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Reducing the Roughness of the Kerf for Brass Sheet Cutting with the Laser MicroJet® by a Systematic Parameter Study

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Abstract

The Laser MicroJet® technology uses a 532 nm ns-laser coupled into a water jet for precision cutting. The water jet is used to guide the laser and also cools the work piece so that a heat affected zone in the material is reduced or even eliminated and the kerf is parallel. The Laser MicroJet® is widely used for processing of various materials such as metals, hard materials and semiconductors.
This paper shows how the roughness on the kerf of 0.2 mm brass sheet can be reduced to < 0.2 µm by choosing laser parameters and processing strategy. A systematic study for cutting of brass sheet with a thickness of 0.2 mm is carried out in which laser parameters including frequency, pulse width and laser power are varied. Using three different laser systems in this study the pulse width ranges from 7-350 ns. Additionally different processing parameters are tested such as feeding speed, nozzle size and number of passes.
This work provides the users of Laser MicroJet® a deeper understanding of the relation between kerf roughness, laser parameter and process strategy. We observed that multiple passes lead to higher roughness so that cutting with one pass is preferred. Above a threshold peak intensity, which enables to cut through with one pass, the roughness decreases for higher peak intensities with the same fluence. However, for too high peak intensities and energies per unit length, the cooling effect of the water jet is not sufficient so that a heat affected zone evolves and the roughness increases. Same as known from dry laser cutting, with low pulse widths, low roughness down to 0.2 µm on the kerf can be achieved.

Keywords: water coupled laser, thin metal, precision cutting, cold cutting;

1. Introduction

Thin metal sheet cutting is applied in various industries in which high precision is required. Watch industry is such an application -High precision, good surface quality and a reduction of heat damage and mechanical stress is desired. This paper presents that the roughness on the kerf surface of 0.2 mm brass sheet for cutting with the Laser MicroJet® technology can be reduced to Ra < 0.2 µm. This is achieved with a systematic laser parameter study. This work provides the users of the Laser MicroJet® a deeper understanding of the relation between kerf roughness, laser parameter and process strategy. Some of the results can also be transferred to dry laser cutting.

1.1. Laser MircoJet® technology

The laser MircoJet® technology couples the laser radiation into a thin water jet. Utilizing the difference in the refractive indices of air and water, the laser radiation is guided in the water by total reflection at the air-water interface (Figure 1).

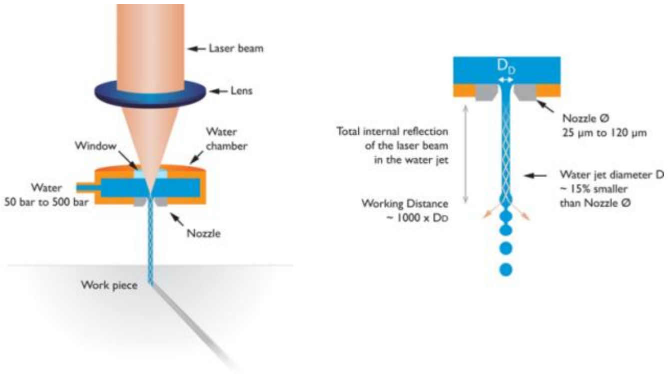


Figure 1 Principle of the coupling of laser beam into the water jet

As it can be seen in the scheme, the beam is focused through a window on the surface of the nozzle. The window separates the water chamber from the air. The water jet is produced by the nozzle at the bottom of the water chamber. Due to the total reflection of the laser between the air and water the laser is entirely contained within the water jet, similar in principle to an optical fiber. The maximum working distance is roughly 1000 times the diameter of the nozzle. The diameter of the nozzle used is between 25 µm and 120 µm. The water jet cools the substrate while removing the molten material from the cut and avoids contamination. The combination of a laser beam and a water jet makes the Laser MicroJet® capable of achieving the advantages of both water and laser cutting into one operation. This is why this cutting technology is very suitable for thin metal cutting of watch parts.

