Grooving of Metals by High-Intensity Focused Ultrasound-Assisted Water-Confined Laser Micromachining

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Laser grooving (i.e., the production of surface grooves through laser machining) has several advantages and many current or potential industrial applications. However, conventional laser grooving in air may often suffer from quality defects such as debris depositions. A new machining process, with the name "ultrasound-assisted water-confined laser micromachining" (UWLM), was previously proposed by the corresponding author. In UWLM, in situ ultrasound is applied during laser machining of a water-immersed workpiece surface region to improve the machining quality and/or efficiency. If the ultrasound is applied using a high-intensity focused ultrasound (HIFU) transducer, the process can be called "HIFU-based UWLM." Despite previous investigations on UWLM, to the authors' best knowledge, experimental studies on surface grooving using a HIFU-based UWLM process have been rarely reported in any paper. Such a study has been presented in this paper (for the first time in a paper to the authors' best knowledge). In this work, surface grooves are produced through the ablation of a moving workpiece immersed in water by laser pulses fired at a pulse repetition rate of 1 kHz or 3 kHz. Each laser pulse is followed by a focused ultrasound pulse (from a HIFU transducer) that reaches the workpiece surface approximately 30 μs later. The laser spot on the workpiece surface is approximately at the same location as the geometrical focal point of the HIFU transducer. Under the conditions investigated, it has been found that typically the grooves produced by the HIFU-based UWLM process appear much cleaner and have much smaller amounts of debris particles and recast material than those produced by laser ablation in air, and they typically have much larger depths than those by laser ablation in water without ultrasound. Some related fundamental physical mechanisms have been discussed. The study suggests that the HIFU-based UWLM process has a great potential to provide a new surface grooving technology with competitive performance. [DOI: 10.1115/1.4050307]

Keywords: laser micromachining, laser grooving, high-intensity focused ultrasound, laser processes, nontraditional manufacturing processes

1 Introduction

Laser grooving, as one of the most common laser machining processes [1], has several advantages, such as good flexibility, high spatial resolution, and non-contact without suffering from problems such as mechanical cutting-tool wear and damages due to mechanical tool-induced forces [2]. Laser grooving is applicable to a broad range of materials, including hard and brittle materials that are difficult to groove using a mechanical tool. Laser grooving has many current or potential applications, such as in dicing of semiconductor wafers [3] and ceramics [4], high-efficiency solar cell fabrication [5], microchannel creating for cooling systems [6] and microfluidics [7], and generation of surface-groove textures on biomedical implants [8] and machine parts [9].

However, laser grooving, like other laser micromachining processes, may often suffer from defects or drawbacks such as debris formation and deposition onto the workpiece, recast layer, and/or heat-affected zone (HAZ) [10–12]. Debris formation and deposition could degrade the quality of the features and the machined-part functionality, and could also decrease machining efficiency. It may often occur in grooving using nanosecond (ns)-pulsed lasers and may also happen even for femtosecond laser grooving at relatively high fluences [13,14]. To decrease related drawback(s) and improve the laser grooving process, studies were performed and reported in the literature about laser grooving of workpieces immersed in water or using hybrid laser-waterjet processing for different workpieces, such as germanium wafers [15], NdFeB [16], and silicon [17]. The studies often found reduced heat-affected zone and/or debris for laser grooving of water-immersed workpieces as compared with laser grooving of "dry" workpieces.

A novel process of machining, with the name of "ultrasound-assisted water-confined laser micromachining" (UWLM), was previously proposed by the corresponding author [18]. In UWLM, a laser beam irradiates the front surface region of a workpiece immersed in water to remove materials and produce or modify features. In addition, in situ ultrasound in water is applied to potentially produce ultrasonic cavitation, generate associated beneficial effect(s) (such as in situ cleaning), and decrease the common defect(s) (e.g., debris deposition) to enhance the machining quality and/or efficiency. The in situ ultrasound can be applied through different approaches, and two of them are through an ultrasonic horn or a high-intensity focused ultrasound (HIFU) transducer, where the corresponding UWLM process can be called "horn-based" and "HIFU-based" UWLM, respectively. The authors' previous investigations on horn-based UWLM are reported in Refs. [19,20], and under the studied conditions, it was found that the horn-based UWLM process could lead to a much smaller amount of debris than laser ablation in air and much higher (up to several times) average material removal depths per pulse than laser ablation in water without ultrasound. In Ref. [20],

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time-resolved shadowgraph-imaging study was also conducted, and the study indicates that in UWLM, the applied ultrasound in water may help clean or reduce bubbles and/or material particles left by previous laser pulse(s) near the ablation location and hence result in a better energy coupling to the workpiece surface for subsequent laser pulse(s) than the situation of laser ablation in water without ultrasound. Reference [21] reports the study by Charee et al. about the production of grooves on a silicon workpiece immersed in water through ultrasonic-assisted laser micromachining. A silicon workpiece was immersed in water through a chamber, and unfocused ultrasound was applied through a transducer that was attached at the chamber bottom. It was indicated in Ref. [21] that under suitable conditions, the grooving process could be improved due to the addition of the ultrasound.

In Refs. [19–21], *unfocused* ultrasound was applied through an ultrasonic horn or using an ultrasonic transducer attached to the water chamber bottom. Reference [22] reports the authors' experimental work on microhole drilling through a UWLM process based on a HIFU transducer. The process can be called "HIFU-based UWLM," and the process setup is significantly different from those in Refs. [19–21] (to the authors' best knowledge, Ref. [22] is the first paper reporting experimental investigations of microhole drilling by HIFU-based UWLM). In the HIFU-based UWLM process studied in Ref. [22], focused ultrasound at a wave frequency of ∼1 MHz was applied using a HIFU transducer that was approximately coaxial with the laser beam, and the laser spot on the workpiece surface is approximately located at the geometrical focal point of the HIFU transducer. Each laser pulse was followed by a short ultrasound pulse that had a controlled duration and reached the workpiece surface at a controlled delay time after the laser pulse. In HIFU-based UWLM, ultrasound can be spatially focused to produce a relatively high ultrasonic power density to potentially enhance ultrasound benefit(s) to the machining process. On the other hand, the ultrasound pulses' duration and timing (relative to the laser pulses) can be suitably controlled to potentially avoid or minimize the possible disturbance of laser beam by ultrasound-induced bubbles. Under the conditions investigated, Ref. [22] shows that with suitable parameters, the HIFU-based UWLM process can drill reasonably clean microholes without a significant debris deposition, and the drilled hole depth can be much higher than that drilled by laser ablation in water without ultrasound (e.g., for a copper workpiece, the depth of the former drilled under suitable parameters can even exceed around six times the latter). In situ time-resolved shadowgraph-imaging and pressure measurements were also conducted in Ref. [22] to help reveal the underlying mechanism and physical process of the HIFU-based UWLM process.

However, despite the authors' previous work reported in Ref. [22] on microhole drilling, an investigation on surface grooving using HIFU-based UWLM has been rarely reported in any paper to the authors' best knowledge. A paper reporting such an investigation would still be very valuable because surface grooving is very different from microhole drilling and it involves a different machined feature geometry and typically much more laser pulses and material removal. This paper is the first paper that presents such an investigation (to the authors' best knowledge), where surface grooving of metal workpieces (304 stainless steel and titanium) using the HIFU-based UWLM process has been studied, in comparison with laser grooving in air and in water without ultrasound. The related fundamental physical mechanisms will also be discussed.

