LASER DRILLING FOR HIGH ASPECT RATIO HOLES AND A HIGH OPEN AREA FRACTION FOR SPACE APPLICATIONS

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Abstract

X-ray collimator optics for space application require an array of high aspect ratio holes of 60:1 with a minimal Tantalum (Ta) thickness of ≥ 2 mm and a very high open area fraction (hole vs. wall fraction) of 70% to achieve high collimator efficiency. Each collimator with a drilled area of 110 mm × 70 mm contains several million holes and need a fast drilling process.

Laser percussion drilling was performed using an IR pulsed disc laser in a 1 mm and 2 mm thick Ta plate. A tightly spaced hexagonal closed packed pattern was used to maximize open area fraction with hole-to-hole spacing as small as 80 µm. However this resulted in a high concentration of debris and a thick recast layer on the remaining walls between the holes. Different process gases were investigated to minimize debris formation and reduce the recast layer thickness. Ramping of pulse energy during the drill cycle was investigated to minimize the adhesion between the substrate and recast layer. Chemical etching was used to remove the debris and recast from the top surface and the inside of the laser-drilled holes. Hole cross-sections showed that a high aspect ratio was achieved with a hole diameter of about Ø50 µm in 2 mm thick Ta. To achieve the shortest drilling time of 200 ms per hole, the process parameters were optimized and a hybrid nozzle, with both horizontal and vertical gas flow, was developed and implemented.

Introduction

The U.S. Naval research laboratory is developing collimator optics for hard X-rays for space application [1]. An array of small holes with high aspect ratio (60:1) in tantalum with the highest possible open area fraction (~70%) is required for best collimator efficiency. The final product is for LOFT (Large Observatory For X-ray Timing), a mission proposal selected by ESA as a candidate mission and measures square meters and is made from smaller tiles, each measuring 70 mm by 110 mm,. The application requires only one or two large panels, but the high number of holes requires a very fast drilling process.

Laser micro hole drilling of Ta has been performed using a diode pumped solid state laser at 532 nm wavelength [2]. Using laser power of 16 watt at 13 kHz with a pulse length of 75 ns and spot diameter of 10 um, hole size of 30 um on entrance and 22 um at exit were achieve in 0. 7 mm Ta.

In the past, several researchers have investigated laser drilling of high aspect ratio holes and high open fractions. High open fraction has been achieved for drilling of thin Al-foils of 15 um thickness [3]. A UV laser with 355nm wavelength, 15 ps pulse length, 1 MHz repetition rate was used to drill holes with diameter < 6 um with a minimal pitch of 12 ums. Micro holes with 10 um in 100 um foil were drilled in copper using femto, pico and nano second laser [4]. For thin copper foil, a few picoseond pulse length was found to be ideal.

Laser drilling research, in addition to pursuing drilling of thinner materials, has explored other application requiring thick metal as well. Laser percussion drilling was used for drilling cooling holes in turbine blade application when higher aspect ratio holes was required [5,6]. High peak power laser (20kW) and high beam quality (<4mm.mrad) was used to drill hole diameters of 230-250 um in 2mm thick HastelloyX at 30 degree angle. These researches also compared drilling process using different process parameters and gases and reported their influence of holes quality and drill time. Laser trepanning drilling is used for drilling deep holes in a number of applications but hole diameter are typically larger in range of 0.15-1 mm. Helical drilling offers higher precision for achieving high quality holes with high aspect ratio [7]. However the achievable hole sizes are >50 um.

From these reported works, it is clear that a number of drilling strategies have been explored for achieving high aspect ratio holes, high open faction areas for very small hole sizes in short drill cycles. This work is focused on achieving a combination of all these challenges simultaneously together. The feasibility of laser percussion drilling high aspect ratio holes with a high open area fraction in tantalum with high speed has been investigated.

Experimental Setup

A Jenoptik pulsed disk laser (IR70) was used for laser drilling. The disk laser emits at 1030 nm wavelength and can provide a maximum average power of 65 W. In most cases, the pulse length (200-1100 ns) could be set independently of the repetition rate (8 kHz – 100 kHz) allowing high flexibility in parameter selection.