1.2. State of the art of precision machining

The technologies applied for achieving precision machining include electric discharged machining (EDM), water jet cutting and dry laser cutting. However each of the technologies has disadvantages for application in high-end watch industry. The result of a comparison study performed by Richmann et al, 2014 shows that the production rate of EDM is too low for thin metal cutting, the surface roughness of water jet cutting is too high (> 1 µm) and ps- and fs-laser cutting showed similar results as the Laser MicroJet® with slightly less cutting speed. These facts are all technical limits for applications in high end watch making.

The application of laser ablation for metal cutting is a well investigated field (Pfeifer et al, 2010, Almeida et al, 2006, and Thwari et al, 2005). Various studies have been performed on different aspects to understand how the laser parameters and process strategy influences the roughness on the kerf. However how the combination of water jet and laser together affects the result is not clear yet. In a previous project performed at Synova, this topic was investigated. The lowest roughness achieved was Ra = 0.30 µm with 15 ns pulse width, pulse energy of 0.1 mJ and feed speed of 0.1 mm/s.

2. Experimental procedure

The experimental setup is described in section 2.1 and the procedure for the analysis of the cut samples is explained in section 2.2.

2.1. Experimental setup

The experiment is performed with the experimental setup shown in Figure 1 (left). The system is composed up of 5 basic parts: the laser source, the optical head, the axis system, the coupling unit, which couples the laser into the water jet, and the high pressure pump. Figure 1 (right) show the optical head and laser transmission through it.

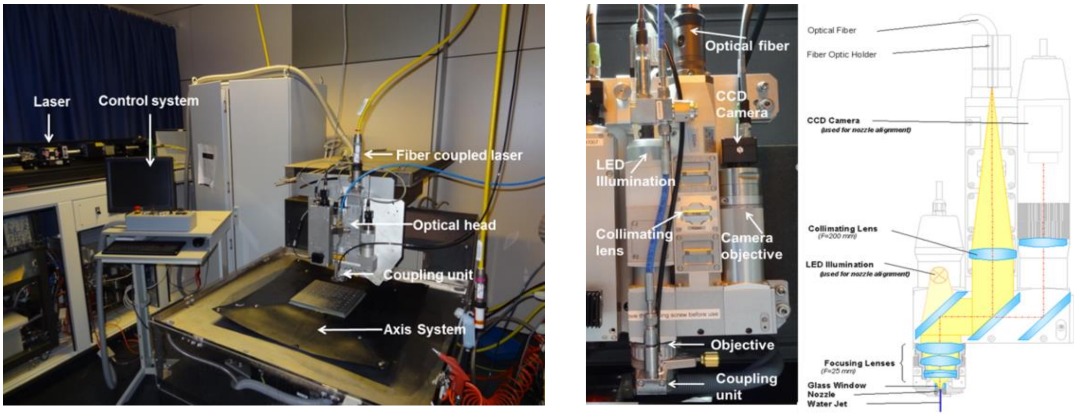


Figure 2: Setup used for the experiments (left); The optical head and the laser transmission through it (right)

Three laser sources are used for the tests with different pulse width ranges (Table 1). The major difference among the three laser sources is the pulse width. For LEE laser the pulse width is bigger than 100 ns. Pulseo has pulse width of 23.4 ns and V-Gen has pulse width between 7 and 18 ns. Besides, LEE laser works with much lower frequency than the other two. As result the fluence and peak intensities of the three laser sources are also in different ranges.

