OBSERVATION OF LASER-INDUCED ABLATION IN SILICONE OIL UNDER VARYING FOCAL CONDITIONS

Thao Thi Phuong Nguyen[1]*, Rie Tanabe[2], Yoshiro Ito[3]

[1]*The University of Danang - University of Science and Technology, Vietnam*
[2]*Fukuoka Institute of Technology, Japan*
[3]*Nagaoka University of Technology, Japan*

*Corresponding author: ngtpthao@dut.udn.vn

(Received: May 17, 2025; Revised: June 20, 2025; Accepted: June 22, 2025)

DOI: 10.31130/ud-jst.2025.23(9C).540E

Abstract - We investigate the effect of focal position on laser ablation of a solid target in silicone oil using photoelasticity imaging technique. By varying the focal plane relative to the target surface, we observe distinct changes in plasma formation, shockwave behavior, and stress wave strength. Results show that the strongest mechanical effect occurs slightly above the focus, where plasma confinement enhances energy density and stress delivery. In contrast, at-focus and under-focus positions lead to weaker stress due to breakdown in the liquid. These findings offer valuable insight for optimizing under liquid-laser-ablation-based applications requiring precise mechanical control, such as laser peening, micromachining, and nanoparticle synthesis.

Key words - Under-liquid laser ablation; focal condition; plasma confining; breakdown

1. Introduction

When a high-intensity laser pulse is focused on a solid sample placed within a liquid medium, the material is ablated and plasma is generated [1]. As the plasma develops, it continues absorbing the laser energy and expands rapidly, causing a shock wave in the liquid and a mechanical impulse into the solid [2]. This technique finds applications in many fields, such as nanoparticle synthesis, micromachining, and laser shock peening. The result of the process depends not only on laser parameters but also on the liquid properties and ablation conditions [3, 4].

In many applications, precisely positioning the laser focus on the target surface is a necessary step. The focal position has a significant impact on plasma formation, energy absorption, and the strength of the induced stress [5]. Typically, the laser is focused tightly at the solid–liquid interface for maximum mechanical efficiency. However, even slight defocusing can lead to different ablation phenomena. These changes affect the shape of the ablation region and process performance, so understanding focal positioning is crucial for optimization.

Water is the most commonly used liquid for laser ablation, but organic liquids like silicone oil are also valuable due to their inert nature, which helps prevent oxidation of reactive materials [6, 7]. Investigating laser ablation in such organic liquids is essential for improving precision applications such as nanoparticle synthesis and the processing of sensitive materials. Although the effect of focal position in water has been thoroughly studied [8], similar investigations in silicone oil are still limited. Prior work has mainly focused on the characteristics of the nanoparticles produced, rather than the ablation dynamics itself. Thus, it is important to explore how focal position influences ablation in organic liquids like silicone oil [9, 10].

In this study, we report a direct observation of laser ablation of epoxy-resin immersed in silicone oil using photoelasticity imaging technique. By varying the laser focal position relative to the target surface, we analyze changes in ablation and shock wave behavior. This contributes to a better understanding of laser–material interaction in organic liquids and aids the optimization of processes like microfabrication and nanoparticle generation.

2. Experimental method

The experiment setup is shown in Figure 1.

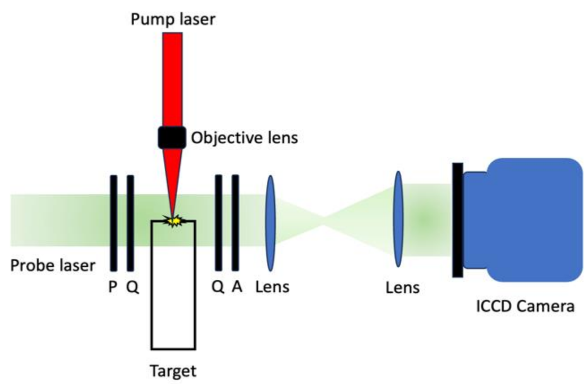

Figure 1. *Experimental setup for laser ablation and photoelasticity imaging. A pulsed laser was focused on an epoxy resin block submerged in silicone oil. Stress waves were visualized using a time-resolved photoelasticity technique with a synchronized pump-probe system (P: Polarizer, Q: Quarter wave plate, A: Analyzer)*

Laser-induced ablation was performed on solid epoxy-resin block submerged in silicone oil. A single pulsed Nd:YAG laser (λ = 1064 nm, pulse duration = 13 ns at fullwidth of half maximum (FWHM)) was focused through an objective lens on to the upper surface of an epoxy resin block. The sample surface is covered with a layer of black paint to maximize the laser absorption and is located 5 mm under the liquid-air free surface. The focal position of the laser system was identified by observing the laser-induced breakdown in air. The relative position between the solid surface and the focal point was precisely adjusted using a translation X-Y-Z stage. Three focal positions were examined: at-focus (laser focused on the target surface), under-focus (focal point located above the target surface), and above-focus (focal point located below the target surface). Each configuration was repeated at least three times to ensure repeatability, and the silicone oil was replaced regularly to minimize the influence of accumulated debris and maintain optical clarity.

