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Axial laser beam cleaning of tiny particles on narrow slot sidewalls

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Abstract
Laser cleaning is a rapidly developed technique in recent years. However, it is difficult to apply it to a slot structure, because the sidewall cannot absorb enough laser energy. Meanwhile, the focusing lens concentrates the laser beam and energy on a small spot size at the focusing position. The defocused laser beam after the focusing position would disperse and spatially enlarge. In this study, an axial laser beam (excimer laser, 248 nm) is focused at a position that is slightly in front of the slot (silicon), which makes the defocused beam propagate into the slot, and the sidewall is able to absorb the laser energy through its dispersion. The slot structure is constructed through a combination of three silicon wafers (two as sidewalls, and one as the bottom of the slot). In this manner the slot width can be controlled well during the experiment. Using this method, tiny particles (fused silica, diameter 5 µm) adhered on the slot sidewall are successfully cleaned. The cleaning threshold and efficiency for multiple slot widths (3.5–13 mm) and pulse numbers (0–40) are experimentally determined. A multi-physics model is established to understand the experimental phenomena. The electromagnetic–thermal–mechanical processes during laser cleaning are also analysed. (Some figures may appear in colour only in the online journal)

1. Introduction
Laser cleaning has been considered a promising technology that is environmental friendly and with non-physical contact on substrates. Generally, it could be classified into dry and steam cleaning. Steam laser cleaning involves water or other liquid medium immersion of the substrate, and pulsed-laser evaporation of the liquid to steam to remove contaminants [1]. In dry laser cleaning, the laser beam is incident on the cleaning sample without interacting with liquids, and thus the cleaning mechanism is different from that for steam cleaning. From the established works, it is known that there are two adhesion forces, van der Waals force and electrostatic force, between the particle and the substrate in a dry cleaning system. For particles with diameters less than a few micrometres, van der Waals force is considered as the only dominant adhesion force [2]. Pulsed-laser irradiation could cause a rapid thermal expansion of the substrate within a short time duration, which produces a strong lifting force that could overcome the van der Waals force to eject the contaminants away from the substrate surface [3–5]. This method was first attempted for cleaning of tiny particles from a solid surface by Tam and Zapka et al [6, 7]. It is also known that the high reflectivity of the particle could significantly reduce the absorption of laser energy on the substrate, especially for metallic particles [8]. Transparent particles are usually found on a silicon surface as the residue after chemical etching in the semiconductor industry [9]. Conversely, laser energy could propagate through them, which boosts the generation of a cleaning force due to the relatively high absorption on the substrate [10].

Usually, laser cleaning of particle contaminants is realized with the sample surface facing vertically to the laser irradiation direction. However, a slot, which is a common structure widely used in industrial applications, is different from a flat surface. Its sidewalls cannot easily absorb enough laser energy to form a cleaning force without damaging the bottom of the slot, since the sidewalls are parallel to the laser irradiation direction.

In the literature, Lee and Watkins developed the laser shock cleaning technique [11]. In this method, an axial laser beam was used to generate the plasma shock wave above the particles through an air breakdown phenomenon. Its strong flow would blow and clean the tiny particles on the surface.
The corresponding shock wave dynamic was analysed by Lim et al [12]. Also, Song et al extended this technique to the field of under water laser cleaning [13]. In their study, a laser beam was focused into the water, which induced shock wave and formed cavitation bubbles. The contaminant was cleaned by the high-speed liquid jet during bubble collapse. In fact, laser shock cleaning is an indirect laser cleaning method [14]. The contaminants (tiny particles) must be removed by other forms of power, such as shock wave, which is initiated by the laser energy. However, it is hard to quantify the shock wave geometry on the material surface since the cleaning area is not precisely defined and the regular or rectilinear cleaning area is not obtained. It also elevates the equipment requirement due to the fact that the high-power laser beam is essential to trigger the shock wave. There has been no report on direct axial dry laser beam cleaning of particles on narrow slots, especially on sidewalls, in the literature.

In this study, we explore the feasibility of using an axially defocused excimer laser beam (λ = 248 nm) to remove the tiny fused silica particles (diameter 5 µm) from the slot sidewalls. The defocused beam after the focusing position propagates into a silicon slot, and successfully removes the particles from the sidewalls. The corresponding cleaning threshold and efficiency for multiple slot widths and pulse numbers are experimentally determined. The surface morphologies of sidewalls before and after cleaning were examined.

2. Experimental procedure

The experimental setup is shown in figure 1(a). A pulsed GSI Lumonics IPEX 848 KrF excimer laser (τ = 15 ns, λ = 248 nm, fmax = 200 Hz) was used as the laser source. The output axial laser beam was focused by a fused silica convex lens (Thorlab LA4984) with a focal length of 200 mm that provides a rectangular spot (3 × 1.5 mm²) with a flat top profile at the focusing position, which was placed at 2 mm in front of the slot. The laser beam divergence was 1 × 3 mrad. The defocused beam propagated into the slot in the same direction. The slot structure was made of three silicon wafers. Two of them were set to be the sidewalls, and interiors were layered by the tiny fused silica particles with 5 µm diameter. The third wafer became the slot bottom. This is a flexible structure. The slot width, d, could be changed by moving the sidewall wafers from 3.5 to 6 mm, as shown in figure 1(b).

