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Laser-induced microjet-assisted ablation for high-quality microfabrication

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Abstract

Liquid-assisted laser ablation has the advantage of relieving thermal effects of common laser ablation processes, whereas the light scattering and shielding effects by laser-induced cavitation bubbles, suspended debris, and turbulent liquid flow generally deteriorate laser beam transmission stability, leading to low energy efficiency and poor surface quality. Here, we report that a continuous and directional high-speed microjet will form in the laser ablation zone if laser-induced primary cavitation bubbles asymmetrically collapse sequentially near the air-liquid interface under a critical thin liquid layer. The laser-induced microjet can instantaneously and directionally remove secondary bubbles and ablation debris around the laser ablation region, and thus a very stable material removal process can be obtained. The shadowgraphs of high-speed camera reveal that the average speed of laser-induced continuous microjet can be as high as 1.1 m s\textsuperscript{-1} in its initial 500 \textmu m displacement. The coupling effect of laser ablation, mechanical impact along with the collapse of cavitation bubbles and flushing of high-speed microjet helps achieve a high material removal rate and significantly improved surface quality. We name this uncovered liquid-assisted laser ablation process as laser-induced microjet-assisted ablation (LIMJAA) based on its unique characteristics. High-quality microgrooves with a large depth-to-width ratio of 5.2 are obtained by LIMJAA with a single-pass laser scanning process in our experiments. LIMJAA is capable of machining various types of difficult-to-process materials with high-quality arrays of micro-channels, square and circle microscale through-holes. The results and disclosed mechanisms in our work provide a deep understanding of the role of laser-induced microjet in improving the processing quality of liquid-assisted laser micromachining.

Supplementary material for this article is available online

Keywords: liquid-assisted laser ablation, laser-induced microjet, cavitation bubbles, laser microfabrication

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1. Introduction

Laser microablation even with ultra-short pulse lasers always encounters problems including recast layers, redeposition of ablation debris, phase transition, and induced cracks, which limit its application prospects [1–3]. Liquid-assisted pulse laser ablation generally induces localized liquid impulse via explosive expansion of laser-induced plasma and cavitation bubbles, which helps to expel debris and heat to improve materials removal efficiency and relieve thermal effects to some extent [4–6]. However, the primary cavitation bubbles generally expand outward randomly leading to liquid turbulence and thus suspended secondary bubbles and ablation debris gather and hinder the laser beam transmission [7]. Thermal effects can be highly reduced, but laser energy usage efficiency is restricted by the shielding effect from suspended secondary bubbles and debris. In addition, irregular ablation traces from light scattering always appear and result in deteriorated surface quality. To solve these problems is crucial to the application of liquid-assisted laser ablation in high-quality microfabrication.

In conventional immersed liquid-assisted laser ablation processes, the scattering and shielding effects of liquid turbulence, suspended bubbles and debris can be avoided by limiting the operating laser repetition rate when the interval time between every two adjacent pulses is long enough to dissipate the disturbances [8]. On this occasion, the allowable repetition rate is generally restricted [9]. Flowing liquid or waterjets are widely applied to solve the intractable problems in liquid-assisted laser ablation, including waterjet assisted underwater laser cutting [10, 11], coaxial waterjet-assisted laser processing [12–14], waterjet-guided laser processing [15–17], overflow-assisted laser machining [18, 19], and hybrid laser-waterjet ablation technology [20–22]. A liquid jet without turbulence and free of bubbles is generally preferred, but hard to obtain. It is also very interesting to be found that the thickness of the liquid layer has a significant impact on the ablation efficiency and surface quality in various liquid-assisted laser ablation methods. Kim et al [23] found that the liquid-assisted laser ablation process results in substantially augmented ablation efficiency, which depends strongly on the thickness of the applied liquid film. Kang and Welch [24] proved that a relatively thinner liquid layer in short-pulsed laser processing is desirable to enhance laser ablation efficiency. Krstulović et al [25] revealed that the efficiency of laser drilling in terms of produced crater volumes changes when water layer thickness is varied from 1 to 20 mm, and a maximum crater volume is attained at water layer thickness of 3 mm. Tangwarodomkun et al [26] found that an obvious groove was formed on the sample with a thin and flowing water layer of 1 mm, while the sample was rather melted and burned in a large region without observing a noticeable groove in a thicker water layer of 2 mm. Wang et al [27] conducted a femtosecond laser drilling of 4H-SiC wafer in liquid and found that micro-through-holes can be achieved with a 0.5 mm thickness of water layer, while failed with a 1 mm thickness of water layer. It is believed that the influence of liquid thickness on the evolution characteristics of laser-induced cavitation bubbles plays a decisive role in laser ablation performances, which has not yet been clarified.

