# Fabrication of Functional Surface using Water Jet Guided Laser Processing: Characteristics of Surface Structuring by Underwater Processing

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*Surface functions, such as wettability, sliding characteristics, and optical properties can be provided by micro and sub-micro scale structures. In various processing methods, we focus on Water Jet Guided Laser (WJGL) processing owing to its advantages of low heat effects and the processed surface with random micro-uneven structures. WJGL processing is different from conventional laser processing in that it uses high-pressure water as a laser waveguide. The laser is coupled to the high-pressure water jet and propagates through it by total internal reflection. It is known that characteristic uneven microstructures are formed on the processed surface in response to complex processes such as the lateral intensity distribution in the water jet, the removal of molten materials, and the cooling of the heated area by the water jet. In this report, underwater processing of the workpiece is proposed as one of the methods to control the intensity distribution. Submerging the workpiece in water may make it possible to manipulate the processed area and the surface structure according to the depth of the water. The characteristics of underwater processing were discussed through the observation of the intensity distribution and the processed surface.*

## 1. Introduction

Surface functions, for example, wettability, friction, and reflection are in high demand in bioengineering and medicine fields. One example of a functional surface is the superhydrophobic structure on the surface of lotus leaves (Fig. 1) [1]. Functional surfaces are typically composed of submicron to micron scale microstructures. Various methods have been employed to process functional surfaces, including mechanical machining, lithography, nanoimprint, and laser processing. In this study, we aim to fabricate functional surfaces using water jet guided laser (WJGL) processing, which is very suitable for microfabrication and forms characteristic microstructures on the processed surface.

WJGL performs removal processing with a pulsed laser. It is distinctive in that it uses high-pressure water as a laser waveguide. As shown in Fig. 2, a high-pressure water jet with a diameter of several tens of micrometers is formed. A laser beam is introduced into it by a focusing lens and propagates through the water jet by total internal reflection, enabling processing at the water jet end [2]. This processing method offers several advantages suitable for precision machining. The cooling effect of the water jet reduces the thermal damage, and debris generated during processing is removed by the high-pressure jet, preventing reattachment of debris. Additionally, the processing can be conducted along the jet, eliminating the need for focal control [3].

It is known that complex three-dimensional microstructures are formed on the processed surface in response to complicated processes of WJGL processing[4]. The lateral intensity distribution in the water jet serves as a starting point for the processing, and removal of molten materials and cooling of heated area by the water jet take effect. Focusing on this point, this study aims to fabricate functional surfaces using water jet guided laser processing by controlling the micro-surface structure.

In this report, underwater processing of the workpiece was proposed as one of the methods to control the micro-surface structure. Submerging the workpiece in water has the potential for unique surface properties and structure fabrication that is not achievable in normal processing. To investigate underwater processing, Chapter 2 focused on the observation of the intensity distribution, while Chapter 3 analyzed the processed surface structures.

## 2. Observation of intensity distribution in underwater processing of the workpiece

### 2.1 Observation device of intensity distribution

In order to observe the lateral intensity distribution in underwater processing, we designed an observation device as shown in Fig. 3. An acrylic tank installed under the WJGL. Only the laser passed through the tank while the water remained within, forming a layer of water. The laser power was reduced using a window and neutral density (ND) filters before being focused onto a high-speed camera through an objective lens and a tube lens. In this manner, the laser cross-section on the tank's bottom surface was captured with magnification. We utilized the high-speed camera to observe the laser, which operates in high frequency pulsed mode, one pulse at a time. The entire setup was covered for waterproof purposes.

### 2.2 Observation conditions

The intensity distribution in underwater processing was observed. The MCS300 modification by Makino Milling Machine Co., Ltd was used for WJGL processing machine. Processing conditions were as follows: laser power of 0.1 W, wavelength of 532 nm, pulse repetition frequency of 10 kHz, pulse width of about 200 ns, jet diameter of 70 µm, water jet pressure of 15 MPa, working distance of 45 mm, and water depth of 22 mm. The shooting conditions were set to a frame rate of 30 kfps and an exposure time of 1/30 ms, which is fast enough to separate the pulses into other frames. The intensity distribution in normal WJGL processing was also observed so as to compare with the underwater results.

