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Microhole Drilling by Double Laser Pulses With Different Pulse Energies

Previous investigations on "double-pulse" nanosecond (ns) laser drilling reported in the literature typically utilize double pulses of equal or similar pulse energies. In this paper, "double-pulse" ns laser drilling using double pulses with energies differing by more than ten times has been studied, where both postprocess workpiece characterizations and in situ time-resolved shadowgraph imaging observations have been performed. A very interesting physical phenomenon has been discovered under the studied conditions: the "double-pulse" ns laser ablation process, where the low-energy pulse precedes the high-energy pulse (called "low-high double-pulse" laser ablation) by a suitable amount of time, can produce significantly higher ablation rates than "high-low double-pulse" or "single-pulse" laser ablation under a similar laser energy input. In particular, "low-high double-pulse" laser ablation at a suitable interpulse separation time can drill through a ∼0.93 mm thick aluminum 7075 workpiece in less than 200 pulse pairs, while "high-low double-pulse" or "single-pulse" laser ablation cannot drill through the workpiece even using 1000 pulse pairs or pulses, respectively. This indicates that "low-high double-pulse" laser ablation has led to a significantly enhanced average ablation rate that is more than five times those for "single-pulse" or "high-low double-pulse" laser ablation. The fundamental physical mechanism for the ablation rate enhancement has been discussed, and a hypothesized explanation has been given. [DOI: 10.1115/1.4040483]

Keywords: laser drilling, laser ablation, double pulse

1 Introduction

Laser drilling has several advantages, such as high spatial resolution and no mechanical tool wear, and has many current and potential applications, such as the drilling for cooling holes, nozzles for inkjet printer and fuel injection, and sieves and filters, etc. [1,2]. Among different types of lasers, nanosecond-pulsed lasers are important lasers for microhole drilling applications. They often have reasonably short durations (and hence can produce reasonably small heat-affected zones) and high achievable beam intensities, and much lower costs than ultrafast lasers.

For many drilling applications, such as cooling hole drilling for a gas turbine engine, a very large number of holes often need to be drilled, and hence it is very desirable to enhance laser drilling efficiency [3]. Previous investigations have been reported in the literature about laser drilling processes, where, instead of sending one laser pulse each time at a certain frequency, a train of two or more laser pulses is fired each time (or a continuous-wave laser beam is combined with a short laser pulse) [4–9]. The investigated processes often show enhanced laser ablation or drilling efficiencies. If each pulse train consists of two pulses (i.e., a pair of pulses) separately by a certain interpulse separation time, t_s, the process can be called "double-pulse" laser ablation or drilling.

"Double-pulse" laser ablation using nanosecond laser pulses of an *equal* or similar pulse energy has been previously studied (e.g., in Refs. [5] and [9]). In Ref. [5], it has been found that material removal rate in laser machining can be significantly enhanced by utilizing double nanosecond laser pulses, where the two pulses within each pulse pair are separated by around tens of nanoseconds. In Ref. [9], laser ablation using double nanosecond laser pulses has been studied under different air pressures from 0.1 to 1013 mbar. At 1013 mbar, the studied "double-pulse" laser ablation process can have significantly higher material removal efficiency than the studied "single-pulse" laser ablation process.

However, the studies in Refs. [5] and [9] employed double nanosecond laser pulses with the same pulse energy, while the previous work on laser drilling using collinear double *nanosecond* laser pulses of *significantly different pulse energies* is not sufficient. Fox [8] has studied a laser drilling process that combines CW (continuous wave) CO_2 laser with a nanosecond laser pulse, while Lehane and Kwok [4] have investigated laser drilling using double laser pulses of different energies that have a typical duration of a few milliseconds or hundreds of microseconds. Obviously, neither of Refs. [8] and [4] has used double *nanosecond* laser pulses.

In this paper, experimental studies have been performed on the microhole drilling of aluminum 7075 through "double-pulse" laser ablation, where the energies of the two nanosecond laser pulses within each pulse pair differ by more than ten times. The laser-drilled samples are characterized by optical and scanning electron microscopes. The transient laser ablation process has been observed through in situ time-resolved shadowgraph imaging. As shown later in more details, a very interesting physical phenomenon has been discovered under the studied conditions: when the low-energy pulse precedes the high-energy pulse (by a suitable amount of time) in each laser pulse pair (called "low-high double-pulse" laser ablation), the average laser ablation rate is

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typically much higher than that when the high-energy pulse precedes the low-energy pulse (called "high-low double-pulse" laser ablation). The average ablation rate is also typically much higher than that for "single-pulse" laser ablation (where the pulse energy is approximately equal to the total energy of each pulse pair for the "double-pulse" laser ablation). For "low-high double-pulse" laser ablation at a suitable interpulse separation time, a ~0.93 mm thick aluminum 7075 workpiece plate can be perforated with less than ~200 pulse pairs at ~3.25 mJ per pulse pair (each pulse pair contains a ~0.25 mJ low-energy pulse followed by a ~3.0 mJ high-energy pulse). However, "high-low double pulse" laser ablation or single-pulse laser ablation cannot perforate the workpiece even using 1000 pulses. A hypothesized explanation has been given on the fundamental mechanism for the ablation rate enhancement for the "low-high double-pulse" laser ablation, but future work is still needed to completely understand the interesting physical phenomenon discovered.