The drill head was mounted with a 100 mm focal length lens and a conical nozzle with 1 mm opening and a nozzle-work piece standoff of 1 mm. Using a 4X beam expander, a spot size of Ø19 µm was achieved at the focus. Gas pressure of 60 psi was used. During drilling, the Ta plate was mounted in the fixture which was kept stationary during the drill cycle. In between the drill cycle, the fixture was translated in two horizontal axes for drilling an array of holes.

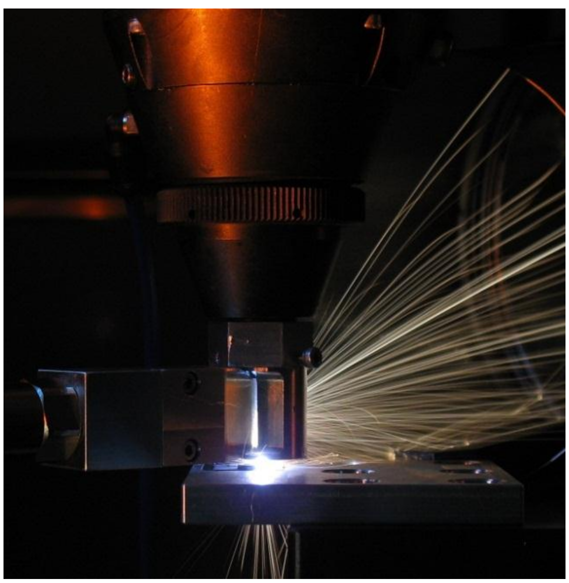


Figure 1 Laser drilling of Tantalum

Process Optimization

To understand the key process parameters that lead to a high hole quality while achieving a high aspect ratio and high open area fraction, an experimental test matrix was established. Effects of peak laser power, pulse energy, hole center-to-center spacing, process gas and inter-pulse shape were investigated.

Table 1 shows the process parameters corresponding to different drilling results shown in Figure 2 for process optimization on 1 mm Ta. Figure 2 shows the drilling test result as a function of pulse energy on horizontal axis and peak power on vertical axis. Note that the pulse length and repetition rate was varied to explore laser boundary conditions.

Table 1 Parameters for drilling 1 mm Ta for process optimization

	Result	Pulse length	Rep rate	Drill time	Pulse energy	Peak power
		ns	kHz	sec	mJ	kW
x	No drilling	500	10	90	0.4	1
a	Wall collapse	1000	20	1	2.5	2.5
b	High taper	200	10	0.05	2.5	12.5
c	Jagged hole	500	10	0.01	4.0	8
d	Optimal	500	10	0.25	2.5	5

The highlighted parameter window shows the laser operation boundaries. Although a higher number of data points were evaluated, only a few selected points are shown on this plot that describes the overall drilling process. Figure 3 shows the hole cross-section for corresponding data points.

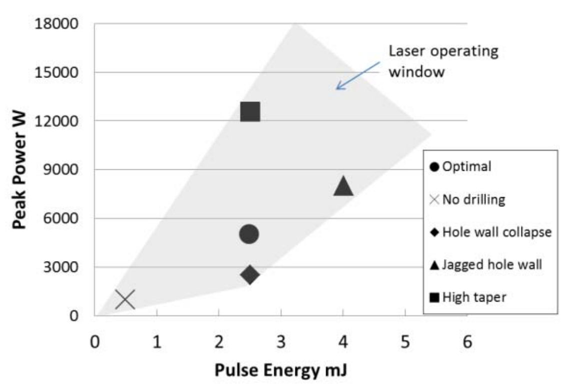
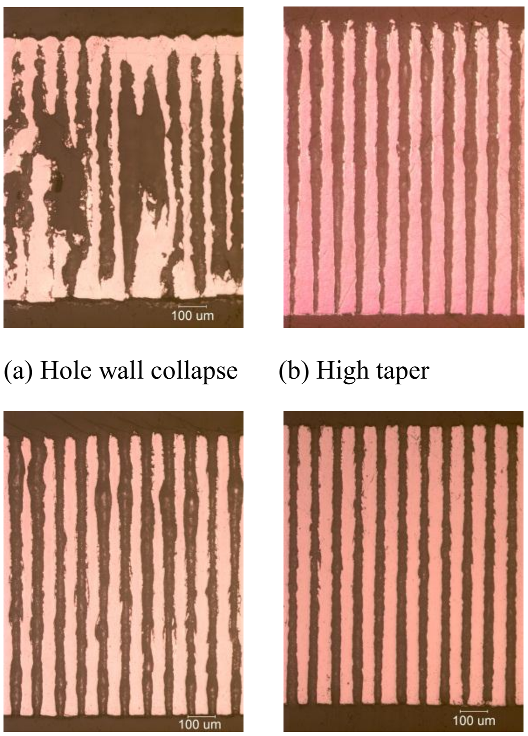


