# Hot or Cold Ablation – That's the Question

## A special simulation tool includes thermal effects for the optimization of ultrafast laser applications in material processing

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**A new generation of ultrafast lasers with high average powers and high repetition rates is coming to the market. Those systems in principle bring together high precision processing and high throughput. But with high average power thermal effects show up the demand for a careful process planning. A new simulation tool from Fraunhofer ILT incorporates such effects and allows for precise process optimization even at high average laser power.**

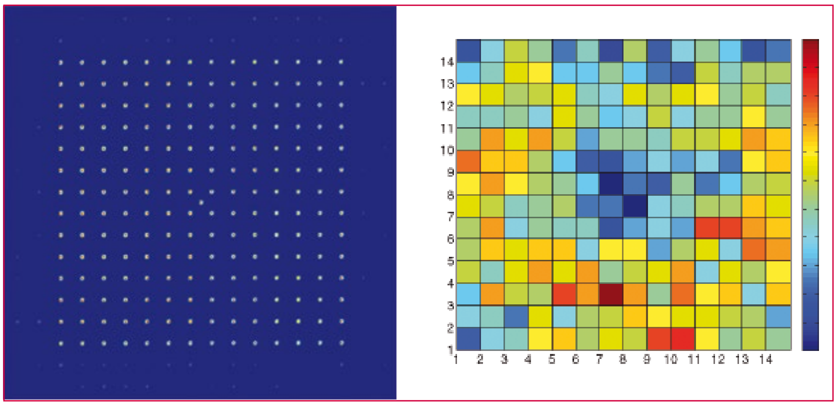

Fig. 1 Lateral spot position error (SPE) of a 14 × 14 beam matrix (left), overall power distribution of 14 × 14 beam matrix on a power meter sensor (right); visible local peak of power density. The power varies between 0 (blue) and 15 % (red; source: S. Eifel, Fh. ILT)

Ultrafast laser systems with their ps or fs laser pulses offer unprecedented precision and low debris for various kinds of material processing. This is well known for a long time already, but just recently high power ultrafast laser systems for industrial applications for high productivity became available. Today, every major laser system provider has an ultrafast laser in his portfolio.

Still, most of those systems have limited power and so the field of commercially interesting applications is also limited. This may change soon since a new generation of high power ultrafast system with average powers of more than 100 W is coming to the market.

When the ultrafast laser community convened in Aachen for the "4th UKP Workshop: Ultrafast Laser Technology" (cf. p. 59) recently, the advent of such new systems and its implications for industrial applications were a main issue. Now that the path towards higher average power is open, the research focus moves towards process technology and application opportunities.

Larger scale applications demand for high productivity. Since the spot size is rather limited, this is usually achieved via a higher processing speed with one spot, i.e. faster scanning. Or one may use multiple laser spots at once. In this article, we will restrict ourselves to multi-beam applications, although all procedures can be applied to fast scanning processes as well.

### About the not-so-cold ablation

In the 1990s ultrafast lasers became famous for their capability of 'cold ablation'. It meant that with the application of single ultrafast pulses material can be ablated without effecting surrounding areas through heat deposition. Until today this is an essential assumption for many biomedical applications using ultrafast pulses such as eye surgery.

Although it contradicts elementary physical understanding, this idea is very persistent. 'Cold ablation' means that ablation and final heating are separated in time due to different time scales for pulse duration and electron-lattice relaxation time. Typically, the electron-lattice relaxation time in metals is in the order of a few up to ten picoseconds. The extreme case of a cold ablation is spallation, where the dominant mechanism is mechanical rupture. Even in spallation after the ablation itself, the ablated as well as the remaining substrate start to melt due to relaxation of mechanical stresses into heat [1].

A fundamental analysis of ablation processes with ultrafast pulses from a Swiss group led by Prof. Beat Neuenschwander brought the evidence that in particular overlaid pulses show substantial and detrimental thermal effects [2]. At low repetition rate, this may in-

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With nearly than 440 employees and more than 19,500 m² net floor space, the Fraunhofer Institute for Laser Technology ILT, founded in 1985, is one of the most important contracting research and development institutes of its sector worldwide. Its experts develop and optimize laser beam sources and laser processes. In close cooperation with its clients, it uses laser technology to solve tasks for production, measurement technology, environment, energy, medical technology and biotechnology, all done in real life situations.

