New random trigger-feature for ultrashort-pulsed laser increases throughput, accuracy and quality in micromachining applications

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ABSTRACT

For most micromachining applications, the laser focus has to be moved across the workpiece, either by steering the beam or by moving the workpiece. To maximize throughput, this movement should be as fast as possible. However, the required positioning accuracy often limits the obtainable speed. Especially the machining of small and complex features with high precision is constrained by the motion-system's maximum acceleration, limiting the obtainable moving spot velocity to very low values. In general, processing speed can vary widely within the same processing job. To obtain optimum quality at maximum throughput, ideally the pulse energy and the pulse-to-pulse pitch on the workpiece are kept constant. This is only possible if laser-pulses can be randomly triggered, synchronized to the current spot velocity. For ultrafast lasers this is not easily possible, as by design they are usually operated at a fixed pulse repetition rate. The pulse frequency can only be changed by dividing down with integer numbers which leads to a rather coarse frequency grid, especially when applied close to the maximum used operating frequency.

This work reports on a new technique allowing random triggering of an ultrafast laser. The resulting timing uncertainty is less than ±25ns, which is negligible for real-world applications, energy stability is <2% rms.

The technique allows using acceleration-ramps of the implemented motion system instead of applying additional override moves or skywriting techniques. This can reduce the processing time by up to 40%.

Results of applying this technique to different processing geometries and strategies will be presented.

Keywords: Ultrashort pulsed laser system, microprocessing, micromachining, random triggering, increase throughput, synchronization, galvo scanner

1. INTRODUCTION

For the optimization of a high throughput and high quality ultrafast laser micromachining process different factors have to be considered. Ideally,

1) Each emitted pulse (or burst of pulses) has the same, optimized energy. This maximizes the specific material removal rate (i.e., ablation efficiency) throughout the process.[1, 2, 3, 4]

2) Each pulse is evenly spaced on the workpiece with an optimized pitch.[5] This minimizes heat affected zones (HAZ) and ensures consistent process quality.

Because the moving spot velocity can vary widely during a processing job, spatial pulse spacing can only be held constant if the pulse repetition frequency (PRF) of the laser follows the scanning speed. From an application point of view, the ideal ultrafast laser would take a black-box approach. This means the laser would accept the arbitrarily-timed electrical-trigger pulses provided by the system component being responsible for the relative movement between the laser beam and workpiece, for example a galvo-scanner controller card or a motion-system. The laser would then emit constant energy optical pulses with minimum timing jitter to minimize spatial jitter on the workpiece. Unfortunately, such ideal ultrafast lasers do not yet exist and most applications hold the PRF constant. To maximize process quality, however, the system

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still needs to maintain even pulse spacing, at least approximately. Scanning velocity can be kept constant throughout the job by operating at the slowest speed required, as determined by the most complex features. This approach is often inefficient and may even make a process uneconomical. Alternatively, the job can be run using variable speed. In this case, pulses will be more densely spaced at slower speeds. However, this often leads to unwanted thermal effects and lower process quality. In effect, the lack of an ideal ultrashort pulsed laser results in a compromise of throughput, quality, or both. For many of today's ultrafast laser applications and markets, this is a significant limitation.

1.1 Shortcomings of pseudo-triggering

Pseudo-triggering is widely used to introduce a measure of flexibility with respect to the timing of the optical pulses when using ultrafast lasers. Pseudo-triggering typically takes one of two approaches, each with their own limitations:

1) Pulse-on-demand (PoD): With PoD, a pulse-picker is located just before the laser's beam exit. The pulse-picker's basic function is to transmit or block any amplified pulses that enter the PoD. This is often called a "trigger function" since it can be configured to transmit one optical pulse upon receiving one external trigger pulse. However, PoD cannot provide true trigger functionality. This is because PoD is just a pulse gating mechanism and so cannot alter the pulse timing. In other words, it does not trigger the generation of optical pulses; rather, it can only select pulses from an often rather slow pulse train at its input. If the PoD receives a trigger at an arbitrary time, there is usually no amplified pulse available, so there is nothing to transmit and the PoD has to wait for the next regular pulse to arrive. The end result is that the timing of optical pulses with respect to the trigger is fairly random. This inhibits accurate positioning of pulses on the workpiece.

