged by the laser irradiation and partly detach from the sample surface under static storage conditions. It is also noticeable that all barnacles still on the sample have not grown and are partly empty from the inside. The influence of the feed rate shows a comparable cleaning performance at 10 mm/s and 60 mm/s. The coating itself shows no degradation or other damage effects as a result of the irradiation, as the laser parameters for the tests were chosen below the destruction threshold of the coating. The reference samples show clear growth and an increase in biofouling.

3.1. Cleaning effect under dynamic immersion conditions in the flow cell

In addition to the cleaning effect under static aging conditions, the following series of tests focused on the influence of a water flow in the flow cell. This makes it possible to simulate a dynamic removal of the lethally

damaged biofouling. In addition, for this series of tests, mainly samples with hard fouling in the form of barnacles were irradiated (see figure 6), since these have particularly strong adhesive forces. The detachment behaviour in combination with dynamic flow conditions was of particular importance. The interim result with the time-delayed cleaning effect under static conditions ③ is already clear, analogous to the previous series of tests. The soft fouling as well as the hard fouling are effectively lethally damaged by the irradiation. On the samples considered, 100 % of the barnacles are lethally damaged for all feed rates and a large part of the soft fouling has died. Furthermore, the biofouling generally loses its adhesive properties, so that it falls off even under static aging conditions.

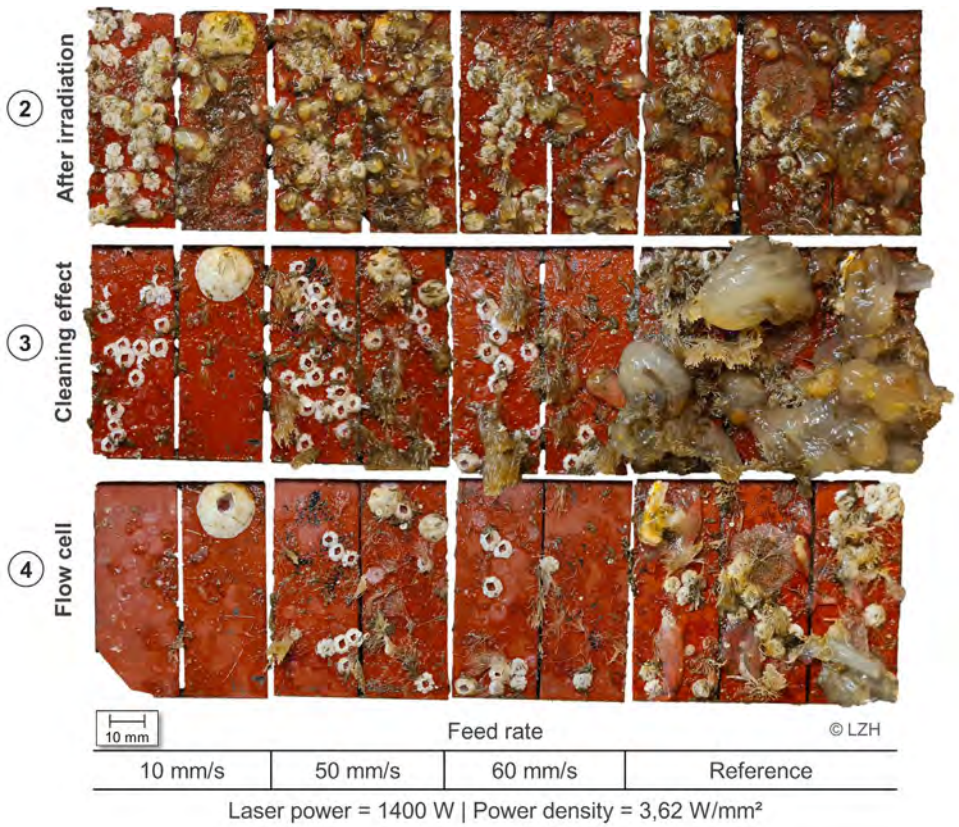

Fig. 6. Results of irradiation of FRC coatings with subsequent re-aging and a final overflow in the flow cell. Comparison of different feed rates. The circled numbers indicate the documentation time point, which was defined in Figure 4.

