Deliverable 2.2: Process limits fine cutting of metal

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Contents

1 Version History

Version	Summary of Change	Written By	Approver	Date
0.1	First Draft (Confidential)	Enda McCague		
1.0	Second (Public)	Enda McCague	Marwan Abdou-Ahmed	

2 Deliverable overview and objectives

This document should provide an overview of the prerequisite studies and experimentation carried out on femtosecond processing of metals in anticipation of the arrival of the >150W (and up to 200W) system to the partners facilities (namely C4L). All investigations and trials are carried out at the partner's facilities (C4L) on existing processing setups. The fundamental ablation mechanism, ablation rates, processing strategies, and optimization of the cut surface quality are studied.

The fundamental knowledge gathered in these investigations will serve as input for the laser and systems development and will enable the subsequent development of optimized and efficient processing strategies. The fundamental mechanisms will first be evaluated on simplified geometries, with the objective of transferring the process know-how to more complex geometries and then on to watch parts.

2.1 Description of related task(s)

Under the definition of work package 2 (process development) as outlined in the description of work the task related accountability of this WP is split into two. The study of process limits for fine cutting of metals is directly related to task 2.2: fundamental process development fine cutting of metals. Once this study is completed and the process is well understood, it is used as the input for upscaling the applications on the high-power system, which is the work of task 2.4: upscaling of applications for high throughput. Thus, the sole task to be completed with the current deliverable, D2.2 is task 2.2. However, this deliverable has further responsibility as it partially fulfills the objective and serves as the input for task 2.4.

2.1.1 Task 2.2 – Fundamental process development fine cutting of metals

The objective of this task is to establish what the influence of laser, scanner and other experimental parameters have on the processing of metal parts with a femtosecond laser source. This study is undertaken with the objective of developing process relevant know how, which will serve as input for the process development on the high-power system, and should lead to the development of optimized, more efficient processing strategies.

This objective is achieved by undertaking a study of the effect of fundamental laser parameters (such as pulse energy, rep rate and pulse duration) on key characteristics of the processed metal parts such as surface roughness, existence of a burr etc., ablation depth. Process characteristics such as ablation rates and process efficiency will be measured, in an effort to gain a comprehensive understanding of the process. Additionally, different laser delivery methods will be tested, in an effort to speed up integration, and have a provisional understanding of their application specific effects before upscaling to the higher power system.
All trials are to be carried out on materials which are specified in deliverable 1.1 – End user application specifications, namely brass and Steel, two materials chosen for their relevance to the watch industry; a critical end user market for this project. Additionally, the interdependencies of the investigated process characteristics are to be presented, for example ablation rate and surface quality.
The characteristics detailed will be studied on simplified geometries and will be transferred to the KPI geometry detailed in deliverable 1.1 – end-user application specifications once the process is up scaled to the 200W system.

3 Review of relevant literature

During the interaction of low intensity short laser pulses with metal targets, the laser energy is absorbed by free electrons due to inverse Bremsstrahlung. Once the laser energy is incident on a non-reflective target material it is absorbed and undergoes a temporal evolution. As the energy is absorbed into the electronic subsystem, the first step in this evolution is the thermalization of the electron subsystem itself; this takes place on a very fast timescale. This energy is then transferred to the lattice of the material, and finally the energy is lost due to the original electron heat being transported into the bulk material by conduction. One can separate the temperatures of the electron subsystem and the lattice subsystem based on the relative difference in the timescales involved in heating. From this assumption a one–dimensional, two-temperature model can be formed, where the only source term is from absorbed laser energy:

$$S = I(t)A\,\alpha\exp(-\alpha z)$$

Where I(t) is the laser intensity, A is the surface transmissivity (1-R), α is the material absorption coefficient and z is the depth perpendicular to the surface.

The timescale for fast electron cooling, and a considerable energy transfer to the lattice is of the order of 1 ps (Prolko et al.)[1]. Thus, illuminating the target with a laser pulse of pulse duration of the order of 100 femtoseconds, means that time timescale of the laser pulse is considerably less than the timescale for electron cooling. This allows one to make the assumption in the one dimensional two temperature model that the electron-lattice coupling can be neglected (as it happens on a much longer timescale). Additionally, the electron heat conduction term is neglected, based on the condition that the heat affected zone on this timescale is much smaller than the penetration depth squared. Based on these assumptions and simplifications which have been put forward by Chichkov et al.[2] the following conclusion can be made:
The ablation depth z_{abl}, can be expressed as a function of the fluence Ø:

$$z_{abl} = \delta \cdot \ln(\frac{\emptyset}{\emptyset_{th}})$$

(Where $\emptyset_{th}$ the threshold fluence and δ the (optical) energy penetration depth.)

This has been proven to be the case by experimentation (Momma et al. [3])

Two regimes of thermodynamic behavior for ultra-short pulses result based on this expression: the low fluence regime where the optical penetration depth dominates and the high fluence regime where the energy transport is dominated by the heat diffusion of the hot electrons.
Neuenschwander et al. have showed that for a top hat beam the efficiency of the ablation process depends on the ratio between the applied fluence and the threshold fluence: $\emptyset_{th}/\emptyset$, and that the

[1] *Pronko, P.P., Dutta, S.K., Du, D. and Singh, R.K., 1995. Thermophysical effects in laser processing of materials with picosecond and femtosecond pulses. Journal of Applied Physics, 78(10), pp.6233-6240.*
[2] *Chichkov, B.N., Momma, C., Nolte, S., Von Alvensleben, F. and Tünnermann, A., 1996. Femtosecond, picosecond and nanosecond laser ablation of solids. Applied Physics A, 63(2), pp.109-115.*
[3] Momma, C., Nolte, S., Chichkov, B.N., Alvensleben, F.V. and Tünnermann, A., 1997. Precise laser ablation with ultrashort pulses. Applied surface science, 109, pp.15-19.

efficiency shows a maximum value of 1/e. At this maximum efficiency there is a theoretical ablated volume per pulse of:

$$\Delta V = \pi \cdot {w_0}^2 \cdot \delta$$

This shows that the ablation process can clearly be optimized, and that the maximum removal rate is dictated by the threshold fluence and the energy penetration depth. The dependency of these two parameters: threshold fluence $\emptyset_{th}$, and energy penetration depth δ on pulse duration for various metal target materials has also been studied[4]. For copper (figure 1) the threshold fluence is effectively unaffected by reducing pulse durations below 10 ps; an increased ablation rate at lower pulse durations is accounted for by an increasing energy penetration depth with reducing pulse duration. For copper there is an associated increase in the theoretical maximum removal rate of approx. 75% when the pulse duration is reduced from 10ps to 500fs.

