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Cleaning surfaces from food residues with pulsed laser

Peter Cam[a*], Fabio Sivillica[a], Simon Hänni[a], Fabrizio Orlando[b], Steffen Ohr[c], Joachim Schoelkopf[b], Patrick Schwaller[a]

[a]*Institute for Applied Laser, Photonics and Surface Technologies ALPS, Bern University of Applied Sciences, Pestalozzistrasse 20, CH-3400 Burgdorf, Switzerland*
[b]*Omya International AG, Baslerstrasse 42, CH-4665 Oftringen, Switzerland*
[c]*Sihl Group, Bolligenstr.93, CH-3006 Bern*

Abstract

Currently, cleaning of food residues is mostly performed with water-based technologies. In the future, however, water-free methods such as treatments by laser could gain importance for achieving environmental sustainability. In this study the possibility of removing food residues on surfaces with nanosecond laser pulses is discussed.
The investigation was limited to three substrates: stainless steel, ceramic and glass. Coatings of black tea, caramelized sugar and onion skin brew were selected as representative contamination layers. Laser treatment was performed with a pulsed nanosecond laser system at 1064 nm wavelength.
Parameters for a thorough cleaning of the substrate without surface modification were found for black tea and onion skin brew coatings. It was found that only a little amount of laser irradiation is absorbed by the contamination and that the cleaning process is initiated mainly by the substrate's heat up. Details of the removal process and approaches to remove also a (semi-) transparent sugar coating will be discussed.

Keywords: Surface treatment; laser cleaning

1. Introduction

Cleaning processes of surfaces from organic contaminations like food residues are mostly done with water-based methods. However, as water scarcity is one of the greatest challenges worldwide, it is

* Corresponding author. Tel.: +41 (0)34 426 42 53; fax: +41 (0)34 423 15 13.
E-mail address: peter.cam@bfh.ch.

worthwhile to investigate the potential of water-free cleaning technologies to ensure environmental sustainability. Laser treatment of surfaces by short (nanosecond) and ultrashort (pico- and femtosecond) laser pulses are already well established in a large variety of application fields: Examples are micromachining of metallic surfaces (Neuenschwander et al. (2014), Jaeggi et al. (2011)), removing metallic and dielectric thin coatings and many more (Veiko et al. (2008), Buccolieri et al. (2013), Ramil et al. (2017), Pozo-Antonio et al. (2015)). It therefore appears obvious to apply laser treatment also on systems like food residues on surfaces. The main challenge for laser cleaning on such type of systems is the fact that the contaminated surfaces cannot be considered as being "well-defined": Contaminations are in general not distributed uniformly over the substrate surface, and variable thickness as well as inhomogeneities in the composition have to be expected. These aspects complicate the determination of reliable and stable laser treatment parameters.

In this work the focus will be on some basic aspects regarding the interaction of nanosecond laser pulses at 1064 nm wavelength with organic residues on surfaces typically used as tableware, namely: stainless steel, ceramic and glass.

Finally, it shall be noted that investigating the potential of laser cleaning on rather "ill-defined" samples like the ones presented here may also be beneficial in other domains like the cleaning of artwork.

2. Experimental setup

The experiments were performed in 3 steps: (i) sample preparation by applying food residue contaminations on the proper substrate, (ii) laser irradiation of the sample and (iii) analysis of the substrates in removed residues to check whether the substrate is affected by the laser irradiation if removal is successful.

2.1. Samples preparation with food residue contamination

The study was limited to three substrates commonly used in the food industry and to three organic residues. Stainless steel (1.4404), glass (microscope slide) and ceramic material (tile, DIN EN 159) were chosen as substrate. Contaminations layers were made from black tea, onion skin brew and caramelized sugar.

As a boundary condition it is required that the dried layers have a homogeneous thickness and a low surface roughness. In addition, the coatings shall not be removable with a dry cloth.

Black tea and onion skin brew contaminations were applied on the substrates as liquids either by direct pipetting onto the heated substrate (see fig. 1a) or by dip-coating followed by drying (see fig. 1b). It was observed that the dip-coating approach yields better results regarding coating quality and reproducibility, as well as thicker layers between 10 – 30 µm compared to <10 µm achieved with pipetting. Moreover, with dip coating sharp edges of residue layers could be achieved by using adhesive tape protecting uncoated zones.