### 2.3 Discussions of the observed intensity distribution

Figure 4 presents representative images among those capturing the pulses. The upper row is the results of normal processing and the lower row is that of underwater processing. In underwater processing, intensity distributions were successfully observed like normal processing. A comparison was made between the two processing's results:

(i) The intensity distributions in both cases were approximately circular with a diameter of around 70 µm, and no significant diameter variations were observed.

(ii) In underwater processing, some pulses exhibited missing parts in the intensity distribution, as seen in Fig. 4 with red circles.

(iii) In underwater processing, the position where the intensity distribution was observed shifted for each pulse (the variation in the centroid position of the intensity distribution was 0.66 µm for normal processing, 2.9 µm for underwater processing).

(iv) Furthermore, underwater processing showed greater variations in speckle patterns, which were numerous fine spots forming intensity distributions. (To evaluate the similarity for each processing, Zero-means Normalized Cross-Correlation (ZNCC) was calculated. Larger values indicate higher similarity. The values were 0.94 for normal processing, 0.79 for underwater processing).

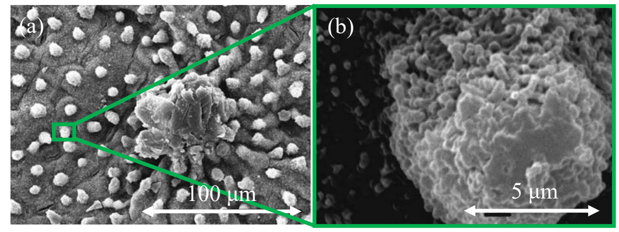

Fig. 1 Example of functional surface structures (Lotus leaf) [1]. (a) Low magnification enlarged image. (b) High magnification enlarged image (zoomed-in section indicated by the green rectangle in (a)).

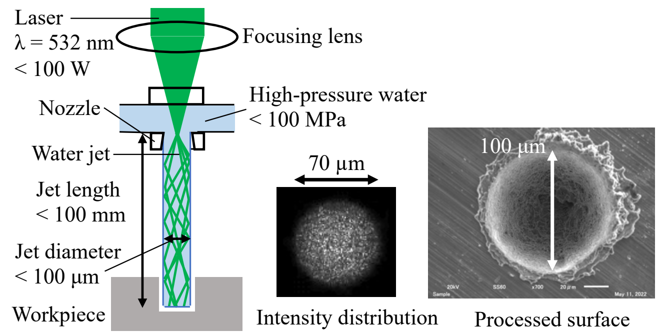

Fig. 2 Schematic diagram of WJGL processing.

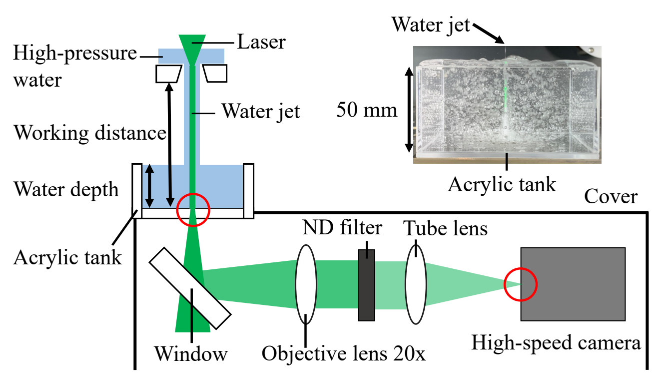

Fig. 3 Schematic diagram of observation device.