2) Trigger/SYNC: Some ultrafast lasers locate the pulse picker after the seed laser; i.e., before the amplifiers. The advantage with this positioning is that pulses from the seed laser have a very high repetition rate. This gives the pulse picker more pulses to choose from, in principle making more accurate pulse timing possible. However, arbitrary triggering before the amplifiers can result in considerable pulse energy fluctuations and potentially damage the laser. For this reason, access to this pulse picker is usually restricted to a few special cases, such as for occasional timing jumps (useful for polygon scanners) and repetitive external triggering within a predefined and rather limited PRF range. [6]

The primary difference between these two methods is a tradeoff between stability and jitter. PoD provides optical pulses with excellent energy stability but large timing jitter. Trigger/SYNC, in contrast, provides optical pulses with reasonable timing jitter but poor energy stability. The two methods can be combined to create a compromise that may be acceptable in some specific cases. Unfortunately, combining the two methods typically achieves pulse energy variations around 10-20% with timing jitter on the order of a microsecond. This is far from what today's applications need.

1.2 New random trigger-feature

To overcome the stability and quality limitations of pseudo-triggers, we introduce a new random trigger feature called AccuTrig™ (from "Accurate Triggering"). This feature is offered by Lumentum Inc. for its PicoBlade® 2 micromaching lasers and future ultrashort-pulsed laser models. [7]

The performance of any laser trigger function is characterized by its pulse energy fluctuations and the timing jitter (electrical to optical) under irregular or arbitrary triggering conditions. Arbitrary refers to those times when the PRF may not be well-defined. Even under such challenging conditions, AccuTrig achieves energy fluctuations on the order of 1-2% root mean square (RMS) with a timing uncertainty of less than ±25 ns. This level of stability and accuracy means that even at relatively fast scanning speeds of 20 m/s, the pulse positioning uncertainty on the workpiece stays below ±0.5 µm, which is negligible for almost all practical micromachining applications. AccuTrig can be used in single-pulse operation as well as with FlexBurst™ capabilities, with MegaBurst™ technology that enables the highest burst energies on the industrial laser market, and real-time power modulation capabilities.

1.3 Benefits of the new random trigger-feature

A random trigger feature offers several benefits over pseudo-triggering in real-world applications:

1) Higher throughput through reduced processing time. A random trigger can increase the throughput in multiple ways: using the acceleration- and deceleration ramps of a galvo- or motion system already for the laser process eliminates extra ways introduced by lead-in and lead-out moves (e.g. skywriting). It can be shown that this can reduce the processing time by up to 40%. Because the laser PRF can follow the current moving-spot velocity, a process can run at any time at the respective maximum possible speed for specific geometry-features rather than the lowest speed defined by the smallest feature of the whole geometry.

2) Improved quality. Keeping the lateral pulse-overlap constant keeps surface roughness and engraving depth consistent and well under control.
3) Improved accuracy. The superior timing-jitter practically eliminate position jitter on the workpiece leading e.g. to steeper wall angles and higher spatial resolution, especially for multi-pass processes. It also eliminates the need for difficult synchronization-mechanisms between the laser source and the beam steering system. [5, 8]

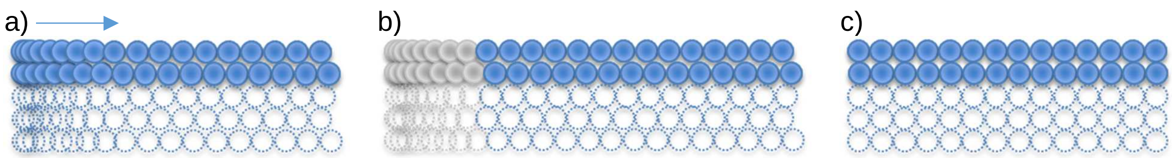

Figure 1. Beginning of a marking (vector- or raster-based): a) standard setup, leading to deep marks at the edge, b) skywriting, requiring extra time, and resulting in uneven edge, c) AccuTrig (eliminating the need for skywriting and synchronization)

2. THEORY

To determine the potential reduction of processing time using AccuTrig over conventional skywriting techniques, we use for simplicity the example of marking a straight line with constant pulse overlap. Such a line consists of three different sections: first a constant acceleration of the part in motion (mirror or stage), second a section with constant velocity and last a constant deceleration down to zero velocity. This results in the velocity versus time diagram of Figure 2.