2 Experimental Setup

Figure 1(*a*) shows the schematic diagram of the experimental setup used in this work for the double-pulse laser drilling process and the relevant time-resolved observation through the shadowgraph imaging method. In the experiment, two nanosecond lasers at the wavelength of ~532 nm are used. In each pair of laser pulses, the high-energy pulse comes from laser A (Spectra-Physics, Santa Clara, CA, Quanta-Ray INDI), and the laser pulse has a full-width-at-half-maximum (FWHM) duration of ~7 ns. The low-energy pulse comes from laser B (Bright Solutions, Pavia, Italy, Onda), which is a diode-pumped solid-state laser, and the laser pulse has a FWHM duration of ~4 ns. The laser beams from the two lasers are combined through a beam splitter, and then pass through a focusing lens (which has a focal length of ~75 mm) and irradiate onto the workpiece (aluminum 7075, from McMaster-Carr, Elmhurst, IL). The laser beam spot radius on the workpiece surface for laser A and laser B was very approximately estimated to be around ~34 μm and ~25 μm, respectively, from the crater size induced by single-pulse ablation using a laser pulse from laser A and laser B, respectively, on an aluminum 7075 workpiece. The estimation was based on the rough assumptions that: (i) the laser intensity and fluence have a Gaussian distribution on the workpiece surface; (ii) the local laser fluence at the crater boundary is equal to the laser ablation threshold; and (iii) the ablation threshold is equal to that obtained in Ref. [10] for aluminum ablated by 4.5 ns and 532 nm pulsed laser in air (which is ~1.2 J/cm^2). Careful alignment has been performed such that there is no obvious decentration between the two laser spots on the workpiece surface.

Figure 1(*b*) shows the pulse format for the "double-pulse" drilling process in this study. Each laser pulse pair has one high-energy pulse (pulse energy: ~3.0 mJ; from laser A) and one low-energy pulse (pulse energy: ~0.25 mJ from laser B). The temporal distance between the two pulses within each pulse pair, t_s, is defined as negative when the low-energy pulse precedes the high-energy pulse, and as positive when the high-energy pulse precedes the low-energy pulse. In the study, the value of t_s is controlled using a digital delay generator (Berkeley Nucleonics, model 577), two channels of which send pulse-triggering signals to the two lasers, respectively. The value of t_s is varied in the range of $-15\,\mu$s to $+15\,\mu$s in the experiments reported in this paper. Due to the jitter time involved in all the relevant components in the experimental setup, the actual value of t_s has an uncertainty of around ±10 ns. During all the drilling experiments (except the shadowgraph imaging experiments introduced later), the laser pulse pairs are sent out at a repetition rate of 5 Hz (i.e., five pairs of pulses are sent out per second).

As a comparison, "single-pulse" laser drilling experiments have also been performed, where one single pulse (instead of one pair of pulses) is sent out each time from laser A at a pulse repetition rate of 5 Hz as shown in Fig. 1(*c*) (i.e., 5 pulses are sent out per second). Each single pulse has a pulse energy of ~3.25 mJ, which is approximately equal to the total energy for one pair of pulses in the "double-pulse" laser drilling experiments. The pulse energies given in Fig. 1 are measured using an energy sensor (Coherent, J-25MT-10 kHz) by placing the sensor between the focusing lens and the beam splitter shown in Fig. 1(*a*).

In this work, the workpiece used is an aluminum 7075 alloy plate (McMaster-Carr), which has a thickness of ~0.93 mm and is polished using the 2000-grit sandpaper in the final polishing step. Both shallow-hole drilling and deep or through-hole drilling experiments have been performed. In the shallow hole drilling experiments, 5, 10, and 15 pulses or pairs of pulses have been used in the "single-pulse" and the "double-pulse" laser drilling process, respectively. An optical microscope (Olympus, BH2) has been used to determine the hole depth [11,12]. In the deep or through-hole drilling experiments, 1000 pulses and 1000 pairs of pulses (with varied interpulse temporal separation, t_s) have been used in the "single-pulse" and the "double-pulse" laser drilling process, respectively. If the workpiece can be drilled through during the experiment, the pulse number that is needed for the perforation is determined through visually monitoring the light emission from the workpiece backside [13] (the light emission from the backside is expected to start occurring approximately at

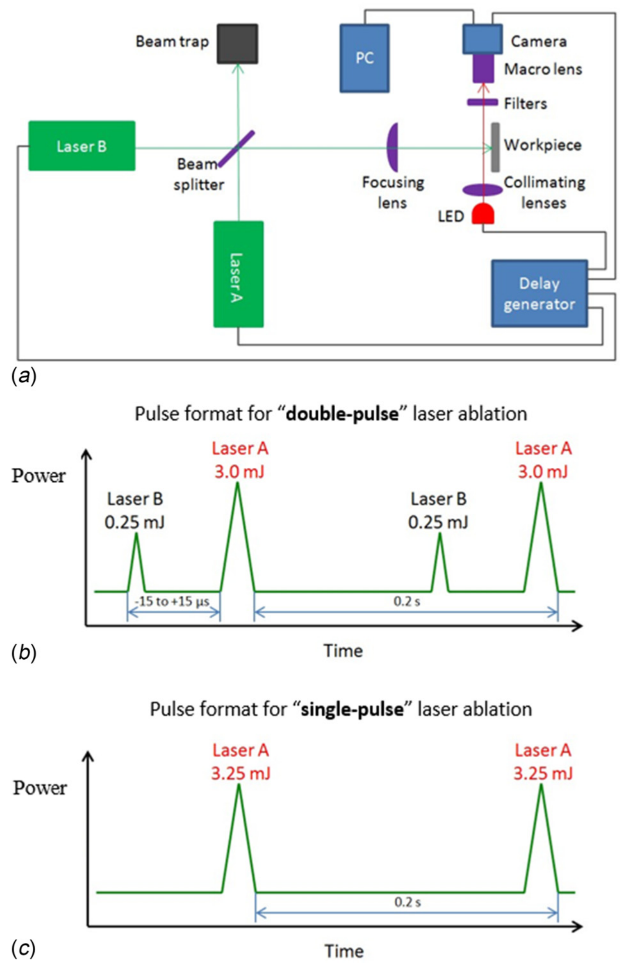

Fig. 1 (*a*) Schematic diagram of the setup for the "double-pulse" laser drilling and the related shadowgraph imaging experiments in this work (not drawn to scale and not drawn to denote all the exact actual shapes, sizes, and/or details; only some major components are shown), (*b*) schematic of laser pulse format (i.e., laser beam power versus time) for the "double-pulse" laser drilling experiment, and (*c*) schematic of laser pulse format for the "single-pulse" laser drilling experiment. The plots in (*b*) and (*c*) do not represent the exact actual temporal shapes of the laser pulses.

the moment of perforation and is expected to be due to laser-induced plasma plume, etc.). The measurement uncertainty using this approach is estimated to be within around 5 pulses. The entrance and the exit (if the workpiece is perforated) sides of the holes drilled with 1000 pulses (or 1000 pairs of pulses) are observed using a scanning electron microscope (SEM) (JEOL, JSM-T330). The results plotted in Figs. 2–4 are typically based on four holes drilled under each experimental condition.

