High-speed cutting of thin materials with a Q-switched laser in a water-jet vs. conventional laser cutting with a free running laser

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ABSTRACT

Cutting of thin material, c.f. stencils, stents and thin wafers, is an important market for laser machining. Traditionally this task is performed using flash-lamp pumped, free-running Nd:YAG lasers.

Using the water-jet guided laser technology, we experienced that the use of Q-switched lasers leads to superior results while cutting a variety of thin materials. In this technique, the laser is conducted to the work piece by total internal reflection in a thin stable water-jet, comparable to the core of an optical fiber. Utilizing this system, we obtain burr-free, slightly tapered cuts at the same speed as the classical laser cutting and without distinguishable heat affected zone. The main difference is, except the water-jet usage, the pulse duration which is approximately 400 ns instead of 20 to 200 µs in the case of free running lasers. Up to 40’000 high quality apertures per hour can be achieved in stencil mask cutting with the new system.

We will compare qualitatively the two possibilities: conventional laser cutting with free-running lasers and water-jet guided laser cutting with Q-switched lasers. The results will be discussed in terms of the different physical effects involved in the material removal upon both methods. In particular the importance of molten material expulsion by the water-jet will be pointed out and compared to the action of the assist-gas.

The mentioned effects show that the combination of short pulse laser and water-jet will be beneficial for the production of a wide range of precision parts.

Keywords: Laser cutting, Q-switched laser, free running laser, pulse length, stencils, metal foil, 1064 nm.

1. INTRODUCTION

Cutting of thin materials is often difficult or impossible with abrasive or mechanical means, due to the sensitivity of the material to forces. Cracking will appear in brittle materials like silicon, and plastic deformation appears in metals typically. For this reason namely wet chemical etching and laser cutting, as low force machining possibilities, are applied in this field.

Focusing on thin metal foil machining, the main advantage of chemical etching is the complete absence of forces and burrs. However the shape of the edges is not well adapted for some applications like solder paste stencils and the reproducibility and precision of the etching process are also minor compared to laser cutting. Classical laser cutting is not completely force free as the assist gas executes a certain pressure onto the metal foil. An important disadvantage with respect to many applications however is the build-up of burrs, usually on the backside of the foil. Also, as the material is simply molten due to the absorbed light energy and removed by the assist gas stream, a heat-affected zone (HAZ) can be distinguished close to the cutting edge. The HAZ is visible by the oxidation around the edge and it also changes the grain size of the metal[1] and thus the mechanical properties close to the edge. In spite of these disadvantages, classical laser cutting is more and more used in industrial stencil production because of the superior precision and the ever-decreasing pitch of electronic components.

The water-jet guided laser is a relatively new technique, which combines the positive aspects of conventional laser cutting and chemical etching. In the following, we will present the improvements in cut quality that are achieved using this technique and we will outline the reasons for the observed effects.

2. EXPERIMENTAL DETAILS

A sketch of the water-jet guided laser cutting system is shown in Figure 1. The used laser for thin metal foil cutting is a multimode Q-switched Nd:YAG laser (SL902, Spectron Laser Systems Ltd. (UK)). We use pure de-ionized and filtered

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water at 5 to 50 MPa for the water-jet. The nozzles are made out of sapphire or diamond in order to generate a long stable portion of the water jet. The laser beam, coming from the fiber delivery of the laser, is collimated, passes a beam expander and is focused through a quartz window into the nozzle. The situation in the coupling unit is very much like in an usual fiber coupling, except the fact that the intensity distribution of the light is flat-top and not Gaussian, due to the mode mixing in the fiber delivery of the laser and the imaging properties of the setup. Once in the water jet, the light is reflected at the air-water interface due to the refractive index step (Figure 2).