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deed not be very relevant. At high repetition rates, the effect becomes visible and the ablation efficiency for ultrafast lasers drops down since thermal effects cumulate similarly to conventional ablation processes.

## What challenges to encounter for realistic ablation processes?

To predict the ablation process in complex realistic scenarios such as multi-beam processing, a detailed simulation of the physical processes during and after the laser absorption is required.

A first step for such an approach is a careful analysis of input parameters and relevant effects. Obviously, heat deposition through successive pulses is essential. Pulse parameters such as (effective) beam profile, pulse energy and pulse repetition rate are to be considered on the laser side. On the material side, the heat penetration processes have to be considered in detail.

For the multi beam approach, some specific considerations have to be taken: First, there is the question of energy distribution among all the beams of the pattern. A few percent difference due to variations in the diffraction efficiency of the micro-optics that generates the beam pattern out of a single beam may lead to severe deviations in the diameter in drilled holes, for example.

Furthermore, the treated surface may be curved or bended. Then the question of the focal depth of the various beams arises: Would it be large enough to warrant for similar focus sizes from all beams across the surface?

Finally, all these effects must be regarded together. Then questions arise such as: How large must the distance between two beams in a pattern be to avoid thermal interaction? Heat and tension effects across the whole workpiece area have to be encountered to find out correct setting for the laser and the process control.

## Simulation from micro to macro

An effective simulation of all those effects can help to gain process understanding and to find out which parameters are effective for achieving an improved ablation process. After all, the simulation tool from Fraunhofer ILT may help users to understand, which parameter is the knob to turn for a systematically optimized result.

It starts with a single beam. The beam is considered with its spatial distribution of laser fluence. The material parameters, the surface geometry and scanning parameters are included within the ablation model. This micro model allows for the calculation of the heat distribution and the surface evolution during an ablation process.

The next step is to encounter consecutive pulses. They evaporate more material and deposit more heat that is spreading out through the bulk material on a larger time scale than the ablation process. Taking the hole's shape into account, the temperature distribution is calculated over time.

Then the model can be expanded towards a multi-beam model. The energy distribution among the different beams of the pattern is taken into account. Heat flux from multiple holes processed in parallel is included.

This is a very relevant point: If there is a heat flux from multiple laser spots, than the beams in the center of a beam matrix may see increased temperatures on the material than beams on the perimeter which leads to different processing results and to distortion (Fig. 2). Furthermore, the thermal and mechanical properties of the material change with each piece of material removed.

In order to simulate the processing of larger workpieces, a macro perspective on the work piece is created, involving the effects of all beams as one unified heat source. Therewith it becomes possible to build a heat map over the total workpiece and to calculate the resulting distortion.

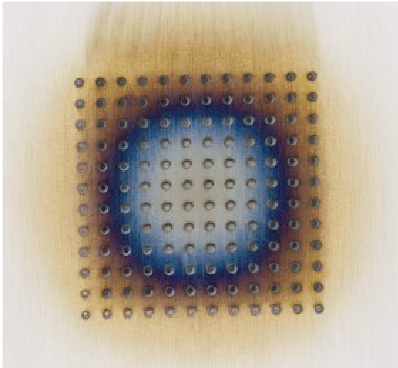

Fig. 2 Thermal flux between different holes of a pattern may lead to increased heat load in the center of the pattern. The annealing color in the center corresponds to a temperature of about 360 °C (630 K).

The simulation tool can be used to evaluate the chosen process parameters' influence and helps to identify the reasons for insufficient quality in process results such as shown in Fig. 2. There, the heat flow between the single spots is much too large and there might be substantial tensions as well. Fig. 3a shows the simulation result for such a process and heat as well as tension effects are well reproduced.