Table 1 Parameters of the three laser sources used

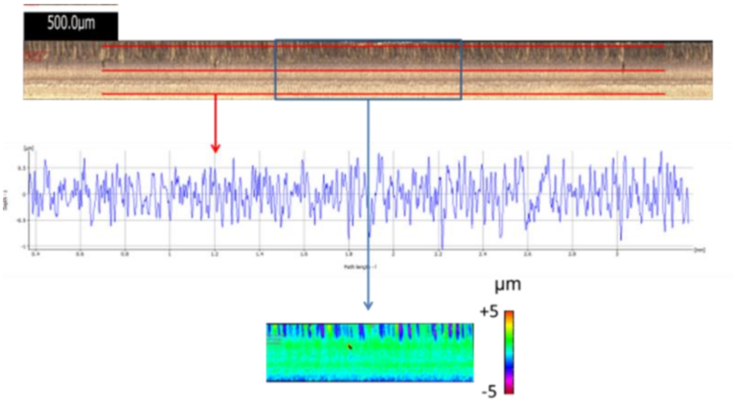
Laser	Frequency f [kHz]	Pulse width τ [ns]	Laser power P_L[W]	Feed speed v [mm/s]	Nozzle diameter $Ø_N$[µm]	Fluence F[J/cm²]	Peak Intensity I_{peak} [GW/cm²]
LEE	6 - 24	100-350	3,6,12	0.2, 0.5, 1.0	30,40,50	28.9-231.0	0.14-1.54
Pulseo	50 - 150	23	10,15,20	0.2	40	24.0-58.0	0.43-1.22
V-Gen	80 – 150	7-18	3,6,12	0.2	40	2.3-13.3	0.14-1.31

2.2. Roughness measurement

The roughness measurement in the experiment is done with an Alicona® Infinite Focus Microscope. The roughness of the kerf surface of the cut metal is measured. Both profile roughness Ra and surface roughness Sa are measured for the samples. An example of the measurement is given in

Figure 3 (left). And the settings of the microscope for the measurement are given in

Figure 3 (right).



Vertical resolution	100 nm
Lateral resolution	2 µm
Objective magnification	20×
Profile length [mm]	3
Profile width [µm]	6.9
Cut-off wavelength [µm]	250
Surface size [mm²]	1.0×0.2

Figure 3 Example of the roughness measurement (left) and the settings of the microscope for the measurement

Three profiles on top, middle and bottom of the kerf surface respectively are measured for the profile roughness. And a surface of 0.2 × 1 mm^2 is chosen in the middle of the kerf to measure the surface roughness Sa. Three samples of each set of the parameters are measured and averaged to be used for analysis and comparison.

3. Experimental results

In the following the experimental results are demonstrated depending on the five magnitudes number of passes, pulse width, pulse energy, overlap between the pulses and cut through threshold. The formulas for calculating some of the magnitudes are listed in the following.

$$P_{Energy} = \frac{P_l}{f} \tag{1}$$

$$I_{peak} = \frac{P_l}{f \cdot A_{jet} \cdot \tau} \tag{2}$$

$$O_{\%} = 1 - \frac{v}{f \cdot \phi_{jet}} \tag{3}$$

P_l: Average laser power

f : Frequency

τ: Pulse width
$\emptyset_{jet}$: Surface area of the water jet
V: feed speed
$\emptyset_{jet}$: Diameter of the water jet

The pulse energy depends on the laser power and the laser frequency (1). The peak intensity is pulse energy divided by the pulse width (2). The overlap represents how much the emitted laser pulses superpose (3).

3.1. Number of passes

In some preliminary cutting experiments, for some parameters the sample cannot be cut through with a single pass. Additionally the profile roughness at the top of the surface and the bottom of the surface can be different by a factor of 5. This is observed on many samples. One example is shown in Figure 4

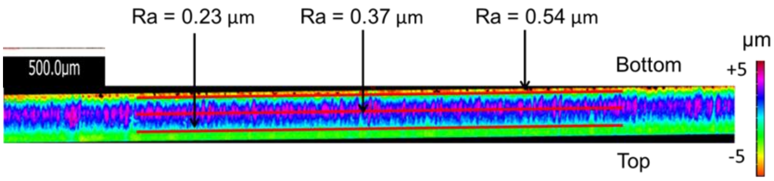


Figure 4: Profile roughness measurement of one sample, the three red lines represent the positions of the measured profile roughness of the top, middle and bottom

A possible explanation is that the material on the top absorbs enough energy to ablate the material, but at the bottom part the energy is already too low to fully ablate the material. Based on this theory, it is tested weather a multi-pass or single pass cutting strategy lead to lower roughness and a more homogeneous surface. The parameters used are listed in

Table 2.

