ULTRA^3

Ultra-short, ultra-fast and ultra-precise laser machining by a new synchronisation technique

Ultra-short laser pulses (USP) with durations in the range of a few picoseconds (ps, 10^{-12}) down to a few hundred femtoseconds (fs, 10^{-15}) are gaining importance for industrial laser micro-processing. Applications such as the drilling of injection nozzles, cutting of chemical strengthened glasses, trimming and surface structuring represent only a few processes already realised in industry. To illustrate the shortness of USP one should have in mind that light would only need 200fs to propagate the distance of 60µm (*ca.* thickness of a human hair).

When a USP is absorbed by a material, the interaction time is extremely short and the energy in the pulse is locally deposited in a very narrow range. On a surface this leads to an almost instantaneous removal of the material, and losses of the deposited energy into the surrounding region by heat conduction are minimised. Thus ultra-short pulses lead to machining with a minimum thermal load, respectively a heat affected zone, if applied in an adequate way with the highest level of quality. Due to these low thermal losses the energy is very efficiently converted, leading, especially for metals, to a significantly higher material removal compared to longer pulses. But to really take benefit of USP one has to consider a few aspects.

First, due to the very short interaction time and the very narrow deposition of the energy, only a small volume will be removed and the corresponding pulse energy rests at a low level, typically in the range of only a few µJ. Indeed the removed volume continuously increases when the average power is raised at a constant repetition rate, as illustrated by the blue bullets in Fig. 1 but this increase becomes less pronounced with increasing average power, i.e. the process loses efficiency and the machining quality drops significantly. In contrast, the removed volume per energy (red bullets), the specific removal rate, shows a maximum value at a certain average power, i.e. for a given pulse energy per area.

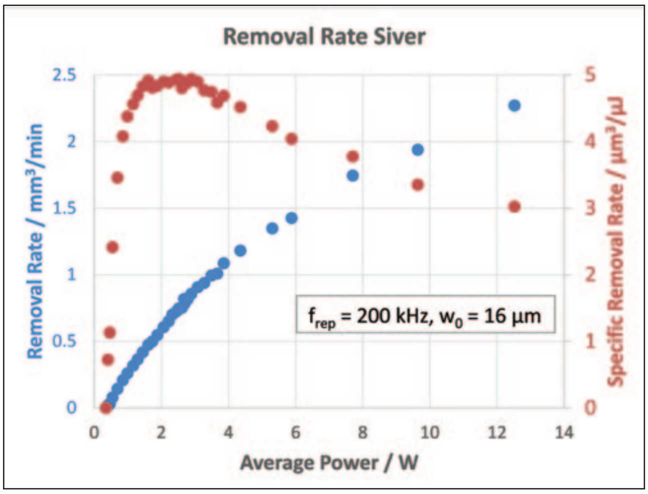

Fig. 1 Removal and specific removal rate for silver

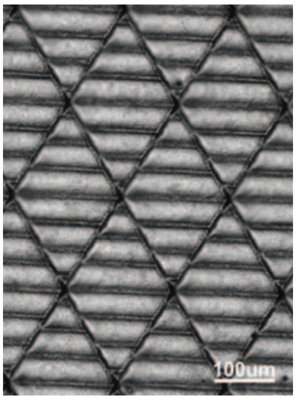

Fig. 2 Shark skin structure in steel

This is of course the desired working point where the deposited energy is converted with highest efficiency. As this point is given by an optimum pulse energy per area this value has to be kept constant when the average power is raised. This is realised by either increasing the number of pulses per cycle (repetition rate) or by increasing spot size and energy per pulse. To guarantee the precision needed for laser micromachining the latter is often not the method of choice, and efficient machining therefore demands high repetition rates. For the presented example and an average power of 10W the demanded repetition rate would already amount 800kHz for silver and would even exceed 4MHz for stainless steel. Such high repetition rates can be offered by today's ultra-short pulsed laser systems.

Secondly, the overlap between two pulses should be in the range of 75% (or less) of the spot diameter to obtain a smooth surface and only moderate heat accumulation. For the upper discussed example (average power 10W, spot radius 16µm) this would result in a minimum marking speed of 9.6m/s for silver and more than 50m/s for stainless steel. Marking speeds up to a few 10m/s are today covered by modern galvo-scanners and speeds up to a few 100m/s are offered by polygon scanners. In recent experiments we could demonstrate that the ablation process is principally scalable to average powers above 300W for copper and brass with removal rates exceeding 40mm^3/min, whereas heat accumulation is strongly limiting the scale-up for stainless steel.