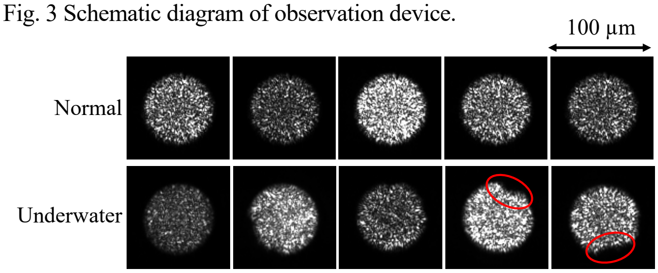

Fig. 4 Observation results of intensity distribution in normal processing and underwater processing.

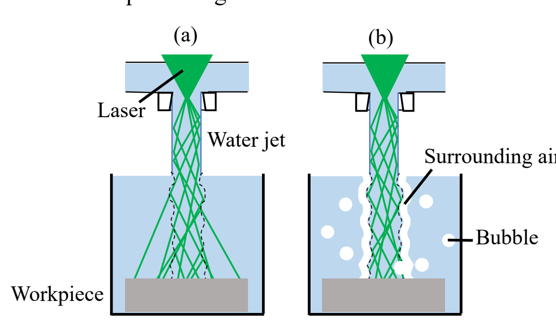

Fig. 5 Model of underwater processing. (a) Unreal model that water guide is collapsed. (b) Real model that water guide is maintained.

Additionally, when the laser was incident on the water-filled tank, many bubbles were generated in the water, as shown in the top right of Fig. 3. This phenomenon was not observed when the tank was not filled with water under normal conditions.

From the obtained results, the laser guidance of water jet didn't lose like Fig. 5(a) in underwater processing. Rather, it maintained at a certain range (Fig. 5(b)), and thus the diameter of the intensity distribution remained unchanged (i). On the other hand, there were also several characteristics that were not seen in normal processing. A significant number of bubbles were generated from the surrounding air layers around the water jet, and some of them penetrated into the water jet, resulting in missing parts in the intensity distribution (ii). Additionally, the water jet's interaction with the surrounding air layers caused the positional fluctuation (iii) and the speckle pattern variation (iv).

While the guidance is maintained during underwater processing, there are also unique characteristics that are not typically seen in normal processing. Next, in Chapter 3, actual processing is performed to clarify the processing characteristics.

## 3. Surface structure processed under water

### 3.1 Processing conditions

Underwater processing was carried out in order to examine the possibility of forming structure and the characteristics of the processed surface. SUS304 was used for the workpiece and processing power at the workpiece was 20 W. The water depth of underwater processing was from 10 mm to 40 mm in increments of 5 mm. The working distance was set to be 10 mm longer than the water depth. Five patterns were set for the numbers of pulses: 1, 100, 1000, 5000 and 10000. Other processing conditions were the same as those of Chapter 2. For comparison, normal processing was also performed under the same conditions. Each experiment was conducted five times.

### 3.2 Surface structure in normal processing

Figure 6(a) shows the surface structure in normal processing for a working distance of 20 mm and one pulse. The processing diameter was 140 µm. The center was lower while the edge was higher than unprocessed surface. When changing the working distance, the structure didn't change very much. When changing the pulse number, the depth increased while the width didn't change as shown in Fig. 6(b). Multiple experiments were conducted under the same conditions, but the same structures were obtained.

### 3.3 Surface structure in underwater processing

Table 1 shows the number of successful underwater processing out of the five attempts. If there was any slight change on the surface, it was considered as a successful processing. "-" means that no experiment was conducted in that condition. It was possible to perform processing even underwater, but the probability of processing showed variations even under the same conditions. As the water depth increased, the probability decreased. It is likely that some pulses were affected by the disturbance of the water jet, leading to insufficient laser energy reaching the workpiece during processing. As the pulse number increased, the probability of successful processing increased.

Figure 7 shows the structures of underwater processing for a water depth of 10 mm and a working distance of 20 mm. When comparing Figure 7(a) and Figure 6(a), which are both single-pulse processed, it is evident that the processing area became narrower, and the convex edge became smoother. Fig. 7(b) was a deep hole with a depth of about 75 µm. As the number of pulses increased, the processing progressed in the depth direction, and not in the width direction.

