Lasers in Manufacturing Conference 2015

Laser Micro-Cutting of Thick Tungsten Sheets

Ramūnas Šniaukas[a], Gediminas Račiukaitis

[a]*Center for Physical Sciences and Technology, Savanoriu Ave. 231, LT-02300 Vilnius, Lithuania. ramunas@fidi.lt*

Abstract

In recent years, laser-based technologies become important or even dominant in industrial applications such as welding or cutting. Further possibilities and innovations are still in progress concerning the area of laser micro processing. Laser technologies enables to manufacture materials with micrometer accuracy, however, there are obstacles to reaching desirable speeds when cutting thick materials (>200 µm).

Different cutting strategies were investigated to achieve the high cutting speed and quality at the same time in a 300 µm thick tungsten with picosecond lasers. A parametric study of laser cutting was performed taking into account trade-offs between precision and cutting speed. Experimental results proved that picosecond lasers are suitable to process quite thick tungsten sheets with micrometer accuracy. Furthermore, improvements in overall performance were achieved by optimizing the beam guiding approach over the full size of the component to cut.

Keywords: Ablation; Micro-cutting; Picosecond laser;

1. Introduction

Far more than a decade laser micro-processing is widely used and investigated field. Every year more and more new state of art lasers are created, which enables much faster and much more precise laser micro-machining of various different materials. The amount of companies, which are changing conventional machining methods into superior – based on laser technologies, is increasing. It is clear that laser-based technologies enable companies not only to reach better quality and faster fabrication, but it provides the technological basis for innovations to emerge (Overton et al. 2015). The main aim of this work is to bring closer laser micro-cutting of thick tungsten sheets from the laboratory into the industry: to investigate possible quality limits and to reach the cutting speed satisfying industry requirements.

Even though the first approach to micro-cutting of tungsten was made by using relatively cheap nanosecond laser, but initial investigation have shown that nanosecond lasers are not suitable for high-precision micro cutting of thick tungsten sheets. Therefore, investigation of micro-cutting with picosecond lasers was conducted. First results were promising and showed the entirely different situation than investigation with nanosecond lasers. This paper discusses methods that were used to reach the desired quality parameters and cutting speed. Presented results show what direction should be carried out in further investigations.

2. Experimental setup

All experiments in this work were carried out using two different specifications 10 ps pulse duration, 1064 nm wavelength, diode-pumped solid-state lasers PL10100 and Atlantic 355-60 (both manufactured by Ekspla). Atlantic 355-60 have internal nonlinear crystals for second harmonics generation – 532 nm wavelength. In case of fundamental harmonics, the laser beam was positioned by galvoscanner SCANgine 14 (ScanLab), for second harmonics HurryScan 14 (ScanLab) was used. The sample in the z direction was positioned by motorized table 8MT167-100 (Standa). Systems were managed by using a computer. Laser average power measurements were carried out with Nova 2 power meter (Ophir). Cuts prepared during the experiments were investigated. Their quality was evaluated from photos taken by BX51 optical microscope (Olympus), scanning electron microscope JSM-6490LV (JOEL) and data from profiler Dektak 150+ (Veeko). After the laser processing, cutting trash remaining on the sample was removed by the ultrasonic bath.

Micro-cutting experiments were conducted using only 300 μm thick tungsten sheets.

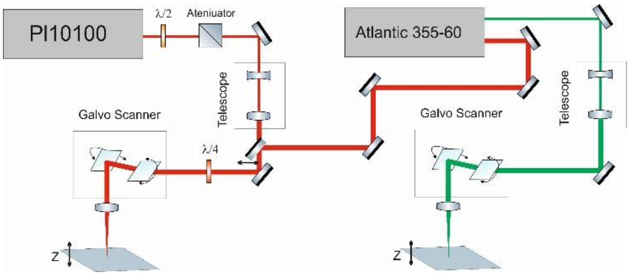

Fig. 1. Experimental setup of both systems.

3. Precise laser micro-cutting

The picosecond laser PL10100 with the wavelength of 1064 nm was used to determine, how precise the tungsten sheets with a thickness of 300 μm can be processed. Experiments were made by cutting 0.5 mm wide square holes, leaving a 0.2 mm spacing and measuring the distance between two consecutive holes on both sides of the sample. Assessment of kerfs was made by evaluating Δ*x* – the difference between spacing of adjacent holes in the upper and lower parts of the specimen see Fig. 2. The effort has been made to achieve kerf as uniform as possible on both sides of the sample.