Figure 2 Process optimization on 1 mm Ta

Clearly, no drilling is achieved at a very low pulse energy PE and a low peak power PP (shown with a cross). Drilling begins when PP and PE are increased but at a low PP and a high PE (high PL and high RR), a complete collapse of internal hole wall structure occurs as shown in Figure 3 (a). Increasing the PP significantly (low PL) while keeping the PE steady results in a high hole wall taper (Figure 3 (b)).

Increasing both PP and PE simultaneously results in jagged hole walls as shown in Figure 3 (c). However, a very short drill time of only 10 ms is required.

Interestingly, approximately in the middle of the process parameter boundaries, a high quality drilling process is achieved as shown by solid circle (Figure 2). This clearly emphasizes the need for the drilling process optimization. The optimal parameters that result in high quality drilled holes shown in Figure 3 (d) are as following: PE – 2.5 mJ; PP – 5 kW; pulse length – 500 ns, repetition rate – 10 kHz and drill time - 0.25 sec.



(a) Hole wall collapse (b) High taper

(c) Jagged hole walls (d) Optimal

Figure 3 Hole cross-section corresponding to data points in Fig 2.

Inter-pulse shaping

Inter-pulse shaping technique was investigated to achieve finer debris to either minimize debris adhesion to the substrate or ease its removal. Inter-pulse shaping was achieved by controlling the temporal intensity in a sequence of pulses which is modulated by an external pulse control as shown in Figure 4. Tests were conducted where the laser energy was incrementally increased either in a short burst profile or in a smooth ramp profile. An external trigger was implemented for synchronization between the motion control and the laser system.

Results showed that no significant difference in debris formation was achieved with or without inter-pulse shaping. Moreover, drill time was increased when inter-pulse shaping was used in the same proportion as the pulse energy was decreased. Therefore, subsequent drilling was conducted without using inter-pulse shaping.

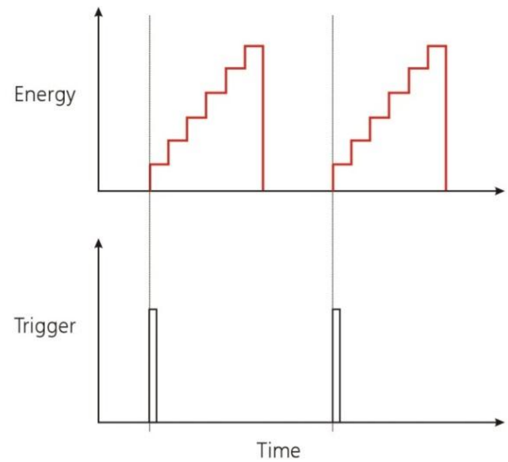


Figure 4 Schematic representation of inter-pulse shaping

Effect of process gas

Five different process gases including nitrogen, helium, oxygen, argon and air were investigated to determine their effect on the drilling process with regard to debris formation and recast layer thickness.