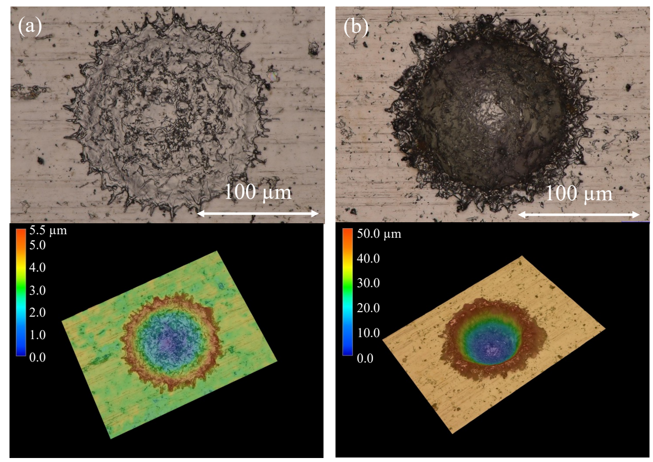


Fig. 6 Observation results of surface structure in normal processing fo r a working distance of 20 mm; (a) 1pulse; (b) 20 pulses.

Table. 1 Number of successful underwater processing out of the f ive attempts.

| Water depth (mm) | Working distance (mm) | Number of successful processing | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 100 | 1000 | 5000 | 10000 |
| 10 | 20 | 4 | 5 | 5 | - | - |
| 15 | 25 | 3 | 5 | 5 | - | - |
| 20 | 30 | 2 | 2 | 5 | - | - |
| 25 | 35 | 0 | 2 | 5 | - | - |
| 30 | 40 | 0 | 0 | 3 | - | - |
| 35 | 45 | - | 0 | 2 | 5 | 5 |
| 40 | 50 | - | 0 | 0 | 0 | 5 |

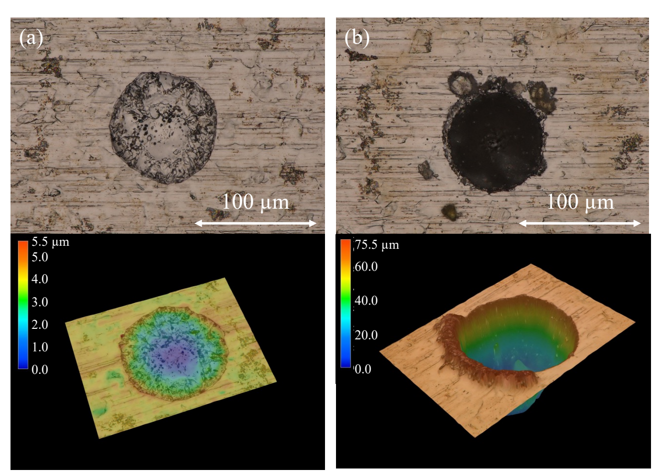


Fig. 7 Observation results of surface structure in underwater processing for a water depth of 10 mm and a working distance of 20 mm; (a) 1 pulse; (b) 100 pulses.

