Heat accumulation in metals under femtosecond irradiation: simulation and experimentation

Research on predicting the quality of laser processing of metals using femtosecond lasers for industrial purposes

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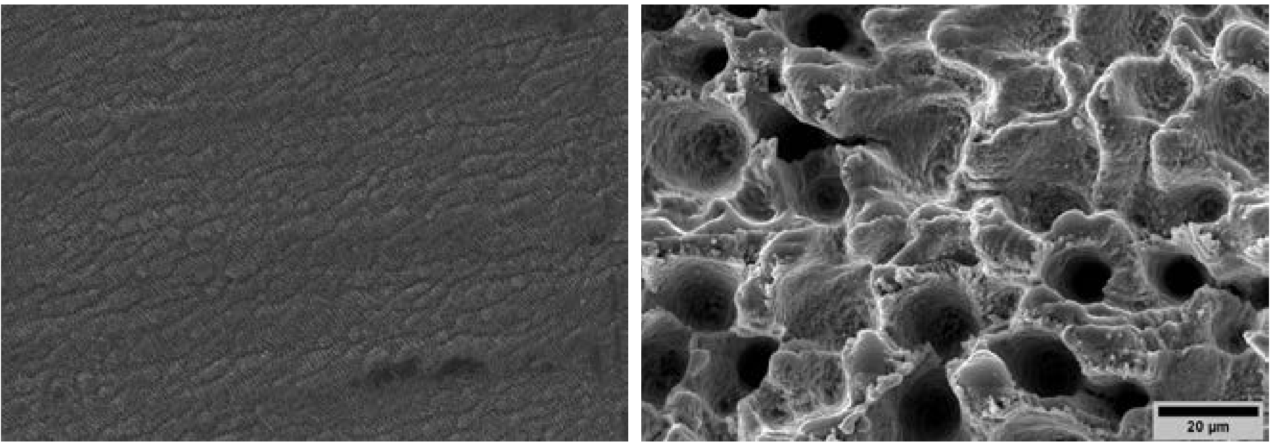

Source all images: LAMpAS Project

▲ SEM images of stainless steel surfaces ablated with a femtosecond laser at 500 kHz, 1 m/s scanning speed and increasing fluences (left to right)

Ultrafast laser micromachining results depend on both the processing parameters and the material properties. The thermal effects are negligible if a good combination of processing parameters is chosen. However, optimizing the processing parameters to achieve the required surface quality on a given material can be quite complex and time consuming. Within the framework of the European LAMpAS project, we developed a model to estimate the heat accumulation on a surface as a function of the laser fluence, scanning speed and line pitch. The simulation results were correlated with experimental ones. The predictions of the model allow evaluation of the heat distribution on the surface, and optimize the ultrafast laser micromachining strategy, yielding negligible thermal damage.

It has been thoroughly demonstrated in recent years that ultrafast lasers are excellent tools for ablating and micromachining virtually all types of materials. They allow the cutting, milling, etching and texturing of surfaces with micrometer precision and the resulting thermal effects are negligible, provided that an optimal set of processing parameters is used. Depending on the material and its thermal properties, if the processing parameters used are not good, typically by combining high fluences with high repetition rates and/or low scanning speeds, the thermal damage can often jeopardize the laser application due to the accumulation of residual heat in the surface regions remaining after ablation.

Aiming at increasing the throughput of ultrashort laser patterning, a high-power (1.5 kW), ultrashort laser operating at a repetition rates up to 10 MHz was used for direct laser interference patterning of surfaces at high scanning speeds, within the framework of the European LAMpAS project (www.lampas.eu). The interferences were created using a DLIP module, and a polygon scanner yielded beam scanning speeds of tens to hundreds of meters per second. Such high speeds, combined with an unconventionally large spot size, help to achieve a surface texturing rate of up to 2 m^2/min, taking full advantage of a high-power ultrashort-pulsed laser. An infrared camera monitored the irradiation zone in real time, and the treated part was verified using an analysis system based on fast-Fourier transform (Fig. 1). This laser-based nano/micro-texturing setup allows surface functionalization with antibacterial, anti-fingerprint and easy-to-clean properties that may be used to generate new decoration finishes.