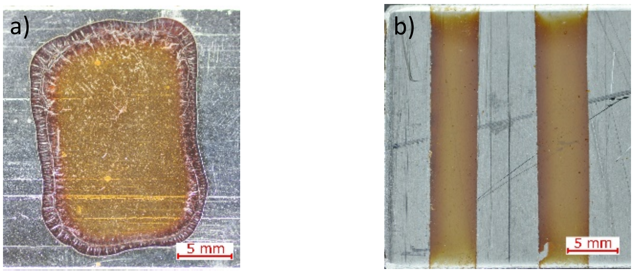

Fig. 1. Stainless steel samples with black tea contamination prepared with pipetting (a) and dip-coating (b)

For caramelized sugar layers, granulated sugar was melted directly over the substrate. This method yields homogeneous layers, however, the thickness is noticeably higher with values >600 µm and it turned out to be more difficult to obtain even layers.

2.2. Laser treatment

A Pyroflex 25-IR pulsed laser system (1064 nm) was used to treat the samples prepared according to the procedure above. Laser irradiation always extends from areas without to areas with organic residues (see fig. 2). At first, the laser parameter set was chosen as wide as possible. The goal is to narrow down the parameters for successful results representing the working range.

Table 1. Large laser parameter field used to determine a suitable working range

Number of iterations	1 - 100
Pulse length	1, 50, 250, 600 ns
Pulse shape	rectangular
Repetition rate	2, 80, 500 kHz
x-Overlap (pulse to pulse)	0 – 99.9 %
y-Overlap (line to line)	50 %
Pulse energy	4 – 500 µJ

After determination of first working parameter sets, the parameter range was, based on the observed results, in some cases slightly modified in the further course of the study.

2.3. Sample analysis

Samples were characterized by two methods: imaging by optical microscopy and quantitative topography measurement by white light interferometry. Laser-treated areas were analyzed and categorized according two criteria: removal of residues and modification of substrate (uncoated and coated zones).

Whether the residue layer was removed or not was judged by eye and with optical microscopy. Layers were then categorized as fully removed, partially removed or not removed.

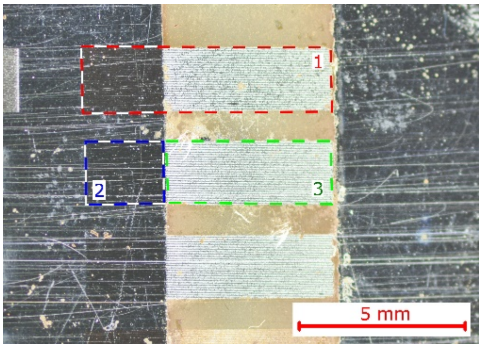

Fig. 2. Laser treated stainless steel sample with treated area (1). The treated area is divided into uncoated (2) and coated (3) zones

The surface roughness mean deviation S_a [µm] was used to evaluate the effect of the laser on the substrate by comparing the difference between treated and untreated areas as $\Delta S_a=|S_a^t - S_a^u|$.

The value of ΔS_a quantifies the substrate modification and is categorized as: no modification ($\Delta S_a \leq 0.05$ µm), slight modification ($0.05<\Delta S_a \leq 0.15$ µm) and significant modification ($\Delta S_a >0.15$ µm).

3. Results

Our experiments showed that laser parameters could be found to remove black tea and onion skin layers on all three substrates. Caramelized sugar could be removed only from the ceramic substrate.

3.1. Removal of residues on stainless steel

Depending on the substrate, there is a distinct difference in the pulse energy required to remove the contamination. For stainless steel, pulse energies as low as 8 µJ can be used for the cleaning without significant modification of the substrate roughness (see table 2).