Table 2 Parameters used to test the influence of the number of passes

Nozzle diameter $\emptyset_N$[µm]	Frequency f [kHz]	Pulse width τ [ns]	Laser power P_L[W]	Fluence F[J/cm²]	Peak Intensity I_{peak} [GW/cm²]
50	80-150	7,17	3-12	1.48-8.87	0.16-0.71

The comparison of the surface roughness Sa for different number of passes is shown in

Figure 5.

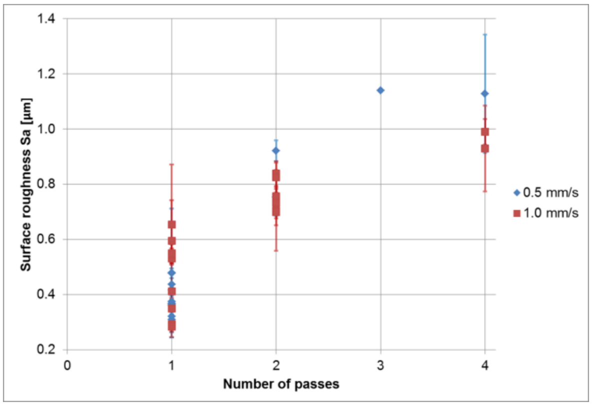


Figure 5: Sa over number of passes for 50 µm nozzle cutting at 0.5 mm/s and 1 mm/s

The diagram shows that the lowest surface roughness is achieved with single pass for both tested speeds. The roughness doubles with the second pass and continues to increase with more number of passes. Further experiments shown are achieved with only one single pass as this is the preferential strategy for achieving lower roughness on the kerf.

3.2. Pulse width

As listed in Table 1, three different lasers used in the test offer laser pulse widths within completely different ranges varying from 7 ns to 350 ns. First of all pulse width within 23 ns to 350 ns are tested. The relevant parameters applied for the samples for comparison are shown in Table 3. The fluence of each group is chosen to be in the same order to be able to investigate only the influence of the pulse width.

Table 3 Parameters used for pulse width comparison

Nozzle diameter	Frequency	Pulse width	Laser power	Fluence	Peak Intensity
$Ø_N$[µm]	f [kHz]	τ [ns]	P_L[W]	F[J/cm²]	I_{peak} [GW/cm²]
40	6-120	7-350	3-20	2.3 -116	0.10-1.22

The roughness achieved with different pulse widths for different fluences are shown in

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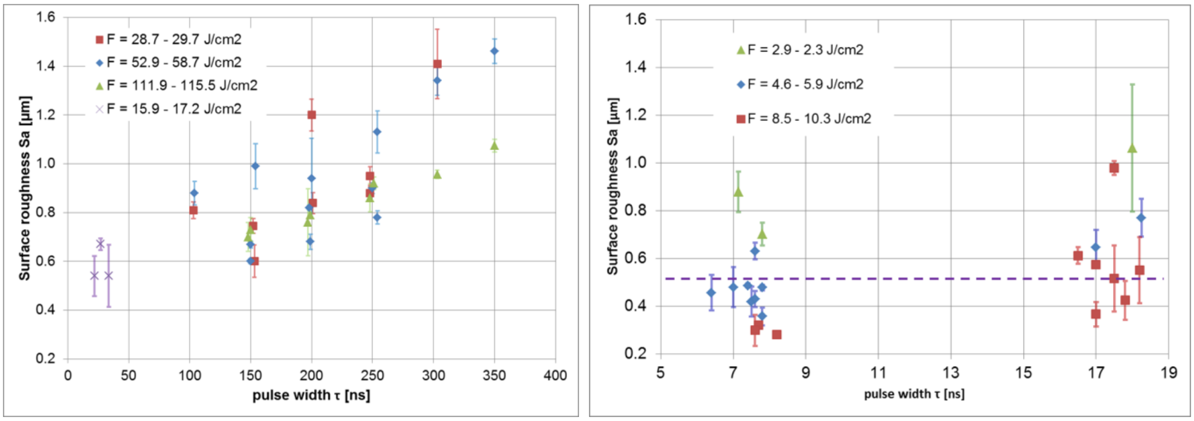