Thirdly, especially for 3D surface texturing, the highest level of precision is often demanded. The structures are usually divided into several slices and in each slice the areas which have to be machined are filled with a parallel hatch. Finally, these slices are marked one by one with a beam guiding system, e.g. a galvo-scanner. Basically, the structure is formed by marking parallel straight lines, which also has its challenges. Sharp edges and steep walls are obtained by switching on the laser pulse train simultaneously to the linear movement of the beam. But during the acceleration and deceleration phase the number of

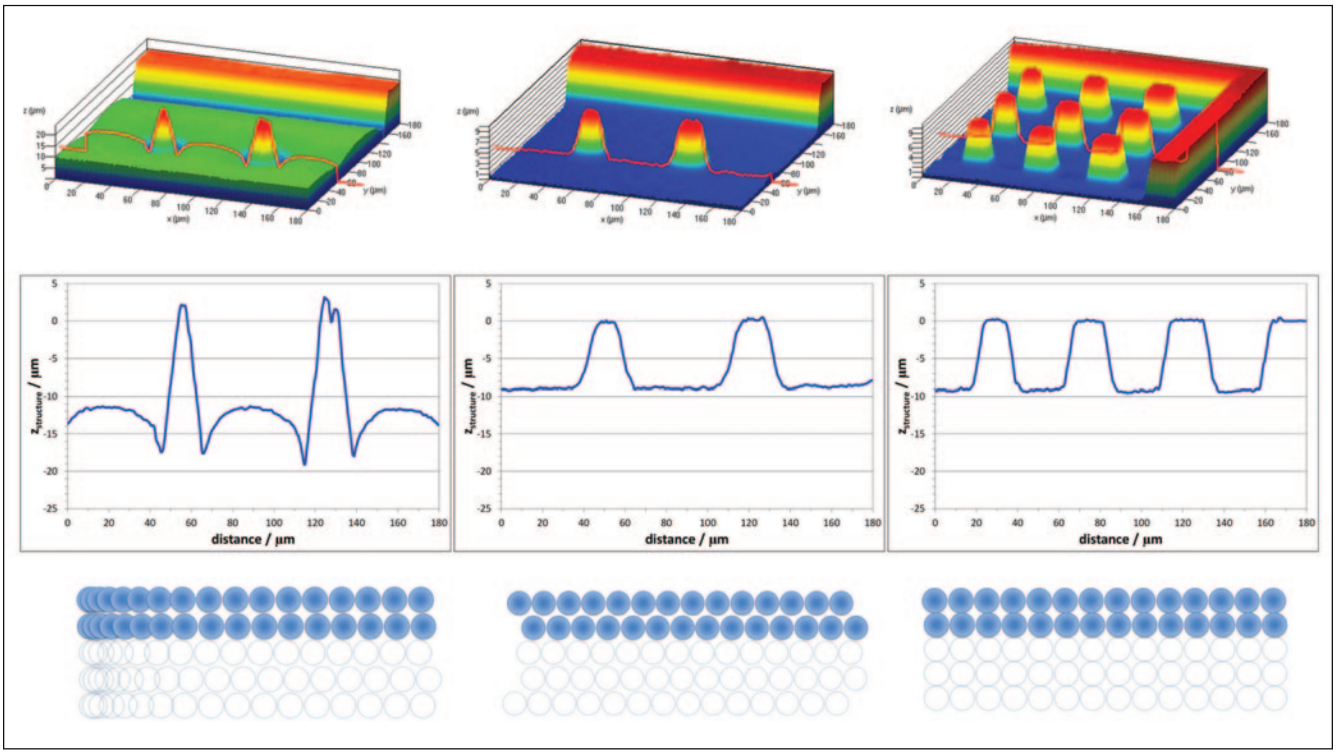

Fig. 3 Marking strategies with acceleration problem (left), Sky-writing (middle) and fully synchronised (right)

pulses per length is higher and a deeper marking at the borders will be obtained, as illustrated on the left in Fig. 3. This problem can be solved by the so-called 'sky writing' mode where the laser pulse train is switched on when the linear movement has reached its desired speed. But this results in a jitter of one pulse-pulse distance, leading to walls that are not as steep, as illustrated in the middle. Only if the pulse train and the linear movement are completely synchronised, as illustrated in the right panel, can sharp edges and steep walls be obtained with flat surfaces at the border.

Normally this synchronisation is obtained by a controlled, exact firing of the single laser pulses, a method which is not applicable to most USP laser systems. Here it is necessary to actively synchronise the mechanical movement of the beam guiding system with the laser pulse train, which is certainly not an easy task, especially for high repetition rates.

During the last four years the Institute for Applied Laser, Photonics and Surface Technologies (ALPS) and the Institute for Intelligent Industrial Systems (I3S) of the Bern University of Applied Sciences have worked extensively on this topic within different projects. As a result we have developed a special control for a galvo-scanner which guarantees that the single laser spots are placed with an absolute accuracy of ±2µm while the beam is moving with up to 24m/s (100mm objective). Or we can use a polygon line scanner reaching a marking speed of 100m/s (190mm objective) with an absolute accuracy of ±5µm for each spot. Metaphorically speaking this means that we hit a post of 10µm in width by throwing a ball from a car with a speed of 360km/h. We do this not by controlling the time when the ball is thrown but by controlling the movement of the car, i.e. the starting time and acceleration phase, in a way that we are at the desired position at the right time.

With this unique technology we are able to machine precise surface structures with high quality and the best precision at highest possible marking speeds. Due to these high speeds, which are not reached by conventional methods, we are able to deal with significantly higher average powers going with higher throughput. As an example we are able to treat steel 1.4301 with an average power above 40W and a repetition rate of 6.8MHz with the highest accuracy and quality. Fig. 2 shows a shark skin structure machined into stainless steel with this method.

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