Acta Materialia Transylvanica 2/1. (2019) 61–68.
https://doi.org/10.33924/amt-2019-01-10
Hungarian: https://doi.org/10.33923/amt-2019-01-10,
https://eda.eme.ro/handle/10598/31420

The Role of Focus Position in Single Pulse Laser Drilling of Highly Reflecting Materials

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Abstract

The laser processing of materials which are highly reflective at laser wavelengths is problematic. We have to take into account that only a small part of the energy is absorbed, the main part being reflected. In this article we examine the laser processing of highly reflective copper and silver at 1070 nm wavelength. In laser drilling of printed circuit boards it is necessary to drill copper layer as well. In highly reflecting materials we can drill smaller holes because of the low energy efficiency. Naturally in single pulse laser drilling the focus position plays a key role: at the focal spot of the laser beam smaller diameter holes are produced, further from the focal spot, higher diameter holes are produced.

Keywords: *laser drilling, focal position, highly reflecting materials.*

1. Introduction

From the literature of laser drilling we distinguish single pulse drilling, percussion drilling (using more than one pulse to produce a hole), trepan drilling for larger holes, and planetary drilling [1]. In this article we will examine single pulse drilling of copper and silver foils. In the laser drilling of printed circuit boards it is necessary to drill copper layers as well [2]. In this article we examine the laser drilling process of copper and silver foils.

2. Properties of the laser system

For the experiments we used an IPG 150/1500-QCW-AC fiber laser. Table 1. lists the properties of this single mode Ytterbium laser.

We would make a mistake, if we took into account into account only the average power of this laser system. If we calculate the pulse power by dividing the pulse energy with pulse length we can get higher values, for example: $P_p = E_p / t_p = 15$ J / 0,01s = 1500W. This means that this 150 W average power laser is more dangerous for the human eye than a continuous wave one with the same average power. In order to protect our eyes we have to wear protective goggles having an appropriate optical density at the laser wavelength; this optical density is defined by the standards.

3. Analysis of the focused beam parameters

In single pulse laser drilling the machining laser system plays a key role, most important are the parameters of the focused laser beam, such as focal spot diameter, and Rayleigh length. The focused laser beam is the tool for machining a work piece without touching it, using only the transfer of the laser's energy.

Table 1. *Technical data of IPG 150/1500-QCW-AC single mode Ytterbium fiber laser*

Wavelength l	1070 nm
Maximal average power	150 W
Maximal pulse power	1500 W
Maximal pulse energy	15 J
Pulse width	0.05–50 ms
Pulse frequency	10–50 kHz
M^2 factor	1.05

The diameter of the laser beam leaving the fiber is 14 microns (d_1); the focal length of the collimating lens is 50 mm (f_1). There is a lens focusing the parallel laser beam to the work piece, its focal length is 50 mm (f_2). The beam expander factor (B_e) setting is 1. On the basis of this given data we can calculate the spot size of the focused laser beam (d_2) with the following equation [3]:

$$d_2 = \frac{4\lambda M^2 f_2}{d_3 \pi} \quad (1)$$

From this equation we obtain 14 microns for the focal spot diameter. Comparing it with an Nd:YAG laser's 81 micron focal spot diameter used for our former research [4] it is extremely small. This means that we can focus the laser energy in a small area producing a smaller cut slit, and we can cut thicker materials.

This difference is caused by the difference in the operation of these lasers influencing the beam quality factor. The Nd:YAG laser has a beam quality factor (M^2) of 3….5, the fiber laser has 1.05. Why is this data so important?

Analysing the other equation (2) of the focused laser beam spot size, we can see that the smaller the M^2 factor the smaller the diameter of the focused spot [5].

$$d_2 = \frac{d_1 f_2}{f_1 B_e} \quad (2)$$

The smaller is the diameter of the focused spot the higher the concentration of the laser energy. We can calculate the parallel laser beam diameter d_3 from this equation, it will be 5.11 mm. There is an important consequence of this laser wavelength (λ): if we use Ytterbium fiber laser (λ = 1.070 micron) instead of CO_2 laser (λ = 10.600 microns) we can focus the beam onto a 10 times smaller spot.

From this data we can calculate the Rayleigh length (Z_R) with equation (3). The Rayleigh length [6] is the distance from the focal spot, in the direction of the laser propagation, where the spot area will be increased by the a factor of two, and the beam radius will be increased by athe factor of√2.