2 Experiments

Figure 1 shows the schematic diagram of the experimental setup for laser grooving using the HIFU-based UWLM process in this study. Nanosecond laser pulses at a certain pulse repetition rate

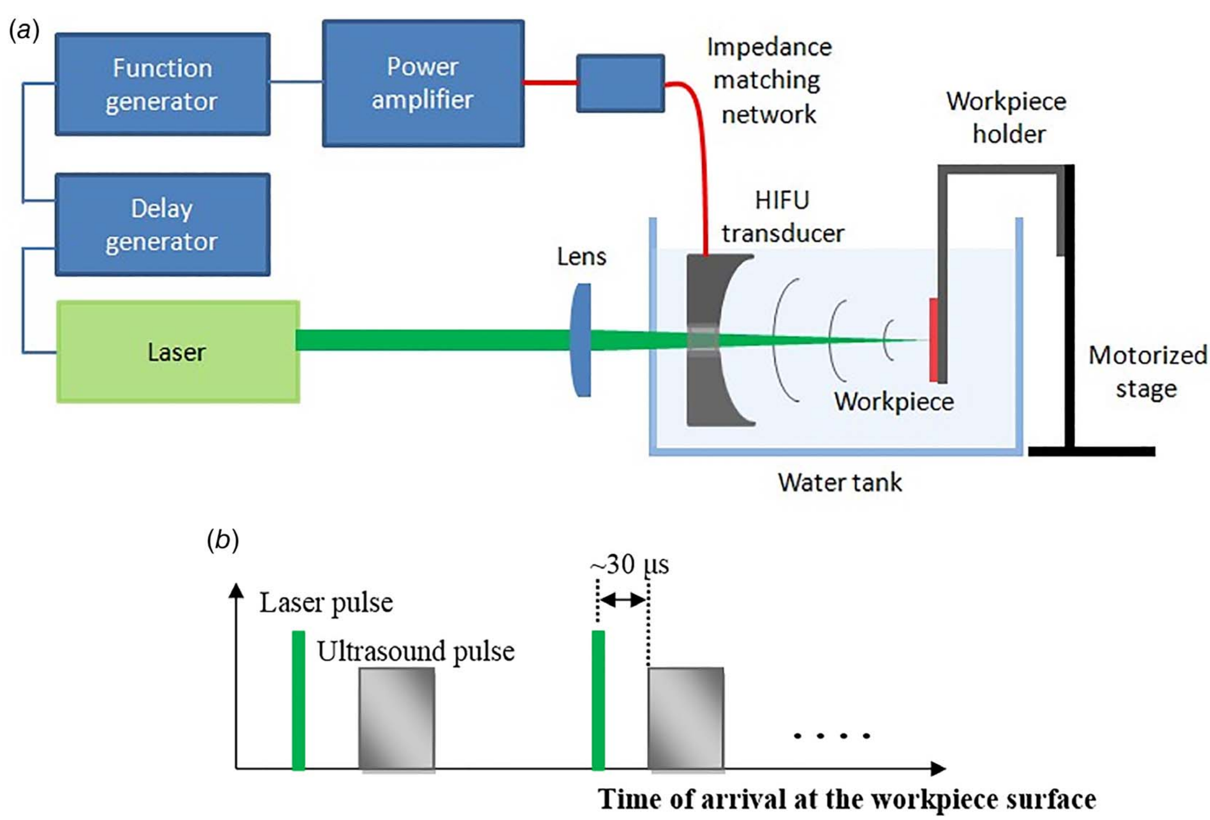

Fig. 1 Schematic diagram of (*a*) the setup in this study for the grooving process using HIFU-based UWLM and (*b*) the relative timing of each laser and ultrasound pulse (not drawn to scale and not necessarily reflecting the exact actual sizes, shapes, or other details; not all components are shown)

(PRR) irradiate the surface of a moving workpiece immersed in water to remove materials and generate the groove, while in situ ultrasound pulses are also delivered to the laser ablation site on the workpiece surface using a HIFU transducer that is approximately coaxial with the laser beam. The rising edge of each focused ultrasound pulse arrives at the workpiece surface at approximately 30 μs after each corresponding laser pulse. More details are given next.

In this study, a short-pulsed laser (Bright Solutions, Onda), which can emit laser pulses with a beam wavelength of ~532 nm and a full-width-at-half-maximum (FWHM) pulse duration of ~4 ns, has been employed to produce grooves on two types of workpieces: 304 stainless steel and titanium Grade 2 (purchased from McMaster-Carr). The stainless steel workpiece comes with a mirror-like surface finish, and hence has been directly used in the experiment without being further grinded. The titanium workpiece is grinded using grit 240 down to grit 2000 sandpapers. During the experiment, a workpiece sample is mounted on a mechanical holder and is placed inside a water tank, and the tank has a linear size of ~120 mm × 120 mm × 125 mm, whose sidewalls are made using borosilicate glass. The workpiece holder is fixed on and translated by a motorized stage, while the laser beam and the HIFU transducer remain stationary. The laser beam transmits through a focusing lens (with a nominal focal length of ~100 mm in air), the tank sidewall made of borosilicate glass, and the central opening of the HIFU transducer before it irradiates the surface of the workpiece.

The HIFU transducer (Sonic Concepts, H-197) used in this work has a geometric focal point that is located at a distance of ~45 mm away from its concave surface that emits ultrasonic waves. To facilitate laser beam propagation, the transducer comes with a central opening (which has a diameter of ~15 mm). The HIFU transducer and the laser beam have been aligned to be approximately coaxial, and the geometrical focal point of the HIFU transducer is approximately at the same location as the laser spot (i.e., the ablation site) on the workpiece surface. To drive the HIFU transducer, a function generator (Agilent, 33220A) is used to generate sine-wave pulses with a wave frequency of ~1 MHz, a pulse duration of 100 μs, and a peak-to-peak amplitude of 0.4 V. The driving sine-wave is amplified by a power amplifier (ENI, A-300) that has a nominal gain of ~55 dB, and then, it passes through an impedance matching network prior to entering the HIFU transducer. As a result of each diving sine-wave pulse, a focused ultrasound pulse (with a duration close to ~100 μs) is sent out by the HIFU transducer. Based on the product specification information of the HIFU transducer from Sonic Concepts and the measured voltage of the transducer, the peak value of the nominal net electrical power (averaged over one cycle of the wave) into the HIFU transducer during the experiment is approximately estimated to be ~300 W. For each pair of laser and ultrasound pulses, the function generator and the laser are triggered at the same time by a delay generator (Berkeley Nucleonics, Model 577). However, due to the much lower sound speed (around 1500 m/s [23]) than the light speed in water, the rising edge of the ultrasound pulse arrives at the workpiece surface at approximately 30 μs after the corresponding laser pulse (it should be noted that during the triggering process, the other time delays due to the involved devices are much smaller than ~30 μs and hence can be neglected). Hence, the delay time of ~30 μs between each ultrasound and laser pulse naturally occurs when the HIFU transducer and the laser are triggered at the same time. As shown later, this delay time value can lead to reasonably good results for UWLM under the conditions studied, and hence has been used in this paper.