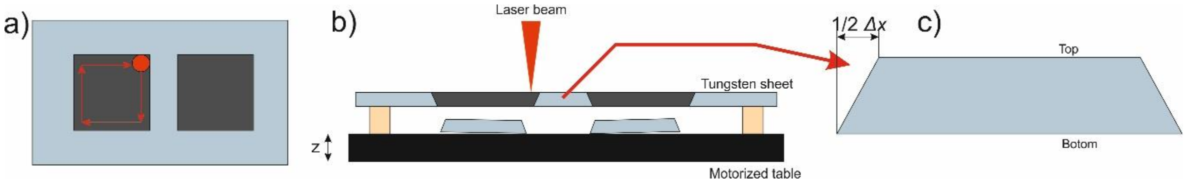

Fig. 2. Cutting of square holes in tungsten sheet. a) top view; b) side view; c) maximized view of the spacing between two adjacent holes, Δx – the difference between spacing of adjacent holes in the upper and lower parts of the specimen.

Square holes were cut with galvoscanner by ablating part of the material during each scan. The 300 mm/s scanning speed and 100 kHz pulse repetition were used during the investigation of best possible cut quality. 300 mm/s is the maximum speed at which the right angles of the holes are not rounded. Different cuts have been made by reducing laser pulse energy from maximum 45 μJ to 35 μJ. Reducing laser pulse energy further will do no good because there is not enough energy to cut through the specimen. Experiments have shown that the cut quality in the used energy range does not depend on laser pulse energy.

Increasing of pulse density from 333 pulses/mm to 2000 pulse/mm also did not have any influence on the difference between spacing of adjacent holes in the upper and lower parts of the specimen. It was experimentally determined that the laser beam must be focused on the surface of specimen, and the waist of focused beam ω_0 should be as narrow as possible (ω_0 = 16 μm was the smallest tested) to achieve the required quality (Δx ≈20 μm).

4. Fast laser micro-cutting technique

The difference in distance between the adjacent holes in the upper and lower sides in range of 20 μm meets the demands raised by the industry. However, the cutting speed was very small when scanning at 300mm/s because to cut through the 0.3 mm thick tungsten sheet with the 45 μJ energy pulses scaning at least 3500 times was needed. Therefore, the actual cutting speed was only 0,085 mm/s. The cutting speed must be increased dramatically (about 60 times) to move the technology of tungsten cutting from the laboratory to the industry.

It was mentioned above that pulse density did not affect the quality of the cut, but it affected the cutting speed by reducing the amount of scans needed (see Fig. 3).

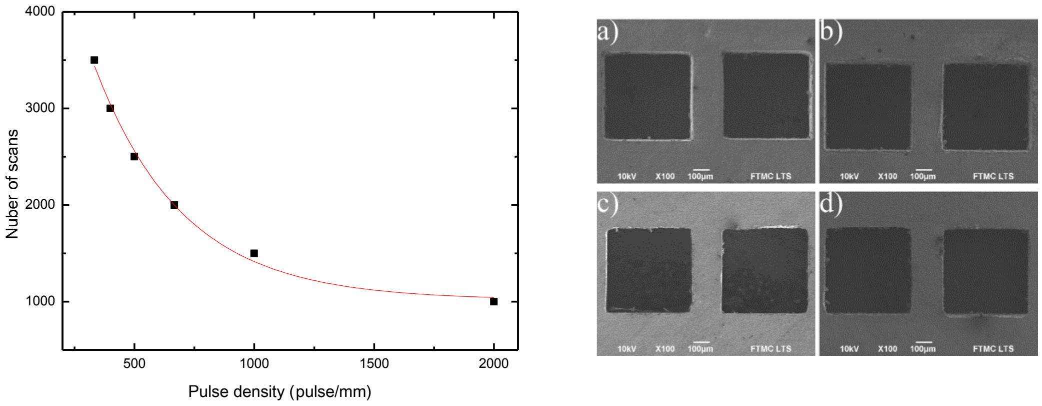

Fig. 3. On the left side the number of scans necessary to cut through the 0.3 mm thick tungsten plate dependence on the pulse density. The average power of 4.5 W at a repetition rate of 100 kHz. The scanning speed was varied from 300 mm/s to 50 mm/s. On the right side, an example of cuts with different pulse density, a), b) top view, (c), d) bottom view. Used parameters: average power – 4.5 W at a repetition rate of 100 kHz. a), d) holes were cut with 333 pulse/mm pulse density, b), d) – 2000 pulse/mm.