Figure 6: Surface roughness Sa for pulse widths τ between 23.4 and 350 ns (left) and for pulse width τ between 7 and 18 ns (right)

on the left shows that for all fluences, the roughness increases with the pulse width. For the parameters tested with pulse widths of 23 ns it is not possible to obtain the same fluence level so that no direct comparison is possible. Nevertheless it shows that the roughness is smaller with shorter pulse widths within all fluence groups. In

right the roughness for pulse widths < 20 ns is shown and the purple dashed line represents the lowest roughness level of the sample processed with 23 ns lasers. In this pulse width regime the trend continues: roughness decreases with lower pulse width down to Sa = 0.28 µm, which is achieved with a pulse width of 7 ns. Compared with pulse widths > 20 ns, the surface roughness can be halved.

3.3. Pulse Energy

As given in equation (1) the pulse energy is determined by the average laser power and frequency. Since it is already verified that the pulse width has very big influence on the roughness, the comparison of influence of the pulse energy needs to be done at a constant pulse width.

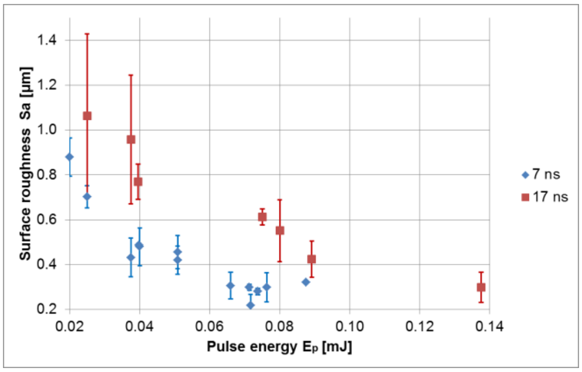
Table 4 gives the parameters of different pulse widths for the comparison.

Table 4 Parameters for pulse width of 7 ns and 17 ns

Nozzle diameter $Ø_N$[µm]	Frequency f [kHz]	Pulse width τ [ns]	Laser power P_L[W]	Fluence F[J/cm²]	Peak Intensity I_{peak} [GW/cm²]
40	80-150	6-250	3-12	2.3-231.0	0.16-1.31

The results of the surface roughness depending on the pulse energy are given in

Figure 7. Again it is distinguished between pulse widths > 100 ns (Figure 7 right) and pulse widths < 100 ns (Figure 7 left).



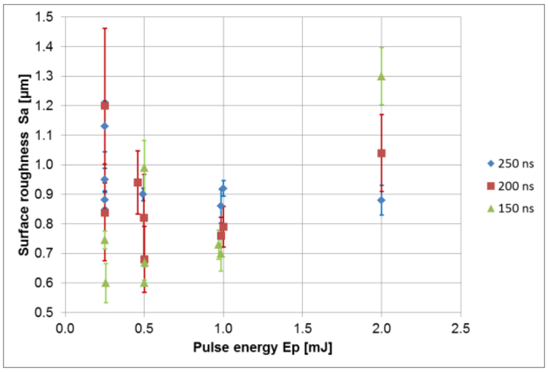


Figure 7: Sa over Ep for pulse width of 7 ns and 17 ns (left), 150 ns, 200 ns and 250 ns pulses (right)

From

Figure 7 left it can be seen that the surface roughness decreases as the pulse energy increases. Since the short pulse laser works at frequency between 80 kHz and 150 kHz, the pulse energy is with much lower than for the long pulsed laser. In this pulse energy range the roughness reduces from around Sa = 1.00µm to Sa 0.22 µm. This result is coherent to the existing research of Pfeifer et al, 2010. However, the case is different when the pulse energy increases too much.