As a comparison, in this study, laser grooving has been performed using (1) HIFU-based UWLM, (2) laser ablation in water without focused ultrasound, and (3) laser ablation in air. For laser grooving in air, the water is drained out of the tank, but the workpiece is still positioned inside the tank. The location of the lens is adjusted in order to approximately compensate the effective focal length change of the lens due to the removal of water from the tank. It has been roughly estimated that the laser spot radius on the workpiece surface in water and in air is approximately ~38 μm and ~29 μm, respectively. The estimation is made based upon the measured crater diameters produced by single-pulse laser ablation in water (without ultrasound) and in air, respectively, for a titanium Grade 2 workpiece. During the estimation, it has been approximately assumed that the local fluence of the laser beam follows a Gaussian distribution, and the fluence at the crater boundary is equal to the ablation threshold (which is roughly assumed to be ~1 J/cm^2, based on the threshold given in Ref. [24] for 4.5-ns laser pulse ablation of titanium in air at the wavelength of 532 nm). In this study, the applied laser pulse energy coming to the lens has been measured to be approximately ~0.21 mJ using an energy sensor (Coherent, J-25MT-10KHZ) placed right before the lens. The laser PRR is set to be 1 or 3 kHz in the experiment. The feed rate (i.e., the relative moving speed of laser spot on the workpiece surface) used in this work is 0.1, 0.2, 0.4, 1, or 2 mm/s. A scanning electron microscope (SEM; JEOL, JSM-T330) has been used to observe and examine surface morphologies of the machined grooves on the workpieces. To observe cross sections of workpiece grooves, the corresponding workpiece is cut using a precision cutoff machine (Struers, Accutom-2), and then, the sample is mounted in epoxy resin and grinded. After this, the cross sections are observed and characterized using an optical microscope (Olympus, BH-2) that is coupled with a digital camera, and the groove depths and widths have been measured based on the digital optical images of the groove cross sections.

3 Results and Discussions

3.1 Surface Morphology and Characteristics of Grooves. Figure 2 shows the typical SEM images for grooves produced on 304 stainless steel workpieces by HIFU-based UWLM (the first row), laser ablation in water without ultrasound (the second row), and laser ablation in air (the third row). The workpiece feed rate is 0.1 mm/s for all the images, while the laser pulse repetition rate is 1 kHz and 3 kHz for the images on the left and the right column, respectively. The grooves produced by laser ablation in air have a significant amount of debris particles and recast material. The debris particles appear even denser in the SEM image for the groove produced at the 3 kHz pulse repetition rate than that at 1 kHz, and under both conditions, thick and irregular recast material layers can be clearly seen around the groove sidewalls in the SEM images. The grooves produced by laser ablation in water without ultrasound have much smaller amounts of debris particles and recast material than those produced by laser ablation in air as can be seen from the SEM images on the second row. However, the grooves appear quite shallow in the images. In addition, the groove becomes much wider at the 3 kHz laser pulse repetition rate than 1 kHz. The grooves manufactured by the HIFU-based UWLM process, as shown in Figs. 2(*a*) and 2(*b*), appear reasonably regular and clean without a significant amount of debris particles or recast material, and the depths appear much larger than those by laser ablation in water without ultrasound under the same laser pulse repetition rate. The groove width shown in the image for the 1 kHz repetition rate is not significantly different from that for 3 kHz.

Figure 3 illustrates the SEM images for the titanium workpieces. The images on the first, second, and third row correspond to the situation of HIFU-based UWLM, laser ablation in water without ultrasound, and laser ablation in air, respectively. The images on the left and the right column correspond to the laser pulse repetition rate of 1 kHz and 3 kHz, respectively. Similar to Fig. 2, the grooves produced by laser ablation in air have a significant amount of debris particles and recast material. On the other hand, the grooves produced by HIFU-based UWLM appear reasonably clean with much smaller amounts of debris particles and recast material than those produced by laser ablation in air, and overall they also appear deeper than those by laser ablation in water without ultrasound in the images under the same laser pulse repetition rate.

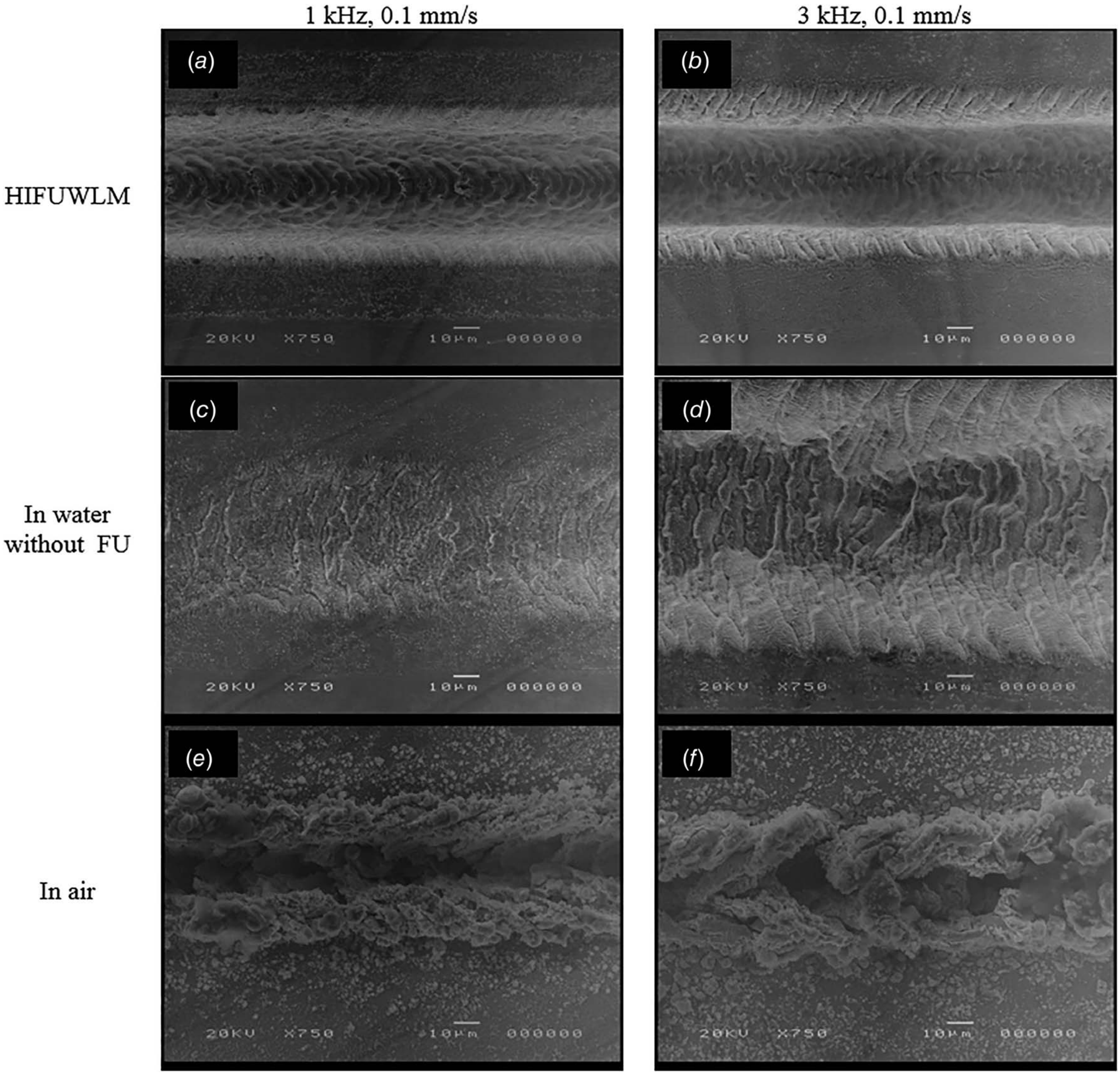

Fig. 2 SEM images for surface grooves produced on 304 stainless steel workpieces through (*a* and *b*) HIFU-based UWLM, (*c* and *d*) laser ablation in water without ultrasound, and (*e* and *f*) laser ablation in air (workpiece feed rate: 0.1 mm/s; laser pulse repetition rate: 1 kHz for the left column and 3 kHz for the right column; HIFUWLM: HIFU-based UWLM; FU: focused ultrasound)

One interesting thing observed in Fig. 3 is that the SEM images for grooves produced by HIFU-based UWLM and by laser ablation in water without ultrasound show many densely packed and cell-like tiny structures (particularly in Figs. 3(*a*), 3(*b*), and 3(*d*)). It is expected that the cell-like structures are mostly not re-deposited debris particles, but should be mainly formed on the workpiece surface due to laser-induced material removal, motion and/or phase changes during the machining process.