A clearer development is seen when the samples in the flow cell are flown with water at a flow rate of 9.3 kn (5.1 m/s) for two minutes, condition ④. The speed is not very fast and corresponds to the normal speed of ships. This initial flow is enough to rinse off further barnacles and soft fouling. The effectiveness of the irradiation is particularly clear when compared to the reference samples. In all three reference samples, all barnacles continue to attach to the surface after the tests in the flow cell. In the irradiated samples, on the other hand, a large part of the barnacles could be removed, and in one sample even all of them.

4. Discussion

The lethal damage to the biofouling initiated by the laser irradiation and an associated cleaning effect can be clearly verified based on the experimental data. Initial results in this direction were already obtained in previous work [21, 22]. Based on these results, this study was able to confirm and expand upon the previous conclusions. Samples with more intensive biofouling growth and greater species diversity were irradiated. In addition to soft fouling, which included sea squirts, sponges, hydrozoans and biofilms, this study also irradiated samples with hard fouling organisms such as barnacles. All these organisms were found to be lethally damaged by laser irradiation.

The colour change of the soft fouling organisms allows conclusions to be drawn about the underlying mechanism of action. The high-energy laser irradiation can cause the pigments present in the cells to reach a saturation point due to the excessive power and energy density, at which they become damaged by the photodestructive properties of the pigments, triggering a colour change. Since the pigments fulfil many different vital functions in the cells and thus in the entire organism, this could be a cause of the lethal damage together with a variety of other factors.

The barnacles remaining on the sample surface after laser irradiation do not show further growth during the renewed in situ period. Furthermore, some of the barnacles are hollow from the inside and only the calcareous skeleton remains. This suggests that these individuals were also fatally injured, resulting in an almost 100% mortality rate. Looking at the dynamic tests in the flow cell, it is clear that a large proportion of the barnacles were lethally damaged, reducing their adhesive force and causing them to detach from the sample surface.

The experiments in the flow cell have shown that by simulating the drag of a ship under water, the cleaning effect tends to be enhanced, especially in the case of hard fouling. However, it has to be mentioned as a limitation that fouling on ships is usually formed under dynamic conditions and therefore the compositions basically differ in some aspects from the fouling formed under static deposition conditions. Nevertheless, especially the results for hard fouling, which is particularly problematic in shipping, show that the approach and the effect of the method are target-oriented and represent promising results for future application.

5. Conclusion

In this work, the lethally damaging effect of laser radiation (448 nm) on biofouling and the resulting time-delayed cleaning effect were investigated. Samples with a more pronounced biofouling growth and a greater variety of species were subjected to irradiation. In addition to soft fouling, which included sea squirts, sponges, hydrozoans and biofilms, samples with hard fouling organisms such as barnacles were also irradiated in this study. All these organisms were found to be lethally damaged by laser irradiation. The main results of this study can be summarised in the following key points:

- Immediately after irradiation, no cleaning effect is visible. However, the soft fouling shows a change in colour in particular, in which the intensity is reduced and a bleaching effect occurs. The colour change is an indication of damage to photodestructive pigments within the cells.
- After a renewed immersion of the irradiated samples for two weeks in the North Sea, the lethal effect on the organisms can be observed. The adhesion forces are weakened and a large part of the biofouling detaches from the surface. This is especially the case for the otherwise so resistant hard fouling such as barnacles.
- The remaining barnacles on the sample surface do not exhibit any growth during the subsequent aging period. Some barnacles are even hollow inside, with only the calcareous skeleton remaining.

These observations suggest that these individuals were also lethally damaged, achieving an almost 100% mortality rate.

- Dynamic flow conditions in the flow cell prove to be effective in cleaning the lethal damaged biofouling. The water flow removes a significantly larger amount of biofouling deposits from the surface compared to static conditions.