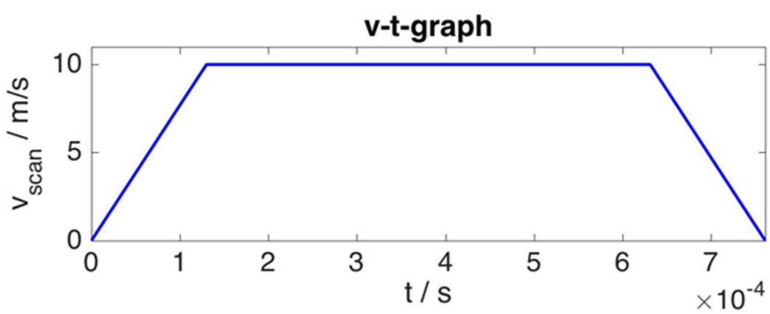

Figure 2. v-t graph for a mark length of 5 mm and an acceleration / deceleration value of 76'800 m/s^2. [9]

The lengths of the individual sections in time and space depend on the target constant velocity, the marking length and the maximum acceleration provided by the system. When using a constant PRF from the laser and skywriting technique, only the section with constant velocity can contribute to the marking process. The time for one motion sequence and equal values for the acceleration and the deceleration then reads:

$$t_{tot,1} = 2 \cdot t_a + t_v = 2 \cdot \frac{v_{const}}{a} + \frac{s_{mark}}{v_{const}}$$

with the acceleration and deceleration a, the constant speed v_{const} and the marking length s_{mark}. Depending on the length of s_{mark} there exists an optimum velocity, leading to a minimal processing time. This optimum velocity is not necessarily the maximum velocity of the motion system. Especially for short marking lengths, if the target marking speed is increased beyond the optimum speed, acceleration- and deceleration times exceed the time reduction of the higher speed during constant velocity period, such that the final processing time increases. The optimum velocity using skywriting can be described by: [9]

$$v_{opt,1} = \sqrt{\frac{s_{mark} \cdot a}{2}}$$

It should be noted that describing this optimum velocity as a function of the marking length shows a fast increase of the optimum velocity which often exceeds the maximum speed offered by the scanning device. Therefore only for small structure lengths the optimum velocity can be chosen to minimize the total machining time. For larger structures always the maximum speed of the scanner has to be used.

With a random trigger functionality (AccuTrig), the sections with varying velocity can be used for the marking process, such that the marking length s_{mark} has to be divided into $2\cdot s_a$ (for the acceleration/deceleration sections) and s_v (for the section with constant velocity), which can be calculated to be:

$$s_v = s_{mark} - 2 \cdot s_a = s_{mark} - \frac{v_{const}^2}{a}$$

With

$$t_a = \frac{v_{const}}{a} \quad \text{and} \quad t_v = \frac{s_v}{v_{const}} = \frac{s_{mark}}{v_{const}} - \frac{v_{const}}{a}$$

the total marking time with AccuTrig then reads:

$$t_{tot,2} = 2 \cdot t_a + t_v = \frac{v_{const}}{a} + \frac{s_{mark}}{v_{const}}$$

and the optimum velocity is given by:

$$v_{opt,2} = \sqrt{s_{mark} \cdot a}$$

which means that the optimum velocity is higher for the same marking length when using the random trigger functionality.

Setting the absolute processing times into relation delivers:

$$\frac{t_{tot,1}}{t_{tot,2}} = \sqrt{2} = 1.41$$

This means that in the given example, if both processes are run at their respective optimum velocity, marking with a fixed PRF and skywriting takes about 40% longer than using AccuTrig and a speed-dependent PRF-control. Of course this is just an estimate because of the oversimplified model. In real-world system, there cannot be an abrupt change between the acceleration phase and the constant-velocity section but more of a smooth transition. This transition will add time to the acceleration section, such that the above mentioned ratio will become even larger. On the other hand, if the acceleration is not constant but increasing over time, the ratio can also become smaller.

