GA–A25867

SUPERPULSE®: A NANOSECOND PULSE FORMAT FOR IMPROVING LASER DRILLING

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JUNE 2007

GENERAL ATOMICS

DISCLAIMER

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This is a preprint of a paper submitted to Photonics Spectra.

Work supported by
the General Atomics IR&D

GENERAL ATOMICS PROJECT 49006
JUNE 2007

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1. INTRODUCTION

Lasers have been used to produce high-aspect-ratio holes (i.e., holes whose depth-to-diameter ratio is much greater than 10:1) for a variety of applications[1] that range from oil galleries in engine blocks[2] to aerospace turbine-engine cooling holes to scientific applications such as components used in laser fusion experiments.[3] Depending on the application, the holes must meet must meet criteria including hole size, straightness, taper, as well as limitations on the formation of recast and debris and the size of the heat affected zone. (The heat affected zone is that region where there is a change in the physical properties of the material, typically caused by thermal conduction from both the laser and laser-produced plasma.)

Very demanding applications require high-aspect-ratio holes that are straight and have little or no heat affected zone in materials such as ceramics, semiconductors, and metals. We have found that using a train of carefully timed pairs of laser pulses — instead of using a train of single laser pulses — to drill small, high-aspect-ratio holes vastly improves the results. In addition, for drilling very small (i.e., less than 20 μm diameter) high-aspect-ratio holes, we believe the laser-produced plasmas ultimately set the minimum size of the hole that can be drilled.

2. SUPERPULSE® DESCRIPTION AND KEY RESULTS

Figure 1 shows the SuperPulse (double-pulse) format and compares it to the conventional laser-processing format. The SuperPulse format consists of a pair of nominally 4-ns (FWHM) laser pulses, separated by a delay that ranges from 20 to 200 ns depending on the application. In the work presented here, the peak laser irradiance at focus is typically between 5×10^9 W/cm^2 and 10^{11} W/cm^2. The laser wavelength is 532 nm and the processing is done using a gas assist consisting of shop air treated by a desiccator, or when drilling the holes less than 10 μm diameter in beryllium, in a vacuum chamber. We find that keeping the humidity below 40% when processing in air prevents undesirable laser-induced air breakdown in front of the target. For safety considerations when processing beryllium (beryllium dust is highly toxic), a vacuum chamber is a practical solution, and it also eliminates air-breakdown issues.

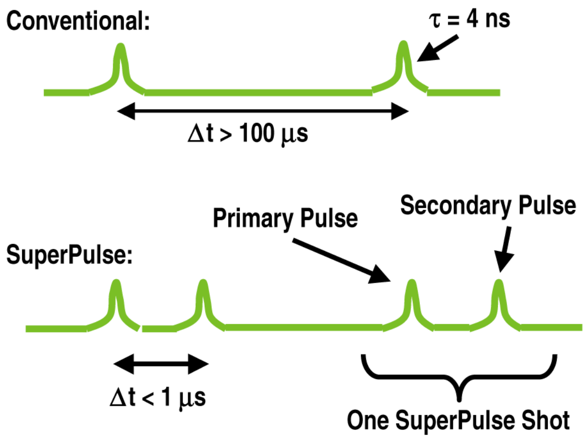

Fig. 1. The SuperPulse format consists of two pulses separated by a delay time ranging from 20 to 200 ns.

Figure 2 shows an increase in drilling speed achieved by switching from the conventional format to SuperPulse format for percussion drilling through holes in stainless steel and in silicon. (Percussion drilling is a technique whereby the laser is always focused at the same point on the target). Figure 3 shows an example of the improvement in hole quality in percussion drilling.

We have also found that the SuperPulse format improves our ability to control both taper and recast in helical drilling, and that we can reduce the amount of time — and accordingly the number of laser shots — between the piercing of the work piece by the laser and the production of a complete hole. (Helical drilling is a technique whereby the focus traverses a circle slightly smaller than the diameter of the hole during drilling). This is important for back wall protection — when the drilled hole's exit is near an object that cannot tolerate excessive laser strikes.