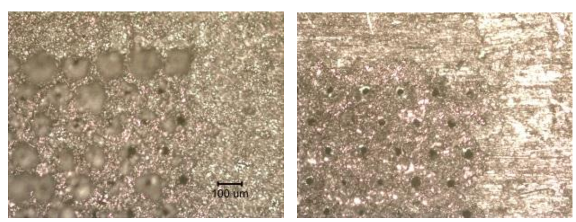
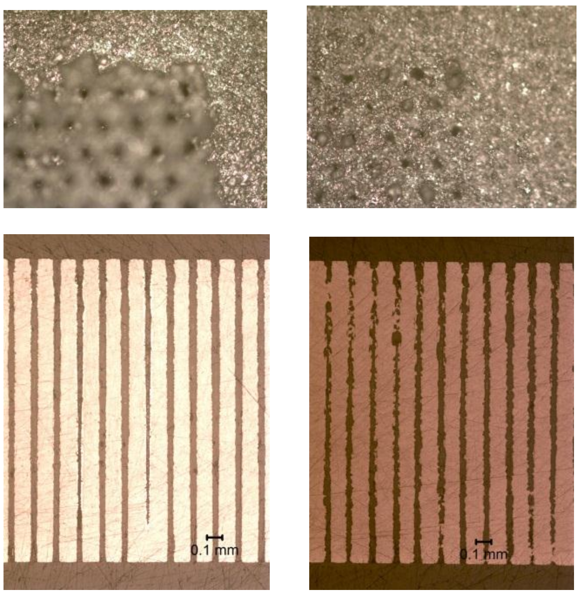


Figure 5 Surface of drilled holes 'as is' (left) and surface after the debris was removed using a sharp knife (right)

Drilling with oxygen resulted in a severe surface melting and debris formation. High debris and thick recast layer was formed when argon was used. Both nitrogen and helium resulted in minimal debris and recast layer. Also the small amount of debris could be easily scraped off using sharp knife as shown in Figure 5.

Drilling with air resulted in higher debris compared to nitrogen and helium and in variation in hole size as shown in cross-section in Figure 6. Drilling with helium resulted in the smallest hole diameter but jagged hole walls as shown in Figure 6.



Air Helium

Figure 6 Drilled surface (top) and cross-section (bottom) with air (left) and helium (right)

Shortest Drilling Time

High velocity particles are constantly ejected from drilled hole during the laser drilling process. Due to a high aspect ratio of drilled holes, the particle velocity is even greater. To prevent the optics from drilling debris, typically a coaxial gas is supplied vertically downwards at a high pressure. However, this result in a significant cooling of the interaction zone and therefore increase in the drilling time. To avoid increasing the drilling time while preventing optics from drilling debris, a hybrid nozzle (Figure 1) was designed and fabricated to provide a high pressure from horizontal side and a very low pressure vertically downwards. This nozzle was mounted directly onto the fixed optic head. This nozzle arrangement was very effective in preventing the cover glass from the drilling debris. Using this arrangement and process parameters (pulse energy – 5.5 mJ; peak power – 11 kW; pulse length – 500 ns; repetition rate – 8 kHz, gas - nitrogen), shortest drilling time of 200 ms was achieved in 2 mm thick tantalum plate. However, this also resulted in higher debris and thick recast layer on the Ta plate even after etching for 20 min (see Figure 7). The total drill time per hole including positioning time was not optimized and was > 1 sec.

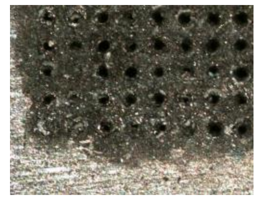
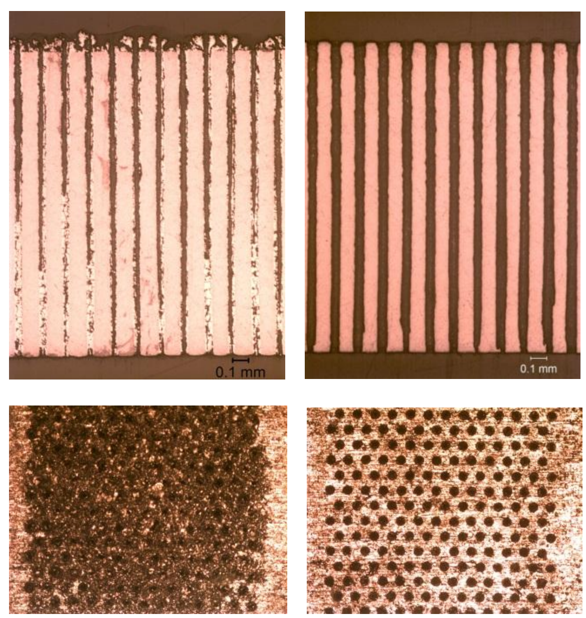


Figure 7 Drilled surface with shortest drill time of 200 ms shows significant debris even after etching for 20 min

Chemical Etching

Although the process optimization resulted in a minimal debris and a thin recast layer on the drilled surface, inside most of the drilled holes, there was still a significant remelt attachment left when observed with backlight. Therefore chemical etching was used to open plugged holes, clean hole entrance and exit.