4.1. Most efficient ablation parameters discover model

One of the factors hindering the penetration of laser micromachining technology into the industry is that it is necessary to carry out a number of investigations to transfer the technology from one material to another.

However, there are models designed to facilitate the optimal choice of parameters. One of them is dedicated to finding the most efficient ablation parameters (Jaeggi et al. 2014). Experimentally it is proven (Raciukaitis et al. 2009; Lauer et al. 2014; Jaeggi et al. 2014), that there is an optimal pulse energy density F_{opt}, by using which the material ablation becomes the most efficient. The optimum pulse energy density can be calculated by the following formula:

$$F_{0,opt} = e^2 \cdot F_{th}. \qquad (1)$$

The ablation process is very inefficient using the pulse energy density less than optimal, and above the optimum pulse energy density, evaporated material forms plasma and machining quality decreases.

The ablation threshold of tungsten was determined by the diameter of ablated holes. First, on the tungsten surface holes were ablated, each hole with five laser pulses. The holes were ablated by using different laser pulse energies from 0.1 μJ to 108 μJ. The ablation threshold by default is measured by using a single laser pulse, not 5. However, with only one pulse it was impossible to determine where the tungsten colour change was due to its thermal damage and where the crater formed by the laser ablation. Dependence of the measured diameters on the pulse energy E_{p} was evaluated, and two linear approximations were applied to the data: in the low pulse energy area (0.16 μJ – 2.5 μJ) and in the area of high pulse energy (3.13 μJ – 107.3 μJ). From the linear fit slope focused laser beam radius was estimated because the slope is equal to $2\omega_0^2$. Calculated radius value with used pulse energy E_{p} can be put in formula:

$$F_0 = \frac{2E_p}{\pi\omega_0^2}, \qquad (2)$$

to find F_0. By extrapolating to $D^2 = 0$, we get two ablation threshold values: the soft ablation threshold F_{th}^{α} 0.57 J/cm^2 and strong ablation threshold F_{th}^{γ} = 12.13 J/cm^2 (Fig. 4a).

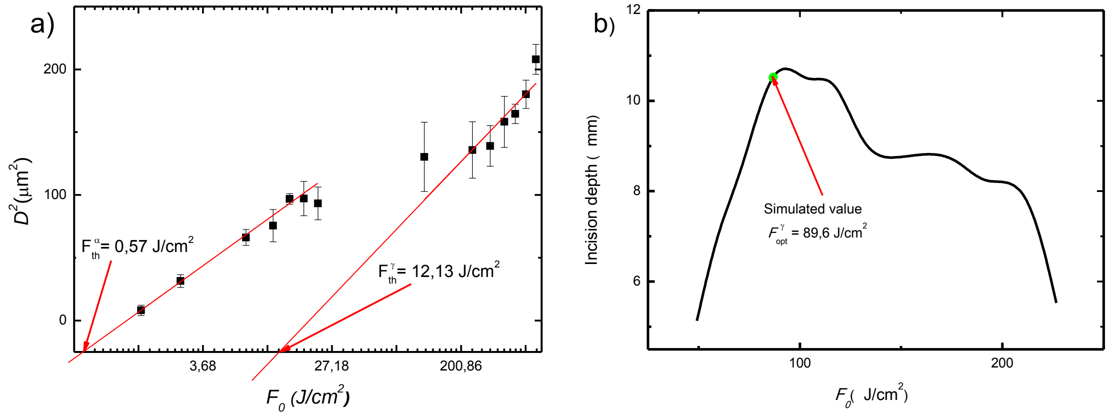

Fig. 4. a) The squared diameter, D^2, of the ablated craters in tungsten, as a function of the peak laser fluence, F_0. By extrapolation to $D^2 = 0$ ablation threshold fluence is calculated: soft ablation threshold fluence F_{th}^{α} = 0.57 J/cm^2, strong ablation threshold fluence F_{th}^{γ} = 12.13 J/cm^2; b) Incision made by scanning once as a function of the peak laser fluence, F_0 with constant pulse density. Deepest incision was made with $F_0 \approx 90$ J/cm^2 which agrees greatly with simulated value.

Equation (1) was used to calculate the optimal fluence for the soft and strong ablation regimes: F_{opt}^{α} = 4.21 J/cm^2 and F_{opt}^{γ} = 89.6 J/cm^2, respectively. However, the tungsten sheets were too thick for soft ablation to pierce trough the specimen.