The cavitation bubbles in liquid-assisted laser ablation originate from the high-temperature and high-pressure plasma induced by high-energy laser pulses [28, 29]. When the sample immersion depth in liquid reduces to a relatively low level, cavitation bubbles will experience an asymmetric collapse process due to the boundary effect, which generally induces a fast liquid ejection, namely laser-induced microjet [30–32]. The separated laser-induced microjet after irradiation of each single laser pulse has been studied and mainly applied in areas including needle-free drug injection [33] and microdroplet deposition for 3D printing [34]. Also, the high-speed microjet induced by cavitation bubble collapse creates a single micro-pit [35] and forms a microgroove [36] on aluminum foils, which is named laser-induced cavitation forming. To the best of our knowledge, the role of laser-induced microjet in liquid-assisted laser micromachining has not yet been systematically studied and intentionally used for stably removing bubbles and ablation debris to enhance laser microablation performances.

In this paper, we studied the influence of laser-induced cavitation bubbles on laser ablation performances under a critical thin liquid layer. We found that a continuous and directional high-speed laser-induced microjet can be formed with continuous asymmetrical collapse of laser-induced cavitation bubbles. The laser-induced microjet can carry off suspended secondary bubbles and ablation debris instantaneously to improve laser ablation performances. The temporal evolution of the continuous microjet and materials removal mechanisms are systematically studied. We named this uncovered liquid-assisted laser micromachining process as laser-induced microjet-assisted ablation (LIMJAA) based on the revealed unique phenomena and mechanisms. For difficult-to-process materials, the LIMJAA method has been proven to be capable of fabricating high-quality microstructures with largely improved material removal efficiency without the assistance of external flowing liquid.

2. Experimental setup

The schematic overview and practical image of the experimental setup for LIMJAA are shown in figures 1 and S1 of supplementary materials (available online at stacks.iop.org/ IJEM/4035101/mmedia), respectively. A femtosecond laser system (Spectra-Physics, Spirit One 1040-8-SHG) delivers laser pulses with a central wavelength of 520 nm and a pulse duration of 300 fs. The relative motion of the sample and laser spot is controlled by three-dimensional motorized moving stages (Newport, XMS100-S). The XY plane (horizontal plane) has a movement range of 100 × 100 mm² with a minimum step resolution of 0.01 μm and adjustable scanning speeds from 1 μm s⁻¹ to 300 mm s⁻¹; the motion along Z-axis has a step resolution of 0.06 μm and a maximum speed of 2 mm s⁻¹. A plan achromat objective with a numerical aperture of 0.1 is used to focus the laser beam. Accordingly, the focused laser beam waist radius $\omega_0$ is estimated to be 4.3 μm. The focused laser beam waist radius and ablation
threshold fluence of materials in our work are calculated by using the method proposed by Liu [37], seeing figure S2 in supplementary materials for more details. Table 1 summarizes the range of all sample materials and experimental parameters. To observe the generation and evolution characteristics of laser-induced cavitation bubbles and microjets, a high-speed video camera (PCO, DIMAX HS1) with the highest frame rate of 10,000 frames per second is used to directly observe the evolution of liquid media in a wide range of time scales (from 100 microseconds to hundreds of milliseconds) after the femtosecond laser-induced breakdown in liquid. A back-side LED-2 light source is employed to illuminate the liquid and highlight the cavitation bubbles. Moreover, a 520 nm notch filter is equipped at the inlet of the objective lens to obstruct the high-intensity reflected light from the laser beam.

