A STUDY OF MATERIAL REMOVAL RATES USING THE DOUBLE PULSE FORMAT WITH NANOSECOND PULSE LASER ON METALS

Paper 401

B.R. Campbell, T. M. Lehecka, J.G. Thomas, V.V. Semak

Penn State Electro-Optics Center, 222 Northpointe Blvd.
Freeport, PA 16229, USA, bcampbell@eoc.psu.edu

Abstract

Using a commercial nanosecond pulse laser system, experiments were conducted to measure and compare conventional percussion drilling performance with the double pulse machining method. The quality of the hole is considered along with drilling rate to measure the performance of the double pulse format. The data shows a significant performance enhancement by redistributing energy into a double pulse with temporal spacing between 25 and 200ns. Redistributing energy from the first pulse to the second pulse also improved drilling speed.

Introduction

The simplest form of laser drilling uses a steady stream of laser pulses with a fixed repetition rate to percussion drill through a sample. Several studies have been conducted to examine the drilling rates and quality of holes produced by these methods. [1,2,3,4,5,6,7] Over the past few years a variation on this method has been explored using a train of double pulses where the inter-pulse spacing was much less than the spacing between the pulse groups. [8,9,10,11,12,13,14,] A commercial laser system, the General Atomics SuperPulse laser, exploits this double pulse method of laser drilling to improve hole quality for nanosecond pulse drilling. The results published by General Atomics show that the double pulse method could increase drilling speed by a factor of up to ten times. [11] Work done with picosecond systems that have a double pulse capability have shown mixed results, but, to date, have not demonstrated benefits as pronounced as with nanosecond pulse lasers. [12,13,14]

Procedure

A laser micromachining workstation with motion control software was used to measure the time needed to percussion drill through a thin sheet of metal [15,16]. Aerotech A3200 software operated the laser shutter and controlled the exposure time of the laser on the sample. The software also monitored the real time signals from a photodiode placed under the sample. When the system detected the breakthrough of laser light, the drilling time was recorded. To compensate for delays due to signal processing and computer operations, a baseline test was run without a sample, which showed a consistent 27ms lag time. The 27ms lag was subtracted out of all data to get accurate breakthrough times. To set boundaries for reasonable data, the minimum time accepted was restricted to 75ms and the maximum was 5s. This limited the range of energies and sample thicknesses to those that produced data between these limits. The photodiode trigger level to signal breakthrough was set high enough to avoid triggering by ambient room light, vision system illumination, and scattered laser light.

The laser was focused with a 400mm focal length lens to a spot size of approximately 100 microns. The focal spot size was not directly measured but the size of the hole made by the laser served as an estimate for the spot size based on the damage threshold. Using the range of hole sizes produced, reasonable estimates for fluence can be made. For example, to convert a 100μm diameter spot from energy per shot to fluence, we multiplied the energy in units of mJ's by a factor of 12.7 to convert to J/cm^2 per shot. The nominal energy of 1mJ (10W at 10kHz) per shot converts to 12.7 J/cm^2 for a single pulse or 6.35 J/cm^2 for each of the pulses in a double pulse shot. Since the pulse duration was 5.5ns, the power density during the pulse was calculated to be 2.3×10^9 W/cm^2 for a single 1mJ pulse.

Measurements were made of maximum drilling rate through a thin sheet of metal by drilling 10 identical holes to determine an average time for light to break through the material. From the sample set of 10 holes, the standard deviation was calculated and included on graphs of drilling time as error bars. A mirror was placed beneath the sample, to direct the light onto a photodiode to signal when the metal had been penetrated. Using Aerotech software to monitor the feedback from the photodiode, a test set could be initiated and the breakthrough time data would be tracked and recorded by the program for analysis. To confirm repeatability, certain tests were repeated on different parts of the sample and the results were found to be in good agreement. If additional holes beyond the required minimum were made, the results were factored into the reported data, resulting in some sample sets being 30 to 40 holes instead of the standard number of 10 holes.

The materials tested were aluminum and titanium with thicknesses of 500 and 508 microns respectively. The two-inch square samples were clamped into a sample holder, suspending them tightly over the mirror/photodiode assembly. The sample holder was positioned using Aerotech motion stages. The laser light incident through the focusing lens and beam path to the photodiode were aligned to ensure that the first light to break through the sample would be directed onto the photodiode.