Stress wave propagation were visualized using a time-resolved photoelasticity imaging technique [11]. In this arrangement, a circular polariscope made from polarizer, quarter-wave plate, and analyzers was used to convert the in-plane stress into fringe patterns. We used a pump-and-probe arrangement for time-resolved image capturing: a second fundamental Nd:YAG laser (532 nm, 6 ns pulse FWHM) illuminated the sample at adjustable delay times. A high-speed ICCD camera synchronized with a delay generator captured the stress distribution in the silicone oil at specific time intervals after laser irradiation, typically around 1500 ns. This setup enabled real-time visualization of shock wave fronts and the semi-quantitative comparison of wave strength under different focal conditions. All experiments were carried out at room temperature under atmospheric pressure.

3. Results and discussion

Figure 2 shows laser ablation of a solid target in silicone oil under different focal conditions. Figure 2(a) captures laser-induced breakdown in silicone oil at 100 ns. The laser was focused above the target surface. Instead of the typical teardrop-shaped plasma seen in air or water [8], a breakdown zone forms as a column with an irregular shape. This suggests that energy is absorbed nearly simultaneously along the laser path. The geometric focal point of the laser beam is marked in the image. The red lines indicate the relative positions of the target surface with respect to the laser focal region. The increment between consecutive positions was 0.2 mm. Positions 9 and 10 correspond to the under-focus condition, where the focal point was located 0.4 mm and 0.6 mm above the surface, respectively. Positions 6 to 8 represent the right-focus condition, with the focal point within ±0.2 mm of the surface. Positions 1 to 5 correspond to the above-focus condition, where the focal point was positioned between 1.2 mm and 0.4 mm below the surface. Figures (b) to (k) show how the ablation evolves at each of these positions, captured at a delay time of 1500 ns.