Figure 7 right shows that the pulse energy is between 0.3 mJ and 2.0 mJ for pulse widths of 150 ns to 250 ns. When the pulse energy is between 0.3 mJ and 1.5 mJ, the surface roughness decreases with higher pulse energy. However, when the pulse energy increases to around 2.0 mJ the roughness increases from 0.7 µm to about 1.3 µm. Except for the case with 250 ns pulse width, where the roughness is at a stable level. This effect is much more severe for the shorter pulse width tested than for the long pulses. An explanation to this result is that when the pulse energy is too high, the cooling effect of the water jet is not sufficient high anymore to eliminate the heat damage and the samples are burnt. This can be seen in microscope photos which are shown in

Figure 8.

Figure 8: Comparison of samples processed with low pulse energy of 0.25 mJ with Sa = 0.30 µm (up) and the one processed with high pulse energy of 2.0 mJ with Sa = 1.46 µm (bottom), picture taken with Alicona® microscope. Both for pulse widths t_P = 150 ns

For low pulse energy of 0.25 mJ the surface is bright and smooth, with the original color of brass. And the surface roughness is low at Sa = 0.75 µm. When the pulse energy is 2.0 mJ, the surface becomes dark and the roughness rises to Sa = 1.46 µm. For pulse width > 100 ns high pulse energies of > 1 mJ lead to higher roughness due to heat accumulation. For shorter pulse widths a heating effect is not investigated in the tested parameter field.

3.4. Overlap

Three parameters have influence on the overlap: the frequency f, the nozzle diameter $Ø_N$ and the feed speed v (equation (2)). To investigate the influence of the overlap, other parameters that also have big influence on the cutting quality like fluence and peak intensity are kept constant for each group of data. Four different groups of parameters are tested (Table 5).

Table 5 Parameters used for comparison of influence of overlap on surface roughness

Group	Frequency f [kHz]	Pulse width τ [ns]	Laser power P_L[W]	Feed speed v [mm/s]	Nozzle diameter $Ø_N$[µm]	Fluence F[J/cm²]	Peak Intensity I_{peak} [GW/cm²]
1	80	7	5.9 ± 0.2	0.2, 0.5, 1.0	40	8.4	1.0
2	120	7	6.0	0.2, 0.5, 1.0	40	5.8	0.8
3	150	7	6.0	0.2, 0.5, 1.0	40	4.6	0.6
4	80	17	6.0	0.2, 0.5, 1.0	40	8.7	0.5

The surface roughness depending on the overlap is shown in

Figure 9

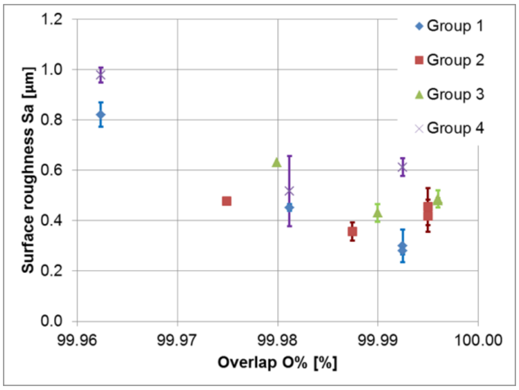


Figure 9: Surface roughness Sa over Overlap for the four groups of laser parameters

The only difference of the parameter for the three points in each group is the feed speed. From the graph it is observed that for all the four cases, the surface roughness decreases when the overlap goes up to between 99.96% and 99.98% by a factor of 2, e.g. for group 1 and group 4. For group 2 and group 3 the decrease is less significant since the difference in overlap is not as big. However, as the overlap increases to more than 99.99%, the change of surface roughness becomes smaller than 0.1µm (from around Sa 0.6 µm to Sa 0.5 µm); for group 2 - 4 the surface roughness actually increases by about 0.1 µm. This can be due to the fact that as the overlap is already big enough (>99.99%), the overlap does not really influence the roughness any more. When considering the difference between the different groups, the major influential factor is the frequency which leads to slightly higher overlap of the pulses for higher frequencies. Based on the observation from the graph above, it is recommended to choose the overlap bigger that 99.98% to achieve small surface roughness. By choosing a relatively large frequency, it is possible to choose also higher feed speed to ensure the overlap is high enough at the same time to improve the processing efficiency.