Time-resolved shadowgraph imaging has also been performed for in situ observations of the laser drilling processes. Figure 1(*a*) has also shown the major components for the shadowgraph imaging observation. A high-brightness red-colored LED (light-emitting diode) (Luminus Devices, Inc., SST-90-R), which is driven by a pulsed electric current supply (not drawn in Fig. 1 for simplicity), is applied as the light source for illumination. The LED light first goes through the collimating lenses (which are used to decrease the divergence of the LED light), and then it illuminates the region of interest above the workpiece being drilled, and enters a CMOS camera (Point Grey, BFLY-U3-23S6M-C, 1920 × 1200 pixels), and eventually in this way a shadowgraph image is obtained in the camera. The camera is coupled with a macro lens (Canon, MP-E 65 mm), which is operated at a 5× magnification. In front of the macrolens, a notch filter (Thorlabs, NF533-17) and two bandpass filters (Omega Optical, 625BP70 and 630AF50/25R) are placed to block or reduce light (if any) that is not desirable for the shadowgraph imaging observation. The notch filter is mainly used to block most of the scattered laser light (if any), while the bandpass filters are mainly used to block most of the laser-induced plasma plume optical emission (and other light), if any, that is outside the filters' passing wavelength range of ∼605–655 nm. The LED illumination light pulse employed in this work has a FWHM duration that is around 200 ns. One shadowgraph image can be taken each time, after a certain number of laser pulses (or pairs of laser pulses) is fired and at a certain delay time relative to the last previous laser pulse (for "single-pulse" ablation) or the last previous high-energy laser pulse (for "double-pulse" laser ablation). The delay time is controlled using a digital delay generator (Berkeley Nucleonics, model 577), which send triggering signals (at controlled timing) to the laser(s), the LED driver, and the camera.

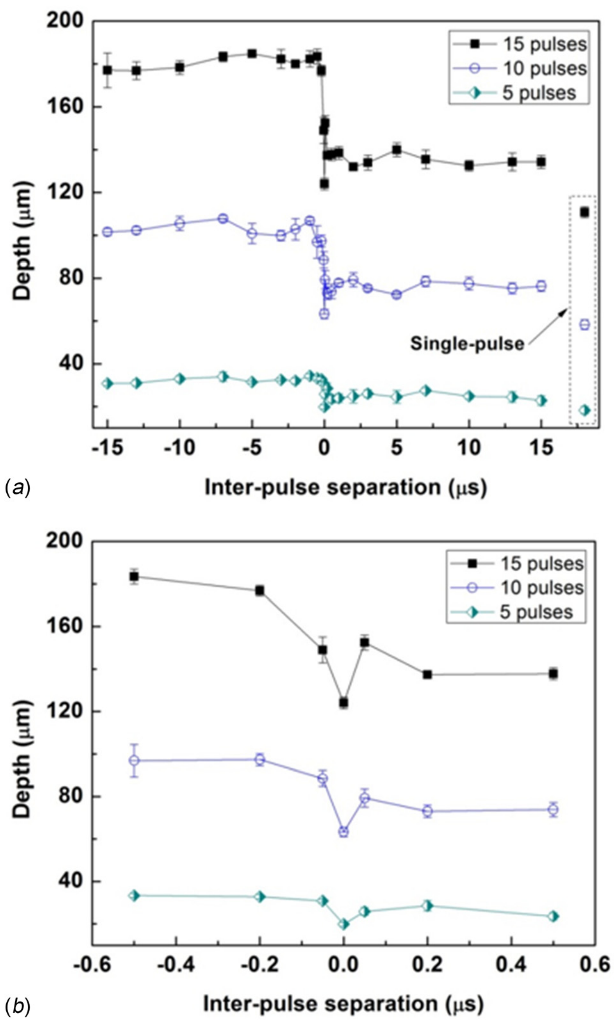

Fig. 2 (*a*) The depths of holes drilled through "double-pulse" laser ablation using 5, 10, and 15 pulse pairs versus the inter-pulse separation time in the range of −15 μs to +15 μs (as a comparison, the depths of holes drilled by "single-pulse" laser ablation are also shown; workpiece: aluminum 7075), and (*b*) an enlarged view of (*a*) when the interpulse separation time is in the range of −0.5 μs to +0.5 μs (in (*a*) and (*b*), "pulses" means "pulse pairs" for "double-pulse" laser ablation)

3 Results and Discussion

Figure 2(*a*) shows the depths of the microholes drilled by "double-pulse" laser ablation versus the interpulse temporal separation within each pulse pair, t_s. The value of t_s is varied from −15 μs to +15 μs. The results for holes drilled by 5, 10, and 15 pulse pairs have been shown. Figure 2(*b*) is simply an enlarged view of Fig. 2(*a*) when t_s is in the range of −0.5 μs to +0.5 μs.

As introduced earlier, a negative value of t_s corresponds to the situation where the low-energy pulse of ∼0.25 mJ precedes the high-energy pulse of ∼3.0 mJ in each pulse pair (called "low-high double-pulse" laser ablation), while a positive value of t_s corresponds to the opposite situation ("high-low double-pulse" laser ablation). It can be seen from Fig. 2 that the drilled hole depths when t_s is negative (to be more specific, when $t_s \leq$ around −0.2 μs) are typically obviously larger than those when t_s is positive, and the latter are typically slightly larger than the hole depths when $t_s = 0$. In other words, "low-high double-pulse" laser ablation with t_s in the range of around −0.2 to −15 μs has significantly enhanced the ablation rate under the conditions in Fig. 2. At 15 pulse pairs, the corresponding average ablation rate per pulse pair for "low-high double-pulse" laser ablation (with t_s in the range of −0.2 to −15 μs) is more than ∼10 μm, and is roughly around 30% higher than that for "high-low double-pulse" laser ablation (with t_s in the range of 0.2 to 15 μs). It can also be seen from Fig. 2 that typically the hole depth does not change very significantly when t_s is varied from −0.2 μs to −15 μs, or when t_s is varied from +0.2 μs to +15 μs. In other words, the major depth change occurs in the t_s range of −0.2 μs to +0.2 μs.