3.2 Cross Sections and Geometric Dimensions of Grooves. Figure 4 shows optical microscopic images for cross sections of grooves produced on 304 stainless steel workpieces through HIFU-based UWLM (the first row), laser ablation in water without ultrasound (the second row), and laser ablation in air (the third row). The workpiece feed rate for all the images is 0.1 mm/s. The laser pulse repetition rate is 1 kHz and 3 kHz for the images on the left and the right column, respectively.

Figures 4(*e*) and 4(*f*) show that the grooves produced by laser ablation in air have significant recast layers, both inside the grooves (e.g., along the groove sidewalls) and outside (but near) the grooves. It appears from the images that some portions of the recast layers seem to be metallurgically bonded with adjacent materials of the workpiece. The groove produced by laser ablation in air at the pulse repetition rate of 3 kHz shown in Fig. 4(*f*) has the largest cross-sectional depth among all the groove cross sections shown in Fig. 4. However, in the image, the recast material appears to have “bridged” the left and right sidewalls inside the groove over a large depth, which has made the “effective” groove depth in the image much smaller than the total depth. Some previous work in the literature (e.g., [25]) also reported the formation of blockage due to recast material during laser grooving of a metal workpiece.

Figure 4(*c*) shows that the groove produced by laser ablation in water without ultrasound has much less recast material than that produced by laser ablation in air under the same laser pulse

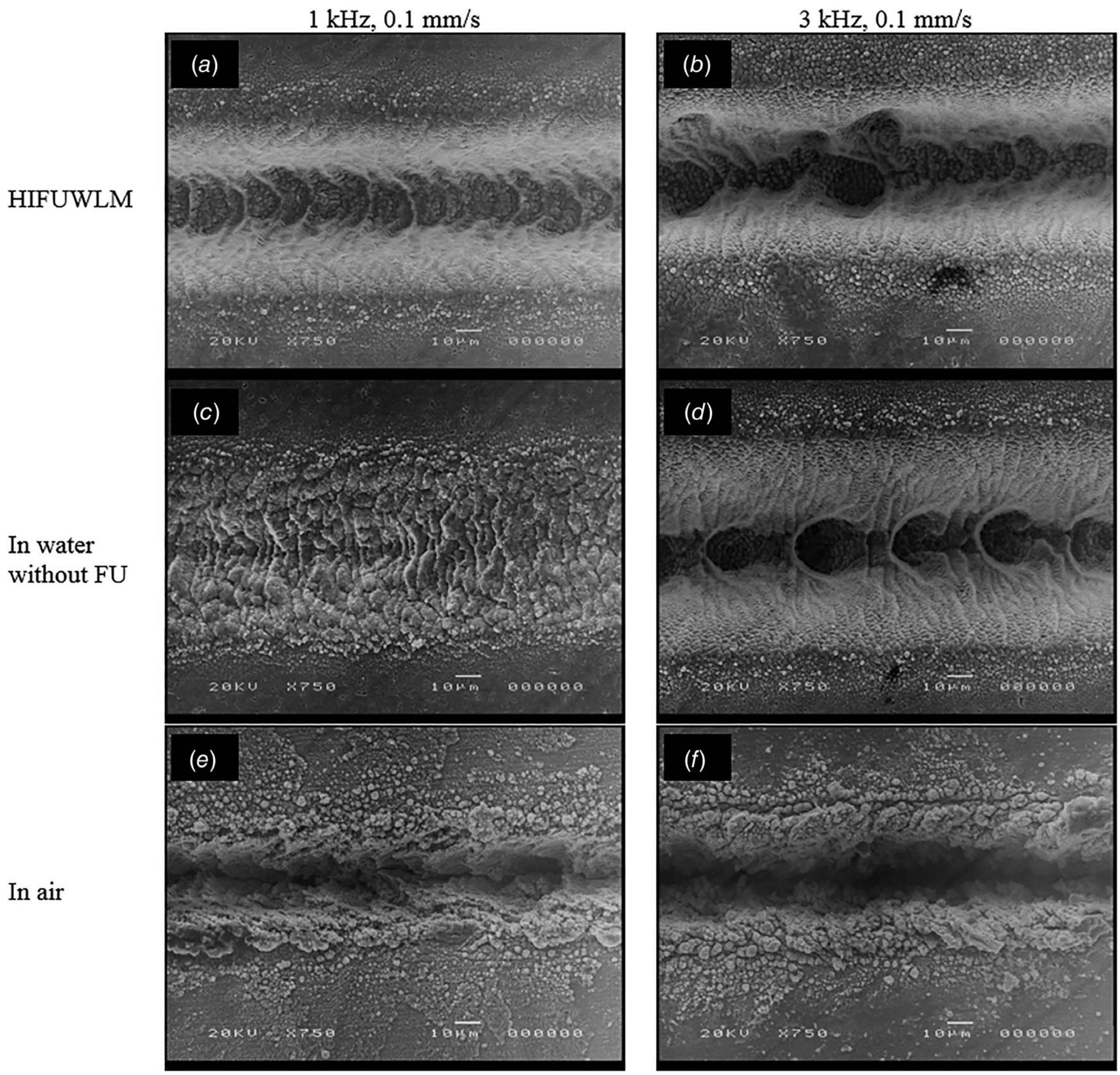

Fig. 3 SEM images for surface grooves produced on titanium workpieces through (*a* and *b*) HIFU-based UWLM, (*c* and *d*) laser ablation in water without ultrasound, and (*e* and *f*) laser ablation in air (workpiece feed rate: 0.1 mm/s; laser pulse repetition rate: 1 kHz for the left column and 3 kHz for the right column)

repetition rate shown in Fig. 4(*e*). However, the groove is also significantly shallower. The groove depth is increased when the laser pulse repetition rate is increased to 3 kHz as shown in Fig. 4(*d*), but the groove has also become much wider. The groove width in Fig. 4(*d*) is much larger than the nominal laser spot diameter on the workpiece surface (estimated through a process as introduced earlier), and hence, the lateral spatial precision or resolution of the grooving process has significantly deteriorated.

Figure 4(*a*) shows that the groove produced by HIFU-based UWLM at the 1 kHz laser pulse repetition rate appears quite "clean" without a significant recast layer observable in the image, and it is deeper than both the groove produced by laser ablation in water without ultrasound (shown in Fig. 4(*c*)) and the groove by laser ablation in air (shown in Fig. 4(*e*)) under the same laser pulse repetition rate. When the laser pulse repetition rate is increased from 1 kHz to 3 kHz, Fig. 4(*b*) shows that the groove produced by HIFU-based UWLM is still reasonably clean without significant recast material observable in the image. The groove produced by HIFU-based UWLM (shown in Fig. 4(*b*)) is deeper and narrower than that by laser ablation in water without ultrasound (shown in Fig. 4(*d*)). It is shallower than that by laser ablation in air (shown in Fig. 4(*f*)). However, as discussed earlier, due to the recast material, the groove "effective depth" (i.e., the groove depth above the "bridging" recast material) in Fig. 4(*f*) is much smaller than its total depth.

