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Enhanced drilling using a dual-pulse Nd:YAG laser

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Abstract. A new method for improving the efficiency of laser drilling has been developed. Two synchronized free-running laser pulses from a tandem-head Nd:YAG laser are capable of drilling through 1/8-in-thick stainless-steel targets at a stand-off distance of 1 m without gas-assist. The combination of a high-energy laser pulse for melting with a properly tailored high-intensity laser pulse for liquid expulsion results in the efficient drilling of metal targets. We argue that the improvement in drilling is due to the recoil pressure generated by rapid evaporation of the molten material by the second laser pulse.

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Laser drilling and cutting of metals are established industrial processes. They are applied in many different production lines. There have been some attempts to understand the laser–material interaction process with the aim of improving the efficiency of laser drilling and cutting [1–4]. It has been found that material is removed in both the vapor and the liquid states. The intense laser energy used for laser drilling is sufficient to melt and subsequently vaporize the material. This vaporization process creates a recoil pressure, which is responsible for expelling the liquid. The amount of material ejected in the liquid state has a direct effect on the laser drilling/cutting efficiency due to the fact that the material is removed without the loss of additional energy required for vaporization. Many theoretical models have been developed in an attempt to characterize the dynamics of the laser drilling process [5–9].

In most instances, a gas jet is used to assist the drilling/cutting of the material. In the case of stand-off drilling/cutting at a distance without gas-assist, the efficiency is rather low. The problem is due to resolidification of the molten pool. Increasing the laser power does not work well. Several novel methods for improving the efficiency of material removal in laser drilling have been developed. Fox [10] combined a cw CO_2 laser with Q-switched Nd:glass laser pulses to achieve a factor of two increase in the drilling efficiency of carbon steel. The Q-switched pulse was responsible for the ejection of liquid metal, which had not yet consumed the latent heat of vaporization, resulting in a higher drilling efficiency. This experiment was theoretically modeled by Robin and Nordin [11] and Towle et al. [12]. Another novel technique was reported by Kim et al. [13]. They reported that the laser penetration efficiency was enhanced by amplitude-modulating a free-running Nd:YAG laser. They attributed this improvement to a reduction in the plasma screening effect due to the repetitive chopping of the laser beam, along with possible acoustic resonance effects of the molten metal.

In this paper, we propose and demonstrate a new method for increasing laser drilling efficiency using two synchronized free-running Nd:YAG laser pulses. We show that a Q-switched pulse is not necessary for explosive liquid expulsion. In fact, a free-running pulse is much better for liquid expulsion because of the absence of plasma screening. We show that by using a tandem free-running pulse arrangement, the laser drilling/cutting efficiency can be greatly enhanced. This new method allows the drilling of 3/16 in steel plates at a laser-target distance of over 1 m without gas-assist and with a relatively small combined laser energy of 25 J. Conventional laser drilling cannot penetrate even a 1/8 in plate at this distance.

1 Experimental procedure and results

The experimental set-up is shown in Fig. 1. Two flash lamp-pumped Nd:YAG laser heads were placed in tandem inside a single laser resonator. This arrangement ensured that the optical path of the two pulses were identical. Each laser head was pumped by independent pulse forming networks (PFN) and operated in the "free-running" mode. We define the pulses from laser head 1 and laser head 2 as pulse 1 and pulse 2, respectively. Typical experimental conditions consisted of an energy of 22.5 J in 3.5 ms full-width at half-maximum (FWHM) for pulse 1, and 2.5 J, 0.15 ms FWHM for pulse 2. The total energy was therefore 25 J. Various other combinations of pulses were used by changing the PFNs.

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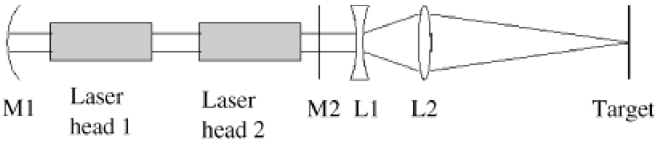

Fig. 1. Schematic diagram of the tandem laser system. M1, total reflector; M2, output mirror; L1 and L2, telescope

A telescope, consisting of two lenses with focal lengths of −50 mm and +330 mm, respectively, was employed to focus the laser at any distance. The negative lens was used to expand the laser beam before focussing. In the present experiment, the laser spot size was approximately 1 mm in diameter at a distance of 1 m. Power densities for pulse 1 and pulse 2 were approximately 5×10^5 W/cm^2 and 1.5×10^6 W/cm^2, respectively. The target material used in these experiments was type 303 stainless steel. A helium–neon laser used to align the tandem-head laser was also used for targeting.