As a comparison, the depths of holes drilled through "single-pulse" laser ablation using 5, 10, and 15 pulses of ∼3.25 mJ are also shown in Fig. 2(*a*). The energy of each pulse in the "single-pulse" laser drilling process is equal to the total energy of each pulse pair in the "double-pulse" laser drilling process. The hole depths drilled by "single-pulse" laser ablation typically do not differ very significantly from those by "double-pulse" laser ablation with $t_s = 0$. This is expected because during the "double-pulse" laser ablation, when the high-energy pulse and the low-energy pulse are very close to each other in time, the effect of each pulse pair should be close to a single laser pulse with approximately the same energy and a pulse duration that is also close. However, the hole depths drilled by "single-pulse" laser ablation are typically obviously smaller than those by "double-pulse" laser ablation with t_s not equal to 0.

Figure 3 shows the number of pulse pairs required to perforate a ∼0.93 mm-thick aluminum 7075 workpiece plate through "double-pulse" laser drilling at different interpulse separations within each pulse pair t_s. For $t_s \geq 0$, the workpiece plate cannot be perforated even using 1000 pulse pairs. For t_s in the range of around −0.05 μs to −10 μs, only around ∼174 to ∼210 pulse pairs are needed to perforate the workpiece (typically four holes are drilled under each condition, and the variation in the required pulse pair number for perforation is reasonably small among the four holes drilled under the same condition as indicated by the error bars, which represent the standard deviations of the experimental results under each condition). For $t_s = -13$ and $-15\,\mu$s, although it is usually still possible to drill through the workpiece, the number of pulse pairs needed for the perforation tends to have a large variation even for holes drilled under the same t_s. Furthermore, for $t_s = -13$ and $-15\,\mu$s, the hole reclosure phenomenon could often be observed during the drilling process, and in some situations, the hole cannot be reopened even by using all the subsequent laser pulse pairs up to a total of 1000 pulse pairs. That is, the light emission from the workpiece backside first starts due to perforation (and the corresponding pulse pair number is used for Fig. 3) and then disappears during the drilling process using the subsequent laser pulses, and the postprocess observation shows the workpiece is eventually in an unperforated status where illumination light cannot propagate through the hole. Hole closure was also observed during the lase drilling process studied in Ref. [13]. It is expected that the hole "reclosure" phenomenon observed in the current study should be mainly due to the accumulation of resolidified material onto the hole sidewall during the laser drilling process [13]. When a sufficient amount of material is accumulated, the hole can be blocked, causing a reclosure of the hole. The accumulated material onto the hole sidewall may disturb the laser beam and negatively influence the effective laser energy and/or power density coupled onto the material inside the hole; and as a result, the blocking material in the hole sometimes cannot be effectively removed to re-open the hole.

The inset in Fig. 3 shows the number of pulse pairs required for workpiece perforation versus t_s in the range of $-0.05\,\mu$s to $-3\,\mu$s. It shows that the minimum required pulse pair number for perforation occurs at around $t_s = -0.2\,\mu$s, which is around ~174 pulse pairs. This corresponds to an average ablation rate of over ~5 μm per pulse pair. For the drilling process using "single-pulse" laser ablation (not shown in Fig. 3), where each single pulse has about the same energy as each pulse pair in the "double-pulse" laser ablation, the workpiece cannot be penetrated even using 1000 pulses. In a short summary, Fig. 3 shows that under the studied conditions, "low-high double-pulse" laser ablation with t_s in the range of around -50 ns to around $-10\,\mu$s has a much stronger capability and higher efficiency in drilling the deep and through microholes than the "high-low double-pulse" laser ablation.

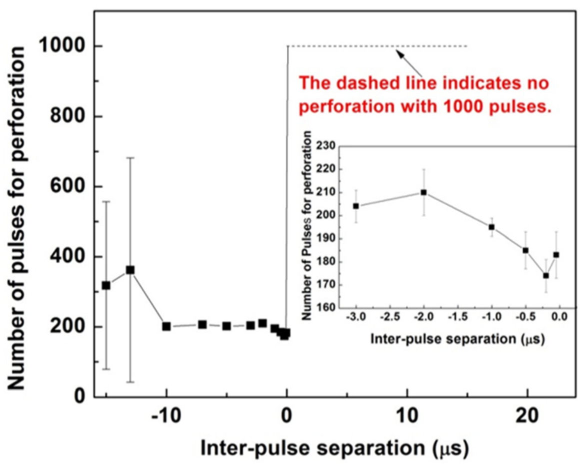

Fig. 3 The number of pulse pairs that is needed to perforate the workpiece plate versus the interpulse separation time for "double-pulse" laser drilling (workpiece: aluminum 7075 plate that is ~0.93 mm thick). When the interpulse separation time is larger than or equal to zero, the plotted dashed line means that the workpiece plate was not perforated even using 1000 laser pulse pairs. The inset shows the number of pulse pairs needed for perforation versus the interpulse separation time in the range of $-0.05\,\mu$s to $-3\,\mu$s (in the figure, "pulses" means "pulse pairs" for "double-pulse" laser ablation).