In summary, under the conditions studied, Fig. 4 shows that for laser ablation in water without ultrasound, the produced groove is very shallow at the 1 kHz laser pulse repetition rate; the groove at 3 kHz becomes deeper, but also much wider causing severe degradation of the lateral resolution or precision of the grooving process. For laser ablation in air, the produced groove at the 3 kHz pulse repetition rate is still narrow and deep, but has a significant amount of recast material, seriously affecting the groove quality and "effective" depth. For the HIFU-based UWLM process, the produced grooves have much less debris and recast material than those by laser ablation in air. The groove widths

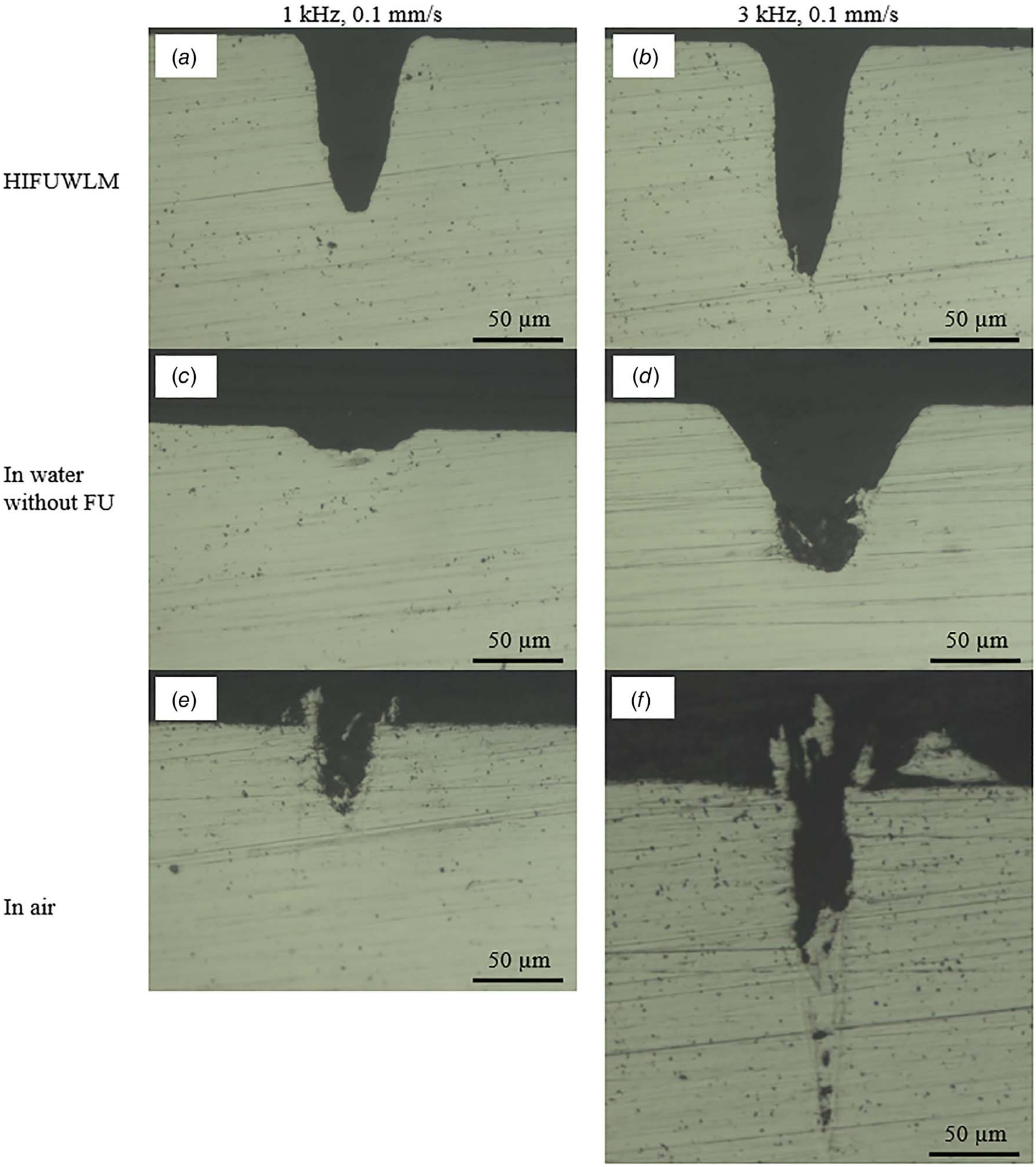

Fig. 4 Optical microscopic images for cross sections of grooves produced in 304 stainless steel workpieces through (*a* and *b*) HIFU-based UWLM, (*c* and *d*) laser ablation in water without ultrasound, and (*e* and *f*) laser ablation in air (workpiece feed rate: 0.1 mm/s; laser pulse repetition rate: 1 kHz for the left column and 3 kHz for the right column)

are similar at both 1 kHz and 3 kHz and reasonably close to the nominal laser spot size. Compared with the groove in Fig. 4(*d*), the much smaller width of the groove in Fig. 4(*b*) could greatly increase the difficulty of material removal from the groove bottom; however, the UWLM-produced groove in Fig. 4(*b*) is still much deeper than that in Fig. 4(*d*) by laser ablation in water without ultrasound.

For stainless steel grooves produced with 3 kHz laser pulse repetition rate and 0.1 mm/s workpiece moving speed, as shown later in Fig. 5, the average groove depth of the measured multiple cross sections for UWLM (~141 μm) is ~74% larger than that for laser ablation in water without ultrasound (~82 μm). As shown later in Fig. 6, the groove widths by laser ablation in water without ultrasound have a very large standard deviation (some widths may be much smaller than that in Fig. 4(*d*)). However, the average width is still ~99 μm, much larger than the estimated nominal laser spot diameter on the workpiece surface or the average width by UWLM (~74 μm). For the measured multiple cross sections for Figs. 5 and 6, the groove average width × average depth product for UWLM is ~29% larger than that for laser ablation in water