The deposition of energy at such a rate, combined with the complexity of

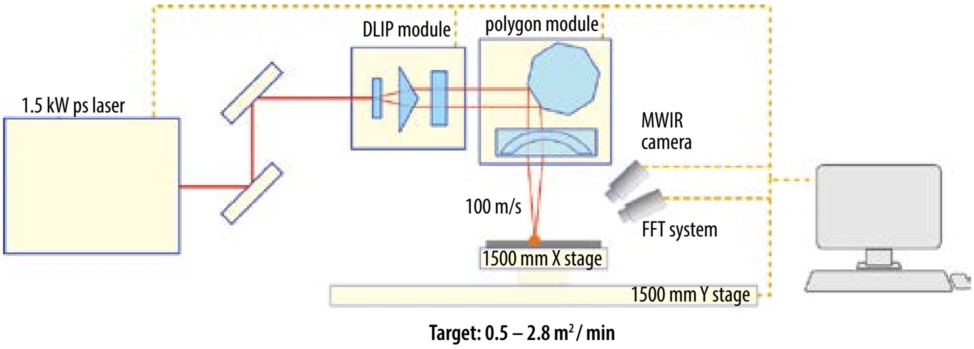

Fig. 1 Schematic illustration of the LAmpAS setup

the ultrashort-pulsed laser-material interaction, required careful management and optimization of the processing parameters to minimize the thermal damage. To this end, we developed a model to estimate the heat accumulation on a surface as a function of the laser energy deposition parameters and the way the beam moves throughout the surface.

Heat accumulation model

The extent of the thermal effects obtained under laser irradiation depend on the processing parameters and the thermal properties of the material. An approach to estimate the heat accumulation at the ablation surface consists of assuming that part of the deposited energy is not used in ablation or the vaporization/sublimation of the material, but remains in the target in the form of heat that then diffuses into the bulk (**Fig. 2**). This residual thermal energy can be quantified using a calorimetric setup, and accounts for about twenty to forty percent of the incident energy. The residual heat conduction through the material can then be analyzed within the framework of classic thermodynamics. The depth of material that is thermally affected depends on the deposited thermal energy and on the thermal properties of the material [1, 2].

According to Bauer et al. 2015, the temperatures reached by the material after irradiation with a single ultrashort laser pulse with energies leading to ablation can be estimated if we take into account that the heat is concentrated in the most superficial layer of the ablation surface in a time scale shorter than the time required for heat conduction to the bulk. This residual thermal energy can then be considered as an instantaneous superficial point heat source, and the temperature distribution below this surface after a single laser pulse can be calculated by applying the heat conduction equation. For a Gaussian surface heat source, the temperature distribution within an infinite homogeneous solid after a single laser pulse is given by:

$$T_{(x_c, y_c)}^{\text{single pulse}}(x, y, z, t) = \frac{2E_{\text{thermal}}}{\pi\rho c_p \sqrt{\pi\kappa t}\,(8\kappa t+\omega_0^2)} \exp\left[\frac{(x-x_c)^2+(y-y_c)^2}{4\kappa t}\left(\frac{\omega_0^2}{8\kappa t+\omega_0^2}-1\right)\right] \exp\left(\frac{-z^2}{4\kappa t}\right) \quad (1)$$

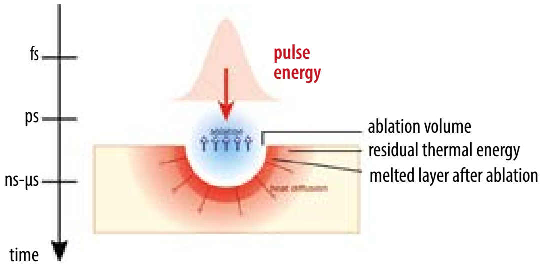

Fig. 2 Illustration of the energy distribution after ultrashort laser irradiation. Adapted from Bauer et al.

where $(x - x_c)$, $(y - y_c)$, and z describe the distances from the center of the point source (x_c, y_c), ω_0 is the spot radius at $1/e^2$ of the maximum intensity, t the time after the energy pulse, c_p the material average heat capacity, ρ the mass density and κ the thermal diffusivity.

