Thrust noise minimization in long-term laser ablation of propellant material in the nanosecond and picosecond regime

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Abstract. The avoidance of any moving parts in a microthruster exhibits a great potential for low-noise thrust generation in the micronewton range. This is required, e.g., for scientific missions that need attitude and orbit control systems with exquisite precision. Laser ablation propulsion offers the opportunity of permanent inertia-free, electro-optical delivery of laser energy to access the propellant entirely without moving it. New propellant is accessed by ablating the previous surface in layers, essentially damaging the surface with a laser over and over again. The resulting surface properties for different fluences and scanning patterns were investigated for multiple layers of aluminum, copper, and gold. The pulse-length-specific issues of various ablation mechanisms such as vaporization, spallation, and phase explosion are accounted for by the use of a 10-ps laser system and a 500-ps laser system. We show that the surface roughness produced with 500-ps laser pulses is approximately twice the surface roughness generated by using 10-ps laser pulses. Furthermore, with 500-ps pulses, the surface roughness shows low dependency on the fluence for carefully chosen scanning parameters. Therefore, we conclude that laser pulse duration differences in the pico second and nanosecond regimes will not necessarily alter surface roughness properties.

Keywords: surface roughness; laser ablation; short laser pulses; ultrashort laser pulses; thrust noise.

1 Introduction

Laser damage due to laser-focusing on mirror surfaces made of metal easily destroys their optical properties. This is due to the laser-ablative processes generating harsh environmental conditions on the irradiated surfaces. In our case, translating the laser spot, and therefore, the ablation process repeatedly over a surface will eventually lead to surface roughening or even a larger-scaled unevenness over time. Both results are unwanted side effects in the context of laser-ablative propulsion (LAP).

Some space missions for the evaluation of general relativity are based on a satellite encapsulating a test mass to shield it from small external forces. The satellite positioning system, e.g., for the Laser Interferometer Space Antenna (LISA) mission, is expected to need a positioning accuracy below 10 nm. This requirement restricts the forces which can be tolerated from mechanical components, e.g., installed in the thruster system.

To build a thruster without any moving element usually appears to be an impossible task. In the light of LAP, this task, at least in theory, becomes feasible. The MICROLAS concept (micropropulsion by laser ablation) uses electro-optical beam-steering and allows to convert a solid propellant into a series of nNs scaled ablation plumes (Fig. 1). Therefore, the beam-steering does not incorporate any mechanical movement. Furthermore, the propellant itself stays static during thruster operation.

Hence, the MICROLAS concept can be imagined to be one solid arrangement. The access of new propellant is granted by removing the propellant layer by layer. Unwanted changes in surface roughness and unevenness due to the ablation process, therefore, would lead to a laser-induced propellant damage.

The commonly unknown aspect in such a process consists of the behavior of the surface over time. Since surface properties and the ablation process are strictly linked to each other, one can conclude from the previous statement, that the temporal evolution of thrust is unknown, too. Slowly changing surface properties, therefore, will lead to noise of the thrust system in the frequency range well below 1 Hz.

In our recent work, we investigated the surface properties of gold and aluminum after ablation with a 10-ps laser source. Now, we changed the pulse duration to 0.5 ns and performed extensive ablation experiments. The newly generated results allow us to compare the surface characteristics after multiple layers of surface ablation in dependency of spot displacement $\Delta x$, $\Delta y$ and laser fluence $\Phi_L$ for the ultrashort-pulse and the short-pulse regime.

2 Theory

2.1 Spallation and Vaporization

The significant differences in surface roughness after a single ablation event can be ascribed to the particular ablation mechanisms. Since for ultrashort laser pulses, almost the entire laser energy is temporarily stored in the electron gas before it is coupled into the ion lattice, stress confinement of
the target provokes that spallation and, for higher fluences, phase explosion are the predominant mechanisms. The material is ablated when the rarefraction wave which follows on the initial shock wave exceeds the specific spall strength. Therefore, the heat affected zone of the propellant is rather small and the remaining target material is comparatively cold and exhibits a smooth surface. If the pulse duration is longer than the electron–phonon coupling time \( \tau_i \) of the material, however, laser heating still continues during the laser pulse, which yields a rather large heat affected zone. This implies various thermal effects, e.g., vaporization and the formation of a crater rim. Taking into account the pulse durations \( \tau_{l,1} \) and \( \tau_{l,2} \) of the two laser systems in use and the material-specific electron–phonon coupling times, copper and gold have \( \tau_{l,1} = 10 \text{ ps} < \tau_i < \tau_{l,2} = 500 \text{ ps} \). This marks the so-called picosecond regime for \( \tau_{l,1} \) for Cu, Au, and the nanosecond regime for \( \tau_{l,2} \), respectively. In contrast to this, for Al, \( \tau_{l,1} \) is in the range of \( \tau_i \) which might suggest some kind of transition.