The thickness of thin liquid film covered on the top surface of samples is tuned by the equipment as depicted in figure S3 of supplementary materials. An online liquid film thickness measurement unit with a CMOS camera is set up for

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**Table 1.** Experimental parameters and sample specifications.

| Parameter                          | Value                        |
|-----------------------------------|------------------------------|
| Laser processing conditions       |                              |
| Laser wavelength $\lambda$ (nm)   | 520                          |
| Laser beam profile                | Gaussian                     |
| Beam polarization state           | Linear polarization          |
| Objective lens                    | $4 \times$ (NA 0.1)          |
| Pulse duration $\tau_p$ (fs)      | 300                          |
| Laser beam waist radius $\omega_0$ ($\mu$m) | 4.3                  |
| Repetition rate $R_f$ (kHz)       | 1, 10, 40                    |
| Scanning speed $v_{scan}$ ($\mu$m s$^{-1}$) | 10, 20, 50, 100, 200, 500, 1000, 2000, 5000 |
| Pulse energy $E$ ($\mu$J)         | 4, 8, 12, 16, 20             |
| Samples                           |                              |
| Material                          | Thickness                    |
| 4H-SiC wafer                      | 350 $\mu$m, 200 $\mu$m       |
| Stainless steel strip             | 100 $\mu$m                   |
| Fe-based metallic glass strip     | 25 $\mu$m                    |
| Single crystal silicon wafer      | 100 $\mu$m                   |
measuring the liquid film thickness during laser ablation as shown in figure S4 of supplementary materials. N-butyl alcohol with low surface tension and refraction index of 1.3993 is used as the assistant liquid medium in this work.

The surface morphology of samples after laser ablation is measured by a scanning electron microscope (SEM, Zeiss Merlin). A 3D laser scanning confocal microscope (LSCM, VK-X1000, Keyence) is used to measure the width, depth, and cross-sectional profile of the fabricated microstructures.

3. Principle of LIMJAA

3.1. Formation of a continuous high-speed laser-induced microjet

When a laser pulse with enough energy is focused into liquid, a laser-induced plasma will generate and expand to form a cavitation bubble. If the cavitation bubble propagates near an interface boundary, an asymmetrical collapse will occur, which generally leads to a directional single microjet [38]. To make use of the boundary effect and asymmetrical collapse of laser-induced cavitation bubbles to form a continuous microjet, we firstly studied the effect of the depth of focal plane in liquid on the initial speed of a single microjet. As the experimental results shown in section S4 of supplementary materials, the initial speed firstly increases and then decreases when the depth of the focal plane in liquid gradually increases. According to the results, we set the focal plane depth to be optimal 120 $\mu$m below the air-liquid interface, which makes the initial speed of laser-induced microjet to be the maximum. This is also the criterion for determining the thickness of liquid film in the practical LIMJAA process.

We then photographed the continuous laser irradiation process in liquid with laser repetition rate of 1 kHz within 100 ms as shown in figure 2(a). The shadowgraphs are taken every 1 ms. The first laser pulse arrives and induces a primary cavitation bubble at $t = 0$ ms. Starting from $t = 1$ ms, it can be seen that the collapse-induced secondary bubbles move downwards. At the same time, the primary cavitation bubble produced by the second pulse is undergoing expansion and collapse. In the same way, the collapse of every primary cavitation bubble will produce a pulsed downward microjet. As the femtosecond pulsed laser constantly irradiates inside the liquid medium under a relatively high repetition rate, the pulsed microjet can accumulate and accelerate to form a rapid and steady continuous liquid jet. The moving paths of secondary bubbles induced by each pulse are tracked over time as revealed in figures 2(b) and (c). It is found in figure 2(b) that the early collapse-induced secondary bubbles tend to move sideways with a big divergence angle, while the later collapse-induced secondary bubbles move straight downward after irradiation of more pulses as shown in figure 2(c). Here, we defined the average speed of laser-induced continuous microjet $v_{nj}$ as the average speed of secondary bubbles in their initial 500 $\mu$m displacement perpendicular to the air-liquid interface. Figure 2(d) shows the changing of the average speed of laser-induced continuous microjet $v_{nj}$ versus the numbers of irradiated laser pulses $N_p$ associated with the exponential fitted trend line. The results show that the laser-induced microjet is gradually accelerated to a steady speed of about 1.1 m s$^{-1}$ after approximately 35 pulses of laser irradiation.