Figure 4 reflects the effect of the interpulse separation time t_s in "double-pulse" laser drilling on the equivalent diameter of the drilled hole exit (where the "diameter" is the diameter of an "equivalent" circle of the same area, and was determined from the areas of the hole exits measured on the corresponding SEM images). For $t_s \geq 0$, the workpiece is not drilled through, and hence the hole exit diameters are all set as 0 in the figure. When t_s is between $-0.05\,\mu$s and $-10\,\mu$s, the hole diameter on the hole exit side is around 40 to 60 μm. To get a large hole exit diameter, the optimal value of t_s seems to be in the range of around -0.2 to $-3\,\mu$s. The holes drilled with $t_s = -13$ and $-15\,\mu$s have a small average hole exit diameter, and the diameters of multiple holes drilled under the same t_s have large variations (indicated by the large error bars), where one important reason is the hole closure phenomenon that frequently occurs during the "double-pulse" laser drilling process under these values of t_s (if after a total of 1000 laser pulse pairs, a hole is still in an un-perforated closure status, where illumination light cannot propagate through the hole, then the exit diameter of the hole is counted as zero in obtaining the data for Fig. 4).

Figure 5 shows the SEM images taken for the entrance or exit side for holes drilled on ~0.93 mm thick aluminum 7075 workpieces, where for each hole, 1000 pulse pairs (for "double-pulse" laser ablation) or 1000 pulses (for "single-pulse" laser ablation) were fired. Figures 5(*a*), 5(*c*), 5(*e*) and 5(*f*) show the entrance side of the holes drilled by "double-pulse" laser ablation with t_s of $-15\,\mu$s, $-1\,\mu$s, $+10\,\mu$s, and by "single-pulse" laser ablation, respectively. Around these hole entrances, raised rim and scattered spatter can be clearly observed, which are expected to be mainly due to the motion and resolidification of the molten workpiece material and/or melt droplet ejection induced during the laser ablation process [14,15]. Figure 5(*b*) shows the exit side of a hole drilled by "double-pulse" laser ablation with $t_s = -15\,\mu$s. For this particular hole, the workpiece perforation was observed at the ~219th pulse pair during the drilling process. However, hole closure occurred after some additional laser pulses were sent and the subsequent laser pulses could not effectively re-open the hole. The postprocess observation shows that illumination light cannot propagate through the hole, and hence the hole is eventually in an unperforated and closure status although a small opening can be seen in the SEM image in Fig. 5(*b*). Figure 5(*d*) shows the exit of a hole drilled by "double-pulse" laser ablation with $t_s = -1\,\mu$s. The hole exit size appears to be reasonably large and close to the

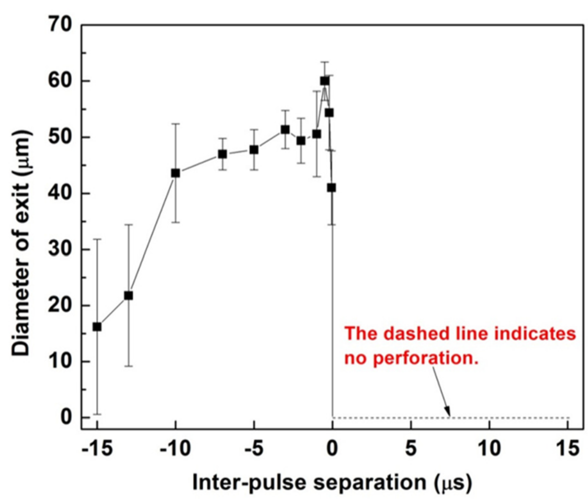

Fig. 4 The hole exit diameter produced by "double-pulse" laser drilling versus the interpulse separation time (1000 pulse pairs are used in the drilling)

hole entrance size shown in Fig. 5(*c*) (which is often desirable in many drilling applications).

In a short summary, Figs. 4 and 5 show that, under the investigated conditions, to get a large hole exit diameter when using "double-pulse" laser ablation to drill deep through holes in the aluminum 7075 workpiece, the low-energy pulse should precede the high-energy pulse by an optimal amount of time of around $\sim$200 ns to $\sim$3 μs in each pulse pair. It should also be noted that for Figs. 3 and 4, typically $\sim$4 holes are drilled under the same interpulse separation time t_s, and the error bars in the figures represent the standard deviations for the multiple hole-drilling experimental results. In Fig. 3, the large error bars at $t_s = -13$ and $-15\,\mu$s are mainly due to certain experimental result(s) significantly larger than the average value at the same t_s, while in Fig. 4, the large error bars at $t_s = -13$ and $-15\,\mu$s are mainly due to certain experimental result(s) significantly smaller than the average value.

Besides postprocess characterizations of laser-drilled workpieces, time-resolved in situ observation of the drilling process has also been performed in this study through shadowgraph imaging. Figure 6 shows the shadowgraph images for "double-pulse" laser ablation with $t_s = -1\,\mu$s (the first column), $t_s = +1\,\mu$s (the second column), and "single-pulse" laser ablation (the third column). For each given column, the images at different rows correspond to different delay times ($\sim$3, $\sim$5, $\sim$10, $\sim$20, and $\sim$30 μs). For the first and the second columns, each image is taken after roughly around 40 previous laser pulse pairs are fired during the drilling process, and the labeled delay time is counted from the high-energy pulse in the last preceding pulse pair. For the third column, each image is taken after roughly around 40 previous pulses are fired, and the labeled delay time is counted from the last preceding pulse. It should be noted that the $\sim$40 previous laser pulses or pulse pairs were fired one by one manually instead of at a fixed frequency of 5 Hz. In the first shadowgraph photo on the first row, the approximate workpiece surface location is indicated by a white dotted line. Because the workpiece has a polished and smooth surface, a rough mirror image of things on the right side of the line has been formed on the left side of the line.