The temporal output pulse shape of the tandem-head laser with a triggering delay of 3 ms is shown in Fig. 2. The timing of the triggering of the two laser pulses was achieved using a multichannel digital delay pulse generator. Experimentally, it was observed that there was a 10% loss in the peak power of the second pulse when fired in conjunction with the first pulse. This effect is most likely due to transient thermal lensing effects arising from intense pumping of laser head 1.

Figure 3 is a plot of the number of shots necessary to completely penetrate a 1/16-in-thick stainless-steel target as a function of the time delay between pulse 1 and pulse 2. Here we define one shot as a combination of pulse 1 and pulse 2. The time delay is referenced to the onset of pulse 1. It can be seen that there was a range of delays between 3–8 ms where four shots were used to drill through the sample. At the optimal delay time of 6 ms, only two laser shots were needed. In all the experiments, the time between laser shots was about 1 s, so there was probably no interaction between the laser shots. The target should have cooled down significantly before the arrival of the next laser pulse.

When there was just the initial 22.5 J laser pulse, it took 54 laser shots for penetration to be achieved. Hence the addition of the second low-energy shorter pulse reduced the energy requirement by 27 times provided the timing of pulse 2 was properly adjusted. This optimal timing was due to the interaction of the molten metal with pulse 2. This enhancement is very significant. In Fig. 3, we also mark the number of pulses needed for drilling for negative delays, and for very long positive delays. In these cases, the two laser pulses essentially did not overlap. It took 35 laser shots for penetration. We believe that both pulse 1 and pulse 2 removed material, so that the number of pulses needed was lower than that of just pulse 1 alone.

Figure 4 shows a similar result for a 1/8-in-thick sample. Here, with delays between 4–8 ms, seven shots were needed to completely penetrate the target. At the optimal delay of 6 ms, only six shots were necessary. At delays smaller than 1 ms and greater than 10 ms, drilling was not possible at all. Additionally, it was impossible to penetrate this target using independent pulses of either pulse 1 or pulse 2. Hence the increase in drilling efficiency was infinite for this case!

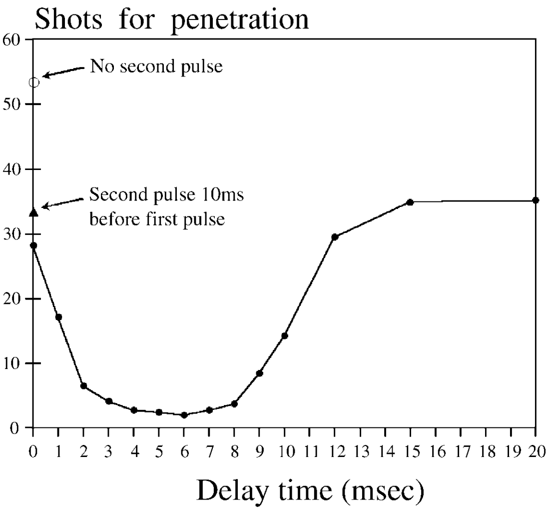

Fig. 3. Number of laser shots required to drill through a 1/16 in stainless-steel sample vs. the time delay between the two pulses

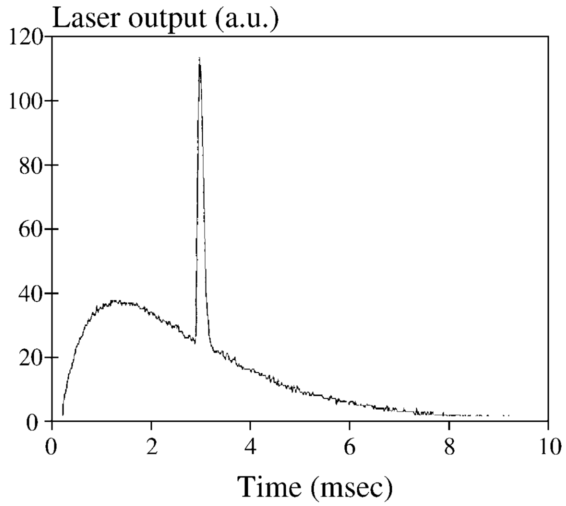

Fig. 2. Typical laser output. The time delay between the two peaks can be adjusted freely