In most cases we assume the laser beam to be in focus within the double of the Rayleigh length. The equation of the Rayleigh length is similar to the equation of the focused laser beam spot size, but in Rayleigh length equation f_2 and d_3 are toin the power of two. We can calculate the Rayleigh length from the above mentioned data, it will be 137 microns

$$Z_r = \frac{4\lambda M^2 f_2^2}{d_3^2 \pi} \quad (3)$$

Of course d_2 and Z_r are only approximations. For example in some articles M^2 is absent from these equations, which is strange. When the beam expander is a set of lenses with a zoom-system, this can make the focal spot larger so the focusing capability of the lenses are weaker.

The calculated d_2 and Z_r values indicate that it is better to leave the beam expander from the system, while the 14 microns focal spot from the unexpanded beam is small enough. If we expand the beam, the focal spot size will be smaller, but the value becomes also smaller. That means a bigger divergence of the beam, in other words, the beam, in a short distance towards laser propagation can easily be out of focus.

On the other hand the computed d_2 and Z_r values are only derived from geometric values. In truth the volume of the material we can melt with one pulse depends on many factors, the first factor being the power of the pulse concentrated on the focal spot, it can be maximum 1500 W.

The other factors are the relevant physical parameters of the material: density, melting point, specific heat coefficient, reflection on the wavelength of the laser. We will further discuss these factors ain chapter 4. According to the publication of Pulzor Művek company [7] operating this laser on stainless steel can be cut up to 1 mm thickness, and copper-alloys up to 0,4 mm. These thicknesses are two times larger than the computed Rayleigh-length.

The Ytterbium single mode fiber laser and the CNC work piece positioning system was mounted together, and programmed by Pulzor Művek, Hungary. This firm used his own CAM program generating CNC code form CAD data.

4. The properties of the processed materials

Why is it a great challenge to drill materials which are highly reflective at laser wave-lengths? Let's analyze a basic expression with the power entering the work piece: one part is reflected, the other is absorbed, and the third part is transmitted [8]:

$$P_1 = P_2 + P_3 + P_4 \quad (4)$$

Here P_1 is the whole power coming from the laser head, P_2 is the reflected, P_3 is the absorbed, and P_4 is the transmitted part. For bulk material the transmitted part is negligible, so the higher part of the power is reflected, the lower part is absorbed by the material we want to process by laser light. If P_1=1, then P_3 is the absorption coefficient (a) of the material. P_2 is the reflective coefficient (r) for the given material and wavelength. Processing materials which are highly reflective at the laser wavelength, the major part of pulse energy is reflected, only a small part absorbed and used for melting the workpiece (see Table 2.).

We used 1.4304 stainless steel for our former research [4] We can predict from the data of Table 2. that the laser processing of silver and copper will be more difficult than the stainless steel. It will turn out that the extremely small focused spot size, and the high power density will help us to overcome this difficulty.

The high amount of reflected energy can cause harm to the laser [11]. During the research work the laser head was vertical, and the drilled material was stretched out at 8° angle from horizontal plane, so the incoming and reflected beam's angle was 16° preventing the reflected laser radiation returning to resonator.

4.1. The research work

We designed an instrument which stretches a metal foil at a given angle which can be set by a gauge block. This instrument fulfils the principle of a sinus mechanism. A 17.5 mm gauge block set comes to an 8.11° angle measured from horizontal plane. The research instrument mounted on the laser can be seen on Figures 1. and 2.

The common experimental data were:
- relative focus set at laser head: –2.6 mm;
- process gas: nitrogen at 5 bar pressure.

5. Drilling performed on copper foil

We drilled 50 microns thin copper foil with different laser pulse energy. We set the pulse length 0, 2 ms constant value. We changed the output power between 60-80 %, this predicted the pulse power. We calculated the pulse energy by multiplying the pulse power by the pulse length. The laser pulse parameters can be seen in Table 3.

In Figure 3. the laser drilled set of holes can be seen under the stereo microscope with backlight illumination. The bottom of the image was close to the laser head. The pulse grows from the right side to the left. The higher energy can make holes closer to the laser head. The holes on the top of Figure 3. get into each other, while the velocity was low, and the pulse frequency was constant.