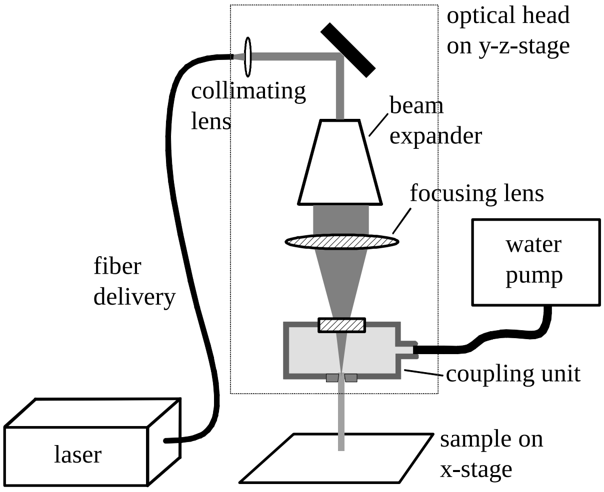

Figure 1: Schematic of the water-jet guided laser setup

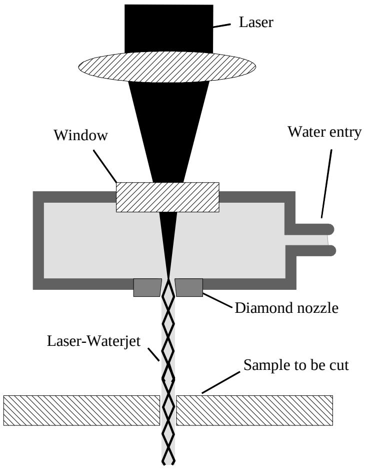

Figure 2: Detailed sketch of the coupling unit

The samples are clamped onto a motorized stage, and during the cutting process the samples are moved under the water-jet guided laser beam (laser-water-jet), or the optical head moves in the perpendicular direction. The z-variation of the stage is only necessary in order to adapt to the different working distances of differently sized nozzles at different water pressures [2] and is not used during the cutting procedure.

3. RESULTS AND DISCUSSION

Figure 3 shows comparison photographs: The upper line represents typical edges as they are obtained with a conventional (commercial) laser stencil cutting machine using a free running Nd:YAG Laser in 150 µm thick stainless steel foil. The laser parameters of the samples in Figure 3a and Figure 3b are summarized in Table 1.

Average laser power	Pulse repetition rate	Pulse length	Assist gas	Laser beam diameter
19 W	1’600 Hz	120 µs	Air, 15 bar	40 µm

Table 1: Classical laser processing parameters for 150-µm thick stainless steel foil. Optimized for quality and speed. Samples are shown in Figure 3, upper line.

More generally the pulse durations of the free running YAG lasers are limited to $\tau > 20$ µs, the pulse repetition rate is $f < 4$ kHz, and the average laser power is typically 20 W for the required beam quality (fine cutting). The above parameters are quite typical for stencil cutting in general. The pulse duration is adapted according to the thickness of the steel foil, longer pulses are used for thicker materials. See for example [3] who use 190 µs pulse duration for 200 µm thick samples.

The second line of Figure 3 shows the result of the optimized water-jet guided laser processing. The used Q-switched Nd:YAG-laser has a maximum average power of 65 W. The process parameters are summarized in Table 2. Comparing the parameters and the cutting speed of both methods, which is very similar (about 4.5 mm/s to 5 mm/s), we can state that both processes work with similar energy efficiency.

Average laser power	Pulse repetition rate	Pulse length	Water jet pressure	Laser-beam /water-jet diameter
22 W	25’000 Hz	0.4 µs	330 bar	50 µm or 75 µm

Table 2: Water jet guided laser-processing parameters for 150- µm thick stainless steel foil. Optimized for quality and speed. The average laser power value takes into account the losses in the 36 mm long water-jet due to absorption. The average power directly after the fiber delivery is 33W.