For multipulse irradiation, the distance between pulses is $t_{\text{p-p}} = 1/\text{PRR}$, where PRR is the pulse repetition rate. If the beam is scanned on the surface at a speed v, the spot displacement is $dx = v \cdot t_{\text{p-p}}$ and has to be accounted for by adjusting the center coordinates of the gaussian beam. The temperature distribution after N pulses is thus given by:

$$T(x, y, z, t) = \sum_{n=0}^{N} T_{(x_{cn}, y_{cn})}^{\text{single pulse}}(x, y, z, t + n\,t_{\text{p-p}}) \quad (2)$$

Companies

LASEA

Created in 1999, Lasea is a high-tech Belgian SME which has unique expertise in the design, manufacture and use of laser systems for industrial purposes. More specifically, Lasea offers cutting-edge laser solutions capable of responding to the needs of companies whose production lines include plastic welding, marking, and surface treatment. Its laser products and services are expertise and prototype development, OEM systems, laser workstations and turnkey machines. Lasea is based in the Liège Science Park, allowing it to have strong partnerships with regional Universities and the Space Center. With presently 65 employees, Lasea has manufactured laser production lines all over the world (Europe, US, Australia ...).

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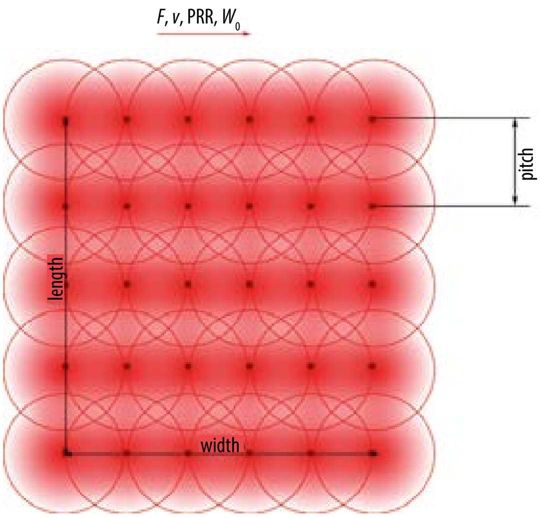

Fig. 3 Disposition of points at which the temperature is determined over an area produced by scanning the beam over parallel lines distanced by a pitch, with a certain fluence, scanning speed and pulse repetition rate.

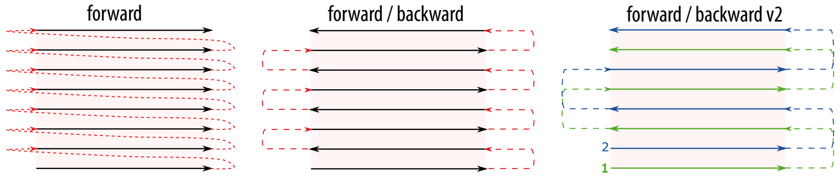

Fig. 4 Scanning strategies simulated. The continuous vectors represent the laser lines, and the dashed vectors represent the lead-in and lead-out lines causing the delays during the irradiation process.

This same approach can be used to determine the maximum temperature reached per point on a treated surface produced by hatching parallel laser lines that are distanced by a certain pitch with a determined speed and repetition rate, as illustrated in **Fig. 3**. We considered that heat propagates from the surface to the bulk of the semi-infinite solid equally in all directions (*x*, *y*, *z*). We tested three different scanning strategies, by moving the beam in relation to the sample forward, or in two different forward and backward patterns (see black lines in **Fig. 4**). To these lines we added the time delays corresponding to the acceleration and deceleration ramp times at the beginning and end of each line respectively, as illustrated by the red dashed lines in **Fig. 3**. This is the typical behavior of a beam moved in relation to the specimen, both when a galvo scanner or mechanical stages are used.