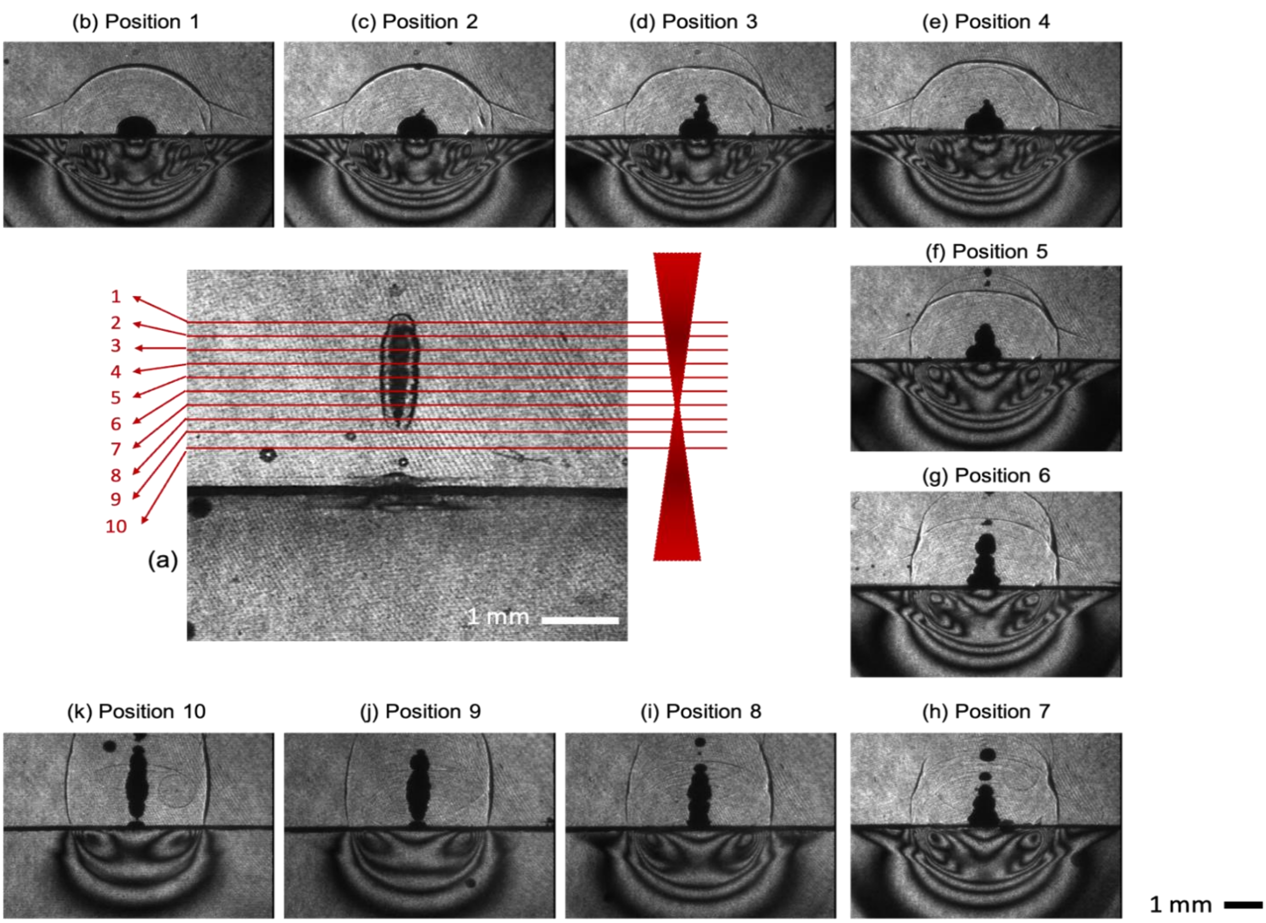

Figure 2. *Laser ablation of epoxy resin immersed in silicone oil at varying focal positions with a pulse energy of 60 mJ. (a) Laser-induced breakdown observed at 100 ns when the laser is focused within the liquid. (b)–(k) Ablation dynamics at different focal positions captured at 1500 ns delay*

At positions 1 and 2, we observe a typical pattern of laser-induced ablation in liquid, resembling what has been reported in laser shock experiments conducted in water. The black line in the center marks the target surface, with silicone oil above and the solid material below. In the silicone oil, concentric black and white fringes which indicate the stress waves are clearly visible. A single shock front and a hemispherical cavitation bubble can also be seen, representing a standard ablation scenario [11].

As we move to positions 3 through 5, the laser-induced breakdown begins to occurring above the target surface. This change results in a more irregularly shaped cavitation bubble, suggesting that the interaction region between the laser and the medium is less confined.

At positions 6 to 8, the breakdown in the liquid becomes more dominant, forming a long, column-like plasma channel. Multiple shock fronts appear in the liquid region, indicating strong and complex energy deposition along the beam path.

At positions 9 and 10, two distinct effects are observed. The majority of the laser energy is absorbed within the silicone oil, generating a long breakdown zone. Below this region, a small hemispherical bubble is formed by residual laser energy reaching and interacting with the target surface. The shockwaves in the liquid at these positions primarily result from the breakdown occurring within the fluid itself, rather than from direct interaction with the solid.

The strength of the induced stress wave can be semi-quantitatively evaluated by counting the number of elastic fringes [11]**.** Observations indicate that positions 1 to 5 exhibit four fringes, while positions 6 to 8 show a reduced number of fringes to three. At positions 9 and 10, not only does the number of fringes decrease significantly, but the fringe pattern also becomes distorted.

Since the number of fringes correlates with stress magnitude: more fringes indicating a stronger stress wave, we propose that the above-focus condition (positions 1 to 5) produces the most pronounced mechanical effect. In contrast, the at-focus condition shows a reduce of stress intensity, likely due to the expansion of the breakdown zone, which lowers the plasma energy density.

Under the under-focus condition, most of the laser energy is absorbed by the plasma formed in the liquid before it reaches the target. As a result, only a small fraction of energy interacts with the solid, leading to weaker stress generation. The observed fringes in this case are primarily attributed to the shock wave in the liquid impinging on the target surface, rather than direct ablation.

Our observations suggest that optimal stress wave generation and mechanical coupling do not necessarily occur at the geometric focus, but rather at a slightly above-focus position, where the laser fluence is below the breakdown threshold in the liquid. At this location, the plasma remains confined in a semi-hemispherical zone, allowing for a higher energy density and, consequently, a stronger impact on the target surface.

This insight is particularly important for applications such as laser shock peening and laser-based material processing, where maximizing stress or material removal is desired. Furthermore, operating in the above-focus regime helps to avoid laser breakdown within the liquid, which often leads to irregular cavitation bubble dynamics and complex shockwave patterns. Such irregularities can negatively impact processes requiring well-controlled mechanical effects, such as nanoparticle synthesis or micromachining.

On the other hand, if the goal is to generate a mechanical effect on the surface while minimizing direct laser-induced damage, the under-focus condition may be preferable. In this regime, most of the laser energy is absorbed by the plasma formed in the liquid before reaching the target. As a result, the mechanical effect on the solid arises primarily from the shockwave impinging upon the surface, rather than from direct ablation.