To test this theoretically calculated optimal laser fluence, another experiment was conducted. Incisions were made on the surface of tungsten sheet by scanning lines with different laser fluences; the pulse overlap was maintained constant. The depth of the incisions was measured by profiler Dektak 150+. Results are shoved in the graph (Fig. 4b). The deepest incision was made when $F_0 \approx 90$ J/cm^2. This value corresponds quite accurately with the calculated theoretically F^{γ}_{opt} value.

4.2. Different methods of laser micro-cutting

To achieve maximum cutting speed as high as possible, the optimal cutting method and most suitable scanning equipment must be determined. Investigation and comparison of two methods with galvoscanner and one with polygon scanner were made. A galvoscanner reaches its maximum speed only while scanning straight lines (at least a few millimeter long). Therefore, to reach the maximum speed while using the vector method was impossible. However, the raster method shows the high potential, and the speed of several meters per second can be achieved (scanning speed highly depends on specifications of galvanometer and lens focal length).

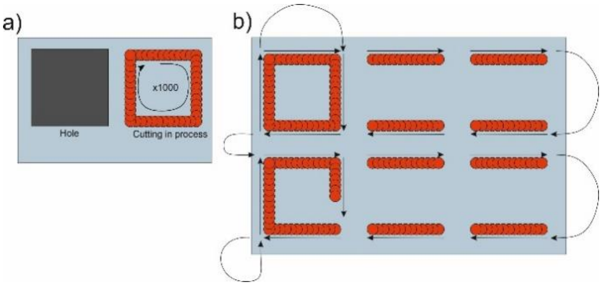

Fig. 5. Comparison of different scanning techniques: a) vector – each square hole is cut separately; b) raster – all holes are being cut at the same time.

To determine the best way to cut the above-described structures, the research of technical possibilities was carried out, during which the maximum possible cutting speed was calculated for galvoscanners available in the market. The maximum scanning speed of the galvoscanner is 12 m/s using a 160 mm focal length lens. By using such lens, the working field is approximately 120 mm. Thus, using the galvoscanner, the largest array of holes, which can be cut, consists of no more than 10000 holes. The research results are presented in the graph (Fig. 6a).

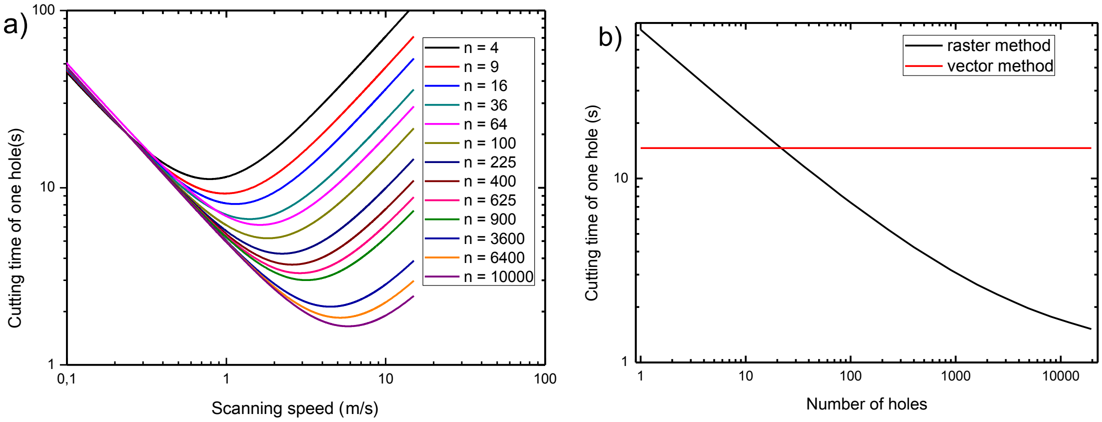

Fig. 6. a) Dependence of the time to cut one hole on scanning speed of galvoscanner while using raster method of cutting. Optimal 6 m/s cutting speed is possible when the cutting no less than 10000 holes at a time. The shortest average cutting time for one hole while scanning 1000 times is 1.65 s; b) Cutting time of one hole dependence on number of holes while scanning 1000 times with raster and vector methods. Raster method is more efficient when cutting more than 20 holes.

From the graph (Fig 6a), we can see that the working field dimensions are not sufficient to use the full potential of a maximum speed of the galvoscanner. Maximum speed of 6 m/s can be achieved during the cutting of 10000 holes, the optimum cutting duration of one hole is 1.65 s.