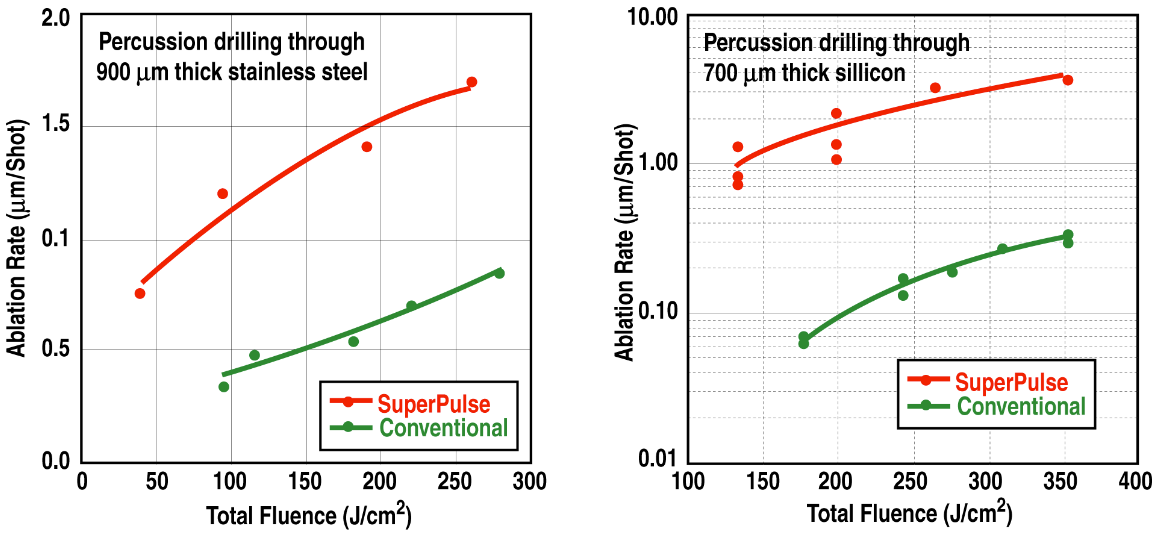

Fig. 2. Percussion drilling through holes by using a 250 mm focusing lens yielded a comparison of SuperPulse and conventional ablation rates. The total fluence is obtained by dividing the energy focused onto the target for each laser[9] cycle by the area of the focal spot. Thus, for conventional technique, it is the pulse energy divided by the area; and for the SuperPulse technique, it is the sum of the energies of the primary and the secondary laser pulse divided by the area.

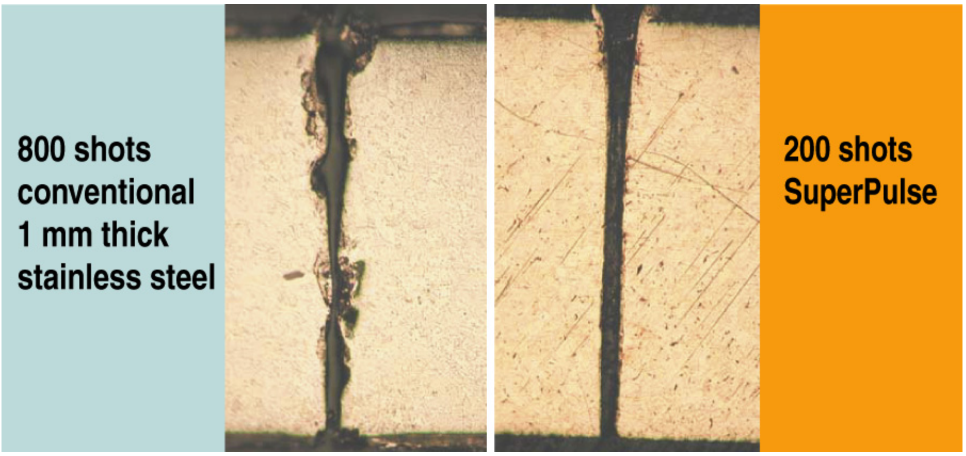

Fig. 3. This comparison shows the improvement in quality control of percussion drilling that can be achieved using the SuperPulse format with a nanosecond laser.[9] The laser was focused using a 250-mm lens. The holes are roughly 40 μm in diameter.

Figure 4 shows a ~5-µm-diameter hole that has been drilled in a 170 μm thick spherical beryllium shell. Our experience with small-diameter holes like this is that aspect ratios as high as 35:1 can be achieved. We believe the plasma produced by the laser is the limiting factor on achieving greater aspect ratios in such small-diameter holes, and we will discuss this later in this article.