3. EXPERIMENTAL SETUPS

Two different experimental setups have been implemented. Both setups use a PicoBlade® 2 laser source from Lumentum, generating 10-ps pulses. All experiments have been conducted with 1064 nm wavelength.

3.1 Fixed-optics setup

The focusing optics in this setup has a focal length of 16 mm. The laser beam is routed through a beam expander and a λ/4-waveplate for circular polarization. The resulting $1/e^2$ spot diameter is about 2 µm (calculated). The workpiece is moved underneath the optics with an XY-table from Aerotech (model PlanarDL 200) which offers a travel of 200 mm at a maximum velocity of 319 mm/s for the individual axes. The motion controllers are equipped with DualPSO capability (PSO: Position Synchronized Output), delivering a position-synchronized trigger output in the addressable XY-plane. This allows processing with equidistant pulses on the workpiece.

3.2 Galvanometer-scanner setup

The galvo-scanner used in the experiments is a watercooled intelli*SCAN* III 14 head from Scanlab. The laser beam is routed through a beam expander before it is coupled with two mirrors into the galvo head. Right before the scanner a λ/4-waveplate is installed, generating circular polarization. Using a 100 mm telecentric focusing lens results in a $1/e^2$ spot diameter of 20 µm. For all experiments Scanlab’s speed dependent laser control feature of the RTC controller card is used to obtain a laser trigger signal proportional to the effective moving spot velocity on the workpiece.

4. EXPERIMENTAL RESULTS

4.1 Fixed optics experiments

For comparing the position-accuracy at varying processing speeds achievable with AccuTrig versus pseudo-triggering, spatially separated single pulses with a pitch of 6 µm are applied on polished silicon wafers as sample material. Using a moving spot velocity of 300 mm/s (being close to upper limit of the used motion system) a pitch of 6 µm means a laser PRF of 50 kHz. The laser spot is guided over the workpiece in a meander-like structure with varying radii at the turning points (Figure 3, left), creating a strongly varying moving spot velocity profile (Figure 3, right). The generated traces are then evaluated qualitatively at five different positions (Pos *1-5*).

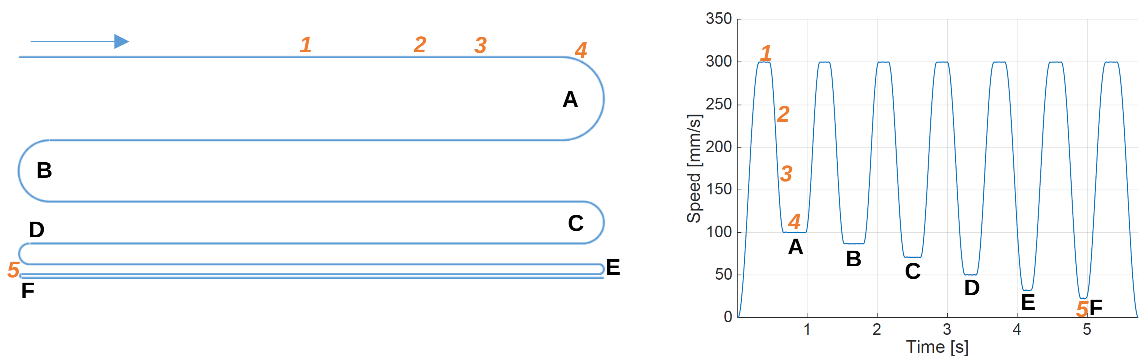

Figure 3. Left: Meander-trajectory with varying radii at the turning points (A-F: 10/7.5/5/2.5/1/0.5 mm), creating a strongly varying speed profile (right). The pulse pitch is then evaluated qualitatively along the trajectory.

In addition to the comparison between pseudo-triggering and AccuTrig, we also performed the same experiment using a constant PRF as a baseline.