The surface plots depicted in **Figs. 5 & 6** illustrate the maximum temperatures per point of the surface when laser milling areas 100 × 100 and 500 × 500 μm^2 wide respectively on stainless steel, using 1 J/cm^2 peak fluence, 500 kHz repetition rate, 2 m/s scanning speed, 15 µm spot radius and 15 µm of distance between parallel line scans. Heat accumulation was simulated with and without a 200 µs ramp of acceleration, plus deceleration delays for the three proposed scanning strategies. The area hatching is done from bottom to top, thus in the positive direction of the y axis. The pixel resolution of these surface plots is equivalent to the laser pulse-to-pulse distance. These results show that surface heat accumulation with ultrashort laser milling depends highly on the size of the treated area for the same set of laser processing parameters. Heat tends to accumulate more towards the end of the milling area, as this zone already starts to warm up at the beginning of the area treatment, so the temperature offset is already high when the beam finally hits this region, thus reaching higher temperatures compared with the beginning of the treated part that started out cold. We also observe that not taking the time into account that the beam is off, to carry out the movement from one line to the next one, leads to an overestimation of the maximum temperatures reached because the material has time to cool down in between hatches. It is in any case virtually impossible to scan an area with beam-off times negligible enough for thermal diffusivity in metals, so this is an approach that would allow us to more realistically estimate the temperatures reached.

The results demonstrate that the scanning strategy used does influence the heat distribution on the surface, although this effect is more evident on the 100 × 100 μm^2 simulated area, which is most likely due to the combined effect of the spatial and temporal distribution of pulses as heat sources. For the larger treated area, the time necessary to scan each line is longer, so the beam takes longer to come back closer to each sur-

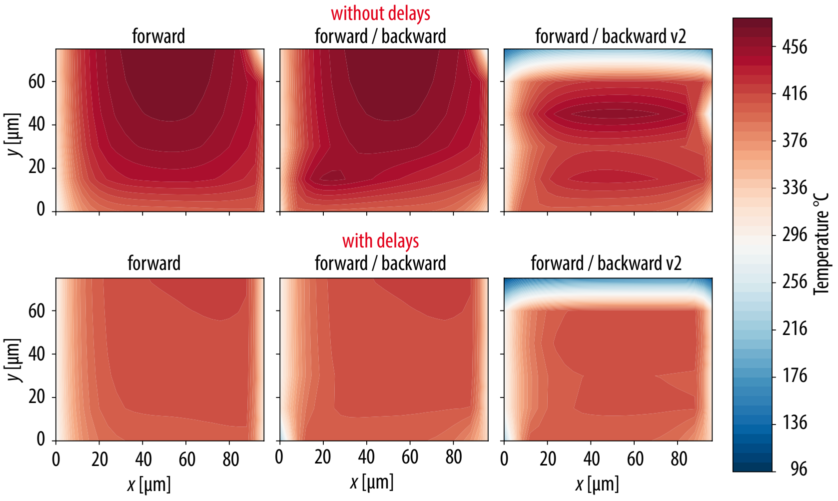

Fig. 5 Surface plots depicting the maximum temperature felt per point of surface upon laser milling an area 100 × 100 μm^2 wide, using 1 J/cm^2 peak fluence, 500 kHz repetition rate, 2 m/s scanning speed, 15 µm spot radius and 15 µm of distance between parallel line scans, using the three scanning strategies and with and without acceleration and deceleration times.

INSTITUTE

University of Dresden

The Technische Universität Dresden (TUD) is one of eleven German universities that were identified by the German government as a ‘University of Excellence’. TUD has about 35,000 students and over 9,000 employees, 520 professors among them, and is the largest university in Saxony today. Furthermore, TUD has been denominated as a graduate school and a cluster of excellence in Germany’s excellence initiative.

https://tu-dresden.de

face point, giving it time to cool down in the meantime.

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[1] *F. Bauer* et al.: Opt. Exp., **23** (2015) 2, 1035-1043

[2] *R. Weber* et al.: Opt. Exp. **22** (2014) 9, 11312-11324.