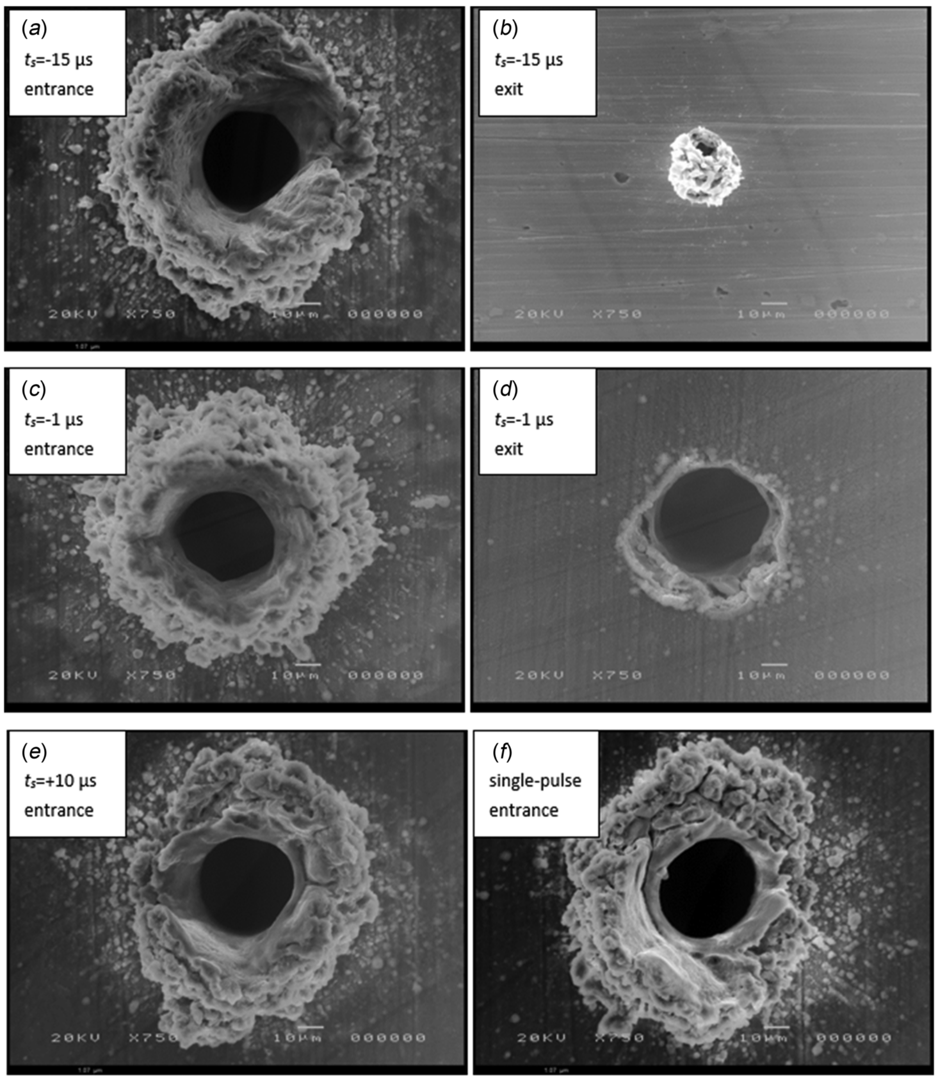

Fig. 5 Scanning electron microscope images of the entrance or exit side for holes drilled by "double-pulse" laser ablation using 1000 pulse pairs ((*a*)–(*e*)), or by "single-pulse" laser ablation using 1000 pulses (*f*) (workpiece: $\sim$0.93 mm thick aluminum 7075): (*a*) entrance, and (*b*) exit for a hole drilled through "double-pulse" laser ablation with an interpulse separation time of $t_s = -15\,\mu$s; (*c*) entrance, and (*d*) exit for a hole drilled through "double-pulse" laser ablation with $t_s = -1\,\mu$s; (*e*) entrance for a hole drilled through "double-pulse" laser ablation with $t_s = +10\,\mu$s; and (*f*) entrance for a hole drilled through "single-pulse" laser ablation using the pulse format in Fig. 1(*c*)

When the images on the first column are compared with those on the second column, it is very clear that for "double-pulse" laser ablation with $t_s = -1\,\mu$s (the first column), much more significant material ejection (which are expected to be melt droplets) from the workpiece can be observed in the images for all the delay times in the figure. The ejected droplets appear to be finer and closer to the workpiece surface for the earlier delay times, and farther away from the workpiece at the later delay times. On the other hand, for the "double-pulse" laser ablation with $t_s = +1\,\mu$s (the second column), much less material ejection can be seen in the images. In particular, for the images at the delay time of $\sim$20 and $\sim$30 μs, almost no obvious material ejections can be seen in the images, which seems to suggest that the melt ejection process lasts shorter than that for $t_s = -1\,\mu$s. When the images on the first column are compared with those on the third column, overall less material ejections are observed for the "single-pulse" laser ablation (the third column), particularly at the later delay time of $\sim$20 and $\sim$30 μs. It should be noted that the shadowgraph imaging setup used in this work is mainly used to observe material ejection in the condensed-phase form from the workpiece (e.g., melt ejection), while material removal through other mechanisms may be difficult to clearly see through the setup.

As introduced earlier, this study has discovered a very interesting physical phenomenon under the investigated conditions: for "double-pulse" nanosecond laser ablation, when the low-energy pulse precedes the high-energy pulse by a suitable amount of time, the ablation rate can be significantly enhanced compared with "single-pulse" laser ablation, or "double-pulse" laser ablation with the opposite pulse sequence in each pulse pair. The enhancement becomes much more obvious when drilling deep microholes than relatively shallow holes (see the results in Fig. 3 versus those in Fig. 2). A hypothesized explanation will be given next on the fundamental mechanisms for the above interesting physical phenomenon (lots of future work is still needed to test the hypothesized explanation and gain a full understanding):

(a) It is expected that both the "high-energy" pulse and the "low-energy" pulse in Fig. 1(*b*) alone have a sufficiently high intensity to generate plasma during laser—workpiece interactions (their fluences are much higher than the plasma threshold reported in Ref. [16] for 532 nm and 5 ns laser pulse ablation of aluminum).
(b) A plasma plume may include both the ionized vapor from the workpiece and the ionized ambient air, which may