To find the time needed to carry out one scan of a square shaped hole, 100000 non-stop scans were carried out and the total scan time was measured. This value was used to simulate the optimal parameters of the vector cutting method. Calculations showed that the vector cutting is superior over the raster method if the number of holes is less than 20 (Fig. 6b.). From the results, it becomes clear that cutting of tungsten with the vector cutting method is not optimal.

Experiments were made using the raster method in the scanning speed range from 50 mm/s to 1500 mm/s using the Atlantic 355-60 laser. As was expected - no change in the quality or the required number of scanning were observed. Scanning faster than 1.5 m/s was not possible because of a software limitations. By using the Atlantic 355-60 laser with the optimal parameter of the raster method, the cutting speed of 0.6 mm/s can be reached. This laser enables up to 8 times faster cutting speed than the PL10100 laser. However, even with a more powerful laser (with a larger pulse repetition rate achieving, the required cutting speed (≈5 mm/s) is impossible.

Polygon scanners can perform only raster scan. To cut the square holes with a polygon scanner, a scanning of dotted line until piercing trough the material should be made. Then a motorized positioning stage should be used to move the specimen by 1 mm and then performed another dotted line scan, and then moving of specimen by 0.2 mm and then another scan. This process continues until all the horizontal lines are cut out. Later, a specimen should be rotated 90° by motorized rotational stage, and then the identical process should be repeated with the vertical lines.

During evaluation of possibilities to use a polygon scanner, it is necessary to consider not only the scanner specifications, but also of the used linear positioning stage and rotational stage. Polygon scanners currently available on the market have the following specifications: scanning speed 20 m/s – 100m/s (100 – 400 lines per second), length of the scan line 170 mm. By using this kind of a scanner, it is possible produce a 19600 square matrix of holes. The best-motorised stages on the market have the translation speed of 2m/s, and acceleration of 30 m/s^2. The maximum speed of the rotational table is 200 rpm, acceleration – 400 rad/s^2. Taking into account just described specifications, calculations were made, how long it would take to scan square holes at maximum speed, matrix consisting of 19600 holes. It turns out that the sample rotation and positioning before re-starting the cut perpendicular to the direction of made before, duration is irrelevant, because it takes less than a thousandth of the total cutting duration. With the maximum scanning parameters, one hole cutting would take just 0.07 s when scanning 1000 times. However, this value does not meet the reality because, in order to achieve such cutting, laser pulse repetition rate should reach 200 MHz, it is certainly not realistic. However, with the actual specifications that meet market opportunities offered by picosecond lasers (up to ~ 8 MHz), we obtain the optimal one hole cutting time - 0.29 seconds. That is more than five times lower duration than using a galvoscanner in optimal mode. To get this value, the polygon scanner speed should be reduced to a minimum of 25 m/s speed and 8 MHz pulse repetition frequency of the laser used. By using such a system desired cutting speed is not only achieved, but is even exceeded by 2.5 times.

5. Summary and Conclusion

During the tungsten laser micro-cutting research, it was found that the steepness of kerf to a large extent depends on focused beam waist and must be focused on the surface of the specimen. Even while using the same cutting method, the hole dimensions and quality still vary because of different cut away product removal. To avoid this blowing of compressed air on the specimen surface should be tried. Determination of parameters for the most efficient laser micro-cutting can be made by the most efficient ablation parameters.

To maximize the cutting speed without sacrificing its quality, it is necessary to maintain the optimal pulse overlap and fluence, but increase the scanning speed. That can be achieved by using of polygon scanners. Currently, laser positioning systems is limiting of the picosecond laser capabilities. Therefore, improvements and new research should be conducted in the field of picosecond laser with bigger laser pulse repetition rate manufacturing.

References

Jaeggi, B. et al., 2014. High-throughput and high-precision laser micromachining with ps-pulses in synchronized mode with a fast polygon line scanner . In p. 89670Q–89670Q–10.

Lauer, B., Jäggi, B. & Neuenschwander, B., 2014. Influence of the Pulse Duration onto the Material Removal Rate and Machining Quality for Different Types of Steel. *Physics Procedia*, 56(0), pp.963–972.

Overton, G. et al., 2015. Laser Marketplace 2015: Lasers surround us in the Year of Light. *Laser Focus World*, 51(01), p.127.

Raciukaitis, G. et al., 2009. Use of High Repetition Rate and High Power Lasers in Microfabrication: How to Keep the Efficiency High? *Journal of Laser Micro/Nanoengineering*, 4(3), pp.186–191.