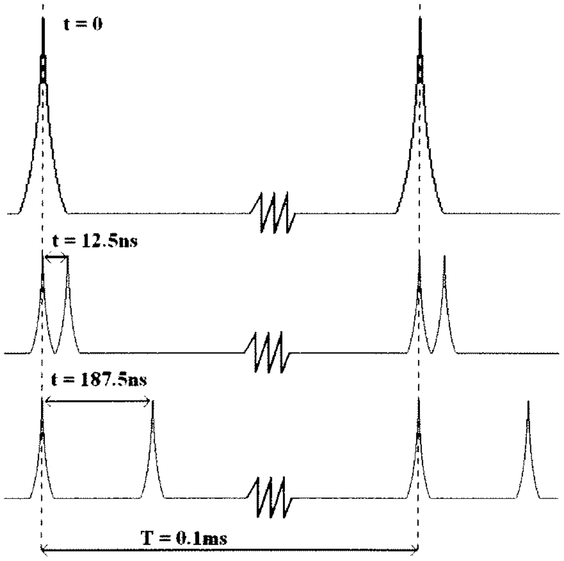

Figure 1. Example of conventional and double pulse configurations for the SuperPulse laser for no double pulse spacing (t=0), minimum (t=12.5ns), and maximum (t=187.5ns) pulse spacing. The first pulse is generated by a different laser than the second pulse within the SuperPulse laser system.

To compare the drilling rate of a conventional pulse train to the double pulse format, a few baseline terms must be defined. A "shot" is defined as a single pulse or close grouping of pulses where the spacing between the pulses in the group is much less than the spacing between groups. Figure 1 shows the three possible scenarios for the SuperPulse laser. The first is the traditional 10kHz pulse train with 0.1ms pulse spacing. The second and third example show double pulse shots at the shortest (12.5ns) and longest (187.5 ns) pulse separations allowed by the SuperPulse system. The energy from the single pulse in the first example is divided into two pulses for the double pulse shots. Instead of reporting the energy per pulse, the energy will be described as "energy per shot". In literature about the double pulse method, there are several opposing methods for comparing single pulse trains to double pulse trains when describing their energy content and drilling time (removal rate). For comparing laser pulse configuration performance, the method preferred by the authors maintains a philosophy of photon conservation, where comparisons of improvements in processing speed don't alter the number of photons used during a complete cycle of the laser system (the reciprocal of the repetition rate). Energy is redistributed from a single pulse into two or more pulses, but the total energy per shot remains constant.

The laser used for the experiments was a commercially available nanosecond laser which can operate in a double pulse format. It is a diode pumped solid state laser that operates at 532nm with the optimal power at a repetition rate of 10kHz. The laser is capable of generating double pulse spacing with a nanosecond timescale separation by using two individual lasers which are combined along the same beam path. By changing the trigger delay of the Q-Switch, the relative spacing between the two laser pulses can be changed from 0 to 187.5ns in intervals of 12.5 ns. But at the optimized 10kHz repetition rate, each double pulse is separated by 0.1ms. The relative energy of each pulse can also be controlled, so tests with equal energy and different energies for each pulse were explored. This is done by isolating the power output of each of the two lasers and adjusting them separately to the desired power level, maintaining the overall average power. For a 10W total power and 1:1 spit, the lasers were each set at 5W. For the 1:2 ratio, laser 1 was set to 3.3W and Laser 2 at 6.7W. A representation of the various power ratios is shown in Figure 2.

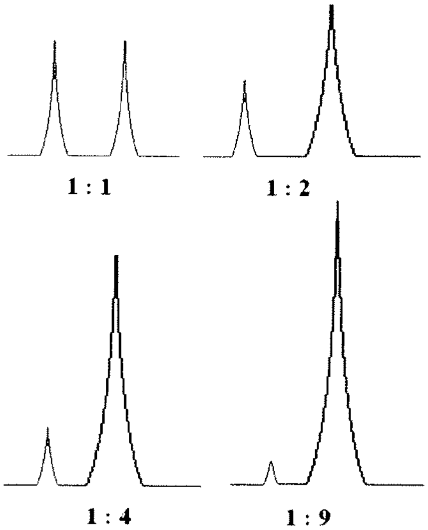

Figure 2. Example of energy ratios for the two pulses in a double pulse configuration.