### 2.2 Correlation Between Surface Roughness and Thrust Noise

To further motivate the determination of the surface roughness, one might take a look at theoretical predictions correlating the surface roughness with the absorbed energy. As soon as multiple scattering takes place, the laser absorption is raised significantly, which in turn decreases the ablation threshold \( \Phi_{\text{thr}} \). The (cold) absorption on highly reflecting materials as, e.g., aluminum can be approximated linearly by the effective number of reflections. For a given surface correlation length and a Gaussian height distribution, this results in a linear correlation to surface roughness \( S_a \), easily doubling the absorbed laser intensity. With the above knowledge and a few assumptions, a linear approximation can be deduced to indicate the amount of thrust noise \( \sigma[F] \) introduced. \( \sigma[A] \) depicts the standard deviation of \( A \), \( E[A] \) its mean or expected value. First, we may assume that the average surface roughness \( E[S_a] \) and the surface correlation length \( \tau_i \) are of the same size. \( \tau_i \) represents the characteristic width of the autocorrelation function of the surface profile. Keeping \( \tau_i \) constant for all, \( S_a \) introduces a linear shift of the absorbed fluence \( \Phi_{\text{abs}}(S_a) \) depending on the surface roughness \( S_a \). This again translates the fluence-dependent coupling coefficient \( c_n(\Phi) \) half way to its maximizing fluence \( \Phi_{\text{max}}(2\Phi_{\text{abs}} \approx \Phi_{\text{max}}/2) \) can be deduced dividing \( c_n(\Phi_{\text{max}}) \) by \( \Phi_{\text{max}} \). Finally, adding the relation from Bergström et al. for aluminum, \( \sigma(\Phi_{\text{abs}}) \approx 3\Phi(\sigma[S_a]/E[S_a]) \), leads to the following approximation:

\[
\sigma[F] \approx \frac{c_n(\Phi_{\text{max}})}{\Phi_{\text{max}}} \cdot P_{\text{laser}} \cdot \sigma(\Phi_{\text{eff}}(S_a))
\]

\[
\Rightarrow \frac{F_{\text{thr}}}{\Phi_{\text{max}}} \cdot \frac{3\Phi_{\text{max}}}{2} \cdot \frac{\sigma[S_a]}{E[S_a]},
\]

\[
\Rightarrow F_{\text{thr}} \cdot \sigma[F] \approx \sigma[F]_{\text{perpendicular}} \approx F_{\text{thr}} \cdot \sigma[\gamma]
\]

The approximation states that under relevant process parameters one may obtain a relative thrust noise proportional to the relative deviation in surface roughness. The surface roughness variations may be due to roughness variations in time as well as surface positions. In the latter case, an additional source of error has to be considered. The surface might have a large scale roughness or rather unevenness. Since the thrust vector typically points perpendicular to the local surface, this leads to a misaligned thrust vector, which primarily will generate thrust noise perpendicular to the desired thrust direction. Similar to the previous calculation, a simple geometric consideration leads to

\[
\sigma[F_{\text{perpendicular}}] \approx F_{\text{thr}} \cdot \sigma[\gamma]
\]

depending on the uncertainty in the slope \( \sigma[\gamma] \) of the surface in rad. To connect these approximations with, e.g., the LISA requirements of a power spectral density \( \text{PSD}(f) = WN^2 \) starting from 0 Hz up to \( f_{\text{max}} \), in this case, the following relation has to be considered:

\[
\int_0^{f_{\text{max}}} df WN^2 = \sigma^2[F] \Rightarrow WN \cdot f_{\text{max}} = \sigma^2[F]
\]

\[
\Rightarrow WN = \frac{\sigma[F]}{\sqrt{f_{\text{max}}}}
\]
3 Materials and Methods

3.1 Experiments

The scanning of multiple layers of material was performed using hatching patterns. A hatching pattern describes the procedure of turning the scan direction $\alpha$, in our case by 10 deg, after every layer has been scanned. With this method, 18 layers were removed and the generated surface was analyzed using a white light interferometer (Veeco NT9100). While the hatching angle was fixed to 10 deg, the laser fluence, and therefore, the crater radius $r_c$ varied. Furthermore, the line and spot displacement were kept equal $\Delta y = \Delta x$ and varied to create different amounts of ablation crater overlap (Fig. 2).