As shown in movie S1 of supplementary materials, the macroscopic movement of secondary bubbles implies the evolution of laser-induced continuous microjet when the laser beam continuously irradiates near the air-liquid interface. Therefore, we conclude that when pulse laser constantly irradiates in liquid medium with a critical shallow depth, the asymmetrical expansion and collapse of primary cavitation bubbles occur continuously, theoretically resulting in a continuous steady high-speed microjet.
cess, the liquid thickness on the sample surface is set to be
the LIMJAA process under laser scanning conditions. Therefore, we define
in figure 3(a) will be always generated. Therefore, a
to the sample surface below the air-liquid interface, the cavitation bubbles generation and asymmetrical col-
section in the laser scanning cutting process. When the laser
be observed on this occasion due to the instantaneous col-
the grooves and fluctuated groove surface profiles are found in
the ablation zone, and the diameter of bubbles can be as large as several tens of
microometers. When a critical thin liquid is used, the asym-
the ablation zone during laser ablation in air. If the
ample scanning direction. No obvious cavitation bubbles can
in figure 3(b). The dynamic evolution process of the laser-induced microjet is
showed in figures 4(d)–(i). Recast layers and redepositions of ablation debris can be observed after laser ablation in air
as depicted in figures 4(d) and (g). As for the laser ablation
the grooves and fluctuated groove surface profiles are found as
shown in figures 4(d) and (g). Bubbles, debris, and even molten
materials can be expelled instantaneously from the ablation zone by the mechanical impact of laser-induced high-speed microjet to achieve a high-quality microfabrication process. The different groove morphologies shown in figures 4(d) and (g) of SiC and stainless steel may be attributed to the distinct ablation products of different materials. The accumulated heat causes the melt of stainless steel and leads to more recast layers that hinder the laser beam. On the contrary, the semiconductor SiC hardly undergoes the melting process but directly decomposes to its elemental constituents, silicon and carbon as well as their oxides, which can be taken away by laser-induced microjet.

3.2. Role of the continuous high-speed laser-induced microjet in laser scanning ablation

In practical liquid-assisted laser ablation processes, we should consider the effects of both air-liquid and liquid-solid interfaces. It has to be mentioned that in the situation of immersed liquid the asymmetric collapse of cavitation bubbles near the solid sample boundary will lead to a microjet perpendicular to the sample [38]. This microjet always spreads randomly in all directions after encountering the solid surface, when a directional microjet cannot be formed. This is also one of the reasons why we choose a critical thin liquid film. Due to the laser scanning ablation, a curved kerf in the ablation zone as shown in figure 3(a) will be always generated. Therefore, a tilted 4H-SiC wafer placed just below the air-liquid interface as shown in figure 3(b) is used to mimic the ablated curved kerf section in the laser scanning cutting process. When the laser beam focuses on the sample surface below the air-liquid interface, the cavitation bubbles generation and asymmetrical collapse phenomena occur if the depth of liquid is small enough. The collapse-induced secondary bubbles carried by the microjet are reflected after encountering the rigid sample boundary and move to the lower right as shown in figure 3(b). The dynamic evolution process of the laser-induced microjet is shown in movie S2 of supplementary materials. As illustrated in figure 3(a), the secondary bubbles and ablation debris can be carried away instantaneously from the ablation zone by the directional high-speed microjet, which can help to eliminate the light-scattering and shielding effects of suspended bubbles and debris to get a high-efficiency and stable laser ablation process under laser scanning conditions. Therefore, we define this process as laser-induced microjet-assisted ablation.