Table 2. *Absorption coefficient (a), and reflection (r) of materials used for the former and this research*

Material	a	r
Stainless steel [9]	0.31	0.69
Silver [10]	0.03	0.97
Copper [10]	0.04	0.96

Table 3. *Laser pulse data of copper foil drilling, one row represents setting for a set of holes*

Pulse length (ms)	Pulse energy (mJ)	Pulse power (W)
0.2	198	989
0.2	213	1067
0.2	229	1145
0.2	245	1225
0.2	259	1296

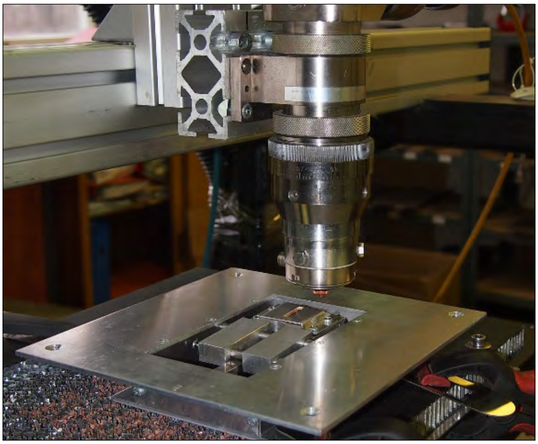

Figure 1. *The foil strecher mounted on the laser*

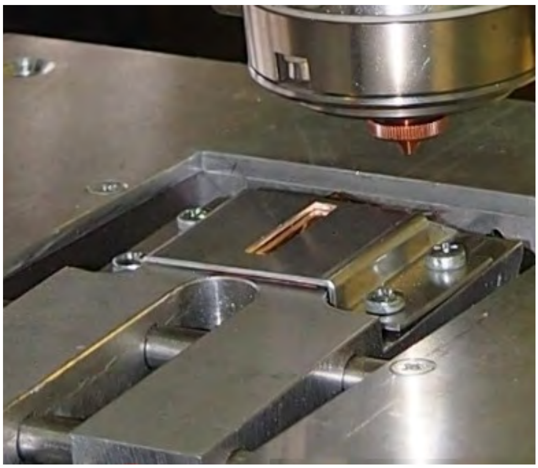

Figure 2. *Main parts of the foil strecher device*

The laser head was fixed, we set the workpiece positioning acceleration to 10 mm/s^2, and the maximal velocity to 20 mm/s. We had to measure the distance of the holes to calculate its vertical coordinate according to the focused laser beam propagation axis.

Figure 4. shows the interaction of the melting threshold energy (E_k) and the focused beam cross section. Far from the focal spot the laser beam intensity profile is low, the energy on a given area is not enough to melt the volume for drilling through the material, and it melts only the surface of the copper foil as can be seen on Figure 5. In Figures 4. and 8. f. we can identify the same regions of drilled holes:

- Region 2: we can see holes with the diameter smaller than the maximal diameter, here only the top of the energy distribution of the beam cuts the melting threshold.
- Region 3: here are the holes with the maximal diameter.
- Region 4: we can see holes with the smallest diameter, because here is the focal spot of the beam, here is the maximal concentration of the energy.
- Region 5: here are the holes with the maximal diameter, as in region 3.

In Figure 6. we can see a microscopic image of a hole close to the laser head. Here the nitrogen process gas was at the highest pressure, it dispersed the molten material around the hole. Because of this, in this region it is not easy to measure the diameter of the holes, the holes are like craters having conical surface with smaller diameter at the bottom.

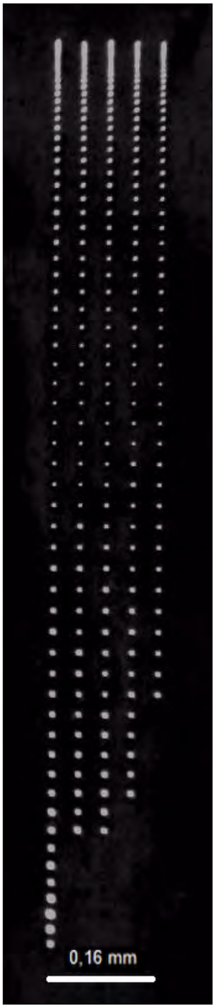

Figure 3. *Laser drilled holes on copper foil under the stereo microscope with backlight illumination*