The laser incidence angle $\theta$ (Fig. 1) was set to 0 deg. This allowed to use a conventional scanning setup and access the entire target surface. Laser absorption and coupling coefficient show only a minor dependency up to an incidence angle of 60 deg.12 As a laser source, a solid-state 10-ps pulse duration system (Duetto, Time Bandwidth/Lumentum) was used, while a rather small microchip laser (PNP-B08010, Teem Photonics) was able to deliver a pulse duration of 0.5 ns. To omit laser power variations, a Faraday isolator was introduced after the microchip laserhead. Both laser systems emit at a wavelength of 1064 nm and are capable of delivering tens of microjoules pulse energy. Laser power was detected by a separated light beam and a pulse energy measuring head (PE9-F, Ophir). To calibrate the effective pulse energy available at the target, simultaneous power measurements with a second laser power head (Lorbeer et al.: Thrust noise minimization in long-term laser ablation of propellant material in the nanosecond and picosecond regime). Ablation pattern scheme.4 Parameters for a hatching scan are spot displacement $\Delta x$, line displacement $\Delta y$, hatching angle $\alpha$, and spot radius $r_s$.

The scanning of multiple layers of material was performed while maintaining the hatching angle $\alpha$ at 10 deg, after every layer has been scanned. With this method, 18 layers were removed, and the generated surface was analyzed using a white light interferometer (Veeco NT9100). During the scanning process, the laser beam was directed towards the target material at a wavelength of 1064 nm. The laser power was measured using a separate light beam and a pulse energy measurement head (PE9-F, Ophir). To ensure accurate power measurements, a second laser power head was utilized.

3.2 Simulations

Hatching patterns were simulated by linear superposition of idealized single ablation crater profiles. The concept includes the introduction of an idealized ablation crater using the radially dependent fluence $\Phi(r)$ of a Gaussian laser spot to calculate a radially dependent depth $d_a$:

$$d_a(\Phi_r) = d_a(\Phi_{peak} - r) = a \left[ \ln \left( \frac{\Phi_{peak}}{\Phi_{thr}} \right) - \frac{2 \cdot r^2}{r_s^2} \right].$$

The function can be fitted to the experimental or simulation data via parameters $a$ and $\Phi_{thr}$, where $\Phi_{peak}$ denotes the peak fluence of a Gaussian-shaped laser spot and $\Phi_{thr}$ the material threshold fluence. This function always leads to a parabolic profile and is defined for a laser fluence above the threshold ($\Phi_r \geq \Phi_{thr}$). The crater radius $r_c$ defines the distance of the center to the rim of the crater:

$$r_c(\Phi_{peak}) = \frac{r_s}{\sqrt{2}} \sqrt{\ln \left( \frac{\Phi_{peak}}{\Phi_{thr}} \right)}.$$
Placing these depth profiles in two-dimensional (2-D) hatching patterns (Fig. 2) and adding their depths linearly lead to an approximated simulation of pattern induced surface roughness. These virtual hatching patterns can be adapted to the physical parameters of the measurements and thereby allow to deduce and compare the expected surface roughness $S_a$.

3.3 Evaluation

Figure 1 shows the surface of a processed cavity. To determine the surface roughness, a region of interest was chosen and the average deviation from the mean value of all chosen pixel values was interpreted as the surface roughness $S_a$.

4 Results and Discussion

4.1 Fourier Interpretation

If the ablation depth can be added linearly to predict the performance of a chosen hatching pattern, a Fourier interpretation and prediction for the results can be performed. Figure 4 shows the Fourier transformation of the ablation depth of a single crater (similar to Fig. 3). It can be seen that the amplitude of the signal decays for higher spatial frequencies $k_x$ and $k_y$. The Fourier representation of a perfectly flat surface would be given by one single signal at the zero frequency ($k_x = k_y = 0$). A simple hatching pattern as, e.g., a regular grid, can be interpreted as a folding of the crater with the grid. In Fourier space, this is equivalent to the multiplication of the Fourier spectrum of the crater profile (contour plot in Fig. 4) with the Fourier transformation of the hatching grid. Since the Fourier transformation of a regular grid with grid constant $\Delta x$ results in a regular grid, with inversely proportional grid constants $2\pi/\Delta x$, a grid with a higher density or larger crater overlap $O_c = 1 - (\Delta x/d_c)$ (smaller $\Delta x$) will push the grid points away from the zero frequency (colored rectangles in Fig. 4). Due to the decay at higher frequencies and the multiplication in Fourier space, less and less amplitude next to the zero frequency will be accumulated and, due to the concentric rings of the FT crater profile, will produce modulations contributing to the surface roughness $S_a$ as shown in Fig. 5.