Un-etched (drilled ‘as is’) Chemically Etched

Figure 8 Effect of chemical etching on debris removal

Transene tantalum etchant 111 was used for post drill chemical etching tests. The etching time was determined to be 7 minutes for 2 mm Ta through an incremental increase in very small steps. After each etching cycle, samples were cleaned and holes were observed with backlight to determine remelt attachment inside the holes.

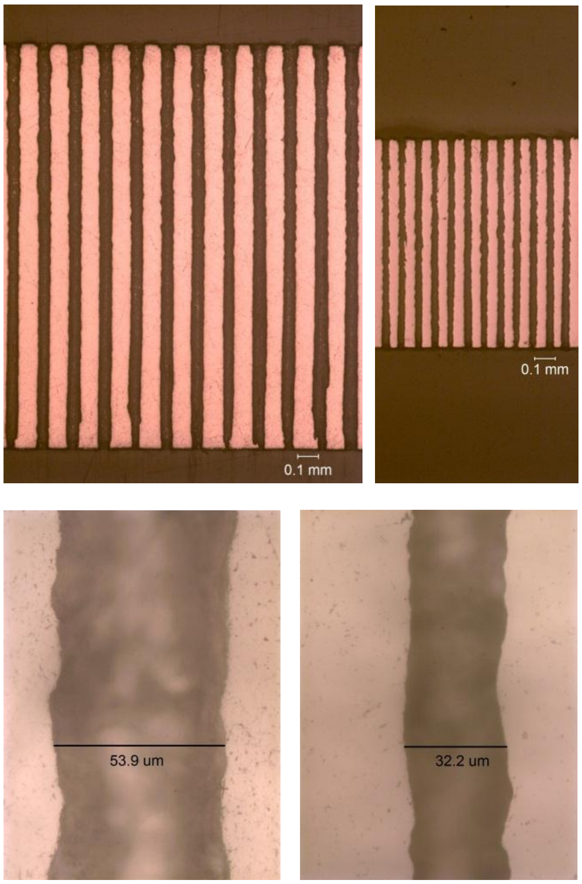


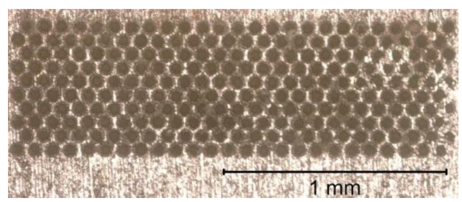
Figure 9 Best achieved drilling result in 2 mm Ta (left) and 1 mm Ta (right). The close-up of holes show diameter of ~54 µm in 2 mm (left) and ~ 32 µm in 1 mm (right).

By comparing an un-etched hole with a chemically etched hole (Figure 8), it is clear that all remelt attachments inside the hole are etched away, holes look clean at entrance and exit. However there is an increase in hole size after etching. Figure 9 shows the optimal drilling result in 2 mm and 1 mm Ta post chemical etching. Excellent hole quality across the entire drilled length is achieved. Very high hole straightness is achieved and almost no heat affected zone is visible. For 2 mm thick Ta, following parameters resulted in optimal hole quality: pulse energy – 5.5 mJ; peak power – 11 kW; pulse length – 500 ns; repetition rate – 8 kHz, gas - nitrogen and drill time – 1 sec. The optimal parameter for drilling 2 mm is mainly driven by the maximum available pulse energy (5.5 mJ) and peak power (11 kW) of the laser which is only available at lowest repetition rate of 8 kHz and longest pulse length of 500 ns (at 8 kHz). Optimal parameters used for drilling 1 mm Ta has been discussed in section 'process optimization'.