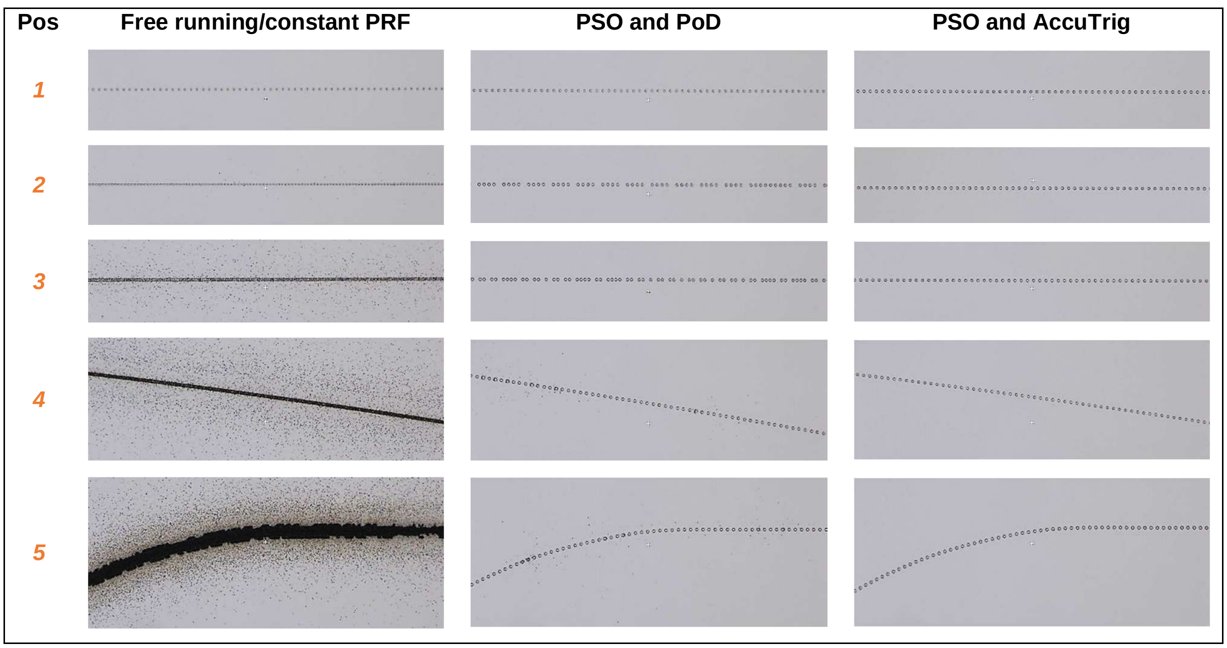

Figure 4. Single-shot processing of polished silicon wafers with fixed optics. Left column: free running laser with constant PRF; center column: pseudo-triggering using the PoD; right column: real random triggering with AccuTrig.
For the different listed positions, please refer to Figure 3, left.

Position *1* is in the center of the uppermost linear section. Here acceleration of the stage has been completed such that the moving spot velocity is constant. As a consequence, all three different strategies show the same results: evenly spaced pulses with a pitch of 6 µm. This is of course only true for the fixed PRF because all parameters were set to exactly match.

Following the linear section, the motion system starts to slow down in position *2*, such that it later can perform the turn with the required position accuracy (set such that the deviation from the programmed trajectory is <3 µm). Now the results between the three strategies vary significantly: the free running system with constant PRF shows close to equidistant pulse spacing but with reduced pitch. Due to a beat-note, pseudo-triggering shows repetitive gaps along the trace while the segments in between exhibit a reduced pulse-to-pulse distance. The overall number of pulses for a defined length is still the same as in the case of constant velocity (in our case 58 pulse for the observed segment) such that in average, the pulse-pitch is still 6 µm along the trace, but as can be clearly seen, locally the pitch varies significantly. This variation can cause significant quality-issues in real world applications. The AccuTrig sample still shows an equidistant, constant pulse-to-pulse distance of 6 µm.