Silicone oil exhibits distinct physical properties compared to water, including higher viscosity, lower density, a higher refractive index, and a reduced threshold for optical breakdown. These characteristics influence both the plasma formation dynamics and the magnitude of stress generated during laser ablation [12]. Despite these differences, the present study demonstrates that the above-focus condition consistently produces stronger and more stable wavefronts, aligning with observations previously reported in water [8]. This consistency suggests that focal confinement may play a generally applicable role in enhancing ablation efficiency across various liquid media. Our findings may help explain previously reported effects of focal adjustment on nanoparticle characteristics [13, 14].

4. Conclusion

In this study, we investigated the influence of laser focal position on stress wave generation during laser ablation of a solid target in silicone oil. Our results show that the mechanical effect on the target surface is highly dependent on the focal condition. the optimal mechanical effect during laser ablation in silicone oil occurs not at the geometric focus but slightly above it. At this position, plasma confinement leads to higher energy density and stronger stress wave generation. At-focus ablation led to expanded plasma zones with lower energy density, while under-focus conditions caused early breakdown in the liquid, absorbing much of the laser energy and limiting the impact on the solid surface. These insights are valuable for optimizing laser-based applications such as shock processing, micromachining, and nanoparticle synthesis.

REFERENCES

[1] A. Chemin, M. W. Fawaz, and D. Amans, “Investigation of the blast pressure following laser ablation at a solid–fluid interface using shock waves dynamics in air and in water”, *Applied Surface Science*, vol. 574, 2022, p. 151592.

[2] L. Zhou, C. Zhu, H. Yuan, X. Mei, J. Jiang, and Z. Lu, “Influence of the laser pulse time profile on residual stress characteristics in laser shock peening”, *Optics Express*, vol. 31, 2023, pp. 18039–18049.

[3] Y. Hironaka, K. Shigemori, N. Ozaki, T. Kurita, and R. Kodama, “Temporal evolution of pressure profiles for laser-induced cavitation bubble on the metal surface”, *Journal of Applied Physics*, vol. 133, 2023, p. 095109.

[4] J. Theerthagiri *et al.*, “Fundamentals and comprehensive insights on pulsed laser synthesis of advanced materials for diverse photo- and electrocatalytic applications”, *Light: Science & Applications*, vol. 11, no. 1, 2022, p. 250.

[5] A. Nath and A. Khare, “Effect of focusing conditions on laser-induced shock waves at titanium–water interface”, *Applied Optics*, vol. 50, no. 19, 2011, pp. 3275–3281.

[6] J. Long, M. Eliceiri, Z. Vangelatos, Y. Rho, L. Wang, Z. Su, X. Xie, Y. Zhang, and C. P. Grigoropoulos, “Early dynamics of cavitation bubbles generated during ns laser ablation of submerged targets”, *Optics Express*, vol. 28, no. 10, 2020, pp. 14300–14309.

[7] D. Zhang, Z. Li, and K. Sugioka, “Laser ablation in liquids for nanomaterial synthesis: diversities of targets and liquids”, *Journal of Physics: Photonics*, vol. 3, no. 4, 2021.

[8] T. T. P. Nguyen, R. Tanabe, and Y. Ito, “Influences of focusing conditions on dynamics of laser ablation at a solid–liquid interface”, *Applied Physics Express*, vol. 6, 2013, p. 122701.

[9] K. A. Elsayed, H. Imam, M. A. Ahmed, and R. Ramadan, “Effect of focusing conditions and laser parameters on the fabrication of gold nanoparticles via laser ablation in liquid”, *Optics & Laser Technology*, vol. 45, 2013, pp. 495–502.

[10] H. Imam, K. Elsayed, M. A. Ahmed, and R. Ramdan, “Effect of experimental parameters on the fabrication of gold nanoparticles via laser ablation”, *Optics and Photonics Journal*, vol. 2, no. 2, 2012, pp. 73–84.

[11] T. T. P. Nguyen, R. Tanabe, and Y. Ito, “Laser-induced shock process in under-liquid regime studied by time-resolved photoelasticity imaging technique”, *Applied Physics Letters*, vol. 102, no. 12, 2013, p. 124103.

[12] T. T. P. Nguyen, R. Tanabe, and Y. Ito, “Influences of focusing conditions on the dynamics of laser ablation at a solid–liquid interface”, *Appl. Phys. Express*, vol. 6, no. 12, 2013, pp. 122701-1–4.

[13] Y. V. Ryabchikov, A. Kana, and I. Mirza, “Performance of Pico-Second Laser-Designed Silicon/Gold Composite Nanoparticles Affected by Precision of Focus Position”, *Crystals*, vol. 15, no. 2, 2025, p. 132.

[14] I. Y. Khairani, G. Mínguez-Vega, C. Doñate-Buendía, and B. Gökce, “Green nanoparticle synthesis at scale: a perspective on overcoming the limits of pulsed laser ablation in liquids for high-throughput production”, *Phys. Chem. Chem. Phys.*, vol. 25, 2023, pp. 19380–19408.