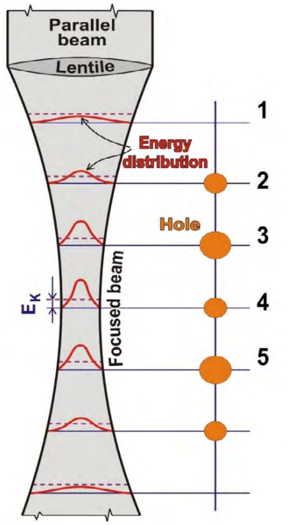

Figure 4. *Interactions of melting threshold energy and the focused beam* [4]

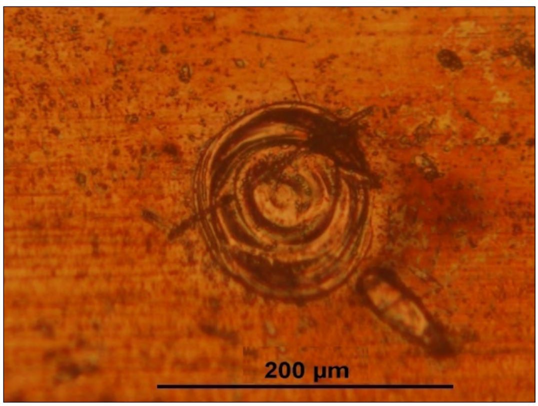

Figure 5. *Below the melting threshold energy there is no hole*

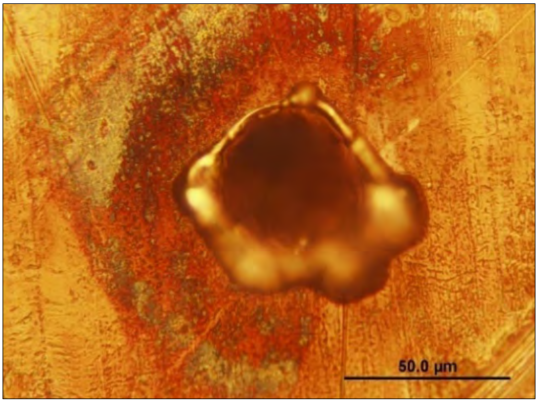

Figure 6. *Microscopic image of a hole made in copper foil near to the laser head*

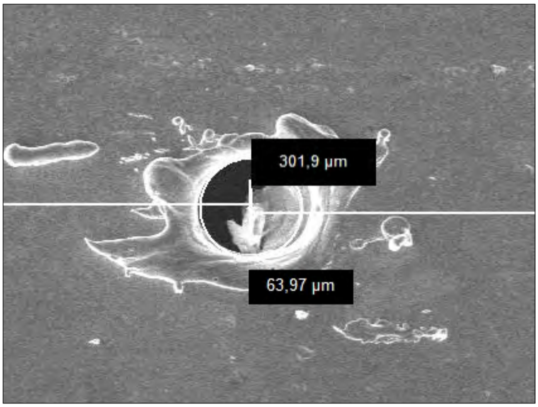

Figure 7. *Microscopic image of a hole near to the laser head with dross adherence. The 301.9 microns are the distance from the neighbouring hole, the 63.97 microns are the three-point measured diameter of the hole*

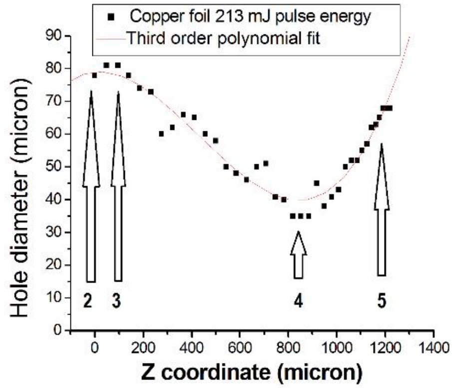

Figure 8. *Hole diameter – Z-coordinate function of copper foil made with 213 mJ pulses, and its regions; Z=0 coordinate is closest to the laser head*