Moving further along the trace to position *3*, where the stage slows down even more, this behavior is further enhanced: for the constant PRF, the pulses start to overlap, such that the surface is engraved, generating some debris. Pseudo-triggering shows a strong position-jitter of the individual pulses leading to unevenly distributed gaps along the trace while AccuTrig still delivers perfectly equidistant pulses at the programmed pitch of 6 µm.

In position *4* the situation changes. Because the stage has reached a constant velocity again which is about a third of the nominal speed, pseudo-triggering and AccuTrig generate the same results: equidistant pulses with correct pitch. This task is easier to accomplish for pseudo-triggering, as it has three times more pulses to choose from. For the free running laser the pulse overlap increases further such that the engraving generates more debris.

Position *5*, which is at the entry of turn F, shows the same results. The constant velocity in the turn is now ten times slower than the nominal speed leading to very severe damage of the sample in case of the free running laser. Pseudo-triggering and AccuTrig still deliver good results.

To summarize above observations: 1) a free-running laser with constant PRF cannot generate high-quality results when the moving-spot velocity varies strongly within a processing job. 2) for processing tasks with strongly varying speeds, pseudo-triggering can perform well only in sections with constant velocity. In Sections with velocity gradients, the position jitter of the released pulses strongly compromises the resulting process-quality. 3) AccuTrig performs well in the above described scenario. Due to its low energy fluctuations of <2% RMS and its low timing jitter of < ±25 ns it delivers consistent quality over a wide range of quickly varying processing speeds with high accuracy. Therefore it allows to operate a given motion system always at its maximum possible speed, reducing processing time and therefore increasing throughput.

4.2 Galvo-scanner experiments

Two experiments have been conducted with the galvo-scanner setup. To verify the above mentioned theoretical considerations and calculations and thereby determine the potential of AccuTrig to reduce processing time while maintaining or improving the processing quality, the scanner setup is used in a first experiment to ablate 2x2 mm^2 squares out of copper. As in above considerations, the squares are ablated with straight lines in one direction only (left to right). The line pitch is chosen to be 5 µm which corresponds to a line-overlap of 75%. For simplicity and to avoid distortions in the depth-profile of the resulting recesses, the processing is conducted with a unidirectional scanning mode using an equal scanning- and jump-speed of 2.5 m/s. Using a PRF of 420 kHz results in an inline overlap of 70.2%. To maximizing the ablation efficiency, an average power of P_{av}=1.39 W is used resulting in an optimum laser peak fluence of 2.1 J/cm^2. [1] Each square is processed with 100 layers. Three different processing strategies are applied: first a normal scanning mode, meaning the laser is operated at a constant PRF and acceleration as well as deceleration-sections of the movement lie within the processing geometry. The second strategy uses skywriting, which is today's most commonly used strategy. Again the laser is operated at constant PRF but acceleration and deceleration are performed in additional lead-in and lead-out moves, lying outside the processing geometry. The laser processing is only conducted at constant velocity resulting in equidistant pulse spacing. The third strategy again uses acceleration and deceleration ramps inside the geometry but this time with variable PRF, adapted to the effective scanning speed, using AccuTrig to ensure equidistant pulse spacing.