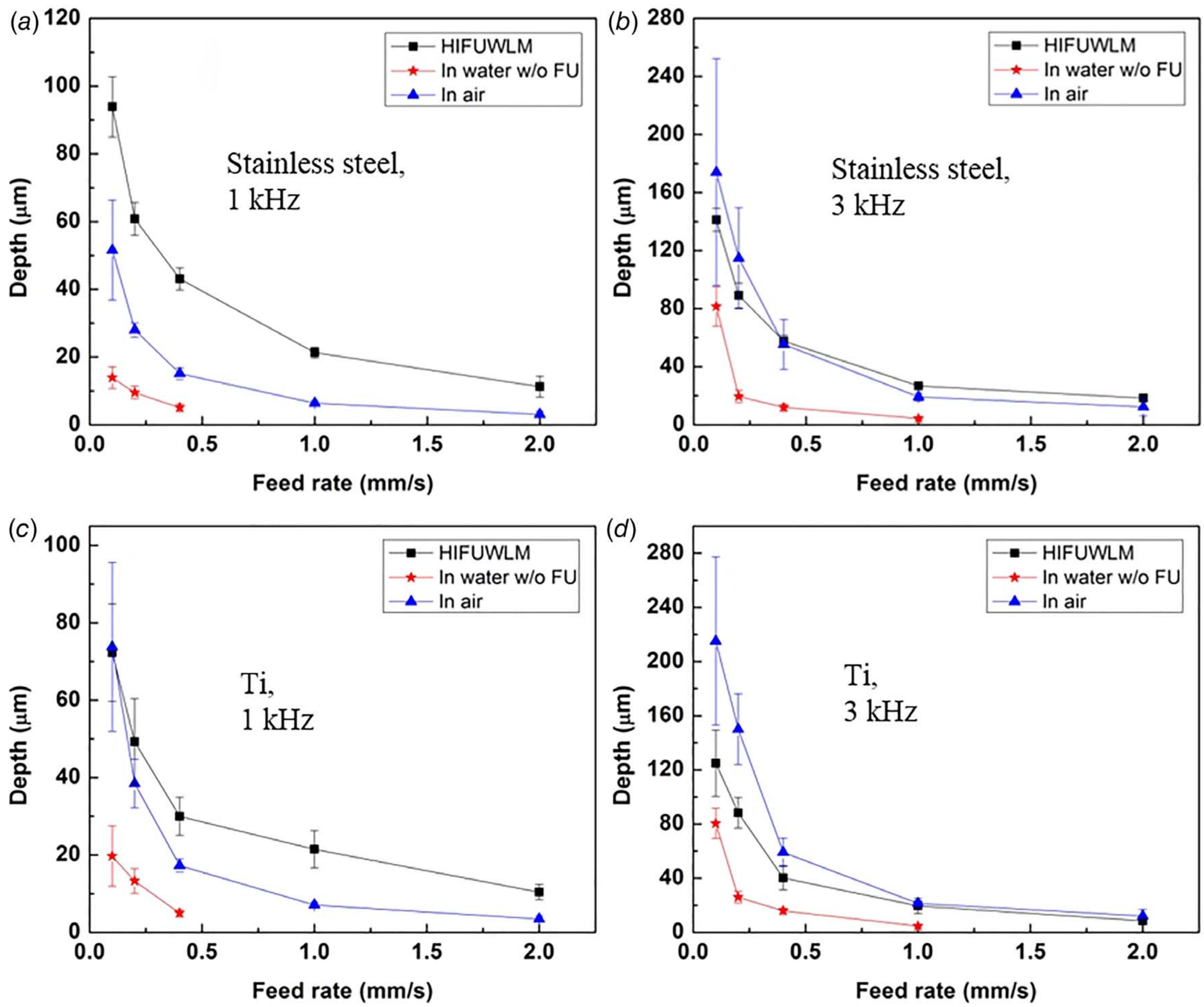

Fig. 5 The produced groove depth versus workpiece feed rate for (*a* and *b*) 304 stainless steel and (*c* and *d*) titanium workpieces (laser pulse repetition rate: 1 kHz for the left column and 3 kHz for the right column)

without ultrasound. Therefore, for the measured stainless steel groove cross sections under 3 kHz laser pulse repetition rate and 0.1 mm/s workpiece moving speed, compared with UWLM, on average laser ablation in water without ultrasound has led to a degraded lateral spatial resolution, much lower groove depth and also obviously lower width × depth product.

Figure 5 shows machined groove depth versus workpiece feed rate for 304 stainless steel (plots on the first row) and for titanium (the second row) under a laser pulse repetition rate of 1 kHz (the left column) and 3 kHz (the right column). In each plot, the feed rate is varied from 0.1 mm/s to 2 mm/s. The error bars in Figs. 5 and 6 represent standard deviations from multiple measurements. Figure 5 shows that for each machining method, under the same laser pulse repetition rate, the machined groove depth decreases as the feed rate increases. Another important trend is that under all the studied conditions presented in Fig. 5, the groove depth produced by HIFU-based UWLM is much higher than that by laser ablation in water without ultrasound under the same feed rate in each plot. For the latter method, the produced groove depths are so small at certain high workpiece feed rates that it is even difficult or impossible to unambiguously locate the grooves in the optical images of the cross sections due to the original workpiece surface roughness. Therefore, some groove depth data points are not given in the figure at relatively high feed rates for laser ablation in water without ultrasound.

Another important trend shown in Fig. 5 is that at the laser pulse repetition rate of 1 kHz, the groove depths produced by laser ablation in air for both types of workpieces are smaller than those produced by HIFU-based UWLM at the same workpiece feed rate in most cases shown (except for titanium at the 0.1-mm/s feed rate, where the depths are close to each other). On the other hand, at the laser pulse repetition rate of 3 kHz and for relative low feed rates, the depths produced by laser ablation in air become larger than those by UWLM. However, the following should be noted: (1) In this study, the estimated laser spot radius (as introduced earlier) on the workpiece surface in water is larger (and hence, the average laser fluence (pulse energy/laser spot area) is expected to be smaller) than that in air. As shown in Fig. 6, the groove widths produced by HIFU-based UWLM are larger than those by laser ablation in air, which is expected to be due to (at least partially) the larger spot size. (2) The images in Figs. 2–4 show a significant amount of recast material inside the grooves produced by laser ablation in air, which could significantly reduce the "effective" or "useful" groove depths for practical applications (e.g., the recast material in Fig. 4(*f*) that bridges the two sidewalls has significantly reduced the "effective" depth in the image). It may be very difficult and time-consuming to remove such recast material through post-machining treatment(s) while still maintain the major groove size and shape. The discussions above indicate that in the studied cases at the laser pulse repetition rate of 3 kHz and for relative

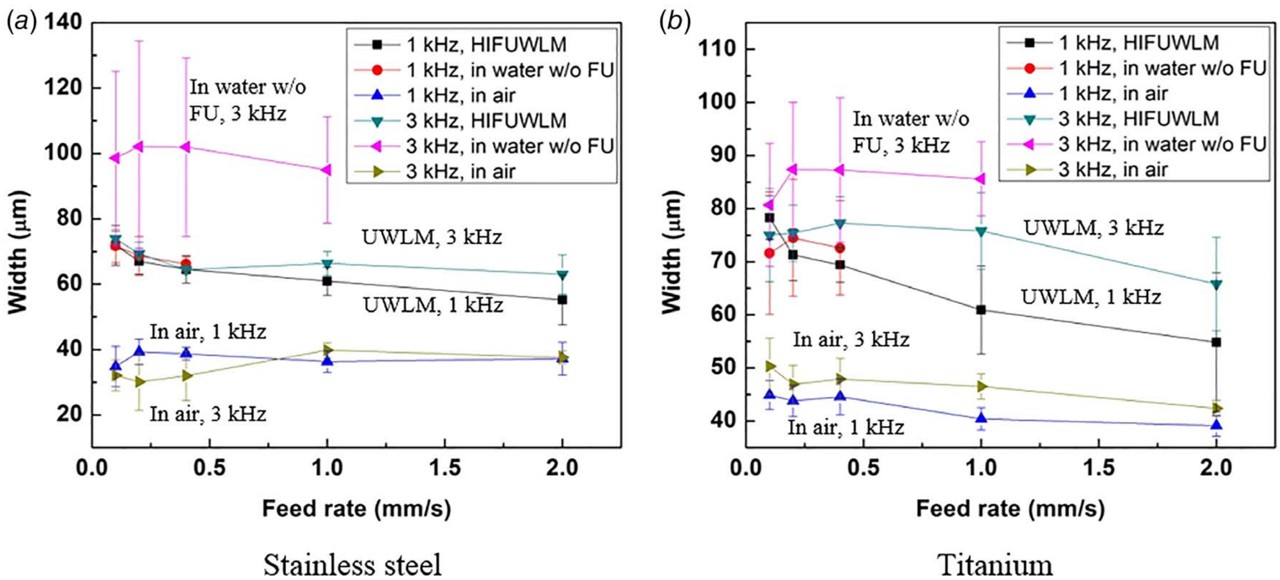

Fig. 6 The produced groove width versus workpiece feed rate for (*a*) 304 stainless steel and (*b*) titanium workpieces under different laser pulse repetition rates of 1 kHz and 3 kHz

low workpiece feed rates, although the groove depths produced by laser ablation in air are larger than those by HIFU-based UWLM, it does not necessarily always mean a higher material removal rate per pulse for the former method, considering the typically smaller groove width and much more recast materials produced by laser ablation in air.