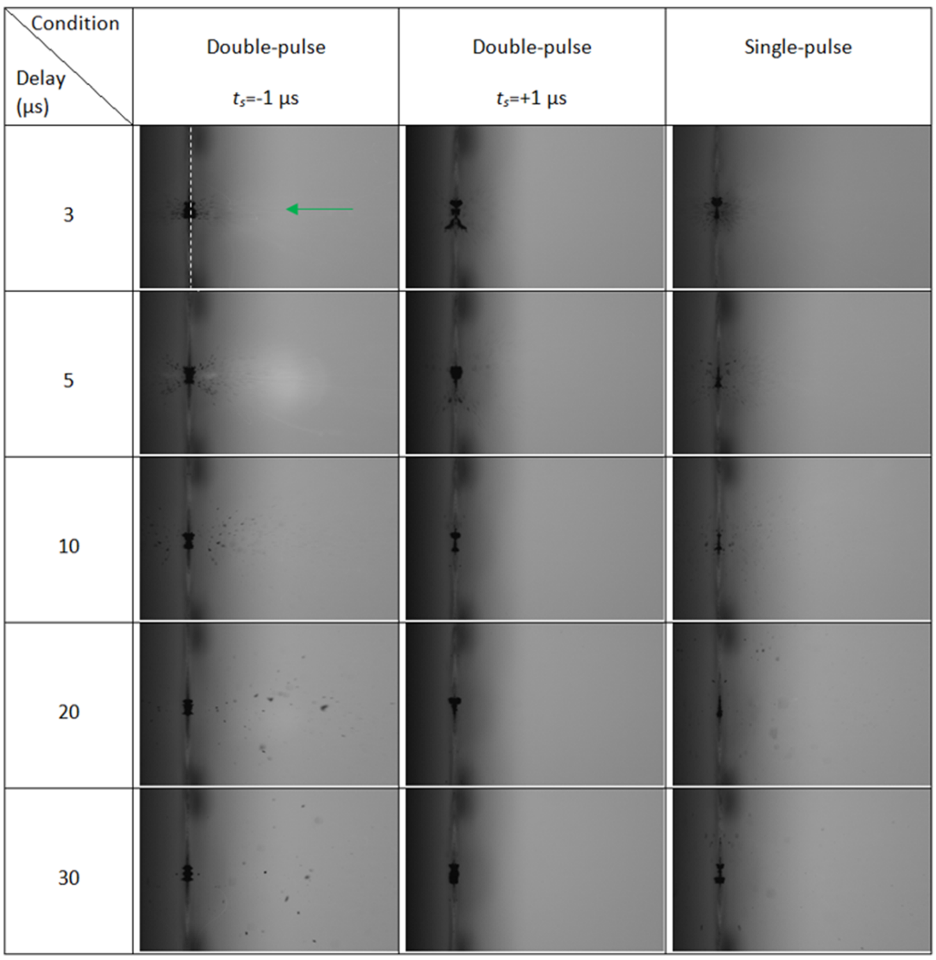

Fig. 6 Shadowgraph images for laser drilling through "double-pulse" laser ablation with an interpulse separation time of $t_s = -1\,\mu$s (the left column) and $t_s = +1\,\mu$s (the center column), and through "single-pulse" laser ablation (the right column), at delay time of 3, 5, 10, 20, and 30 μs relative to the incidence of the corresponding laser pulse, before which a hole is already formed due to ablation by roughly around 40 preceding laser pulse pairs or pulses. In the first image, the workpiece surface is approximately indicated by the dashed line and the laser incidence direction is schematically shown by the arrow. Each image corresponds to an actual physical domain of $\sim$2.25 × 1.41 mm. For "double-pulse" laser ablation, the given delay time is relative to the corresponding high-energy pulse.

absorb a portion of the incoming laser beam energy ("plasma shielding" effect) and hence decrease the laser ablation efficiency [17,18]. In particular, a portion of laser beam energy may also be absorbed by the ionized air in the plasma region.

(c) According to Refs. [9], [19], and [20], for "double-pulse" or "multipulse" laser ablation with *equal* pulse energies, the ablation process by the first laser pulse can generate a local low-gas-density environment right above the target surface, which may decrease the plasma shielding effect and hence increase the ablation rate for the second laser pulse.

It is expected that the above may also happen in the "double-pulse" laser ablation with *significantly different* pulse energies in this study. That is, for the "double-pulse" laser ablation where the low-energy pulse precedes the high-energy pulse (i.e., "low-high double pulse" laser ablation), the first low-energy pulse will generate a plasma plume due to its interaction with the workpiece. The high-temperature plasma plume will expand and push away the ambient air, leaving behind a low-gas-density region right above the workpiece surface (or above the hole bottom wall if a hole already exists). The low-density gaseous region may exist for a certain period, and if the second, high-energy pulse starts ablating the workpiece during this period, then one or both of the following two factors may exist and enhance its ablation rate:

(c.i) The low-gas-density environment is expected to have lower restriction or limit on the expansion front of the ablated material than the original ambient air that has a higher gas density. The reduced "restriction effect" of the ambient gas on the ablated material is expected to be beneficial to material removal from the workpiece.

(c.ii) The plasma induced by laser ablation of the workpiece surface under the local low-gas-density environment may have less "shielding effect" than the plasma induced by laser ablation of the workpiece surface under the original ambient air that has a higher gas density, where a portion of the laser beam energy may also be absorbed by ionized air in the plasma as mentioned in (b). The reduced "plasma shielding effect" may enhance the laser-workpiece energy coupling, and hence increase laser ablation rate.

Because the second, high-energy pulse contains most of the energy for each pulse pair, its ablation rate enhancement will obviously enhance the total ablation rate of the entire pulse pair.

(d) When drilling a deep microhole, the aforementioned "restriction effect" of the ambient gas and the "plasma shielding effect" may become even stronger due to the confinement of the hole sidewall, which may yield higher plasma temperatures and electron densities [21,22].

(d.i) Therefore, factors (c.i) and/or (c.ii), which decrease the above two effects, are expected to more significantly enhance the ablation rate of the second high-energy pulse.

(d.ii) On the other hand, the workpiece materials ablated from the deep hole bottom need to have sufficient kinetic energies to move out of the hole to be eventually "removed," which could make material removal in this case more sensitive to laser-workpiece energy coupling.

The above two factors have explained why material removal efficiency enhancement by "low-high double-pulse" laser ablation is more significant for deep microhole drilling than shallow hole drilling.