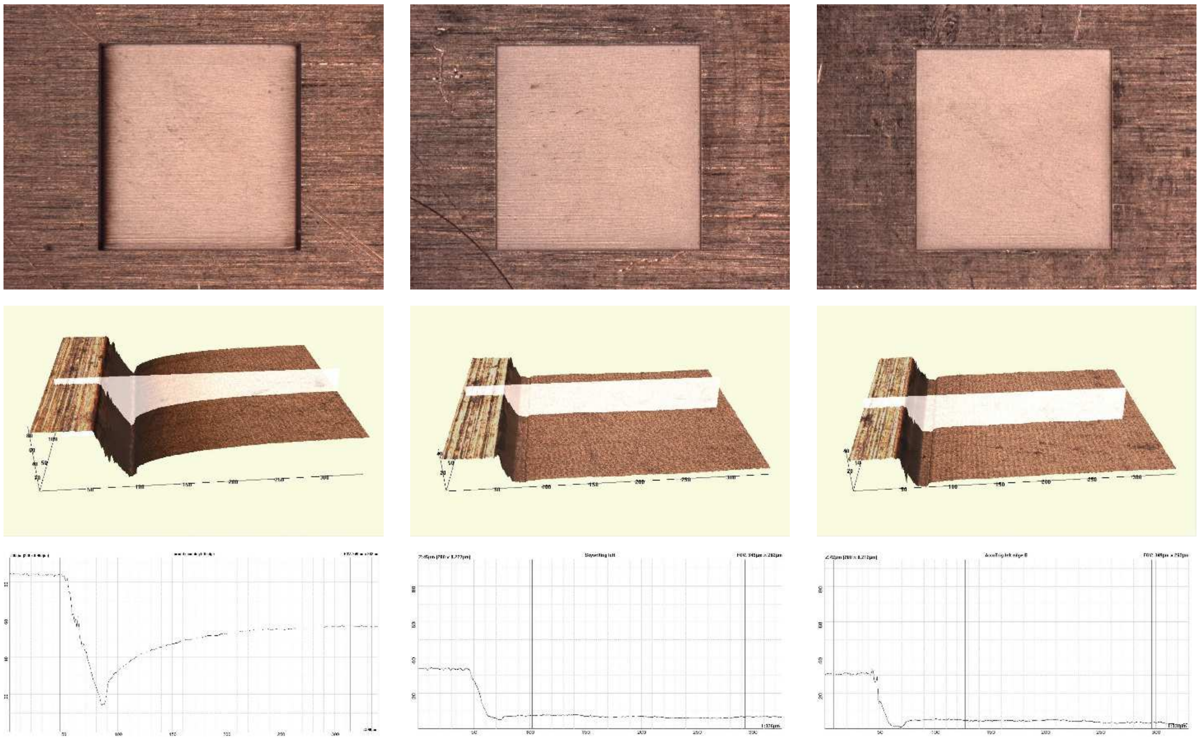

Figure 5. Squares ablated in copper: a) using normal scanning mode and constant PRF, b) using skywriting and constant PRF, c) using AccuTrig and speed-dependent PRF. Top row: overview microscope-image at 50x magnification, middle row: 3D-profile, bottom row: 2D cross-section.

All three squares have basically the same depth in the center of the geometry. Using normal scanning mode leads to deep grooves at the left and right edges of the geometry, and a strong curvature of the bottom surface. The grooves are more than twice as deep as the center part of the square. Also the skywriting- and AccuTrig squares show some small grooves along the edges of the geometry with a width of about 15 µm, but the bottom surface in both cases is evenly flat throughout the square. We assign the small grooves to reflections at the walls as they also appear at the top and bottom edge of the squares and therefore cannot be caused by wrong delays or similar settings. Why these grooves are slightly deeper in the case of AccuTrig compared to the skywriting-sample has yet to be determined. It should be noted here that the smooth surfaces of the squares for c) are obtained by introducing a small random shift in the starting position of each layer whereas an exact positioning would lead to a periodic pattern on the surface. [5]

When comparing the processing times, it is not surprising that processes a) and c) need the same time, as they employ the same scanning strategy. But compared to a) and c), process b), which is using skywriting, is about 50% slower. This nicely confirms our theoretical assumptions from above. As we can see, in a real-world system, due to physical limitation in the transition between the acceleration- and the constant velocity sections of the lines, we are slightly exceeding the simplified theoretical prediction. In this context and for a fair comparison we should mentioned, that in the case of process a) and c) we made a slight mistake with the delay-settings, such that the width of these squares is about 5% smaller compared to that of process b), which also has an effect on processing time ratio. Following Table 1 summarizes the obtained results.

Table 1. Summary of results obtained from squares ablated in copper.