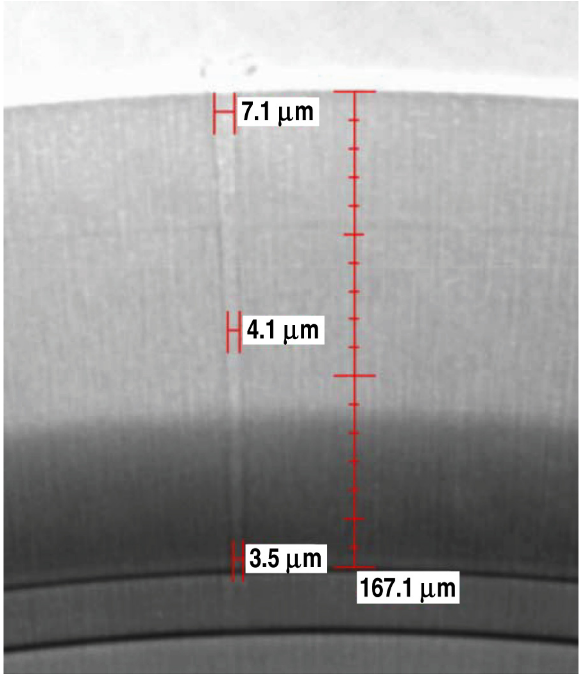

Fig. 4. An x-ray microscope[10] is used to analyze a high-aspect-ratio, small-diameter hole drilled with a nanosecond laser[8] utilizing the SuperPulse format. In this case, it is a fill hole in a layered beryllium capsule, used in inertial-confinement-fusion experiments, were made with the support of the Department of Energy contract DE-AC52-06NA27279, and have previously been documented by Lundgren et al.[3]

3. THE PHYSICAL MECHANISM UNDERLYING THE BENEFITS YIELDED BY USING THE SUPERPULSE FORMAT

In order to formulate a better understanding of the process itself, we have undertaken experimental and computational studies.[4]

We photographed the laser light reflected from the target and the plasma during the first and second laser pulses, to determine the energy distribution at the target. The results show scattered light from the primary laser pulse emanates from the target surface, but that scattered light from the secondary laser pulse emanates from a region of plasma that is in front of the target surface and is microns to tens of microns in size. From this measurement, we infer that the secondary laser pulse is at least partially if not substantially interacting with ablation products produced by the primary laser pulse, and not the target surface itself.

The exact effect of the second pulse becomes an important question. To address this, we fired only the primary laser pulse at a target and then photographed the evolving laser-produced plasma and ablation products at several different times after the pulse struck the target. We achieved temporal resolution by using a separate laser pulse (much lower intensity so as to only illuminate the target) having a different wavelength and a 4-ns pulse duration. We observed that while the ablation plasma decayed in 20 or 30 ns under normal atmospheric conditions, a dark cloud of material remained above the target surface for over a hundred nanoseconds. It is this dark cloud of material that appears to evolve relatively slowly and that the secondary laser pulse strikes, and this is why the separation of the primary and secondary laser pulses ranges from 20–200 ns. We want the secondary laser pulse to hit these slower, cooler, residual ablation products and not the hot, fast, initial ablation plasma, so that the laser energy of the second pulse will be absorbed as close as possible to the target surface.

Two additional items are worth mentioning in relation to this photographic measurement of the residual ablation debris. First, the enhancement in drilling rates for 50 μm diameter holes in steels of thickness between 50 μm and 2 mm is roughly independent of thickness. However, that is not the case for aluminum. We saw no enhancement in 50-µm-thick aluminum, and more than an order of magnitude improvement in 1-mm-thick aluminum. The photographic measurements of the residual ablation products show that for equivalent pulse energies, aluminum produces a much heavier and more persistent cloud of residual ablation products than does steel.

Let us consider the nature of the interaction of the secondary pulse with the dark cloud of material, i.e., the ablation products that remain in the vicinity of the target for a short time after the hot, ionized, ablation plasma dissipates. Does the secondary laser pulse mostly propagate through these ablation products or is it mostly absorbed by them?

In order to assess this, we measured the ablation pressures created by the primary and the secondary laser pulses.