Results and Discussion

During the setup of the experiment it was noticed that the drilling time through a metal was highly dependent on the air pressure used to help evacuate material from the hole and prevent debris from settling on the optics. The airflow was varied from no airflow to 50 psi. Air flow pressures of 10 to 25 psi had the shortest drilling times, as seen in Figure 3. For the double pulse testing, the airflow was maintained near 20 psi . The higher air pressure may be forcing debris back down into the hole, slowing the drilling process. A moderate air flow seems to be helpful in clearing the hole for faster drilling.

Experimentation was conducted using 2-inch square pieces of stainless steel, aluminum, and titanium samples approximately 0.5mm thick, acquired from Goodfellow Inc. The laser was focused with a 10 inch focal length lens, through a protective window, and was brought to focus on the surface of the sample several millimeters below the 1mm opening in the tip of the processing nozzle.

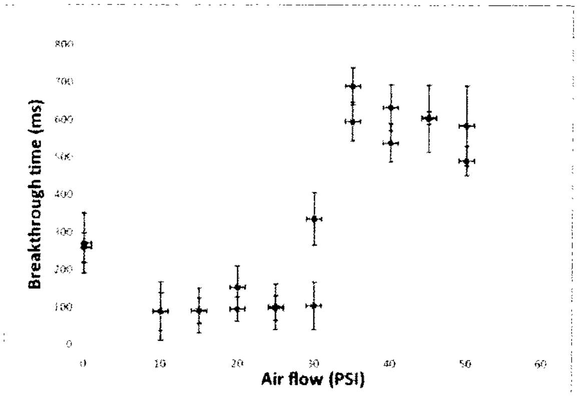

Figure 3 Time needed to drill through a 0.1 mm thick piece of stainless steel as a function of air flow through a nozzle in a laser processing head. Laser power = 10W.

Normal percussion drilling at 10kHz with both 6 and 10 Watts needed nearly 2.5 seconds to break through the aluminum sample in the normal single pulse mode (25,000 shots, 0.6 and 1mJ per pulse respectively). By splitting the power into two equal sized pulses (0.3mJ per pulse for 6 Watts and 0.5mJ for 10 Watts) and running the double pulse shot at 10kHz, the drilling time was dramatically reduced, as seen in Figure 4. For the smallest possible pulse separation of 12.5 ns (about 3 times the pulse duration) the drilling time fell by 20%. The next possible pulse spacing of 25ns saw the 6 Watt drilling time become 40% less time than the single pulse method, and the 10 Watt tests showed 50% less time required(or conversely, twice as fast drilling rate). After using a separation of 37.5ns, the marginal improvement from increasing pulse separation diminished and the effect stabilized. The data consistently shows a nearly 50% reduction in drilling time at 6 Watts using the double pulse method and over 60% reduction at 10Watts. No additional energy was used to get these process improvements, the energy from a single pulse was merely split into two closely spaced pulses.

In Titanium, double pulse testing was conducted using 10 and 13 Watts of laser power, or 0.5 and 0.65 mJ of energy per pulse in the double pulse mode. At a pulse spacing of zero, the pulses combine to have 1 and 1.3mJ, naturally. The Titanium showed similar behavior to the aluminum, reaching the best drilling time with a 37.5ns pulse spacing or longer. For the 10W test the processing time was reduced by 60% by the double pulse method; at 13 Watts the time was reduced up to 70%.

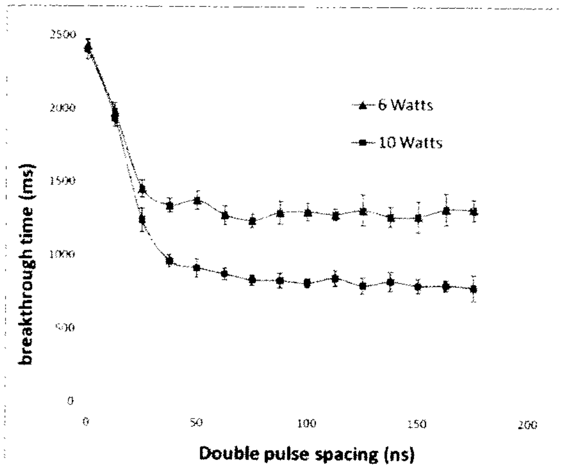

Figure 4 Time needed to drill through 0.5mm thick aluminum for various double pulse spacings at average powers of 6 and 10 Watts.