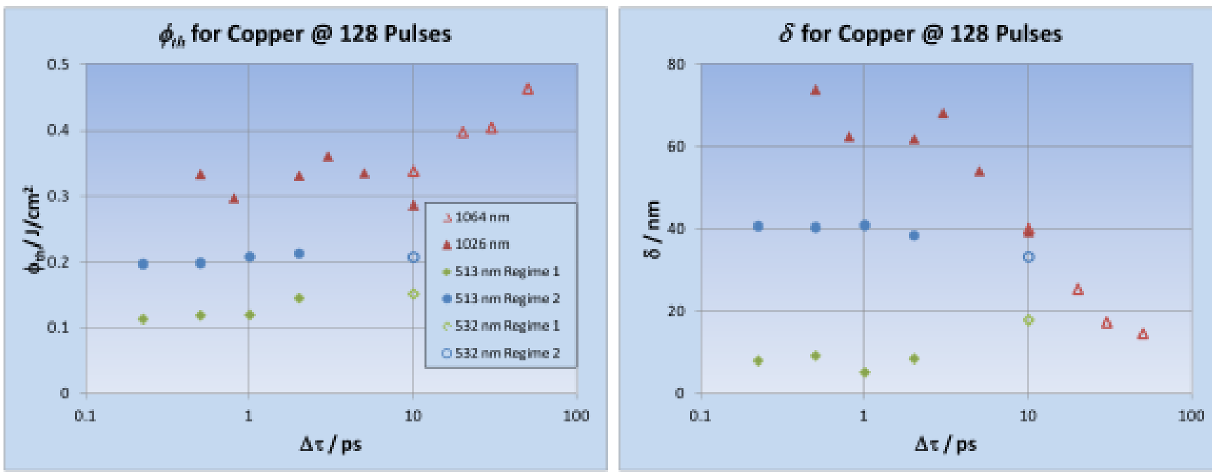

Figure 1: Results from Neuenschwander et al. demonstrating an unchanged threshold fluence below 10ps, and an increasing energy penetration depth below 10ps pulse duration.

Similarly, the threshold fluence for stainless steel (figure 2) is constant below 10ps pulse duration. Again, the increased material removal rate (65% when pulse duration is reduced from 10ps to 500fs) is accounted for by an increasing energy penetration depth.

Additionally, one of the conclusions from SEM analysis of the surface of the ablated zone concluded that for copper the surface quality is unaffected by the pulse duration; for stainless steel there may be a minimal influence.

[4] *Neuenschwander, B., Jaeggi, B. and Schmid, M., 2012. From ps to fs: dependence of the material removal rate and the surface quality on the pulse duration for metals, semiconductors and oxides. In Proceedings of the International Congress on Applications of Laser & Electro-Optics M (Vol. 1004, pp. 959-968).*

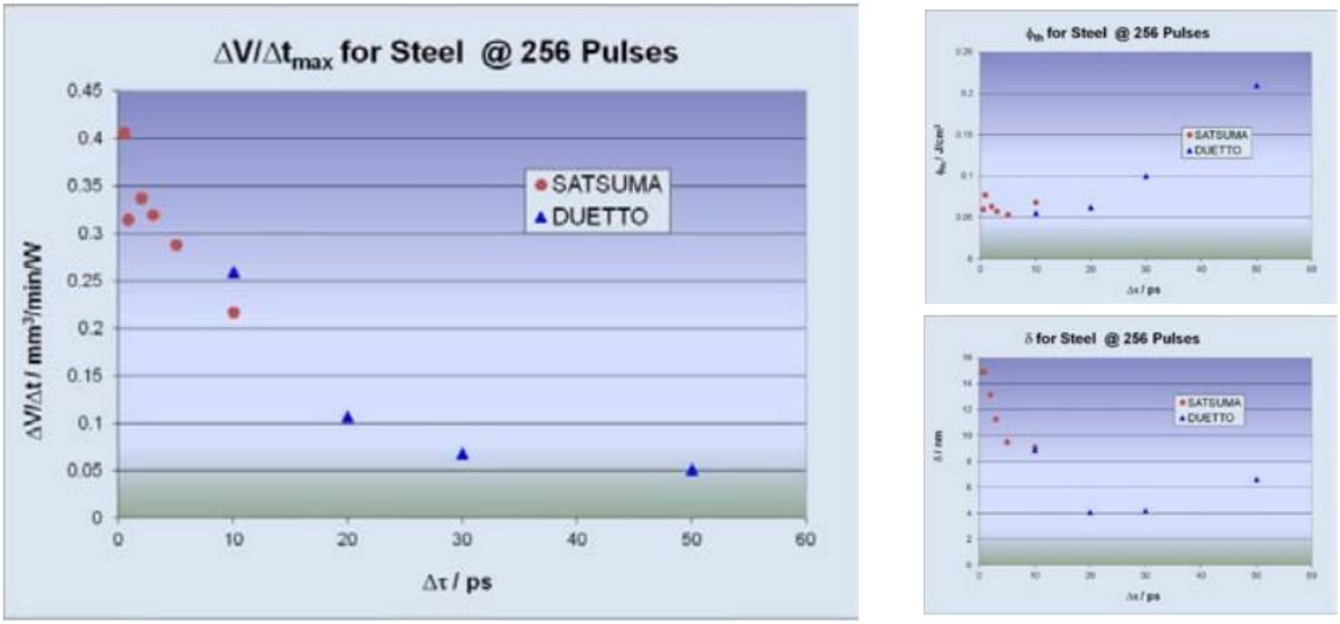

Figure 2: Results from Neuenschwander et al. demonstrating an increasing maximum removal rate for stainless steel. Which can be seen to be caused by an increasing energy penetration depth, as threshold fluence remains unchanged below 10ps