Acknowledgement

The research presented was funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK) as part of the research project "FoulLas - Fouling Removal from Maritime Surfaces by Means of Laser Radiation under Water" under the funding code 03SX489 by the project management organisation “Forschungszentrum Jülich GmbH“. The authors would like to express their sincere thanks to the funding agencies and companies involved for their committed and productive cooperation and support.

References

[1] Maureen Callow. 1990. Ship fouling: problems and solutions. *Chemistry and Industry (London),* 5, 123–127.

[2] Rafael A. Quijada Cordova. 2019. The impact of biofouling on marine environment: a qualitative review of the current antifouling technologies.

[3] M. Bader-Eldin. 2008. *Hull roughness and antifouling paint*. Retrieved from.

[4] Maxim Candries. 2001. *Drag, boundary-layer and roughness characteristics of marine surfaces coated with antifoulings.* Department of Marine Technology. University of Newcastle upon Tyne Newcastle upon Tyne,, UK.

[5] Changhui Song and Weicheng Cui. 2020. Review of Underwater Ship Hull Cleaning Technologies. *J. Marine. Sci. Appl.* 19, 3, 415–429. DOI: https://doi.org/10.1007/s11804-020-00157-z.

[6] G. W. Swain. 2010. The importance of ship hull coatings and maintenance as drivers for environmental sustainability. In *Proceedings of RINA Conference Ship Design Operation for Environmental Sustainability. Royal Institute of Naval Architects, London*.

[7] Agamemnon Apostolidis, John Kokarakis, and Andreas Merikas. 2012. Modeling the Dry-Docking Cost-The Case of Tankers. *Journal of Ship Production and Design* 28, 3, 134–143.

[8] Bart A. Salters and Roelant B. Hietbrink. 2020. *System for anti-biofouling*. Google Patents. Retrieved from.

[9] Tiancui Li, Yonghong Bi, Jiantong Liu, and Chenxi Wu. 2016. Effects of laser irradiation on a bloom forming cyanobacterium Microcystis aeruginosa. *Environmental science and pollution research international* 23, 20, 20297–20306. DOI: https://doi.org/10.1007/s11356-016-7235-7.

[10] Kanavillil Nandakumar, Hideki Obika, Kurissery Sreekumari, Akihiro Utsumi, Toshihiko Ooie, and Tetsuo Yano. 2009. Laser damage to marine plankton and its application to checking biofouling and invasion by aquatic species: a laboratory study. *Biofouling* 25, 2, 95–98. DOI: https://doi.org/10.1080/08927010802546004.

[11] Kanavillil Nandakumar, Hideki Obika, Akihiro Utsumi, Toshihiko Ooie, and Tetsuo Yano. 2004. In vitro laser ablation of laboratory developed biofilms using an Nd:YAG laser of 532 nm wavelength. *Biotechnology and bioengineering* 86, 7, 729–736. DOI: https://doi.org/10.1002/bit.10829.

[12] Kanavillil Nandakumar, Hideki Obika, Akihiro Utsumi, Toshihiko Ooie, and Tetsuo Yano. 2004. In vitro laser ablation of natural marine biofilms. *Applied and environmental microbiology* 70, 11, 6905–6908. DOI: https://doi.org/10.1128/AEM.70.11.6905-6908.2004.

[13] Kanavillil Nandakumar, Hideki Obika, Tatsuya Shinozaki, Toshihiko Ooie, Akihiro Utsumi, and Tetsuo Yano. 2002. Impact of Pulsed Laser Irradiations from Nd:YAG Laser on the Larvae of the Fouling Barnacle Balanus amphitrite. *Biofouling* 18, 4, 257–262. DOI: https://doi.org/10.1080/08927010290032403.

[14] Kanavillil Nandakumar, Hideki Obika, Tatsuya Shinozaki, Toshihiko Ooie, Akihiro Utsumi, and Tetsuo Yano. 2002. Inhibition of bacterial attachment by pulsed Nd:YAG laser irradiations: an in vitro study using marine biofilm-forming bacterium Pseudoalteromonas carrageenovora. *Biotechnology and bioengineering* 80, 5, 552–558. DOI: https://doi.org/10.1002/bit.10416.