Figures 6(*a*) and 6(*b*) show the machined groove width versus the workpiece feed rate for the stainless steel and titanium workpieces, respectively. In Fig. 6(*a*), the following major trends can be seen: (1) Under the same feed rate, the groove widths produced by laser ablation in air are smaller than those by HIFU-based UWLM and those by laser ablation in water without ultrasound. Two important reasons for this are expected to be: (i) smaller nominal laser spot size on the workpiece surface in air (estimated through a process introduced earlier) and (ii) a more significant amount of recast layer material that may be formed on the groove sidewalls and near the workpiece surface. (2) Laser ablation in water without ultrasound at the 3 kHz pulse repetition rate leads to the largest groove width, which is much larger than the nominal laser spot size on the workpiece surface in water. This implies a serious degradation of spatial resolution or precision in the lateral direction for the grooving process. The groove widths become much smaller when the pulse repetition rate decreases from 3 kHz to 1 kHz, where the widths are close to those produced by HIFU-based UWLM. (3) The groove widths produced by HIFU-based UWLM given in Fig. 6(*a*) under both laser pulse repetition rates are typically close to or smaller than the nominal laser spot size on the workpiece surface in water, indicating that the lateral spatial resolution or precision for the grooving process has been maintained. Figure 6(*b*) shows the groove widths of the titanium workpiece. Similar to the stainless steel workpiece, the groove widths produced by laser ablation in water without ultrasound at the 3 kHz pulse repetition rate are the largest, while those by laser ablation in air are the smallest.

3.3 Discussions of Fundamental Physical Mechanisms. The experimental results given in Secs. 3.1 and 3.2 clearly show significantly different grooving results by laser ablation in air, laser ablation in water without ultrasound, and HIFU-based UWLM. In this section, some fundamental physical mechanisms relevant to several major phenomena observe in this experimental study will be discussed.

3.3.1 Grooving by Nanosecond Laser Ablation in Air. During nanosecond laser ablation in air, the removed material may leave the workpiece in the form of melt and/or vapor, etc. The re-deposition of some condensed vapor and the re-solidification of some workpiece melt may cause debris particles and recast material layers. Surface grooving by ns laser ablation in air often involves numerous laser pulses and a relatively large amount of material removal. This could lead to a significant amount of debris particles and/or recast material, as shown in Figs. 2(*e*), 2(*f*), 3(*e*), 3(*f*), 4(*e*), and 4(*f*). Some of the debris particles and/or recast material may be strongly bonded with the workpiece, which could make it difficult and time-consuming to remove them without damaging the groove itself through post-process treatment(s).

3.3.2 Grooving by Nanosecond Laser Ablation in Water Without Ultrasound. During ns laser ablation of a metal workpiece in water, the water layer can help reduce the debris deposition and recast layers on the workpiece. However, laser energy deposition and the induced material removal and phase change at around the workpiece-water interface may generate a cloud of particles and/or bubbles, which could still linger in the water region near the laser ablation site for quite some time even after the end of a laser pulse. The in situ time-resolved shadowgraph images for ns laser microhole drilling in water presented in the authors' previous paper [22] show a cloud of residual particles and/or bubbles near the workpiece ablation site at ∼1 ms after 50 prior laser pulses are fired at 1 kHz. The residual particles and/or bubbles in the laser beam path may absorb and/or scatter a certain portion of the subsequent laser pulse(s) energy. Laser grooving typically involves a larger number of laser pulses, and hence, such absorbing and/or scattering could decrease the laser energy effectively coupled to the workpiece surface and/or redistribute laser energy to an area larger than the nominal laser spot area on the workpiece surface. This should be one important physical mechanism for the smaller groove depths by laser ablation in water without ultrasound compared with those by UWLM and laser ablation in air, as shown in Figs. 4 and 5. The aforementioned potential absorption and/or scattering-induced effect is expected to be more serious as laser pulse repetition rate increases (and hence, adjacent laser pulses are closer in time). This provides a likely explanation for the overall obvious increase of the groove width when laser pulse repetition rate is increased from 1 kHz to 3 kHz for laser ablation in water without ultrasound, as shown in Figs. 4 and 6.

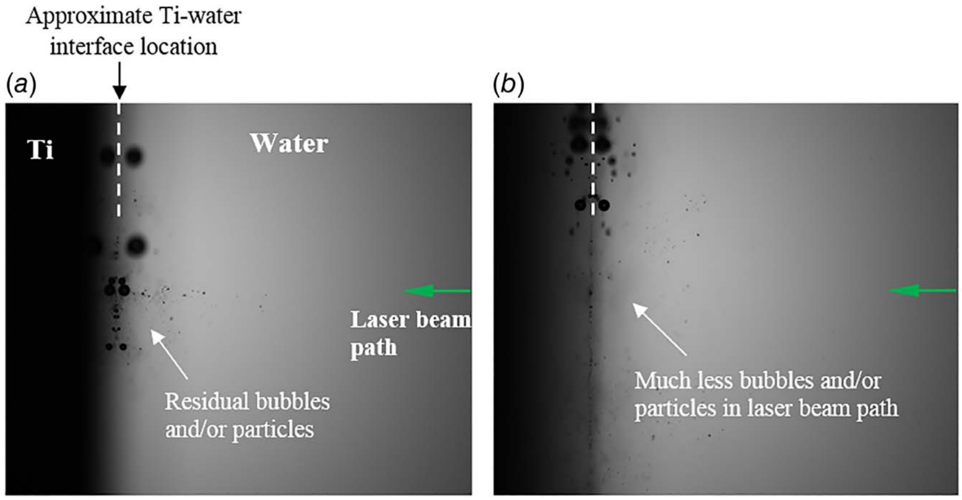

Fig. 7 Shadowgraph images taken at ~1 ms after 50 prior laser pulses are fired to a stationary titanium workpiece at 1 kHz pulse repetition rate for: (*a*) laser ablation in water without ultrasound and (*b*) HIFU-based UWLM (using 100 μs-duration and 0.4 V-magnitude driving sine-wave pulses from the function generator for the HIFU trasnducer). Images are taken from the authors' previous paper [22], where more details can be found [22].

3.3.3 Grooving by HIFU-Based UWLM. During HIFU-based UWLM studied in this paper, shortly after the end of each laser pulse, a focused ultrasound pulse reaches the region around the laser ablation site. A sufficiently intense ultrasonic pulse may generate ultrasonic cavitation in water, where the evolution of the bubbles may emit shock waves [26,27]. The focused ultrasonic energy input, the induced cavitation, and shock waves may promote water flow and also generate transient high pressures, which may result in an "in situ cleaning effect" to help remove many residual particles and/or bubbles left by the previous laser pulse ablation out of laser beam path. The existence and effectiveness of such an effect is supported by the in situ time-resolved shadowgraph images for microhole drilling by HIFU-based UWLM presented in the authors' previous paper [22]. The images (taken at ~1 ms after 50 prior laser pulses are fired at 1 kHz) show that the laser beam path region in water near the workpiece ablation site can appear much cleaner for UWLM than that for laser ablation in water without ultrasound. Some images for a titanium workpiece from Ref. [22] are also given in Fig. 7 of this paper.