The influence of incubation effects must also be considered; it has been known for some time that a material surface can become damaged when irradiated with multiple pulses, at pulse energies far below the single shot ablation threshold. The effect of this has been measured by Mannion et al[5], and the influence of the number of pulses applied to a surface on the ablation threshold can be summarized by the following expression

$$\emptyset_{th}(N) = \emptyset_{th}\,(1)N^{S-1}$$

(where N the number of pulses applied, S the incubation coefficient.) The incubation coefficient has been measured for various metals, summarized in table 1:

Material	S	$\emptyset_{th}$ (1) [J/cm^2]
Stainless steel	0.86 ± 0.03	0.21 ± 0.02
Copper	0.87 ± 0.02	0.58 ± 0.05
Niobium	0.88 ± 0.03	0.19 ± 0.03
Titanium	0.83 ± 0.03	0.28 ± 0.02

Table 1: Results from Mannion et al. detailing the measured values of the incubation coefficient (S) for various metals.

[5] *Mannion, P.T., Magee, J., Coyne, E., O'Connor, G.M. and Glynn, T.J., 2004. The effect of damage accumulation behaviour on ablation thresholds and damage morphology in ultrafast laser micro-machining of common metals in air. Applied surface science, 233(1-4), pp.275-287.*

Process development: fine cutting of Brass

The objective of this process development is to understand the fundamental processes governing femtosecond ablation of brass, at the average power and pulse durations available on the current system. This is undertaken with the objective of planning the upscaling of operations to the 150W system, and with the long-term objective of achieving the KPI's for fine cutting of metals which have been outlined in D.1.3 (Prototypes and progress validation). The relevant KPI`s for the fundamental process development which is undertaken are repeated in table 2 below.

No.	KPI	Values	Validation status
1	**Cutting speed**	Expected : $\geq$ 400 mm/min	
		Validated : $\geq$ 300 mm /min	
		Not validated : < 300 mm/min	
5	**Surface roughness (functional/non-functional)**	Expected : $R_a \leq 0.1$ µm / 0.4 µm	
		Validated : $R_a < 1$ µm / 1 µm	
		Not validated : $R_a \geq 1$ µm	
6	**Shape deviation**	Expected : < ± 2 µm	
		Validated : < ± 5 µm	
		Not validated : > ± 5 µm	
7	**Taper**	Expected : 0˚	
		Validated : Within dimension tolerances	
		Not validated : Above dimension tolerances	
8	**Colouration**	Expected : None	
		Validated : Washable surface oxidation	
		Not validated : Persistent surface oxidation	
9	**Untying of part**	Expected : Fall down in US-bath	
		Validated : Fall down in US-bath with separation cut	
		Not validated : Mechanical removal	

Table 2: Overview of KPI`s relevant for provisional process development (D1.3)

As a trepanning optic is yet to be fully integrated into the system, the trials which were realized were limited to beam delivery using the galvo-scanner. This means that investigating the influence of processing parameters on the taper angle, and in particular the optimization of this KPI cannot be carried out. Of the remaining KPI`s listed in table 2 trialing and characterization of the surface roughness was the first, and most critical process characteristic to be studied.
The process parameters which are trialed in the context of the surface characteristics of the work piece were the following: # Passes, laser frequency, scanning speed, pulse energy, and pulse duration.
Ideally, each parameter should be treated in isolation in order to understand and isolate the effects of each process parameter individually. Due to strong interdependencies of the processing parameters, treating each in complete isolation is not possible.

Therefore, the objectives of each trialing set will be treated in separately; the dependent and independent variables will be detailed, the side effects/ influence of modifying each variable will be included.

The basic material to be used is 0.2mm thick brass with a Cu:Zn ratio of 63:37 (MS63, Allmeson GmbHO), this thickness is in keeping with the KPI, which defines the necessary material thicknesses from 0 1-0.3mm. This specific form of brass is chosen due to its industrial relevance, and importance specifically to the watch making industry.

3.1 Strategies for Brass cutting

The main concern at this stage of the process development, and the KPI which is considered to be the greatest challenge at the moment, is the surface roughness.

Therefore, this is the primary objective of this processing study. For these investigations a simple geometry (2mmx10mm) is cut. This was chosen for simplicity and comparability, additionally it allows for enough space for labels to be engraved on the surface for the characterization step.

3.2 Influence of the number of passes

The initial process parameter to be investigated, in an effort to optimize first the trialing process, is the number of passes. In an effort to isolate the influence of this scanning speed the following parameters remained constant during this trialing process.

Parameter	Symbol	Value	Unit
Average power	P	5	W
Pulse duration	τ_{pulse}	232	fs
Repetition rate	F	166	kHz
Fluence	ϕ	5.86	J/cm^2
Pulse energy	E_{pulse}	30.12	µJ
Overlap		0.03	µm
Scanning speed	S	5	mm/s

Table 3: Fixed process parameters for studying influence of number of passes on processing of brass

From the data obtained (see figure 3), the trend emerges that the average surface roughness (Ra) achieved decreases as the number of passes increases, up to a certain point, and then the Ra increases with increasing number of passes. This process should be easily up scaled, as the scanning speed here is very low (5mm/s), which means that the current processing time is 4.8s per pass. The median number of passes in this experimentation series was 15, at 4.8s per pass with a rectangular of perimeter 24mm, this corresponds to a net processing (cutting) speed of 20 mm/min, well below the target KPI of 400mm/min. Should the upscaling behave in a simple linear fashion, cutting speeds as high as 600mm/min could be expected with 150W average power. However, this cutting speed is achieved with surface roughness measurements of Ra: 2.48 µm and Rz: 24.85 µm which is well outside the targeted KPI`s for surface roughness for functional parts of Ra: 0.1 µm.