4. Results and discussion

4.1. Material removal mechanism of LIMJAA

We first demonstrate the capability of LIMJAA by fabricating microgrooves on the surface of a single crystal 4H-SiC wafer and a stainless steel strip. To realize the LIMJAA process, the liquid thickness on the sample surface is set to be 120 μm, which is consistent with section 3. Laser ablation processes with the same parameters in air and immersed liquid (with a liquid thickness of about 1 mm) are used for comparisons, and the results are shown in figure 4. By using a coaxial CMOS camera, the real-time processing phenomena of three different laser ablation processes are captured as shown in figures 4(a)–(c). It can be seen that ablation debris ejects from the ablation zone during laser ablation in air. If the sample is immersed in a relatively thick liquid, laser-induced bubbles expel around in all directions inside the liquid film, and the diameter of bubbles can be as large as several tens of micrometers. When a critical thin liquid is used, the asymmetrical collapse of laser-induced primary cavitation bubble yields a directional liquid microjet, ejecting inversely to the laser scanning direction. No obvious cavitation bubbles can be observed in the situation of immersed liquid, irregular ablation traces on either side of the grooves can be observed after laser ablation in air as depicted in figures 4(d) and (g). As for the laser ablation in immersed liquid, the ablation debris ejected by laser-induced microjet is scattered around the ablation zone, and the results are shown in figure 4(e) and (h), which are attributed to the light scattering effects of massive bubbles and turbulent flows in the ablation zone. In contrast, smooth grooves free of recast layers and redeposition of debris are obtained by LIMJAA as presented in figures 4(f) and (i). Bubbles, debris, and even molten materials can be expelled instantaneously from the ablation zone by the mechanical impact of laser-induced high-speed microjet to achieve a high-quality microfabrication process. The different groove morphologies shown in figures 4(d) and (g) of SiC and stainless steel may be attributed to the distinct ablation products of different materials. The accumulated heat causes the melt of stainless steel and leads to more recast layers that hinder the laser beam. On the contrary, the semiconductor SiC hardly undergoes the melting process but directly decomposes to its elemental constituents, silicon and carbon as well as their oxides, which can be taken away by laser-induced microjet.

Figure 3. Role of laser-induced microjet in laser scanning ablation process. (a) Schematic of LIMJAA process (b) photograph of laser-induced microjet near the air-liquid and liquid-solid interfaces. The solid lines indicate moving tracks of secondary bubbles produced by laser pulses 16–20. The laser repetition rate is 1 kHz and the laser pulse energy is 8 μJ.
Figure 4. Surface morphologies of microgrooves processed by laser ablation in air, immersed liquid and LIMJAA. (a)–(c) on-line optical photograph of laser scanning processing on 4H-SiC wafer, (d)–(f) surface morphology of processed microgrooves on SiC wafer, (g)–(i) surface morphology of processed microgrooves on stainless steel. The laser repetition rate, pulse energy, and scanning speed are 10 kHz, 8 $\mu$J, and 1000 $\mu$m s$^{-1}$, respectively.

Figure 5. Comparison of (a) ablation depth of microgrooves and (b) MRRs by LIMJAA, laser ablation in air, and immersed liquid with varying scanning speed. The laser repetition rate is 10 kHz and the laser pulse energy is 8 $\mu$J.

Figure 5 shows the related ablation depths and material removal rates (MRRs) on SiC wafers with varying scanning speeds. The MRR is calculated by multiplying the cross-sectional area of the ablation groove by the scanning speed. When fabricating microgrooves on stainless steel in air, large amounts of molten material accumulate in the groove bottoms, thus it is difficult to accurately measure the ablation depths and MRRs. Therefore, the corresponding material removal efficiency on stainless steel is not compared here. The ablation depth of LIMJAA is higher than laser ablation in air and...
immersed liquid, and the gap becomes much larger as the decrease of laser scanning speed, as presented in figure 5(a). Specifically, at a scanning speed of 10 µm s\(^{-1}\), the ablation depth of LIMJAA increases by more than 2.5 times compared to laser ablation in air and approximately 4 times compared to immersed liquid-assisted laser ablation. The ablation depth of LIMJAA shows a continuous rapidly increasing trend with the reduction of scanning speed, while those of laser ablation in air and immersed liquid tend to flatten out. It is reasonable to speculate that the ablation debris and suspended bubbles cannot be carried away instantaneously in the ablation zone when the laser spot overlap ratio is too high, thus the ablation depths and MRRs are restricted by laser ablation in air and immersed liquid. In contrast, two main reasons may account for the improvement of LIMJAA performance: first, the collapse of laser-induced bubble and the high-speed microjet involve additional mechanical force to sample in the thin liquid film, improving ablation efficiency [24]; second, stable and directional laser-induced microjet largely reduces the shielding effect of debris and secondary bubbles on the subsequent laser pulses. Although ablation depths decrease with the increased scanning speed, higher MRRs are accomplished as implied in figure 5(b) due to a lower laser pulse overlap ratio. We can find that the positive impact of laser-induced microjet on MRR exists in all the range of varied laser scanning speeds.