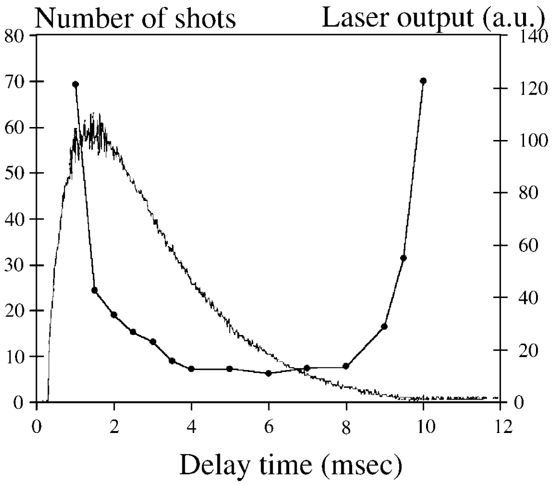

Fig. 4. Number of laser shots required to drill through a 1/8 in stainless-steel sample. In this case, it is impossible to drill through the sample if the delay is less than 1 ms or longer than 10 ms

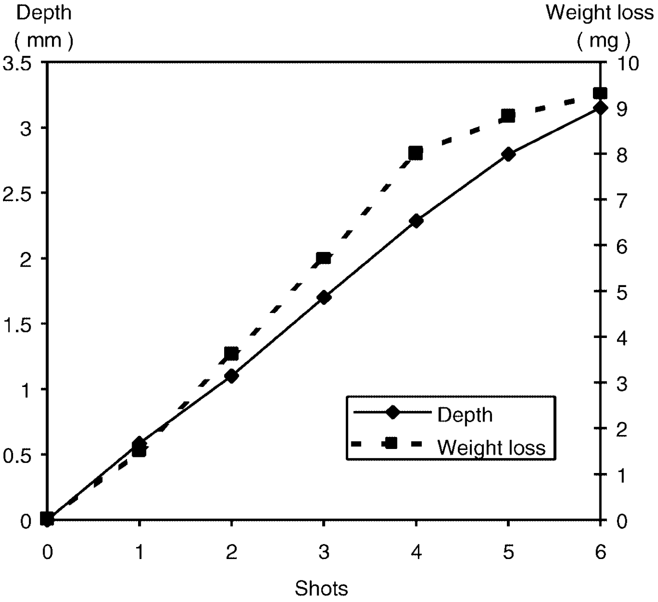

Fig. 5. Penetration depth and weight loss per laser shot for the 1/8 in sample

Figure 5 shows the penetration depth and weight loss in the sample per laser shot for the 1/8-in sample, at the optimal delay of 6 ms between the two laser pulses. The experiment was performed with many samples independently. The weight loss and penetration depth per pulse were 1.5 mg and 0.6 mm, respectively. This implies a hole diameter of 0.55 mm, given that the density of stainless steel is 7.8 g/cm^3. This is consistent with the focal diameter of 1 mm and the measured size of the hole drilled. It can also be seen from Fig. 5 that the drilling depth was proportional to the number of laser shots until penetration was achieved (the maximum depth was the thickness of the sample). This implies that drilling of a deep hole is as efficient as drilling a shallow hole. The weight loss shows some saturation beyond four laser shots. The results for the 1/16 in sample are similar, but the penetration depth is higher at 0.8 mm per laser shot. This is understandable since the heat is more concentrated as heat diffusion is confined in the vertical dimension.

2 Discussion

The dynamic modeling of laser drilling of metals is a complicated process. The calculation of the temperature rise as a function of time in 3D can be performed in a straightforward manner by solving the heat diffusion equation, once the various materials parameters are known [14, 15]. Many parameters, such as the heat capacity, heat diffusivity, heat of fusion and vaporization of the solid and the liquid can be found in the literature. The most important parameter that is missing is the coupling of laser energy into the heated solid, and later the molten liquid. Also not known exactly is the effect of the vaporized plasma on the incoming laser. Much work has gone into such modeling work. For the purpose of the present paper, we are only interested in comparing the drilling energy needed for the single pulse case and the double pulse case. Our discussion will necessarily be qualitative.