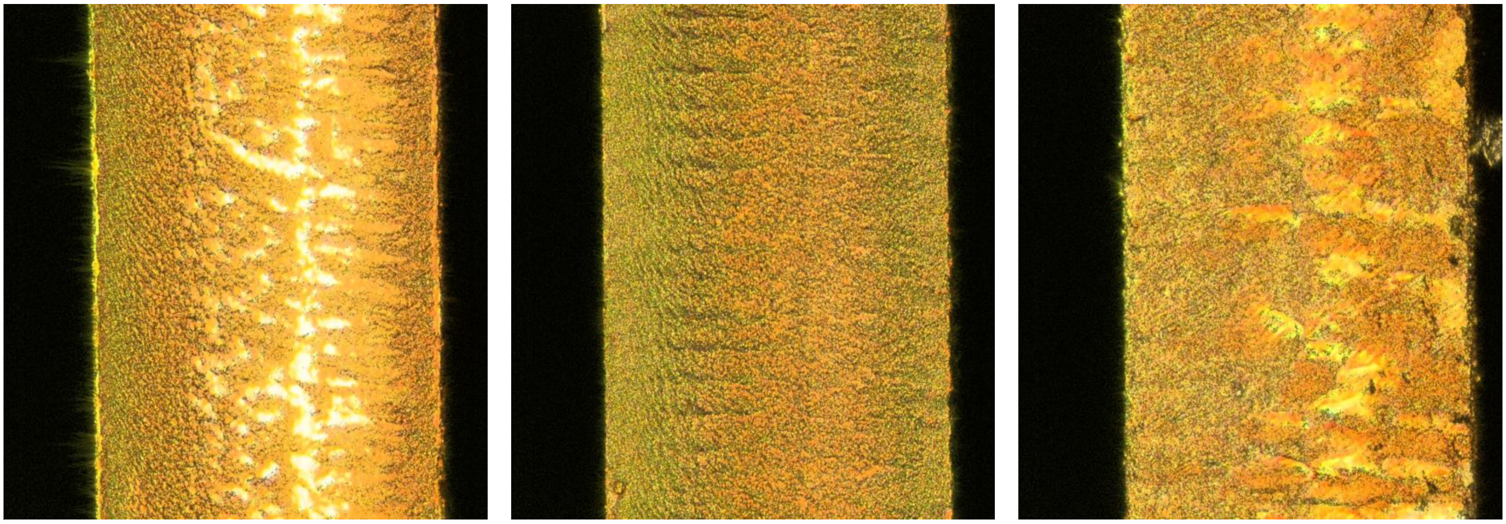

Figure3: Images of the cut surface from L to R, after 5, 15 and 30 passes (Keyence VK-8710K net magnification 1000x)

3.3 Influence of Overlap

The objective of this trialing process was to establish the influence of the pulse to pulse overlap on the cutting of brass. Overlap is varied by modifying the scanning speed, all other laser and scanner parameters are kept constant.

Parameter	Symbol	Value	Unit
Average power	P	5	W
Pulse duration	τ_{pulse}	232	fs
Repetition rate	F	166	kHz
Fluence	ϕ	5.86	J/cm^2
Pulse energy	E_{pulse}	30.12	µJ
# Passes	$\#_{Passes}$	10	NA
Scanning speed	S	1-15 (variable)	mm/s

Table 3: Process parameters for the study of the influence of overlap on processing brass

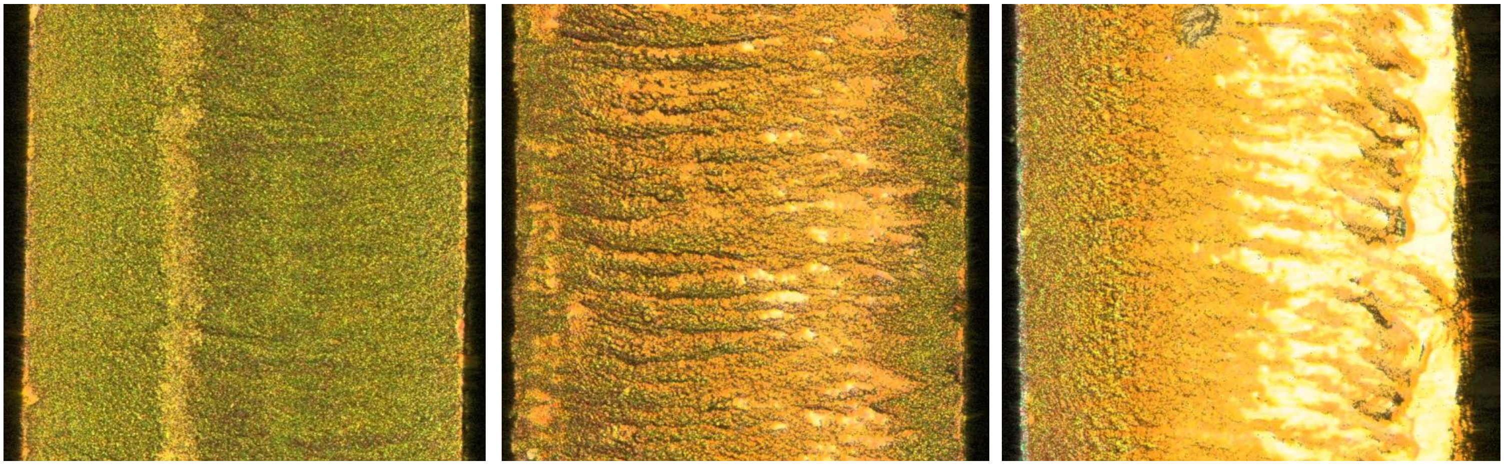

Figure 4: Images of the cut surfaces for varying pulse overlap. (Pulse to pulse overlap distance 0.01 µm , 0.03 µm and 0.09 µm from L-R)

The clear trend from the images presented in fig.4 is that the pulse to pulse overlap has a significant influence on the homogeneity and surface roughness of the target samples.

Clearly for cutting of brass with these parameters a larger overlap is beneficial if a low average Ra measurement is required. However, at the minimum available scanning speed which enables the shortest pulse to pulse overlap distance (and thus largest overlap) achievable at this laser rep. rate, the average surface roughness (Ra:1.7 µm) is still a factor of 17 above that which is required for functional parts (0.1 µm). If upscaling scales linearly, we can expect to achieve this KPI using a rep. rate of 2.8MHz. However, one cannot expect the behavior of scaling for overlap to behave in such a fashion due to the influence of incubation effects which are detailed for brass by Mannion et al. This means that, as expected the KPI for surface roughness cannot be achieved through modifying the overlap alone. Modification of more than this parameter is required.