[15] K. Nandakumar, H. Obika, A. Utsumi, T. Ooie, and T. Yano. 2006. Molecular level damages of low power pulsed laser radiation in a marine bacterium Pseudoalteromonas carrageenovora. *Letters in applied microbiology* 42, 5, 521–526. DOI: https://doi.org/10.1111/j.1472-765X.2006.01897.x.

[16] Kanavillil Nandakumar, Hideki Obika, Tatsuya Shinozaki, Toshihiko Ooie, Akihiro Utsumi, and Tetsuo Yano. 2003. Pulsed laser irradiation impact on two marine diatoms Skeletonema costatum and Chaetoceros gracilis. *Water Research* 37, 10, 2311–2316. DOI: https://doi.org/10.1016/S0043-1354(03)00007-1.

[17] Kanavillil Nandakumar, Hideki Obika, Tatsuya Shinozaki, Toshihiko Ooie, Akihiro Utsumi, and Tetsuo Yano. 2003. Lethal and sub-lethal impacts of pulsed laser irradiations on the larvae of the fouling barnacle Balanus amphitrite. *Biofouling* 19, 3, 169–176. DOI: https://doi.org/10.1080/08927014.2003.10382979.

[18] Kanavillil Nandakumar, Hideki Obika, Tatsuya Shinozaki, Toshihiko Ooie, Akihiro Utsumi, and Tetsuo Yano. 2003. Laser impact assessment in a biofilm-forming bacterium Pseudoalteromonas carrageenovora using a flow cytometric system. *Biotechnology and bioengineering* 82, 4, 399–402. DOI: https://doi.org/10.1002/bit.10585.

[19] R. L. Wingrove. 1983. Laser removal of materials from surfaces. (Apr. 1983). Patent No. WO/1983/001400, Issued April 28th, 1983.

[20] Stanislav Zimbelmann , Benjamin Emde , Jörg Hermsdorf , Tim Heusinger von Waldegge , Dorothea Stübing , Markus Baumann , Stefan Kaierle. 2021. Interaction between laser radiation and antifouling coating underwater. *Lasers in Manufacturing Conference 2021* 2021.

[21] Stanislav Zimbelmann, Jörg Hermsdorf, and Benjamin Emde. 2022. Disinfection of water by using laser radiation. *Procedia CIRP* 111, 766–769. DOI: https://doi.org/10.1016/j.procir.2022.08.123.

[22] Stanislav Zimbelmann, Benjamin Emde, Tim H. von Waldegge, Dorothea Stübing, Markus Baumann, and Jörg Hermsdorf. 2022. Interaction between laser radiation and biofouling for ship hull cleaning. *Procedia CIRP* 111, 705–710. DOI: https://doi.org/10.1016/j.procir.2022.08.013.

[23] A. Y. Bykanova, V. V. Kostenko, and A. Y. Tolstonogov. 2020. Development of the Underwater Robotics Complex for Laser Cleaning of Ships from Biofouling: Experimental Results. *IOP Conf. Ser.: Earth Environ. Sci.* 459, 32061. DOI: https://doi.org/10.1088/1755-1315/459/3/032061.

[24] V. V. Kostenko, A. Y. Bykanova, and A. Y. Tolstonogov. 2019. Underwater Robotics Complex for Inspection and Laser Cleaning of Ships from Biofouling. *IOP Conf. Ser.: Earth Environ. Sci.* 272, 22103. DOI: https://doi.org/10.1088/1755-1315/272/2/022103.

[25] Michael P. Schultz, John A. Finlay, Maureen E. Callow, and James A. Callow. 2000. A turbulent channel flow apparatus for the determination of the adhesion strength of microfouling organisms. *Biofouling* 15, 4, 243–251. DOI: https://doi.org/10.1080/08927010009386315.