Compared to earlier findings, a Fourier domain filter approach shows a similar behavior ($S_a$ in Fig. 5). Furthermore, a strong correlation to the maximum amplitude in Fourier space (next to the zero frequency) after the grid folding process suggests that the inverse grid points closest to the zero frequency dominate the surface roughness (“normalized maximum” in Fig. 5). The Fourier transform of the crater profile (Fig. 4) shows radii with zero contribution. If the Fourier transformed grid points closest to the zero frequency roughly coincide with these areas, their missing contribution to the surface roughness creates a local minimum. This result is reproduced in the roughness plot of Fig. 5.

4.2 Roughness Measurements

The surface roughness clearly shows modulations plotted against spot displacement (Fig. 6) as well as the laser fluence (Fig. 6 left aluminum). Since there is a modulation visible, optimal parameters for the scanning process can be defined. This behavior can be deduced from the simulations of the hatching patterns (Fig. 5). The simulation results also suggest that these optima correlate linearly with the effective crater diameter $d_c$, calculated by Eq. (6). Therefore, it should be possible to plot curves through the roughness plots, which dominantly follow a path of minimum roughness (compare dashed lines in Fig. 6). From Fig. 5, it can be deduced that the first resonance can be expected at 42% crater overlap ($\Delta x = 58\%$ crater diameter). Using the corresponding ablation threshold and spot diameter in Eq. (6) as determined by single ablation crater Liu plots, we introduced separate graphs (dashed lines) in Fig. 6.
Spot displacements in both regimes are chosen slightly differently, since the spot diameter for both laser systems differed ($d_s(10\, \text{ps}) = 47\, \mu\text{m}$ and $d_s(500\, \text{ps}) = 37\, \mu\text{m}$). Therefore, the curves of the 500-ps experiments are drawn for smaller displacements. Surprisingly, the expected behavior can be seen at least partially for aluminum in both pulse regimes as well as for copper at the 500-ps pulse duration. The other measurements differ distinctly from the expected behavior.

The encountered differences can be explained by the incubation effect. This effect has a tendency to reduce the ablation threshold which, taking into account Eq. (6), should lead to an underestimation of the optimum spot displacement. This leads to curves that in the displayed plots (Fig. 6) always lie at lower spot displacements than the actually observed optimum.

Despite the surface roughness, other aspects of the laser-ablative process have to be taken into account, too. Optimum specific impulse $I_{sp}$ and laser impulse coupling coefficient $c_m$ do not necessarily coincide with the optimum of the surface roughness. These values depend on the applied laser fluence $\Phi_f$. For 500-ps pulses, we were able to observe a surface roughness which was almost independent from $\Phi_f$. These optimum spot displacement values, concerning the surface roughness, might allow to benefit from a freely chosen laser fluence.

A surprising aspect in comparing the ultrashort-pulse ablation regime (here 10 ps) and the short-pulse (here 500 ps) ablation regime is the demonstration of similar roughness generated at the optimal spot displacement regions. Single ablation craters in the short-pulse regime, generated by vaporization and melting, typically lead to a chaotic raising
of the crater rim. These effects lead to bigger surface mod-
ulations compared to the ultrashort-pulse regime dominated 
by spallation and phase explosion.\textsuperscript{4} The effect of applying 
multiple layers of densely placed ablation spots appears to 
compensate for this difference effectively.

The last aspect visible in all roughness plots is a low 
surface roughness for low laser fluence. This behavior can 
be explained by the minor amount of material ablated at 
the threshold fluence and below. With no ablation taking 
place, the surface is not expected to become rough. There- 
fore, these values are excluded from the discussion.

5 Conclusion and Outlook

The ablation of the propellant surface poses an essential 
element in the MICROLAS concept. By this, not only thrust is 
generated, but new propellant also becomes accessible in a 
layer by layer manner. We were able to show that with 10-ps laser pulse duration as well as 500-ps laser pulse duration the 
surface roughness can be optimized by choosing an optimal 
spot density. Furthermore, we could show that, for well-
chosen spot densities, the roughness changes by less than 
a factor of two when switching between the regimes. This 
result allows the system optimization to be focused on other 
relevant parameters as, e.g., the specific impulse. Here, sim-
ulations show a great benefit in choosing a short-pulse laser 
system.\textsuperscript{16,17}

Since the measurements only include the ablation of 18 
successive layers, future work will investigate the roughness 
change with longer laser irradiation times. The linear model 
would predict a steady rise of the surface roughness.

Since physical effects as, e.g., melting of the local surface 
are involved in the ablation process, some kind of time-in-
dependent saturation may take place. If so, this again would 
be beneficial for the development of a MICROLAS thruster.

Acknowledgments

We want to thank all staff at the DLR and IFSW which by 
their daily work made it possible to perform the work pre-
sented above.

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