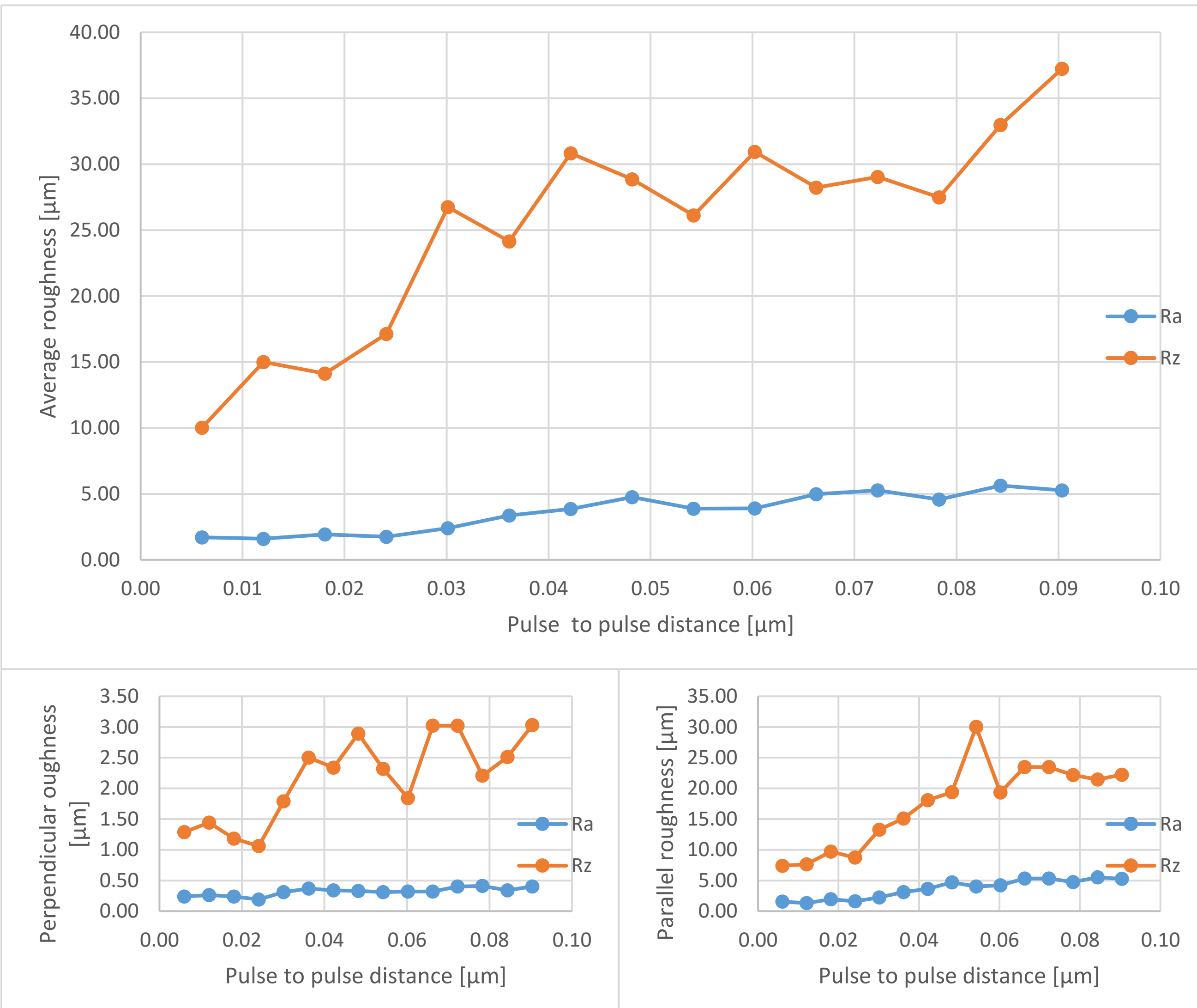

Figure 5: Surface roughness as a function of pulse overlap, for a constant repetition rate and variable scanning speed

The limitation of such a restricted study is that the interdependency of the various processing parameters cannot be exploited to optimize the processing efficiency. Isolating a single variable in the processing parameters offers insight into the qualitative trends one can expect, however, without optimization of the interdependent processing parameters one cannot conclusively evaluate the processing efficiency.

Additionally there is evidence from the images in fig. 4 (in particular at 0.01 µm and 0.09 µm) to suggest that there are two ablation zones in the 0.2 mm thick brass, separated by a boarder in the plane perpendicular to the laser propagation.

3.4 Influence of pulse energy

The objective of this trialing process is to isolate pulse energy as the only variable process parameter in an effort to measure it`s influence on the cutting of brass, and to project for the upscaling to the 150W system. Pulse energy is varied by modifying the pulsed repetition rate of the laser at constant average power. The varying pulse rep rate is compensated for using the external pulse divider /pulse picker of the laser system. As pulse energy is varied, other parameters remain constant.

At the current processing parameters, the cutting process is incomplete for pulse energies below a 20 µJ.

Figure 6: Images of the cut surfaces for varying pulse energy. (From L-R 35 µJ, 65 µJ, 83 µJ)

The main conclusion from this trial is that there is clearly an improvement in surface quality with increasing pulse energy. Consulting fig.5, the suggested border between two ablation zones in the material appears to become evident only at the highest pulse energy tested (85 µJ). When upscaling to pulse energies up to 300 µJ in the Demonstrator 2 system, this will need to be monitored and possibly compensated for.

3.5 Influence of pulse duration

The objective of this trial is to evaluate the influence of pulse duration on the processing of brass. The pulse duration of the system can be changed by altering the compressor position of the CPA module of the laser system. This is relatively straight forward to achieve, as the automated controls of the laser include pulse duration selection.

Below approx. 1000fs, the average roughness appears to have no clear correlation to the pulse duration. However above 1000fs there is a vague trend of increasing average surface roughness with increasing pulse duration.
The images of the cut surfaces present a more coherent trend; fig.6 demonstrates worsening homogeneity of the cut surface with increasing pulse duration. At minimum pulse duration of 232 fs an average surface roughness of 2.46 µm is measured, which is approximately a factor of 25 time the average surface roughness required by the KPI`s for functional parts.