It is important to understand that for the 10^{10} to 10^{11} W/cm^2 intensities we are working with, the 4-ns laser pulse produces a hot, ionized plasma at the surface of the target, and ablated material is accelerated to speeds of many km/s, traveling away from the target surface. According to Newton's third law, one can think of it in the following manner: the same "push" that accelerates ablation products to high speed moving away from the target must also "push" in the opposite direction into the target. This process drives a shock wave into the target, and that shock wave is proportional to the intensity of the laser. This fact allows us to compare the laser-matter interactions that occur during the primary and secondary laser pulses.

We measured the intensity of the shock wave by firing the laser at a thin foil, and then recording the motion of the back surface of the foil interferometrically[5]. The shock-wave intensity — or the pressure it produces — is then from the acceleration of the back surface of the foil. When the primary and the secondary laser pulses had the same intensity, we saw that the pressure produced by the primary laser pulse was a few times greater than the pressure produced by the secondary laser pulse. This tells us that most of the laser energy in the secondary pulse does not travel through the residual ablation products to strike the target surface, but it is absorbed in the residual ablation products. Specular reflection of the secondary pulse from the residual ablation products also appears to be minor. Nearly all the energy is absorbed except near grazing incidence where the specular reflection was < 50%.

These observations can be used to form a phenomenological model of the processes that lead to the enhancement in drilling speeds. We believe a four stage process accounts for the results that are obtained using the SuperPulse format.

1. The primary laser pulse produces a plasma and other ejecta in front of the target, and ablates a certain amount of material.
2. Then there is delay period long enough for the plasma to dissipate but short enough so that other, cooler ablation products remain over the target. For nanosecond pulses striking targets in a ambient atmosphere environment, this delay is typically between 40 and 150 ns. In a vacuum environment, delays can be as short as 20 ns. This is because in vacuum there is no ambient atmosphere to slow the expansion of the plasma and consequently the cooler ablation products are exposed earlier.
3. The secondary laser pulse then heats these residual ablation products. Based on the pressure measurements, we think that the secondary laser pulse is mainly absorbed by the residual ablation products, which would then probably become at least partially another plasma.

4. There are two effects that can take place now with the new plasma and re-heated ablation products. The dominance of each depends on the material properties of the target and the geometry of the hole.
    a. The first effect is enhanced efficiency of ablation. This arises because the pressure produced when the second pulse heats the residual ablation products and turns them into plasma is a fraction of the pressure produced when the primary laser pulse strikes the target. The interferometric measurements show the pressure generated by the primary pulse range from 20,000 to 60,000 atmospheres, and are 2–3 times as great as the pressures produced by secondary laser pulses of equal intensity.[4] Thus, with the hot plasma providing a heat source in contact with the target and relatively little pressure to inhibit material evaporation (think of how a pressure cooker works) ablation proceeds rapidly. This mechanism appears to dominate in materials such as steel that, compared to other metals, require a large amount of energy to vaporize and do not have a high thermal conductivity.
    b. The second mechanism is improve efficiency in clearing ablation products and debris from the hole. Since the residual debris products are heated by the secondary laser pulse, redeposition[6] inside the hole is inhibited. This mechanism appears to dominate in deep, small holes in metals such as aluminum that require a relatively small amount of energy to vaporize and have a high thermal conductivity, and produce a relatively heavy cloud of residual ablation products as was previously described.

The mechanisms for the enhancement of laser micromachining proposed here also do not rely on the presence or on the absence of a pool of melted target material being formed in the hole.[7]

Finally, it should be noted that there is a case we have observed where the SuperPulse format does not yield benefit, and that is in drilling shallow, low-aspect ratio holes in aluminum. The heavy cloud of residual ablation products that the secondary laser pulse strikes may be too thick for the effective transfer of energy to the target and in a shallow high aspect hole, such as 50 μm hole through a 100 μm thick target, the inhibition of hole drilling by redeposition in the hole does not arise due to the open geometry.

4. PLASMAS AND A LIMIT TO THE ASPECT RATIO OF SMALL HOLES?

The foregoing discussion brings to mind three points pertaining to the application of the SuperPulse format to the drilling of small, high-aspect-ratio holes. First, the increased efficiency of material removal means that less energy is used to drill the hole. This means that less energy is available to be conducted into the bore walls to cause defects such as heat affected zones. Second, the tendency of the secondary pulse to clear the ablation products from the hole helps prevent hole occlusion. Third, the effects of a hot ablation plasma flowing out through a long, narrow hole needs to be assessed.