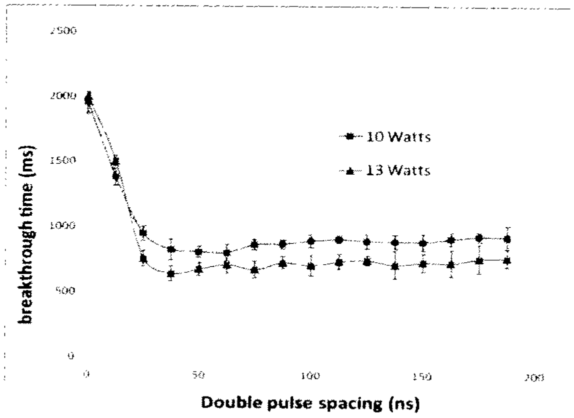

Figure 5 Time needed to drill through 0.508mm thick titanium for various double pulse spacings at average powers of 10 and 13 Watts.

The distribution of the energy within the double pulse shot was altered to determine if the drilling rate could be increased by shifting more power to the second pulse. Three different energy ratios were used (1:2, 1:4, 1:9) in addition to the normal equal distribution of energy. The total amount of energy per shot and average power were equal in each instance. In each case for Titanium, having more energy in the second pulse decreased drilling time (Figure 6). From 25 to 87.5ns pulse spacings, the 1:2 ratio of energy showed the best performance, with a 20% decrease in processing time. Above 100ns pulse spacing, all three ratios were improvements upon the equal division of energy, with decreases of 15-30% in drilling time from the 1:1 ratio.

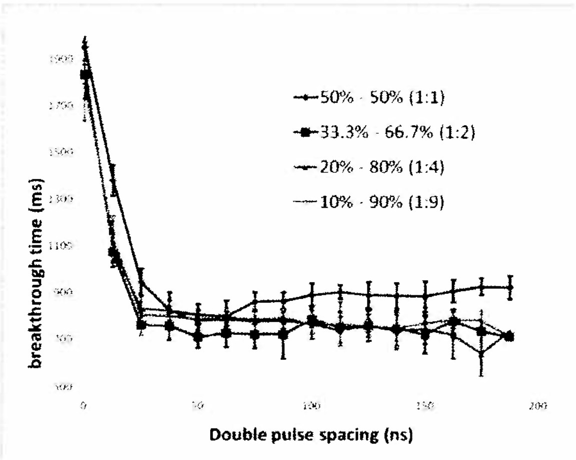

Figure 6 Time needed to drill through 0.508mm titanium using 10W and the double pulse format with various energy distributions for the two pulses.

In other published work, the mechanism for improved material removal involving this double pulse method has been explained with a 4 step phenomenological model [11]. The description of the process relies on the first pulse creating a melted surface producing plasma and ejecta at the target. During the delay period between the first and second pulse, the plasma will dissipate, but the heavier molten ejecta will linger at the target. The ejecta (or melt pool) is then rapidly heated by the second pulse creating pressure at the target. The heated ejecta then becomes the ablation mechanism, by transferring heat through conduction into the solid target below and is more efficient than a laser pulse because of lower pressures than that created by the first pulse. It is thought that the high pressures created by laser pulse removal of the solid surface (as with the first pulse) inhibit drilling, and that the low pressure zone from the heated ejecta allows the ablated material to evacuate more efficiently. The heated ejecta also has more kinetic energy and therefore mobility to evacuate the drilling location. Assuming this model is correct, the effect of shifting energy to the second pulse could establish an optimal condition for the amount of ejecta production with the first pulse compared to the energy dependent ablation ability and material removal attributed to the second pulse. The equal split of energy may be creating more molten material with the first pulse than the second pulse can remove. The shifting of energy to the second pulse reduced the amount of molten ejecta formed, and delivered more energy with the second pulse to use for further ablation and material evacuation in a low pressure situation.

For each of the pulse energy ratios, it should be noted how significant the change in drilling rate is for the 1:9 ratio over having no pulse spacing. For 10Watts at 10kHz for the single pulse case, each pulse contains 1mJ of energy. By splitting that single pulse of 1 mJ into a pulse of 0.1mJ and 0.9mJ, the drilling rate doubled. If the power ratio trend were to be continued, at some point the pulse train would resemble a single pulse per shot situation as the first pulse fades down to a level incapable of creating plasma and melt. This might present a new method to determine threshold of surface modification for a material. The drilling rate as a function of pulse energy ratio could be measured until the double pulse drilling time equals the single pulse time. This would indicate that no surface melt is being formed by the first pulse at that energy level, and the second pulse is interacting with a solid target, which has a slower processing time. For testing presented here 1:9 was the limit of the energy ratio for the 10 Watt test case, because neither laser was capable of exceeding 9 Watts. Further study is warranted to determine the fraction of energy needed in the first pulse to maintain the double pulse benefit, and whether it relates to a useful threshold value.