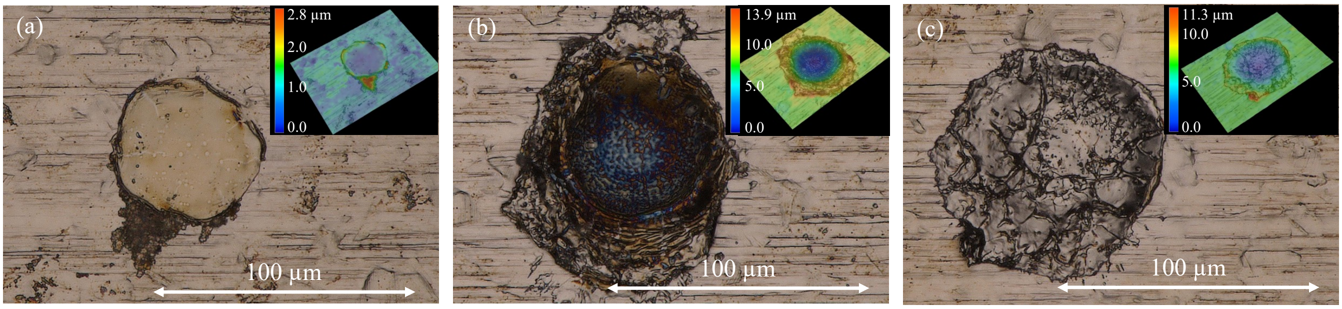


Fig. 8 Three representative results of shallow surface structure in underwater processing. (a) Brown smooth structure. (b) Dark blue and brown str ucture with unevenness. (c) Structure that is not colorful.

Shallow structures with a depth of less than 10 µm formed in underwater processing were classified into three categories as Fig. 8(a), (b) and (c). These shapes are significantly different from those of the normal processing, and it can be said that unique shapes were obtained in underwater processing that cannot be simply explained by reducing the number of pulses alone. Also, unlike in normal processing, the structures were not the same even under the same experimental conditions in underwater processing. The reason why the difference happens is not clear.

The type of Fig. 8(a) was brown. The depth was 1 µm to 5 µm and the diameter was 50 µm to 70 µm. The center lower parts appeared smooth and multiple white radiating lines and round objects were visible. The periphery was higher and wrinkled. The type of Fig. 8(b) was brown and dark bluish color. The bottom surface had a rough structure, and the depth was about 10 µm and the diameter was about 80 µm. The type of Fig. 8(c) was not colorful, the depth was 5 µm and the diameter was about 100 µm, the largest of the three.

### 3.4 Energy dispersive spectrometry

Elemental analysis using energy dispersive spectrometry (EDS) was performed on the workpiece after underwater processing. The results were summarized for each of the three groups and the unprocessed surface (Fig. 9). For reference, the theoretical composition of SUS304 was also shown in Fig. 9.

From the fact that the composition of the unprocessed surface is like the theoretical composition, it can be understood that there is a certain level of validity in the analysis results. While the type of Fig. 8(c) was similar to the unprocessed area, the groups of Fig. 8(a) and (b), which were colorful, had higher proportion in oxygen. This indicates that the formation of an oxide film caused the interference colors corresponding to its thickness[5].

From these results, it can be concluded that underwater processing allowed not only the alteration of structure but also that of physical properties.

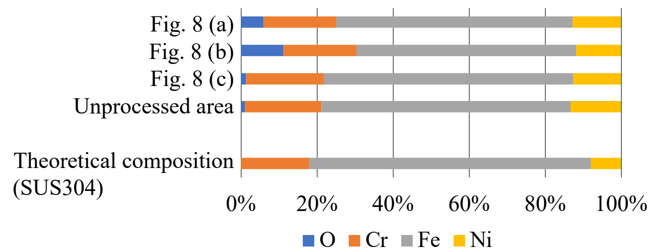


Fig. 9 EDS elemental analysis of the groups of Fig. 9 (a), (b) and (c).

## 4. Conclusions

The purpose of this study was to fabricate functional surfaces using water jet guided laser processing by controlling the micro-surface structure. Underwater processing of the workpiece was proposed as one of the methods. Through the observation of the intensity distribution and the processed surface, the characteristics of underwater processing were discussed. A water jet model of underwater processing was presented that the water guide is maintained while there is interaction between the water jet and surrounding air layers. In underwater processing, there was a lot of variation, and the reproducibility was low. But the three categories of shallow structures had unique structure, color and element composition that couldn't be achieved by normal processing. This indicates that underwater processing has the potential to fabricate functional structures by not only controlling the structure but also the material composition. Further experiments are needed to clarify the principles and enhance the reproducibility and the controllability of the structures.

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