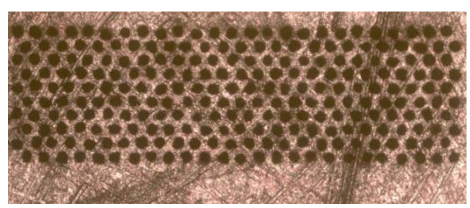
Open Area Fraction and Aspect Ratio

Open area fraction is calculated as the ratio of the total drilled hole area to the total plate area and is defined as a percentage. The total drilled hole area is estimated using the average hole size. To maximize the open fraction, holes need to be positioned in a hexagonally close pattern to achieve minimum average hole-to-hole spacing. Here the center-to-center distance between any two adjacent holes is same in any direction.

However there are two limitations that restrict the minimum center-to-center distance between two adjacent holes. First is the structural strength of the thin remaining wall between the holes (also referred to as septum) and could cause collapse of complete hole array. Second is the rapid widening of the holes at the entrance and the exit during the chemical etching process when the septum becomes too thin and result in a higher average hole size.



(Top)



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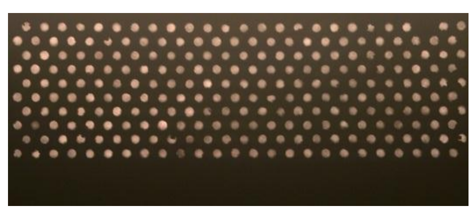

Backlight

Figure 10 Array of drilled hole with entrance side (top), exit side (middle) and with backlight (bottom).

Minimum center-to-center distance (spacing) of 80 µm in 1 mm and 105 µm in 2 mm Ta was achieved. Lower spacing resulted in collapse of complete hole array during the drilling process. Maximum open area fraction of 47% in 2 mm Ta was achieved with an average hole size ~ 73 µm.

Drilling of 1 mm Ta was conducted using the optimal parameters and a minimum spacing of 80 µm and resulted in consistent drilled holes as shown in Figure 10.

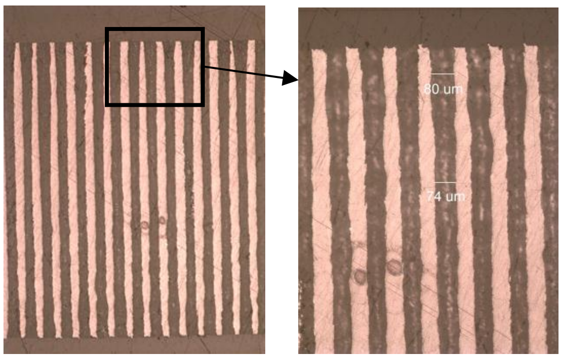

Figure 11 Cross-section of 2 mm Ta with 105 µm spacing and post chemical etching

Higher aspect ratio of ~40 was achieved in 2 mm Ta when spacing of 150 µm was used. However, with a lower spacing of only 105 µm, hole widening resulted in higher average hole size ~ 73 µm (Figure 11). To compensate for decrease in aspect ratio, two Ta plates of 2 mm thickness were overlapped such that drilled holes are aligned and the overall thickness increased to 4 mm. This resulted in a higher aspect ratio of ~ 54.

Summary and Conclusions

Laser drilling of 1 mm and 2 mm tantalum was conducted using an IR pulsed disc laser. Process optimization tests clearly showed that optimal parameter identification is crucial to achieve a high quality drilling process. Non-optimal parameters result in poor quality conditions such as high taper angle, jagged hole walls or collapse of drilled array structure.

Shortest drilling time of 200 ms per hole was achieved for 2 mm Ta by using a hybrid nozzle with both horizontal and vertical gas flow. However this also resulted in higher debris and therefore was found unsuitable to achieve higher open area fraction. Ramping of pulse energy during the drill cycle did not result in minimizing either the debris adhesion to the substrate or the recast layer. Nitrogen was identified as the most suitable gas for this drilling process that resulted in a lower debris and a high hole straightness. Helium resulted in a smaller hole diameter but jagged hole walls and compressed air resulted in a less stable drilling process. Argon and oxygen were found unsuitable.

Significant improvement in hole quality was achieved with chemical etching post drilling process. Suitable etching cycle was developed. Using optimal process parameter, high quality holes with Ø32 µm in 1mm and Ø54 µm in 2 mm Ta were drilled. Using a spacing of 105 µm, maximum open area fraction of 47% was achieved in 2 mm Ta. Using two 2 mm Ta sheets in an overlap configuration, aspect ratio ~ 54 was achieved.

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