The ablation depth by LIMJAA increases correspondingly with the rise of laser pulse energy and pulse repetition rate in certain ranges, due to the instantaneous expel of bubbles and debris in ablation zone. Thus, by choosing optimal laser parameters, microgrooves with high depth-to-width ratio can be obtained theoretically. Here, we demonstrate that a groove with width of 19 µm and depth of 98 µm, namely, a depth-to-width ratio of 5.2 can be fabricated by a single-pass laser scanning process strategy as shown in figure 6. The fabricated microgroove also shows a smooth and clean cross-sectional profile without any recast layer and deposition of debris.

4.2. Practical applications of LIMJAA

We here proved that the novel LIMJAA technology can be used to process different types of materials, including difficult-to-process materials, thermal- and stress-sensitive materials, with high repeatability and stability. For example, figure 7 shows...
high-quality micro-channel array structures fabricated on a difficult-to-process 4H-SiC wafer surface by LIMJAA. This kind of micro-channel array structure shows good application prospects in areas such as the micro-channel heat dissipation system in high-performance miniaturized electronic devices and high-quality microfluidic molds for glass molding.

Another important application of the LIMJAA method is the cutting and micro-drilling of ultra-thin wafers and metal strips, which are generally extremely stress- and thermal-sensitive with poor processing quality by traditional machining methods. The LIMJAA approach can not only achieve efficient MRRs but also obtain a very high surface quality. As depicted in figure 8, we successfully fabricate square and circle micro-through-hole arrays on a variety of typical stress- and thermal-sensitive materials by laser trepan drilling. The processed micro-holes exhibit smooth entrance without redeposition of debris and recast layers. The ripples and distortions at the exit of holes may be caused by the extra multiple reflections of the sidewalls inside the laser-ablated channels, which has been reported in the previous study [39, 40].

5. Conclusions

In this work, the effects of laser-induced microjet in liquid-assisted laser ablation under a critical thin liquid layer are systematically studied. Based on the revealed unique mechanisms and highly improved laser ablation performances, we termed this uncovered liquid-assisted laser micromachining as LIMJAA. In LIMJAA, a continuous high-speed steady microjet can be generated when the sequential expansion and asymmetrical collapse of pulsed laser-induced primary cavitation bubbles occur in a thin liquid film. The laser-induced microjet was observed to achieve an average speed as high as 1.1 m s⁻¹ in its initial 500 μm displacement in our experiment. The microjet is reflected and ejected horizontally after encountering the rigid curve kerf boundary during practical laser ablation processing in a liquid film, which helps to flush away bubbles and debris to sustain steady processing. The combined effects of laser ablation, mechanical impact along with the collapse of cavitation bubbles and flushing of high-speed microjet help achieve a high material removing rate and significantly improved surface quality. Based on the proposed mechanism of LIMJAA, the redeposition of ablation debris is eliminated compared with laser ablation in air. Meanwhile, irregular ablation trace is avoided owing to the stable processing compared with laser ablation in immersed liquid. Typically, by optimizing laser parameters, a smooth microgroove with a depth-to-width ratio of 5.2 can be obtained by a single-pass laser scanning. The proposed method is very robust in materials including the most difficult-to-process materials and is capable of fabricating a high-quality surface array of micro-channels and micro-through-holes. The experimental results and the proposed mechanisms of the LIMJAA approach in this study provide a key step for a better understanding of liquid-assisted pulsed laser ablation technologies, and this new LIMJAA method can be used for high-efficiency and high-quality microfabrication of various difficult-to-process materials.

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Conflict of interest

The authors declare no conflicts of interest.

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