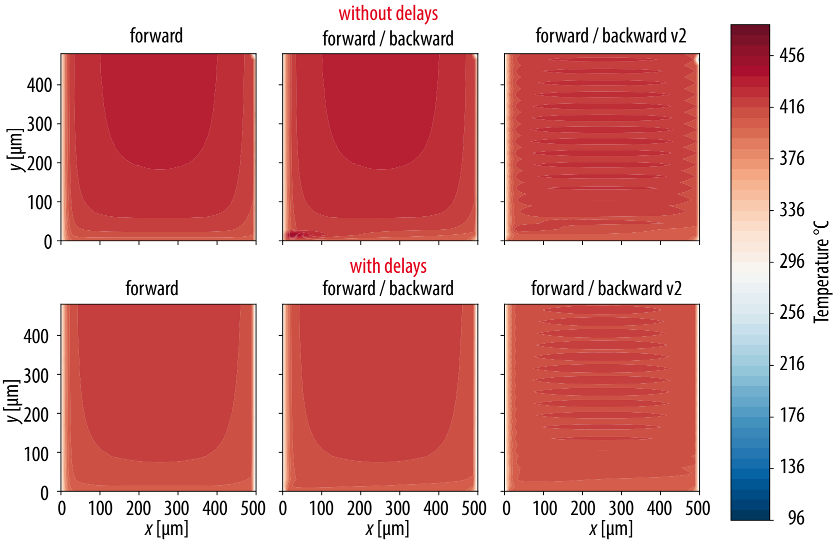
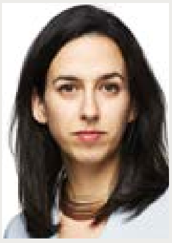
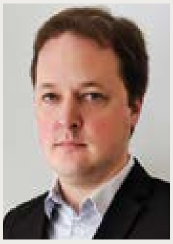


Fig. 6 Surface plots depicting the maximum temperature felt per point of surface upon laser milling an area 500 × 500 µm² wide, using 1 J/cm² peak fluence, 500 kHz repetition rate, 2 m/s scanning speed, 15 µm spot radius and 15 µm of distance between parallel line scans, using the three scanning strategies and with and without acceleration and deceleration times.

Authors

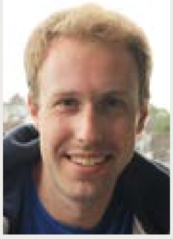


Liliana Cangueiro has been an R&D engineer at Lasea since 2016, working on modelling and process development within the framework of regional or European projects or client demands. She has a background in ultrashort-pulsed laser material processing, surface characterization (microscopy and spectroscopy), laser-material interaction and ablation modeling. She graduated in biomedical engineering at the Nova School of Science and Technology (Lisbon) and obtained her PhD degree on materials engineering at the Instituto Superior Técnico (Lisbon).



David Bruneel works as manager of the process and modelling unit in the R&D department of Lasea. He has long experience of different laser processing techniques and system development with short and ultrashort pulsed lasers: ns, ps, and fs. He obtained his PhD at the Laboratoire Hubert Curien and Fraunhofer IBMT in developing USP process optimization and systems setup, and has now gained more than ten years of experience in previous European and national R&D projects targeted at commercially valuable future applications.

Thomas Kiedrowski studied mechanical engineering at the University of Aachen. From 2003 to 2008 he worked at the Fraunhofer Institute for Laser Technique as project leader in the field of surface technology. In 2009 he received his PhD for his process development of an innovative laser-polishing process. Since 2008, he has been a project leader at Robert Bosch GmbH in micro materials processing. In 2016 he was appointed senior expert for laser applications and system technology. He is also the author of six oral presentations and six patents



Nikolai Schroeder graduated from the Technical University of Dresden with a diploma in mechatronics in 2017, focusing on laser manufacturing technologies. Afterwards he started to work as a research associate at the Fraunhofer IWS Dresden in the field of laser cutting. In 2019, he joined TU Dreden's Institute of Manufacturing Technology. Currently he is doing his PhD under the supervision of Prof Lasagni.

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