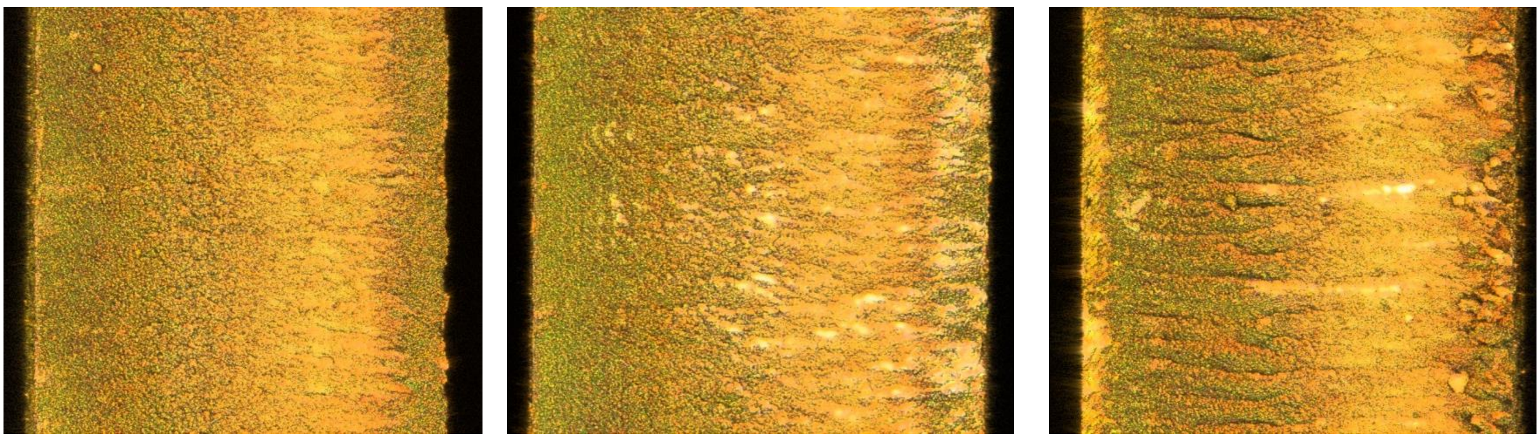

Figure 7: Images of the cut surface for a variable pulse duration. (From L-R 232 fs, 1000 fs, 10000 fs)

The conclusion is that below 1000 fs, the optimization of the processing quality is not clearly correlated with the pulse duration; processing efficiency optimization with pulse duration can be considered on an application dependent basis. It is expected that that with the up-scaled demonstrator 2 system the laser will almost exclusively run at the minimum pulse duration available (approx. 400 fs).

4 Process development: fine cutting of Steel

The objectives for processing of steel are identical to that of brass, detailed in table 2. For the study undertaken here a commercially available grade of steel is used. Steel of a thickness of 0.2mm is selected in line with the KPI set out in D1.3 (Prototypes & progress validation)

The task here is to characterize the effect the various laser and scanner parameters have on the KPI's outlined in table 2, with the primary objective of estimating the effect of upscaling to the 150W system on the process.

All surfaces images and surface data including measurements of Ra and Rz are collected using a commercially available laser scanning microscope (Keyence VK-8710K). Ra and Rz measurements are made for three different geometries for the cut surface: an average roughness measurement (over the entire surface), and two-line roughness measurements (in a direction parallel and perpendicular to the cutting direction).
For all surface images included the cutting direction is from left to right.

4.1 Influence of pulse duration

The objective of this trial is to gauge the effect of varying the pulse duration has on the processing of steel. In an effort to isolate pulse duration as the sole variable, pulse durations in the range 232 fs-10000 fs are tested.

The initial indication from the data is that surface quality is improving with increasing pulse duration. This is an unexpected result and somewhat counterintuitive. Further analysis of the surface images in fig.7 indicates that none of the surfaces could be described as being homogeneous.
A potential explanation for the reduced average surface roughness with increasing pulse duration may be due to the reduced ablation rate at pulse durations above 1000 fs. Above this pulse duration, sample parts are decoupled from the bulk with increasing mechanical pressure (provided by pushing a tweezer tip against the surface), this mechanical decoupling may be tearing the sample from the bulk, which cannot be considered a comparable material removal mechanism. Above 5000 fs pulse duration, for the current processing trials, the sample part can no longer be decoupled from the bulk.