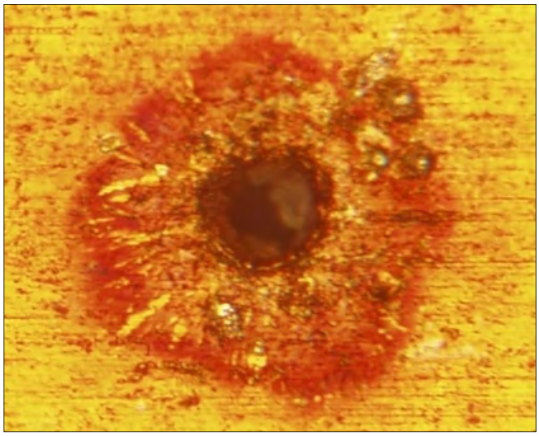

Figure 9. *Microscopic image of a hole near to the laser head*

We can distinguish four zones in these holes:

1. The biggest zone is heat affected zone.
2. Second is the ring of molten material
3. Third is the diameter of the holes at the top, we measured this diameter
4. The smallest is the diameter at the bottom, because of the dross adherence (**Figure 7.**).

In **Figure 9.** we can see a microscopic image of a hole far from the laser head. This hole has a better contrast, easier to measure, it has an ellipsis-like form. Around the hole there is a bigger heat affected zone: here the energy of the laser pulse is not enough to melt the volume for drilling through material because of the high reflection. The 5 hole diameter – Z-coordinate (distance towards laser propagation axis) functions were almost the same independent of the laser pulse data in **Table 3.** because the pulse energy change was only 25 %, and the deviation of the hole diameters was large (see the explanation of **Figure 6.**). One of these hole diameters – Z-coordinate function made with 213 mJ pulses can be seen on **Figure 8.**

6. Drilling performed on silver foil

We drilled 150 micron thin silver foil with different laser pulse lengths. We set the pulse length from 0, 1 ms to 0, 5 ms. We set the output power to 100 %, this predicted the pulse power, it was roughly 1600 W. The silver foil was three times the thickness of the copper, which required higher output power. We calculated the pulse energy by multiplying the pulse power by the pulse length. The laser pulse parameters can be seen in **Table 4.**

Table 4. *Laser pulse data of silver foil drilling, one row represents setting for a set of holes on Figure 10*

Pulse duration (ms)	Pulse energy (mJ)	Pulse power (W)
0,1	148	1481
0,2	317	1583
0,3	475	1584
0,4	636	1589
0,5	792	1583

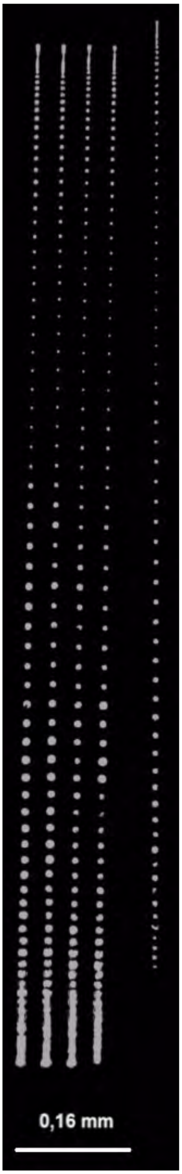

Figure 10. *Laser drilled holes on silver foil under the stereo microscope with backlight illumination*

In **Figure 10.** the laser drilled set of holes can be seen under the stereo microscope with backlight illumination.

The bottom of the image was close to the laser head. The pulse energy grows from right side to the left. At the left side of the image there are holes with 7 % less pulse power, because of this some holes are missing at the bottom of this set of holes. The other four set of holes are similar because the pulse power is constant.

The holes on the top and the bottom of **Figure 10.** Are continuous with each other, while the velocity was low, and the pulse frequency was constant. The workpiece positioning acceleration and the maximal velocity was the same as listed for the copper foil.

In **Figure 4.** and **11.** we can identify the same regions of drilled holes, but we can see only region 3. 4. and 5. because of the higher power level.

In **Figure 12.** we can see a microscopic image of a hole close to the laser head. Here the nitrogen process dispersed the molten material around the hole, but this amount of the molten material was not as big as it was for the copper foil. (**Figure 6.**).

In **Figure 13.** we can see microscopic images of two holes far from the laser head. Around the holes there is a smaller heat affected zone than for the copper drilling.

Figure 11. shows hole diameter – Z-coordinate functions at 636 mJ pulse energy. The deviation of the hole diameters was large, because the solid-state laser's output pulse energy was fluctuating slightly. While they are operating in a nonstationery mode **[12]**.