Based also on the phenomenological model, it is understandable why a picosecond laser would not see the same benefits from this mechanism. The decreased benefit for double pulse drilling with picosecond pulses has been documented in other works [9,12]. In fact, the double pulse format would more often result in longer drilling times. The ablation mechanism described by Forsman et al. [11] that makes the double pulse method more efficient requires a thermal mechanism and timescale for removal that acts over several nanoseconds. A picosecond pulse would create more plasma, but would be less likely to create ejecta, since ultrashort pulses are widely considered to have "non-thermal" ablation process. Experimental data supports the assertion that the double pulse effect is beneficial for nanosecond pulses but not for any timescales shorter than this.

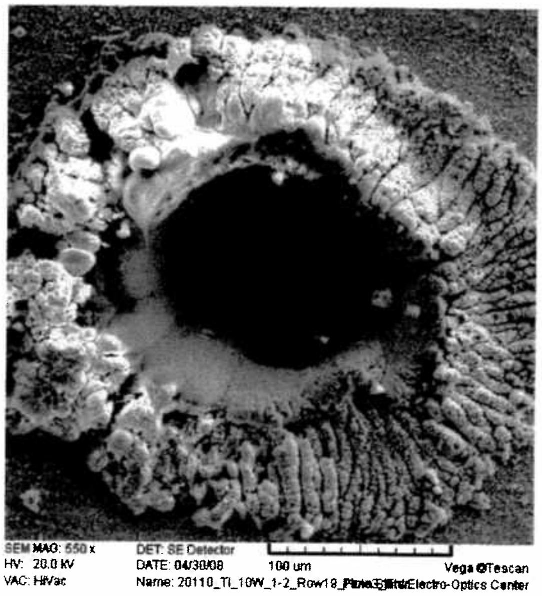

Figure 7 Percussion drilled entrance hole in Titanium with 532nm and 4ns per pulse. Using double pulse format with 10W total power and 1:2 energy ratio.

SEM analysis of the drilled holes revealed the entrance holes had large amounts of melt and debris accumulated around their perimeter (Figure 7) with no post processing or cleaning of the surface. The melt debris didn't have any apparent correlation to the double pulse processing parameters. The exit holes were surprisingly clean. Very little melt or recast accumulated (Figure 8). Other experiments have shown that the surface debris can be reduced by using a trepanning method for material removal. For these experiments, reduction of melt formation was a secondary objective to exploring double pulse effects for material removal rates.

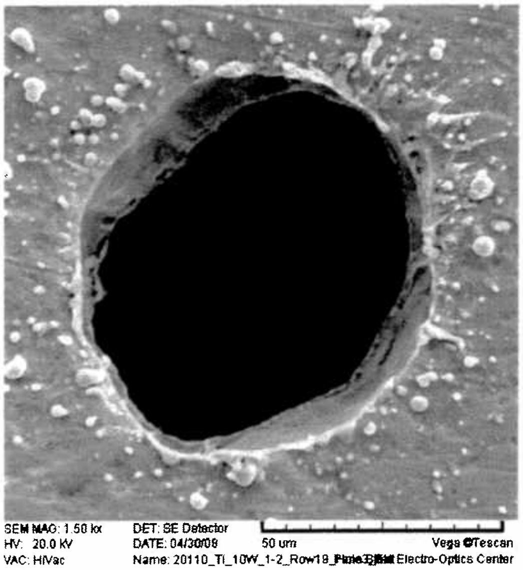

Figure 8 Percussion drilled exit hole in Titanium - 4ns pulses. Using double pulse format with 10W total power and 1:2 energy ratio.

Conclusions

The experiments with the General Atomics SuperPulse laser confirms published works by that company [11] showing improved drilling time using a double pulse format. While they report drill rate increases of up to an order of magnitude, the results reported here only yielded a maximum 2-fold increase in performance for aluminum and titanium from an even energy distribution in the double pulse system. A minimum spacing of 25 ns was needed to approach the maximum process speed improvement. From 25 to 187ns pulse spacing, the double pulse performance enhancement showed consistent improvement over the single pulse format. It was also shown that reducing energy in the first pulse and redistributing it to the second would marginally improve the drilling rate. A 1:2 energy split between the first and second pulse in a shot showed a nearly 3-fold decrease in drilling time for pulse separations between 25 and 100ns in Titanium. Comparisons were made among experiments that used the same amount of laser power but identified better methods to construct a pulse train for maximum throughput.