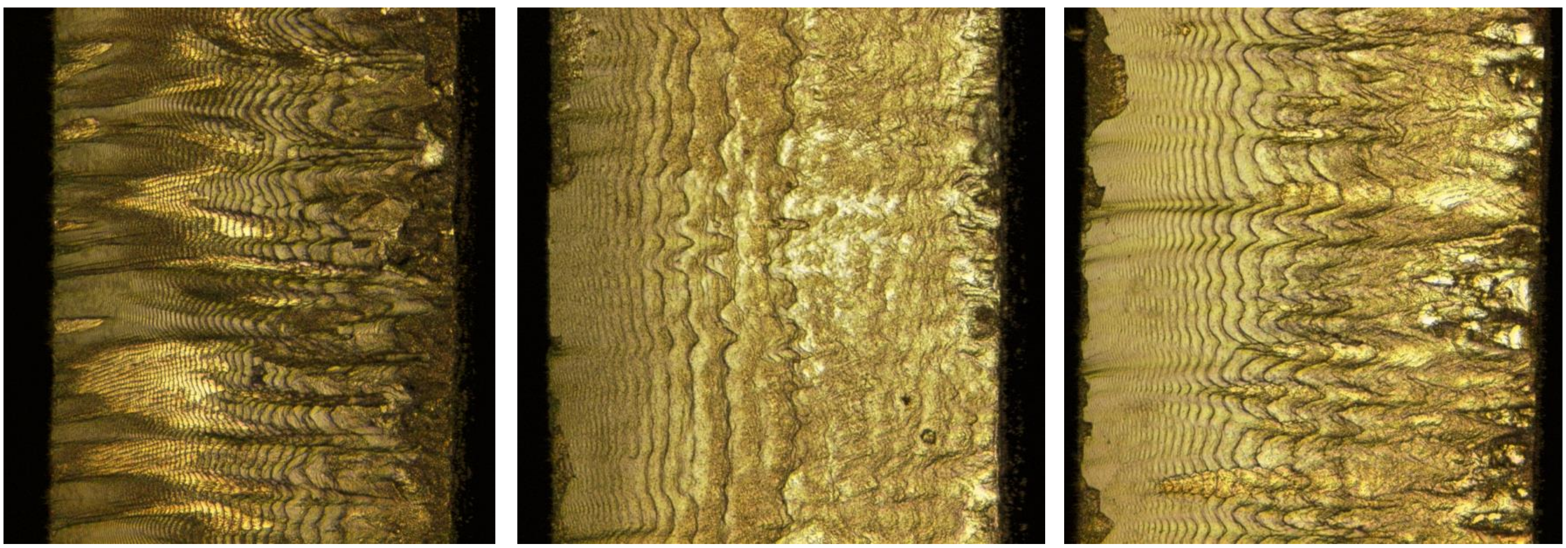

Figure 8: Images of the cut surfaces for varying pulse durations. (From L-R: 232 fs, 1000 fs, 5000 fs)

The main conclusion is that the pulse duration can easily be tuned to optimize the ablation rate, however to fully appreciate the effect of pulse duration on the average surface roughness of the cut samples, other parameters must be optimized in conjunction with pulse duration.

4.2 Influence of Overlap

The objective of this trial is to isolate and understand the effect of varying the pulse to pulse overlap has on the KPI`s outlined in table 2 for the processing of steel, and to project for the upscaling of applications to the 150W system. The overlap is isolated and varied.

The indication from the data is that the trend is for a decreasing average surface roughness with increasing pulse to pulse distance, i.e. decreasing overlap (%). This is inconsistent with the trends observed for processing of brass. As with the study into the influence of pulse duration on the processing of steel, mechanical pressure was required to decouple the sample parts from the bulk material, which potentially influences the surface quality. Inspection of the cut surfaces (fig. 8) shows that the surface is comparatively more homogeneous at a lower pulse to pulse distance (higher overlap).

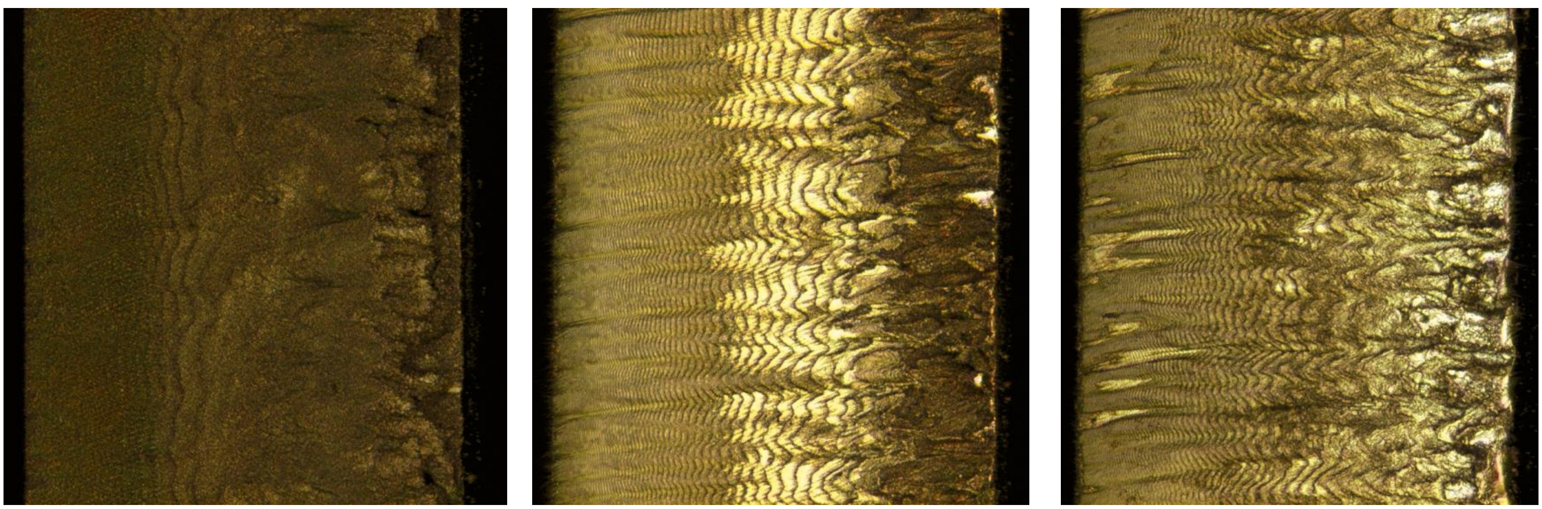

Figure 9: Images of the cut surfaces for varying pulse to pulse distance. (From L-R: 1.4 µm, 7 µm, 14 µm)

4.3 Influence of pulse energy

The objective of this trial is to isolate and measure the influence that varying the laser pulse energy has on the processing of steel.
The pulse energy is altered by varying the repetition rate for a fixed average power; this alteration in rep rate is compensated by using the pulse divider functionality of the system, such that a constant effective rep rate of 60 kHz is achieved.

The trend emerging from the data is that the surface roughness improves with increasing pulse energy; consistent with the trend observed for the processing of brass.
Analysis of the surface images in fig.9 shows a change in direction of surface burrs, which could indicate some kind of mechanical stress (twisting or turning) in the material. Fig.9 clearly shows an improvement in surface quality with increasing pulse energy.