Since the focal spot diameter was extremely small; the other source of the hole diameter's deviation can be plasma formation. The 5 hole diameter – Z-coordinate functions were almost the same independent of the laser pulse data in **Table 3.**

For single pulsed laser drilling not only the pulse energy counts, but also the pulse length in other words, the given energy at the period that is active. From these two factors we can calculate the pulse power $P_p = E_p / t_p$. The pulse power was constant for silver drilling. In laser machining literature the W/cm2 power density is the most important factor in deciding what kind laser machining can be performed.

We can conclude that the stronger factor on the drilled holes diameter is the Z coordinate.

The pulse energy fluctuations do have a significant effect on laser micro-machining, because the use of smaller laser pulses in higher pulse frequency compensate for the fluctuations.

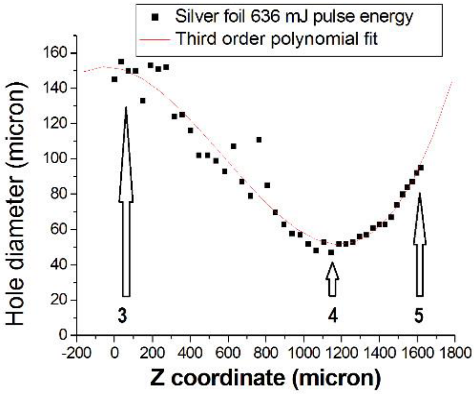

Figure 11. *Hole diameter – Z-coordinate function of silver foil made with 636 mJ pulses, and its regions; Z=0 coordinate is closest to the laser head*

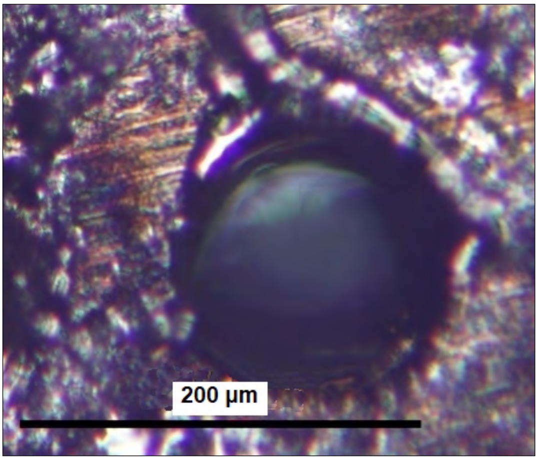

Figure 12. *Microscopic image of a hole made in silver foil near to the laser head*

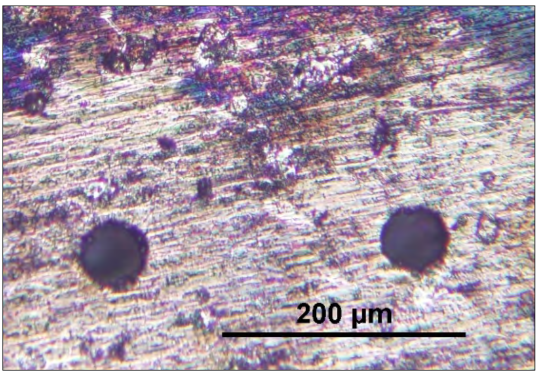

Figure 13. *Microscopic images of two holes in silver far from the laser head. Around the holes there is smaller heat affected zone than for the copper drilling*

7. Conclusions

In the laser processing of materials which are highly reflecting at laser wavelength we must take into account that only a small part of the energy is absorbed; the main part is reflected.

It turned out that the stronger effect on drilled hole diameter was the focal position. The hole diameter – Z-coordinate functions show fluctuations; the possible reasons are:

– nonlinear effects of plasma formation and evaporated material pressure,
– solid-state laser's output pulse energy is fluctuating slightly, because they are operating in a non-stationery mode,
– small irregularities of the surface on the material (50 microns) can cause 10 % change in the drilled hole diameter [13]

The 14 micron focal spot diameter is an extremely small value, we can concentrate the power of the laser pulse in a small area. This high power density compensates the losses caused by reflection of the material.

The good beam quality and the high pulse power of this fiber laser allows the laser drilling of highly reflective, otherwise challenging materials.

Acknowlwdgement

We kindly thank the support of Zsolt Puskás, director of Pulzor Művek, and the production engineer Dávid Vincze in the implementing of the experiments.

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