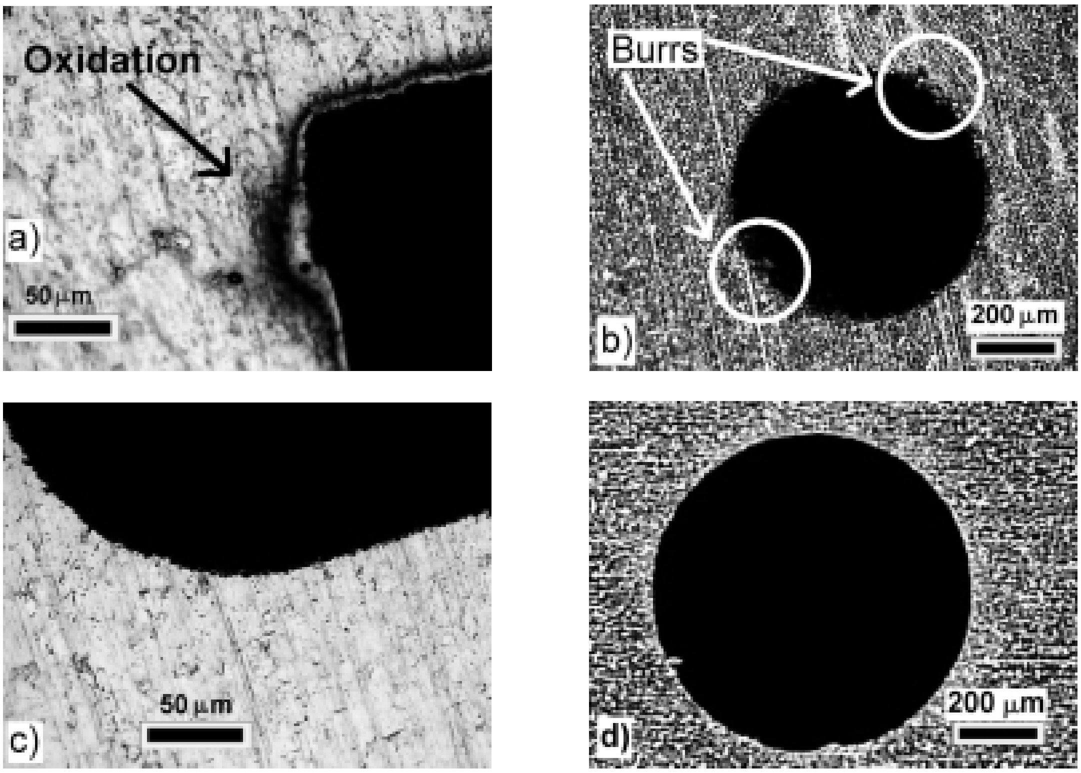

Figure 3: Optical microscope images of stencil apertures in 150 µm thick stainless steel. *Upper row:* Cut quality of a commercial conventional laser-cutting machine. a) Front side view of a corner, b) Backside view of a round aperture. *Lower row:* Cut quality achieved by the water-jet guided laser. c) Front side quality of a rounded corner, d) Backside view of a round aperture.

The width of the oxidation zone near the edge of the classical laser cut (Figure 3a) is approximately 12 µm. No oxidation is visible at the same magnification on the stencil which was cut with the water-jet guided laser (Figure 3c). The problem of burr formation, or particles on the backside of the apertures, is visible in Figure 3b for the classical laser cut. Figure 3d shows a slightly bigger hole that was produced with the water-jet guided laser, illustrating that particles and burrs can completely be avoided using this technique.

It is somewhat difficult to compare the two techniques, conventional and water-jet guided laser cutting, because of the numerous different parameters. However, concerning the oxidation zone, one important point is for sure the pulse duration of the laser.

An approximate expression to characterize the HAZ during non-ablative laser heating is given by the heat penetration length $l_{th} = 2 \cdot \sqrt{D\tau}$, where τ designates the laser pulse duration and D the thermal diffusivity of the heated material [4]. In the ablative case, i.e. during laser cutting, this expression overestimates the visible HAZ as a big part of the heat is used for the phase changes from solid to liquid, and eventually from liquid to vapor. Another part of the laser generated heat is carried away by the hot melt leaving the cutting kerf. For the sample showed in Figure 3a we obtain l_{th} = 44 µm, using the pulse duration given in Table 1 and $D = 4.0\ 10^{-6}$ m^2/s (value from reference[4]).

In spite of this overestimation of the HAZ by the thermal penetration length, we may in a first step assume the square root relationship of the HAZ with respect to the laser pulse duration. Knowing the pulse lengths of 0.4 µs and 120 µs, we can estimate the HAZ of the Q-switched laser to be roughly 17 times smaller than the one caused by the free running laser used for the classical laser cutting. According to this calculation and Figure 3a, one would expect to end up with 12 µm / 17 = 0.7 µm of oxidation zone around the cut with the Q-switched laser. This is small enough to be invisible on Figure 3a and Figure 3c.

The question to address is then: *why do classical laser cutting machines do not use the favorable short Q-switch pulses?* The answer to this scientifically and economically interesting question can be found in the unwritten condition under which the small HAZ for the Q-switched lasers was derived. The above conclusion is only valid if the mechanism of material removal is the same with both lasers. This includes a variety of physical effects and their relative importance for the laser induced material removal. The most important are: (i) material related effects like phase changes and temperature dependent heat conduction; (ii) plasma related effects like plasma intensity, plasma life time, shielding efficiency etc.; and (iii) melt expulsion effects like convective cooling, melt flow velocity profile, assist gas turbulences etc.

If the delicate equilibrium of these effects is changed, the width of the HAZ may be strongly affected as illustrated in Figure 4. The image shows a cut that was produced using the same Q-switched laser as employed for the water-jet guided laser cutting and the same 150 µm thick stainless steel foil and the sample was moved at 4.5 mm/s. However, neither water-jet nor assist gas were used for the melt expulsion, and the result is an impressively larger HAZ together with redeposition on the front side and burrs on the backside.