The results shown above clearly show the important role played by the second pulse in improving the drilling efficiency of stainless steel. At the optimal time delay, for the thin sample, the second pulse reduces by 27 times the number of shots required to drill through the sample. For the thicker sample, without the second pulse at the proper time delay, it is impossible to drill through it at all at 25 J per pulse. It is interesting to note that at the optimal delay of 6 ms, the tandem pulses can remove 0.6 mm of material per shot with the 1/8-in thick sample while for the 1/16-in sample, they can take out 0.8 mm per shot.

An explanation for the results presented in this paper lies in the laser–target interaction mechanism. Pulse 1 has a relatively high energy and low intensity and is capable of melting the metal and producing some evaporation. Pulse 2 has a higher peak power and much lower energy. It removes the molten materials by means of the recoil pressure generated by rapid vaporization of the molten liquid [5–9]. The amount of material removed will depend on the quantity of liquid present when pulse 2 is fired. Experimentally, the maximum volume is present at the optimal delay T_{d} of between 4 ms and 8 ms. T_{d} corresponds to a time when a major portion of pulse 1 has been absorbed by the target. While this is obvious, the fact that pulse 2 should not be delayed too much relative to the peak of pulse 1 is also to be expected. This is because the molten material cools down and resolidifies rapidly if pulse 2 does not arrive on time. In fact, the rapid increase in the number of laser shots required for penetration as a function of time delay provides an important piece of data in calculating the solidification rate and the traveling speed of the liquid–solid interface.

Obviously, the optimal T_{d} depends on the heat diffusivity of the metal. For stainless steel, the heat diffusivity is 0.085 cm^2/s. At the optimal T_{d} of 6 ms, the diffusion length is 0.2 mm, which is smaller than the radius of the molten pool as inferred from Fig. 5. This is consistent with the argument that T_{d} should be as large as possible, to allow for more energy from pulse 1 to be absorbed. Yet T_{d} should be small enough so that not too much heat is diffused away. We expect the optimal delay time to become shorter for more thermally conductive materials such as copper and aluminum, where the thermal diffusivity is 1.14 cm^2/s and 0.9 cm^2/s, respectively.

The idea of using a second pulse to blow away the molten liquid is not new. However, in most previous work a Q-switched laser was used for the second pulse [10]. The drawback with this is the presence of strong plasma screening. The over-dense plasma decouples the target from the laser due to the generation of a laser-supported detonation wave (LSD) [16]. This wave absorbs the incoming radiation and shields the target. The threshold intensity necessary to initiate this effect is of the order of 1×10^7 W/cm^2. Hence the Q-switched laser is not very efficient in blowing off the liquid. Our system makes use of a short free-running laser pulse with an intensity seven times smaller than the LSD threshold. The expulsion of the liquid is believed to be due to the recoil pressure [5] from the rapid vaporization of a thin layer of the liquid. The increase in the drilling efficiency is partially due to the fact that the latent heat of vaporization has not been expended on this molten liquid [9]. For stainless steel, this corresponds to approximately 80% of the energy required to vaporize it.

It is believed that the recoil pressure generated by rapid evaporation is important in expelling the molten liquid. Therefore, pulse 2 should be as short as possible without igniting LSD. The duration of 0.15 ms used here is probably an optimal choice. It is the shortest free-running laser pulse we can generate with a large enough energy content. The 0.15 ms duration of the second pulse, and hence the rapidity of evaporation, is critical in the present scheme. If we simply increase the energy of pulse 1, it will not be as effective because there will be little liquid expulsion. It is the rapidity of evaporation that generates the recoil pressure. We believe that the combination of a long high-energy pulse and a shorter low-energy pulse as used here represents an optimal choice.

3 Conclusions

In conclusion, we have demonstrated the use of a tandem-head laser capable of producing two free-running laser pulses which enhance the laser drilling efficiency of stainless steel. The method was found to be very effective in the removal of material at the stand-off distance of 1 m. The recoil pressure generated by a high intensity laser pulse is responsible for the expulsion of the molten metal produced by a lower intensity, higher energy pulse. The optimization of this process involves firing the high-intensity pulse at the time when maximum melting has occurred during the first pulse. The use of free-running pulses enables efficient removal of materials without any plasma screening effects, which arise when higher intensities are used.

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