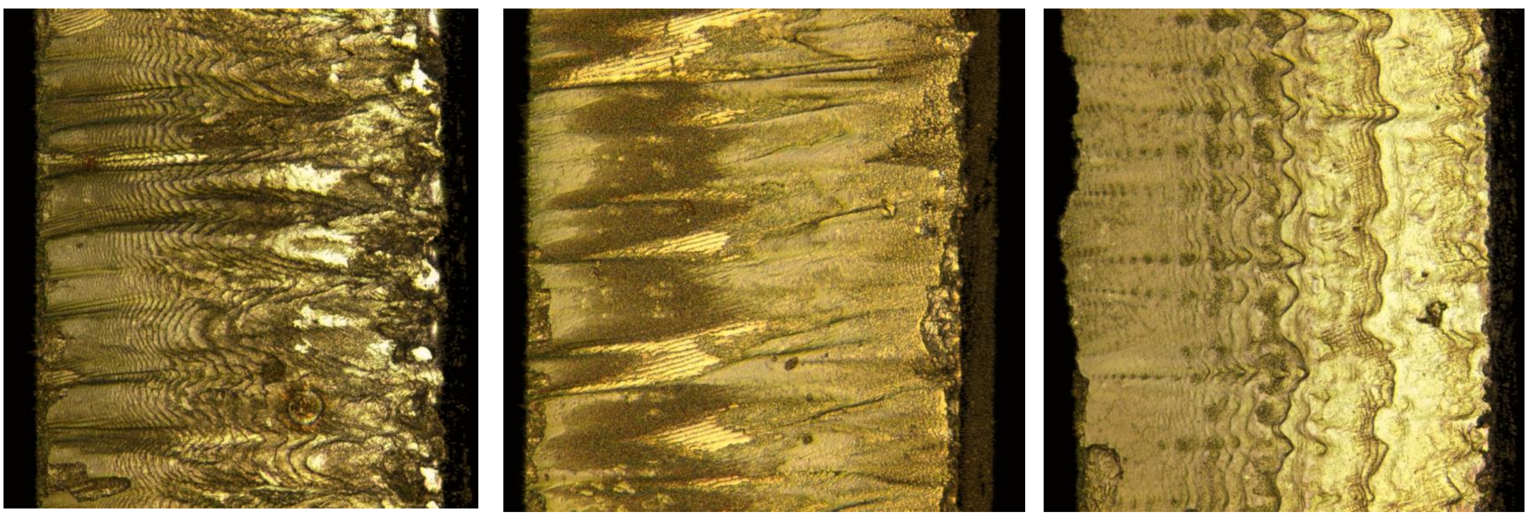

Figure 10: Images of the cut surfaces for varying pulse energy. (From L-R: 55 µJ, 70 µJ, 83 µJ)

For the upscaling of the process to the demonstrator 2 system, it is expected that pulse energies well above 83 µJ will be required to achieve the required surface quality (Ra ≤ 0.1 µm). The results presented here indicate that at 83 µJ, and with the current processing parameters a surface quality of 2.41 µm can be expected, with a net processing time of 48s. This corresponds to a net cutting speed of 30mm/min which is a factor of 13 below the KPI.

The upscaling of this process to the demonstrator 2 system will involve a five-fold increase in rep rate with an associated 3.6-fold increase in pulse energy (300 µJ, available at 330 kHz). In order to achieve the target KPI's, the interdependency of the processing parameters needs to be exploited, which has not been considered here. The central conclusion to be drawn here is that a trend of improving processing quality has been observed with increasing pulse energy.

5 Conclusion

Considering the process of cutting of brass, the first conclusion which can be made is that achieving the target KPI for net cutting speed should initially be relatively straight forward. Trials on the optimization of the number of passes for the 5W system indicate that with linear scaling, an effective cutting speed of 900mm/min can be expected. However, this estimation is based on cutting speed where the surface quality is still at an unacceptable level. In reality to achieve the quality related KPI one can expect a much-reduced cutting speed. Additionally, one of the first tasks on the up-scaled system will be to optimize the number of passes based for each material based on the material removal rate.

A clear correlation between the overlap and the surface roughness has been established. Low galvo-scanner marking speeds when processing brass (5 mm/s) and relatively large rep. rates means that larger overlaps (pulse to pulse distances are of the order of 0.1 µm for a 25 µm spot size) produce optimized surface quality. Thus, in the up scaled system we can expect to require high rep rates in line with high scanning speeds which will be required to reach the KPI´s. It is expected that the main challenge here will be reducing the overlap distance while preventing any harmful thermal saturation effects. The indication is that high pulse energies > 200 µJ (for a 25 µm spot size) will be required for the final system, which in addition to the high rep. rates projected for minimizing the pulse to pulse overlap distance, gives a strong indication that using the full power available will give us the best chance to achieve our KPI´s concerned. The effect of the pulse duration below 1ps appears to be limited to the improving ablation efficiency, which has been extensively studied; no correlation between modifying pulse duration and surface roughness for brass can be made for pulse durations below 1000 fs.

The results for the processing of stainless steel also indicates the overall trend that in order to have a chance of achieving the target KPI`s high pulse energies >> 83 µJ (tested here) (for a 25 µm spot size) and high rep rates >1 MHz will be required. Again, the influence of pulse duration below 1000fs appears to be limited to improving the material removal rate, as no effect on surface roughness can be established. The trend established for the influence of the pulse to pulse overlap for the processing of brass cannot be applied to steel. As steel is processed at much higher galvo-scanner marking speeds (approx. 500 mm/s) the available pulse to pulse overlap distances with the current set up are larger (approx. 5 µm). It appears that an optimal pulse to pulse overlap distance exists and the trend is not as straight forward as improved surface roughness with increasing overlap (as is the case for the processing of brass). The results indicate that consistent with the processing of brass, one sees an improvement in the processing quality with increasing pulse energy. One of the first challenges with the up scaled system will be to optimize the pulse energy, which should reach an optimal value (in terms of fluence) just above the threshold (Neuenschwander et al. [6]).

The study presented focuses on understanding the influence the selected processing parameters have on the processing efficiency when treated in isolation. The advantage in doing so it that qualitative trends can be established, which are of prime value for the upscaling to the demonstrator 2 system. For the final process development on the up-scaled system, further optimization can be achieved by capitalizing on the interdependencies of the various processing parameters.

[6] Neuenschwander, B., Jaeggi, B., Schmid, M. and Hennig, G., 2014. Surface structuring with ultra-short laser pulses: Basics, limitations and needs for high throughput. *Physics Procedia*, *56*, pp.1047-1058.