Table 2. Parameter range for successful removal of residues on stainless steel without significant substrate modification

Residue	Pulse width / ns	x-Overlap / %	Pulse energy / µJ	Number of iterations
Black tea	1	15 – 100	16 – 27	1
Onion brew	1	0 – 100	8 – 14	10
Black tea	50	0 – 100	26 – 40	1
Onion brew	50	0 – 85	20 – 34	10
Onion brew	250	0 – 88	19 – 63	10

It was observed that black tea and onion skin brew residue layers get chipped away by sudden local heat-up of the substrate due to laser irradiation (see fig. 3a). Absorption within the contamination layer does not play a significant role in this case. Chipping starts when the energy transmitted through the residue layer heats up the substrate over a threshold temperature. This threshold is likely dependent on the thickness and type of residue. However, the residue layer causes heat accumulation on the substrate underneath which can rapidly lead to undesired modification of the substrate (see fig. 3b).

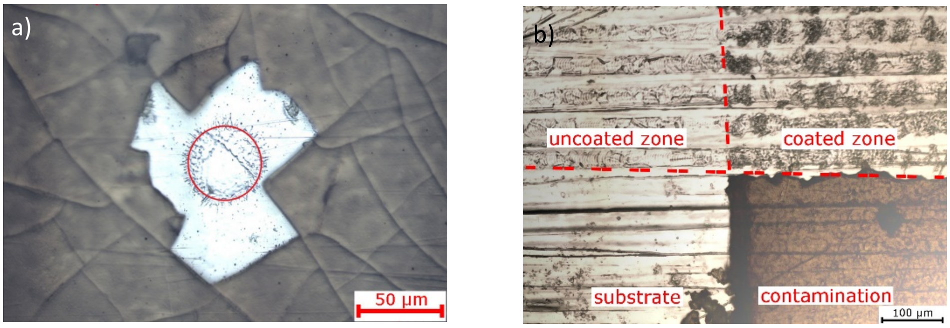

Fig. 3. Removed black tea residue by chipping due to single pulse irradiation (a). Modified substrate at the coated zone underneath black tea contamination layer (b).

An optimal laser parameter space/set could be defined such that the treated contamination can be efficiently removed without affecting the morphology of the substrate (indicated by the dotted circles in fig. 4).

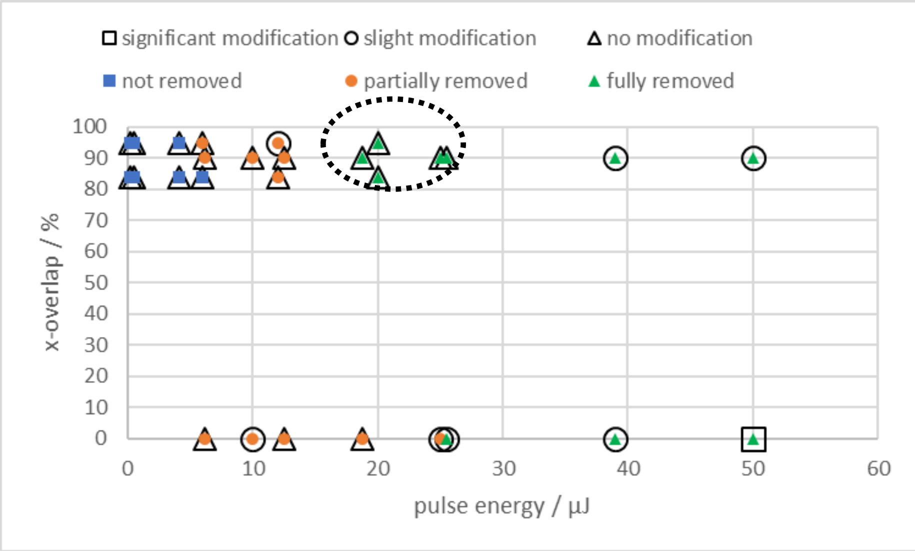

Fig. 4. Treatment results for black tea contamination on stainless steel, all performed with 1ns pulse length and 1 pass. The highlighted zone (dotted circle) represents working area.

An in-depth investigation with parameters close to the optimal set is currently being performed, and the first findings are summarized as follows:

- Pieces of residues can be chipped away using a single pulse, however, pulses with high peak power (>20 kW) tend to modify substrate and are thus not promising.
- The chipping process can be activated reliably at a peak power as low as 1.5 kW and needs only one pass for complete removal of the residues. Further increasing the number of passes is detrimental to the substrate.
- When the peak power is insufficient or if the residue removal is only partial, increasing the laser overlap is counterproductive.