(e) In "double-pulse" laser ablation, where the high-energy pulse precedes the low-energy pulse (called "high-low double-pulse" laser ablation), the first high-energy pulse may still enhance the ablation rate for the following low-energy pulse through factors (c.i) and/or (c.ii). However, because the low-energy pulse only contains less than 10% of the total energy of each pulse pair, the overall enhancement of the total ablation rate of the entire pulse pair will be small. This has explained why the ablation rate in this situation is typically lower than "low-high double-pulse" laser ablation under the studied conditions.

(f) When the interpulse separation time is zero, the two pulses in each pulse pair come at about the same time, and the aforementioned enhancement effect does not exist (or at least is no longer obvious). Hence, the corresponding ablation rate is lower than those for "low-high" and "high-low" double-pulse ablation as shown in Fig. 2.

The explanation given above is still a hypothesis that may require further work to test. Alternative and/or additional mechanism(s) may also play an important role. For example, in "low-high double-pulse" laser ablation, it may be possible that the low-energy pulse can change the state of the workpiece surface at the ablation site in a way to enhance the surface absorption of the following high-energy pulse. Certainly, to the authors, the hypothesized explanation discussed in the previous paragraphs appears to be more likely.

Under the studied conditions in this work, for relatively shallow hole drilling, if the interpulse separation time is varied beyond $-15\,\mu$s in Fig. 2(*a*), the drilled hole depth does not decrease very quickly with the increase of the magnitude of the separation time, and can still be maintained at a relatively high value for some time. However, for deep hole drilling, the results in Figs. 3 and 4 suggest that once the separation time is beyond roughly $-10\,\mu$s, the drilling results, such as the number of pulses for perforation and the diameter of the hole exit, can have very large standard deviations (i.e., large uncertainties). Hence, in this paper, the discussions are limited within a separation time of $-15\,\mu$s.

Finally, it should be noted that although Refs. [4–9], [13] and [18–20] also reported research work on laser drilling and/or laser–material interactions that involved firing a train of two or more laser pulses each time (or combining a continuous-wave laser beam with a short laser pulse, or applying radiation from two pulsed lasers that are not temporally synchronized), they did not focus on the study of microhole drilling using *collinear* double *nanosecond* laser pulses of *significantly different pulse energies* as in this paper. Benedetti et al. [14] used collinear double nanosecond laser pulses of different pulse energies; but it mainly focused on the investigation related to laser-induced breakdown spectroscopy, and did not report the study on through-hole drilling or the drilled hole variation with different interpulse separation times, which is the focus of this paper. Demir et al. [23] reported interesting study on the ablation of TiN coatings using nanosecond pulses of different durations and provided some suggestions on the design of laser pulse shapes. However, the study in Ref. [23] is not on laser ablation using double nanosecond pulses of significantly different pulse energies as in this paper.

4 Conclusions

Microhole drilling of aluminum 7075 workpieces through nanosecond "double-pulse" laser ablation has been studied, where the energies of the two nanosecond laser pulses in each pulse pair differ by more than ten times. During the "double-pulse" laser ablation, the low-energy pulse may precede or follow the high-energy pulse in each pulse pair, which can be called "low-high double-pulse" laser ablation and "high-low double-pulse" laser ablation, respectively. In each pulse pair, the two pulses are separated by an interpulse separation time, t_s, which is defined as negative when the low-energy pulse precedes the high-energy pulse.

Under the studied conditions, it has been found that:

(1) When drilling relatively shallow holes, typically "low-high double-pulse" laser ablation (when t_s is between around

−0.2 and −15 μs) has obviously higher ablation rates than those for "high-low double-pulse" laser ablation.

(2) When drilling deep microholes, the ablation rate enhancement by "low-high double-pulse" laser ablation (when t_s is between around −0.05 and −10 μs) is much more significant: it can drill through a ~0.93 mm thick aluminum 7075 workpiece in roughly around 200 pulse pairs or less, while "single-pulse" or "high-low double-pulse" laser ablation cannot perforate the workpiece even using 1000 pulses or pulse pairs. This indicates that "low-high double-pulse" laser ablation has led to a significantly enhanced average ablation rate (in terms of ablation depth per pulse) that is more than ~5 times those for "single-pulse" or "high-low double-pulse" laser ablation.

(3) When drilling a through microhole in a ~0.93 mm thick aluminum 7075 workpiece, "low-high double-pulse" laser ablation using 1000 pulse pairs can yield a reasonably large hole exit diameter at an optimal t_s in the range of around −0.2 to −3 μs, and the hole has a high aspect ratio of over ~10.

(4) In situ time-resolved shadowgraph imaging experiments show that the material ejection from the workpiece that is observable by the imagining setup appears to be more significant and last longer for "low-high double-pulse" laser ablation (at $t_s = -1$ μs) than "high-low double-pulse" laser ablation (at $t_s = 1$ μs) and "single-pulse" laser ablation.

(5) A hypothesized explanation has been given about the fundamental mechanism for the observed significant ablation rate enhancement by "low-high double-pulse" laser ablation: that is, the low-energy laser pulse ablation may create a low-gas-density environment right above the ablation site of the workpiece surface, which may decrease the "plasma shielding effect" and/or the restriction of the ambient gas on the ablated material expansion, and hence enhance the material removal rate for the following high-energy laser pulse ablation.

(6) The "low-high double-pulse" ns laser ablation, where the low-energy pulse only has an energy that is less than 10% of that for the high-energy pulse, suggests a good potential approach to get high material removal rates and high energy efficiencies in practical ns laser drilling applications. Although a pulse-pair repetition rate of 5 Hz has been used in this study, the aforementioned optimal t_s in the range of around −0.2 to −3 μs implies that very high pulse-pair repetition rates can be potentially used in practical applications.

Future work is still needed on the "low-high double-pulse" ns laser drilling process, including a further test of the given hypothesized explanation about the fundamental mechanism for the observed significant ablation rate enhancement. An important future potential investigation could be to perform laser drilling experiments in vacuum using "low-high double-pulse," "high-low double-pulse," and "single-pulse" ablation. This can potentially help test the proposed hypothesized explanation and clarify the related fundamental mechanism.

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