3.5. Cut through threshold

During the experiments we investigated that several sets of parameters cannot cut through the brass sheet with one single pass. A single magnitude that solely influences the cut through threshold would be very useful. To investigate the cut through threshold four groups of parameters that all have the same pulse energy but different frequencies and laser powers are chosen. For this investigation the pulse energy and the nozzle size, therefore also the fluence, need to be kept constant but the peak intensity varies (Table 6).

Table 6 Parameters for cut through threshold test

Group	Frequency f [kHz]	Pulse width τ [ns]	Laser power P_L[W]	Feed speed v [mm/s]	Nozzle size $Ø_N$[µm]	Pulse Energy Ep [mJ]	Fluence F[J/cm²]	Peak Intensity I_{peak} [GW/cm²]
1	12	100 – 250	3.0	0.2	50	2.5	18.5	0.08 – 0.18
2	18	100 – 250	4.5	0.2	50	2.5	18.5	0.08 – 0.18
3	24	100 – 250	6.0	0.2	50	2.5	18.5	0.08 – 0.18
4	36	100 – 250	12.0	0.2	50	2.5	18.5	0.08 – 0.18

Figure 10 shows whether the parameter combination cuts through or not.

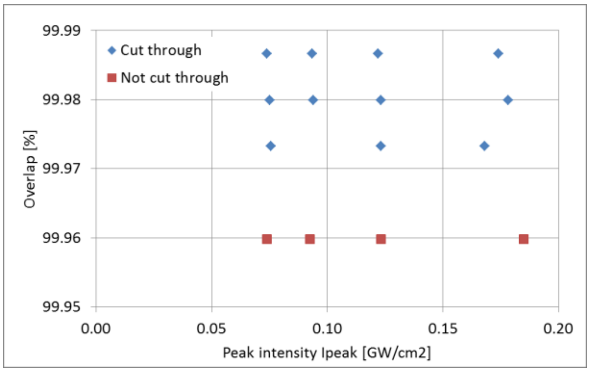


Figure 10 Cutting through behaviour for the parameters shown in Table 7 depending on the overlap and peak intensity.

From the result achieved it is observed that the only magnitude that influences the cut through threshold for one pulse energy is the overlap and is independent of the peak intensity. When the overlap is below 99.97 %, all the points with the different tested peak intensities are not cut through.

4. Summary and outlook

In this project the influence of the laser parameters and process strategy on the roughness on the kerf cut by Laser MicroJet® are investigated individually through an experimental approach.

Single pass cutting is preferable for thin metal cut to achieve a low roughness. The shortest pulse widths tested in this study of 7 ns is recommended to achieve low surface roughness. For short pulse width (<20 ns) the higher pulse energy leads to lower surface roughness. But when using longer pulse width laser > 100 ns the roughness still decreases with the increase of pulse energy until it reaches a threshold around 1.5 mJ for a tested fluence of 115 J/cm^2 and peak intensity of 0.6 GW/cm^2. For pulse energies > 1.5 mJ, the roughness increases due to the heat effects occurring. The overlap is found to influence the roughness and the lowest roughness is found to be achieved at 99.98 % for the fluence 0.8 J/cm^2 of and peak intensity of 5.8 GW/cm^2. An overlap smaller than 99.98 % leads to an increase in surface roughness. While a higher overlap than 99.98% leads to lower cutting speed without decreasing the roughness. For one pulse energy the overlap is the only magnitude that determines the cut through threshold of the metal independent on the peak intensity used. The lowest surface roughness achieved is $Sa = 0.22 \pm 0.05$ µm and $Ra = 0.18 \pm 0.02$ µm.

For a further study the factors including different cutting geometries and water pressure need to be considered. Additionally a further reduction of pulse width is expected to lead to lower roughness.

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