3.2. Removal of residues on glass

Compared to stainless steel, the contamination removal process on a glass substrate is quite different. Here, the laser energy is absorbed almost exclusively by the contamination in an ablation process. Consequently, high pulse energies (>185 µJ) and a large number of iterations are needed compared to the stainless steel substrate (see Table 3). Heat accumulation underneath the residues can lead to significant modification of the glass (see fig. 5a) and even to tiny tension cracks that are invisible to the naked eye (see fig. 5b).

Table 3. Parameters for successful removal of residues on glass while minimizing substrate modification

Residue	Pulse width / ns	x-Overlap / %	Pulse energy / µJ	Number of iterations
Onion brew	50	97.5	218.75	50
Onion brew	250	97.5	187.5	20
Onion brew	250	95	275	20
Onion brew	250	95	187.5	50
Black tea	600	90	277.5	50

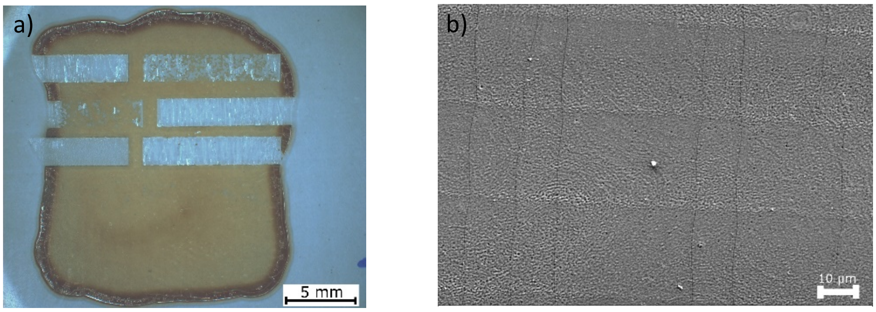

Fig. 5. Laser-treated black tea residues on glass, clearly visible tension cracks due to heat accumulation (a). SEM-image of tiny vertical cracks on glass substrate at laser treated areas (b).

3.3. Removal of residues on ceramics

While ceramic absorbs the laser energy better than glass, it is insufficient to remove the residues solely by a chipping process as observed on stainless steel. It is therefore assumed that a combination of both chipping and ablation occurs. As shown in table 4, the pulse energy required to remove black tea and onion skin brew contaminations on ceramic is roughly 100 µJ, a value that falls in between those measured on the other two substrates.

Table 4. Parameters for successful removal of residues on ceramic while minimizing substrate modification

Residue	Pulse width / ns	x-Overlap / %	Pulse energy / µJ	Number of iterations
Onion brew	250	88 – 95	42 – 87	10
Black tea	600	83 – 90	100 – 220	10
Onion brew	600	88 – 93	65 – 112	10
Sugar	600	96	48	20
Sugar	600	96	48	300

Ceramic is the only substrate on which caramelized sugar could be removed successfully by slowly melting and then vaporizing. However, laser irradiation also causes carbonization of the adjacent sugar, a process which leaves permanent black spots on the substrate. Experiments with sugar are not yet reproducible as they probably need a more refined development of the sample preparation procedure (as indicated in table 4 by the variable number of required cleaning iterations for different sugar coating samples/replicates).

4. Conclusion and outlook

The feasibility of laser-based removal of food residues on stainless steel, glass and ceramic has been shown for black tea and onion skin brew. Most probably, similar organic contaminants could be removed likewise.

It was shown that depending on the substrate material and its laser energy absorption capacity, the removal process of the contamination layer changes from chipping (substrates with high laser energy absorption) to ablation (substrates with high laser energy transmission). The failure in removing caramelized sugar reflects the strong dependence of the cleaning process on the contamination type, form, thickness and transparency. Ongoing investigations aim to bring more clarity on those aspects.

Despite all its limitations, the approach presented in this study helps illustrating the technical challenges of laser irradiation as a cleaning tool and at the same time highlight its potential for application also in related fields like cleaning of artwork or removing paint etc.

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