## What knobs to play with?

Within an optimization loop, various parameters can be optimized. There are pulse parameters, such as pulse energy, spot diameter or repetition rate. Then there are parameters of the pattern such as the spot distribution and the energy distribution among the spots. Also, different optics or filters can be introduced on that point. Fi-

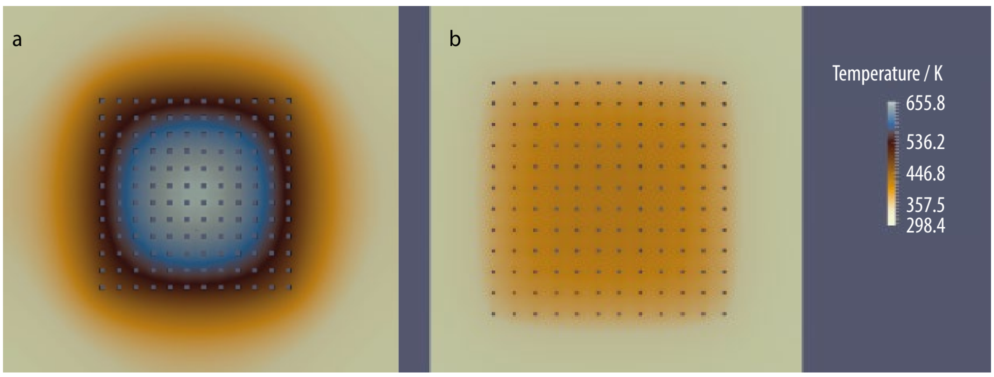


Fig. 3 A simulation with one shot on 12 × 12 beams with 100 µm distance shows that the thermal load is not homogeneous. The level of heating agrees well with that of the experiment shown in Fig. 2 (a).
For an optimization of the process shown in (a), the beam distance was doubled: The distance between adjacent beams is 200 µm. The extent of the beam pattern is doubled as a consequence. In order to realize small distances between the drilled holes, the whole beam pattern can be scanned in small steps (b).

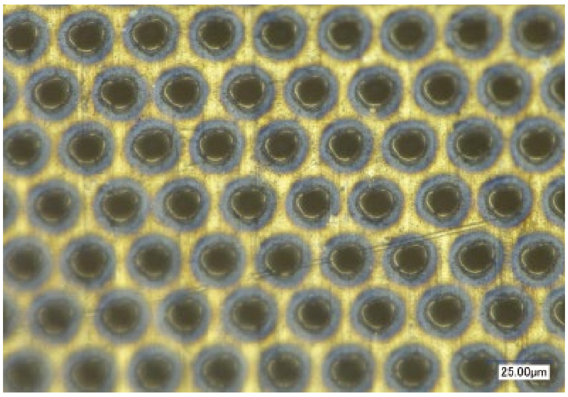


Fig. 4 The final result should be a large pattern of high quality drillings with a distance of 25 µm. The extension of the annealing colors is reduced.

nally, there might be additional process parameters such as cooling, or process gas that can be added to optimize the simulation result.

Fig. 3b shows the simulation result for the first shot of a successfully adjusted process. There, the distance between two drilling beams has been doubled from 100 µm to 200 µm. All beam parameters remained the same. The heat distribution across the processed area is flat, all laser spots "see" a similar surface temperature during the process. This is easily realized if large periodic patterns have to be drilled. For structures with small distance between the drillings, one may consecutively shift the whole beam pattern. The only restriction is that the distance between the beams has to be a multiple of the holes' distance.

Fig. 4 shows a fully perforated foil, achieved with an optimized process in brass. The holes are homogenous in size and shape.

## Perspectives

A simulation tool has been developed that is capable of simulating multi-beam as well as high-speed scanning scenarios or combinations of both. It may help prospective users of ultrafast lasers for material processing in two ways: In the phase of investment planning, the simulation may help to find out which range of machine parameters would be required for a typical range of applications.

For those who already own a laser processing system with ultrashort pulses, it allows for a better process understanding and subsequent process optimization. For a given application, an experienced user can determine a proper set of parameters for efficient processing while staying within given tolerances of the manufacturing precision.

For both cases, the development team from Fraunhofer ILT offers consulting support. The simulation software has been derived from a large scale FEM simulation model via model reduction which leads to a few minutes calculation time per simulation instead of several hours.

Still, the model is under constant improvement. New materials will be added as well as new hole shapes. Other development steps will allow for simulation of other ablation processes like laser water assisted ablation and ablation with millisecond pulses. Another task is the inclusion of feedback effects.

The simulation software is part of the wider Digital Photonic Production initiative of the Fraunhofer ILT. It considers light as the manufacturing tool of the future with highest energy density and almost unlimited precision. It also assigns a superior role to simulation tools as a means for the direct translation of construction data into workpiece properties. A detailed understanding of laser material processing and a close correspondence between simulated and experimental data are prerequisites for such tools.

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## Authors

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