Acknowledgements

This material is based upon work supported by the Office of Naval Research; contract number N00014-05-D-0275, Delivery Order 0007. Any opinions, findings and conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Office of Naval Research.

References

[1] Osterndorf, A.; Kamalage, G.; Klug, U.; Korte, F.; Chichkov, B.N.: Femtosecond versus picosecond laser ablation. Proc. SPIE Vol. 5713 (2005) 1-8

[2] Breitling, D.; Ruf, A.; Dausinger, F: Fundamental aspects in machining of metals with short and ultra short laser pulses. Proc. of SPIE Vol. 5339 (2004) 49-63

[3] Konig, J.; Nolte, S.; Tunnermann, A.: Plasma evolution during metal ablation with ultrashort pulses. Optics Express Vol 13 No 26 (2005) 10597-10607

[4] Pietsch, W.: Effect of Knudsen-layer formation on the initial expansion and angular distribution of a laser produced copper plasma at reduced pressure of air. J. Appl. Phys 79, (1996) 1250-1257

[5] Albert, 0.; et al.: Time Resolved spectroscopy measurements of titanium plasma induced by nanosecond and femtosecond lasers. Appl. Phys A 76 (2003) 319-323

[6] Stoian, R.; Boyle, M.; Thoss, A.; Rosenfeld, A.; Korn, G.; Hertel, I.V.: Dynamic temporal pulse shaping in advanced ultrafast laser material processing. App. Phys A. 77, (2003) 265-269

[7] Lapczyna, M.; Chen, K.P.; Herman, P.R.; Tan, H.W.; Marjoribanks, R.S.: Ultrahigh repetition rate (133MHz) laser ablation of aluminum with 1.2-ps pulses. Appl. Phys A. 69 Suppl. (1999) S883-S886

[8] Lehane, C; Kwok, H.S.: Enhanced drilling using a dual-pulse Nd:YAG laser. Appl. Phys A 73 (2001) 45-48

[9] B.R. Campbell, T.M. Lehecka, V.V. Semak, J.G. Thomas "Effect of the double pulse format for picosecond pulse laser drilling in metals" Proc. ICALEO paper M906 (2007)

[10] B. R. Campbell; L. A. Forster; T. M. Lehecka; J. G. Thomas; V. V. Semak, "Shallow Hole Drilling with Ultrashort Pulse Lasers" Proc. SPIE 6879 (2008)

[11] Forsman, A.C.; Banks, P.S.; Perry, M.D.; Campbell, E.M.; Dodell, A.L.; Armas, M.S.: Double-pulse machining

as a technique for the enhancement of material removal rates in laser machining of metals. Journal of Applied Physics (2005) 98, 033302 1-6

[12] Campbell, B.R. ; Campbell, R.C.; Lehecka, T.M. ; Semak, V.V. ; Thomas, J.G. : Performance of picosecond laser pulse drilling, including an evaluation of the double pulse machining method. Proc. 4th International WLT-Conference on Lasers in Manufacturing (2007) 605-611

[13] Hartmann, C. A.; Fehr, T.; Brajdic, M; Gillner, A.; Investigation on Laser Micro Ablation of Steel Using Short and Ultrashort IR Multipulses. JLMN-Journal of Laser Micro/Nanoengineering Vol. 2, No. 1 (2007) 44-48

[14] Hartmann, C. A.; Gillner, A.; Aydin, U.; Noll, R.; Fehr, T.; Gehlen, C.; Poprawe, R.; Investigation on laser micro ablation of metals ns-multipulses. J.of Phys. Conference Series 59 (2007) 440-444

[15] Semak, V.V.; Thomas, J.G.; Campbell, B.R.: Comparison of drilling rates and material removal dynamics for nanosecond and femtosecond laser pulses. Proc. SPIE Vol.5713 (2005) 516-521

[16] Campbell, B.R.; Semak, V.V.; Thomas, J.G.: Ultrashort Pulse Laser Micromachining Performance Enhancements [M407] ICALEO conference proceedings (2005)