A simple experimental test is to vary the laser power while keeping the rest of the experimental parameters constant, and then observe the changes in the resulting holes. Figure 5 shows the results of such a test in 150 μm thick aluminum foil. In this experiment the laser source was a Sierra,[8] having a wavelength of 532 nm, a pulse duration of 4 ns, and a repetition rate of 10,000 shots/second. The output of this laser was split into two beams and then recombined after one of the beams propagated through a 20-foot-long delay loop. The resulting output was a beam consisting of 10,000 SuperPulses™ per second and each SuperPulse consisted of a primary pulse and a secondary pulse separated by approximately 20 ns. This beam was focused onto the aluminum foil at normal incidence in vacuum using a 1” plano-convex focusing lens that produced a spot diameter is less than 6 µm on the foil. The depth of focus was ~ 100 µm. Each hole was drilled using 2000 laser shots.

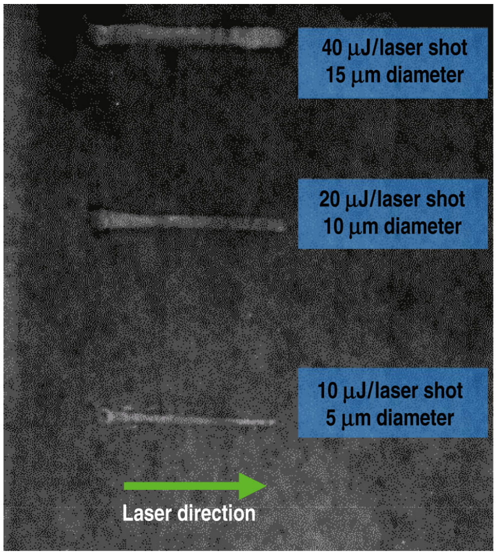

Fig. 5. Increasing the laser power increases the hole size significantly beyond the diameter of the focal spot, which was less than 6 μm. Two-thousand SuperPulse shots were used to drill each hole through a 150 μm thick aluminum foil. These holes were analyzed using an x-ray microscope with the sample held at a 45 degree angle. As a result, in the above image, the holes appear to be shorter than actual size.

The results show that as the power is increased, the hole diameter increases throughout the length of the hole, to diameters substantially greater than the focal spot size. This shows that mechanisms other than direct laser ablation are in play, and in these small holes the plasma expands radially at the same time as it flows out of the hole, thereby ablating the hole walls and enlarging the hole. The greater the laser energy, the hotter the plasma and the more the hole size increases, shown schematically in Fig. 6. It should be kept in mind that this model is fairly crude.

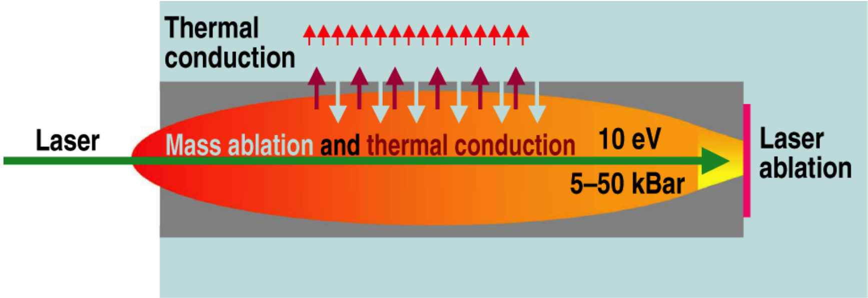

Fig. 6. A crude model of the effects of hot plasmas flowing out through small, high-aspect-ratio holes. The initial plasma is hot (10 eV=100,000 K) and at a high pressure (50 kBar=50,000 atmospheres). It loses thermal energy to the bore walls as it flows out and, in the process, additional material is ablated, enlarging the hole.

One might then ask if drilling at low power will eventually produce very deep and small holes. Unfortunately, in small holes the laser undergoes power losses as it propagates through the hole, so there is a minimum power that can be used to drill a hole of a given depth. It has been our experience that for a 5 μm hole, the greatest aspect ratio we can achieve is approximately 35:1.

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ACKNOWLEDGMENT

This work supported by General Atomics IR&D funding.