	Normal scanning	**Skywriting**	**AccuTrig**
Processing time [s]	76	114	76
Engraving depth (in the flat) [µm]	27.6	26.8	27
Surface roughness S_a (in the flat) [µm]	0.27	0.33	0.28
Groove-depth (at the edge) [µm]	71	29.3	30.5
Groove-width [µm]	~150	15.5	17

The second experiment conducted with the galvo-scanner setup is cutting a thin stainless-steel foil with the following geometry (Figure 6):

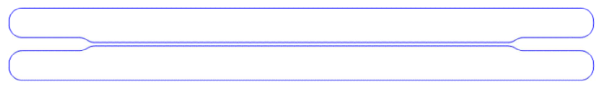

Figure 6. Cutting geometry for a thin stainless steel foil. The center “wire” has a width of 20 µm.

Essentially two longer stripes have to be cut out, leaving a thin “wire” of 20 µm width in the center. The radii in the taper leading to the center wire are 200 µm. This geometry was chosen as production with high throughput is difficult, because the scanning speed varies widely within the geometry, leading to undesired side effects. The nominal scanning speed is 2 m/s and the used laser PRF is 400 kHz. Again, two different processing strategies are used: standard-processing with constant PRF (Figure 7, left) and speed-dependent PRF using AccuTrig (Figure 7, right).

For the purpose of this publication we do not perform the full cut but only engrave about 3-µm deep grooves into the material, as this is more instructive.

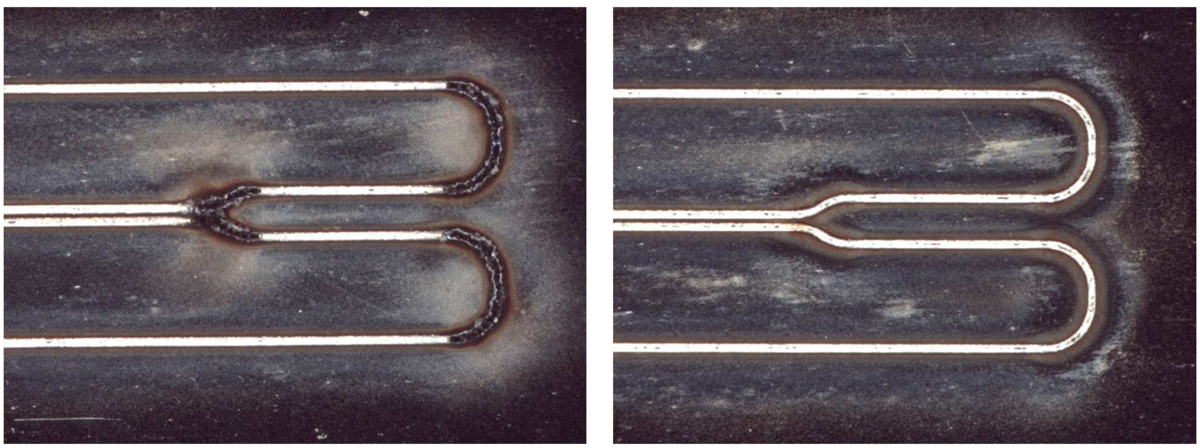

Figure 7. Cutting thin stainless steel foil: using constant PRF leads to strong melting effects, generating large burrs (left); using AccuTrig and speed-dependent PRF results in consistent quality over the entire geometry (right).

Because the scanning speed is dropping from 2 m/s on the straight lines to below 0.5 m/s in the curves, strong melting effects occur when using a constant PRF. These are generating large burrs and even lead to a breaking of the center wire from the taper. Using AccuTrig and speed-dependent PRF on the other hand results in a consistent process quality over the entire geometry.

5. CONCLUSION

We have shown that the new AccuTrig feature offering a random trigger option with a timing jitter of less than ±25 ns and a pulse energy stability of 1-2% RMS will lead to a tremendous increase in processing quality and/or speed for laser micromachining especially of small structures with ultra-short pulses:

- For surface structuring applications using a hatching process, a maximum reduction of the machining time of about 40% could be confirmed while maintaining the flatness of the bottom-surface at the edge of the geometry.
- For marking or cutting applications with almost random traces a constant pulse to pulse distance can be kept, even if the marking speed varies locally. This allows working always with the local maximum speed of the scanning device resulting in a reduction of the machining time, which can exceed one order of magnitude depending on the application.

Thus, the AccuTrig feature will help to increase the speed of many micromachining processes and significantly improve their cost effectiveness.

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