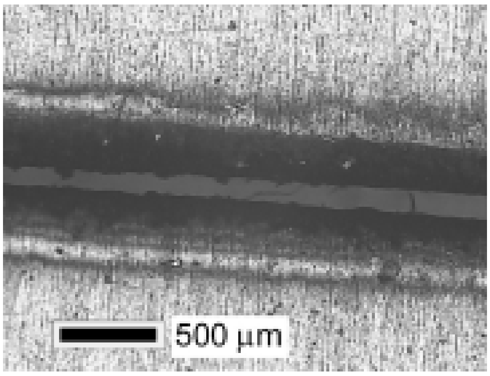

Figure 4: Optical microscope image of a laser cut with neither assist gas nor water-jet. The laser was the same Q-switched laser as used for the water-jet guided laser cutting.

This image does not prove that classical Q-switched laser cutting results in bad cut quality or large HAZ, it only illustrates the sensitivity of the cut quality to changes in the processing conditions. Optimized Q-switched laser cutting of metals often leads to important redeposition of droplets on the front side of the sample, which is difficult to remove[5]. Burr formation too is more important in the case of classical laser cutting with short pulses. As already mentioned before both effects, redeposition and burr formation, are an important disadvantage in solder paste stencil production. This is the reason why commercial stencil cutting machines, that are based on classical laser cutting, do not use Q-switched lasers in spite of the better HAZ that may be reached with these lasers.

To understand qualitatively the physical reasons we only need to consider the changes when using a Q-switched laser instead of a free-running laser: First the Q-switched pulses exhibit higher peak powers than the long pulses. This leads more easily to vapor formation, which expels small droplets of the melt against the assist gas stream. The gas stream cannot change the direction of these small and dense particles because of their relatively high momentum. Once the hot droplets touch the sample surface, they cool down and solder themselves to the surface. Secondly, the short pulse duration causes a small melt life-time. During this smaller time, the same gas jet can move the same volume of melt only over a smaller distance. If the distance that the melt can be moved by the gas jet, is smaller than the sample thickness, burr formation occurs. As it is visible in Figure 3b, even with relatively long pulses and a high assist gas pressure, some burrs/particles remain after traditional laser cutting at the backside of the sample.

Before coming to describe the situation during the water-jet guided laser process, we want to make sure to distinguish classical *cutting* and *drilling* with Q-switched lasers. The above paragraph and the mentioned disadvantages exhibited by Q-switched lasers refer *only* to cutting applications. Q-switched lasers are in fact widely and successfully used for drilling applications (percussion drilling), where fast expulsion of the melt to the top surface is needed and small HAZ and small recast layer thickness could be obtained in blind holes.

We already saw that the gas jet and its relatively low momentum is involved in the negative effects occurring upon classical laser cutting with Q-switched lasers. In the case of water-jet guided laser cutting with Q-switched lasers, the situation is different, because a high momentum medium is used to expel the melt from the cutting kerf. If vapor is formed during water-jet guided laser cutting, the droplets cannot go against the water jet because it has similar density compared to the melt droplets, and high speed (up to 290 m/s). Thus no redeposition is observed in the water-jet guided case (Figure 3c). Similarly burr formation can completely be avoided when working close to the cutting threshold, because the melt is removed very efficiently (Figure 3d).

After stressing so much the high momentum of the used water-jet, it might be useful to mention that the high momentum is not associated to a high force on the sample as the water is directed through the cutting kerf and only touches the melt front. The gas jet on the contrary diverges directly after the nozzle and most of the gas pushes perpendicularly on the sample surface causing a high force on the sample in spite of the lower gas jet momentum.

In summary we can state that the high momentum of the water jet avoids burr formation and redeposition of droplets. In the absence of these effects it is also possible to take advantage of the small HAZ being associated with the short pulse duration. It is however impossible, for the moment, to give quantitative values for the width of the HAZ upon water-jet guided laser cutting. Too many physical processes involved in the material removal are modified by the usage of the water-jet. In the above discussion we neglected for example the changed heat conduction. It is clear that the water jet somehow cools the sample in between the laser pulses, but only a beginning to describe the heat conduction was made recently by Li *et al.*[6]. We also neglected the strongly changed plasma properties, which are subject to active research in the context of laser hardening[7].

4. CONCLUSIONS AND SUMMARY

In conclusion, cutting results of thin metal foils obtained by conventional laser cutting with a free running YAG-laser and by water-jet guided laser cutting using a Q-switched YAG-laser were compared. The cut quality is much better with the water-jet guided laser technique for similar cutting speeds and process efficiency. Namely a much smaller heat affected zone and the absence of burrs were demonstrated. Explanations for the quality differences are proposed, highlighting both, the role of the laser pulse duration and the role of the water jet momentum.

The example shows how the Q-switched laser can become a high quality cutting tool for thin materials when employed in the water-jet guided technique.

5. ACKNOWLEDGEMENTS

We would like to thank Mr. Mahlgraf from LMB (Germany) for the classical test cuts with the Q-switched laser

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