Due to the "in situ cleaning effect," the aforementioned absorption and/or scattering effect to laser beam by the residual bubbles and/or particles is expected to be weaker [22]. Hence, the subsequent laser pulses can be better coupled to the workpiece surface. This was revealed by the authors' previous study in Ref. [22] to be one important mechanism for higher ablation depth per pulse for microhole drilling by UWLM than laser ablation in water without ultrasound. It is expected to be also one important underlying physical mechanism in this laser grooving study for: (i) the much larger groove depths by UWLM than those by laser ablation in water without ultrasound as shown in Figs. 4 and 5 and (ii) the UWLM-induced groove widths close to or smaller than the nominal laser spot size under laser pule repetition rates of both 1 kHz and 3 kHz (as shown in Fig. 6), which are overall obviously smaller than those by laser ablation in water without ultrasound under the repetition rate of 3 kHz.

One interesting thing observed in Fig. 3 is that the groove image (Fig. 3(*d*)) for laser ablation in water without ultrasound at the 3 kHz pulse repetition rate shows periodic craters at the groove

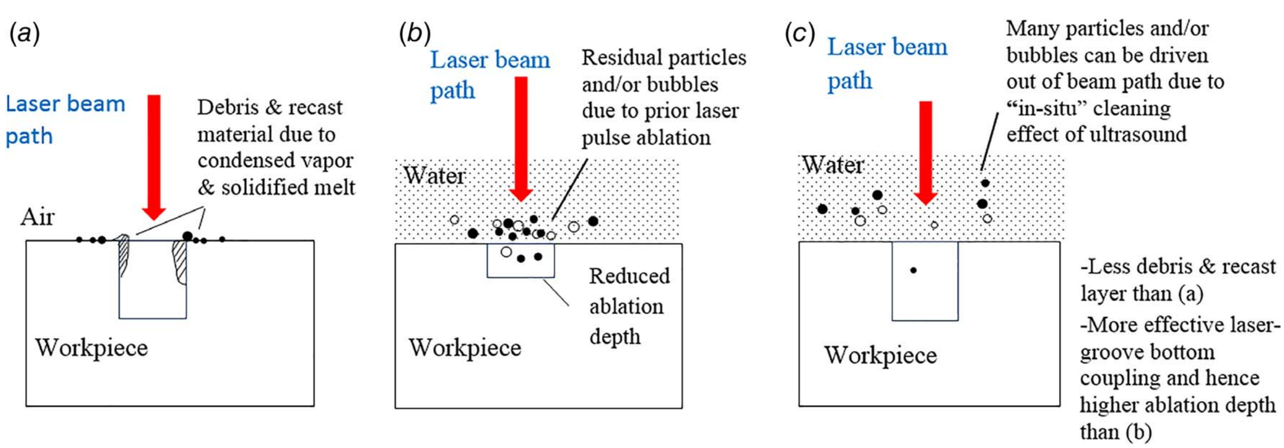

Fig. 8 Schematics of (*a*) laser ablation in air, where vapor condensation and/or melt re-solidification onto the workpiece may cause debris particles and/or recast layers; (*b*) laser ablation in water without ultrasound, where residual particles and/or bubbles induced by previous laser pulse ablation may still linger around the ablation site when the next laser pulse comes and thus hinder effective laser-workpiece energy coupling; and (*c*) UWLM, where many residual particles and/or bubbles can be driven out of laser beam bath due to the "in situ cleaning effect" of the ultrasound, which may enhance laser-workpiece coupling (the schematics are not drawn to scale, and do not necessarily reflect (or fully include) the exact actual details)

bottom wall. The distance between adjacent craters is much larger than (and hence, the cater formation is difficult to be explained by) the minimum step size of the motion stage, or the laser spot displacement between adjacent laser pulses (which is only ~33 nm at the 3 kHz pulse repetition rate). It is expected that the cater formation may be associated with the effect(s) of residual bubbles and/or particles induced by preceding laser pulse(s) on the ablation process of the subsequent laser pulse(s). Such craters also occasionally occur for HIFU-based UWLM at the 3 kHz pulse repetition rate, which are, however, much less frequent than those for laser ablation in water without ultrasound. This could be due to the aforementioned "in situ cleaning effect" of ultrasound, which has reduced the residual bubbles and/or particles produced by previous laser pulse(s) in the laser beam propagation path.

Figure 8 shows schematics roughly demonstrating some features of laser ablation in air, in water without ultrasound, and UWLM. Different from the microhole drilling process studied in the authors' previous paper [22], the laser grooving process in this study involves a very different ablated feature geometry (a groove) and typically a much larger number of laser pulses and more material removal. This study shows that under the conditions investigated, the HIFU-based UWLM can produce grooves with much less debris deposition and recast material than those by laser ablation in air, and with much larger depths than those by laser ablation in water without ultrasound.

It should be kept in mind that the reasonably "clean" grooves as shown in Figs. 2(*a*), 2(*b*), 3(*a*), and 3(*b*) are produced by UWLM with a relatively low-cost nanosecond laser, instead of an ultrashort pulsed laser that typically has a much higher cost per average laser power. It should also be noted that the UWLM process is different from the ultrasonic vibration-assisted laser machining process studied by researchers (e.g., that in Ref. [28]); the latter process involves ultrasonic vibration of a workpiece surface, but does *not* involve (and hence does not utilize the related beneficial effect(s) of) the *immersion* of the ablation region of the workpiece surface *by ultrasound-energized water*, which is, however, a critical part of UWLM.

4 Conclusions

This paper has reported the studies on the production of grooves on 304 stainless steel and titanium workpieces using an ultrasound-assisted water-confined laser micromachining (UWLM) process based on a HIFU transducer. UWLM was a novel machining technology previously proposed by the corresponding author of this paper [18]. During the studied HIFU-based UWLM process, the ablation of a workpiece immersed in water by each laser pulse is followed by a focused ultrasound pulse from a HIFU transducer that reaches the workpiece surface approximately ~30 μs later. As a comparison, the productions of grooves through laser ablation in water without ultrasound and through laser ablation in air have also been investigated. Different laser pulse repetition rates of 1 kHz and 3 kHz have been used, and the workpiece feed rate has been varied in a range of 0.1–2 mm/s. Under the conditions studied, it has been found:

(1) The grooves produced by laser ablation in air typically have a significant amount of debris particles and recast material, which may significantly degrade the quality of the machined grooves.
(2) The grooves produced by laser ablation in water without ultrasound typically have much smaller amounts of debris particles and recast material than those by laser ablation in air. However, the grooves produced at the 1 kHz pulse repetition rate are typically very shallow. As the pulse repetition rate is increased to 3 kHz, the groove depth can be increased. However, the groove has often become much wider, and the width can often be much larger than the nominal laser spot size on the workpiece surface in water. This means that the lateral spatial precision or resolution of the grooving process has often obviously degraded.
(3) The grooves produced by the HIFU-based UWLM process typically appear much cleaner and have much smaller amounts of debris particles and recast material than those by laser ablation in air. The produced groove depths by HIFU-based UWLM are typically much larger than those by laser ablation in water without ultrasound. The produced groove widths by UWLM under both 1 kHz and 3 kHz pulse repetition rates are typically close to or smaller than the nominal laser spot size on the workpiece surface in water, indicating that the lateral spatial precision or resolution for the grooving process has been maintained.

Related fundamental physical mechanisms have been discussed. The water layer helps reduce the amount of debris deposition and recast material on the workpiece, and the in situ cleaning effect of ultrasound is expected to be one important fundamental mechanism for the typically larger groove depths by UWLM than those by laser ablation in water without ultrasound. This study suggests that the HIFU-based UWLM process has a great potential to provide a new surface grooving technology with competitive performance.

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Conflict of Interest Declaration

Please read the Acknowledgment section for relevant conflict of interest declared (if any).

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request, the approval or disapproval of which is at the corresponding author's discretion.

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