Fused silica particles were selected to serve as the contaminants on the sidewalls in this study due to their low reactivity at the wavelength of 248 nm and the relatively simple layering method. The suspension mixed by dry particle powder and deionized water was drawn by a syringe first, and then dripped and naturally dried on the silicon wafer. A monolayer of particles can be readily obtained by controlling the concentrations of the suspension. According to this layering method, particles of various materials (diameter less than 10 µm) could be attempted to evenly adhere to the silicon surface by van der Waals force [5, 15]. After the experiment, we took apart the structure and the cleaning effect on the sidewall could be observed directly.

The cleaning area on the sidewalls could be measured by a photosensitive paper, which was adhered onto the slot sidewall. Its dye would react with the high photonic energy (laser beam) and fade quickly. For this reason, the projection shape of the laser beam on the slot sidewall could be clearly recorded when the beam axially propagated into the slot. The outline of the cleaning area on the sidewalls for a 3.5 mm wide slot is shown in figure 1(c). It is shown that there is a regular trapezium with long ends appearing like a ‘comet’, which is caused by the change in laser fluence on the sidewalls. The length was about 24 mm.

Two sets of experiments were performed. First, the cleaning thresholds (laser pulse number: 50, repetition rate: 50 Hz) for 5 µm diameter particles were determined at slot widths between 3.5 and 13 mm. The magnitudes of energy were measured by an energy meter, which was placed at the defocusing position after the convex lens, and their mean values among the pulses were recorded in the threshold measurement. The slot whose width was smaller than 3.5 mm was not included in this group of experiments, because its dimension was too close to the focal laser spot size (3 × 1.5 mm²). The magnitude of laser energy that propagates into the slot significantly reduced in this circumstance. Second, the cleaning efficiency for multiple laser pulse numbers was
studied at several particular slot widths. In this experiment, the number of particles in unit area before cleaning was generally counted from the morphological pictures of the slot sidewall and considered as 100% remained. And then the coverage values after laser irradiation with particular pulse numbers would be compared with it. The percentage difference between them was defined as the cleaning efficiency in this paper. The corresponding morphologies on the sidewalls were obtained by scanning electron microscopy (SEM, Hitachi S-3400N).

3. Simulation process

3.1. Model description

A multi-physics numerical model was developed to simulate the cleaning process. A commercial finite integral technique (FIT) software package, CST Microwave Studio 2011 (CST), was used in the study. This method, proposed by Weiland, provides a universal spatial discretization scheme, applicable to various electromagnetic problems, ranging from static field calculations to high-frequency applications in time or frequency domain [16]. The electromagnetic intensity field distribution (electric field amplitude) and its power loss were primarily simulated in this case. That part of energy was used as the heat source and coupled into the thermal module in CST. The corresponding transient temperature field distribution could be obtained. From the thermal field results, the cleaning force and simulated cleaning threshold for multiple slot widths were calculated based on a thermal–mechanical model.

3.2. Modelling geometry and materials

The particle was assumed to be ideally spherical and transparent in this study. The model dealt with a single particle sitting on the flat sidewall surface. A plane wave laser beam was angularly irradiated to the model. Based on the focal length of the convex lens (200 mm) and beam projection size (26 × 13 mm²) on the convex lens, the contact angle between the laser wave and the surface could be calculated using the geometrical optics equation. Its value was 3.72°, and the related incidence angle was set to be 86.28° in CST 2011. The geometric sketch of modelling is illustrated in figure 2. The dimension of the sidewall substrate (x and y-axis directions) was considered as infinity. The optical and thermal properties of fused silica (particle) and silicon (sidewall substrate) are summarized in table 1 [17–20]. The absorptivity and reflectivity of the material in the model would be automatically calculated in CST 2011 relying on the material optical parameters, n (refractive index) and k (extinction coefficient).

3.3. Laser source: temporal and spatial profile

In this simulation, the laser source was considered to be linearly polarized (γ-polarized) light with a rectangular flat top spatial profile, a wavelength of 248 nm and a pulse duration of 15 ns. The temporal Gaussian pulse shape for an excimer laser was used in the study [21]:

\[
I_0(t) = I_0 \left( t / \tau_0 \right) ^\beta \exp \left[ \beta \left( 1 - t / \tau_0 \right) \right],
\]

where \( I_0(t) \) and \( I_0 \) are the intensity of the incident beam at time \( t \) and the peak intensity, respectively. The temporal shape factor is defined as \( \beta = 1 \), and the pulse duration \( \tau_0 = 15 \) ns. The spatial profile of the flat top beam is given by

\[
I(x, y) = I_0(t) = \text{const},
\]

where \( I(x, y) \) and \text{const} are the intensity on the \( xy \) plane and the output laser energy constant, respectively.

3.4. Boundary conditions

Unlike most numerical methods, the basic idea of FIT is to apply Maxwell’s equation in an integral form rather than the differential one [22]. This approach shows advantages due to high flexibility in geometric modelling and boundary handling as well as incorporation of arbitrary material distributions and material properties such as anisotropy, non-linearity and dispersion. To obtain better accuracy on the solver Cartesian grids are employed to the current model [23]. Meanwhile, due to the fact that the software is only capable of handling finite size structures, the boundary conditions on the edge of the model were defined as open boundary in both electric and thermal modules. The open boundary condition mimics the situation that materials at the computing boundaries extend themselves to the infinite space.

4. Results

4.1. Cleaning thresholds

Figure 3(a) shows the experimental and simulated cleaning thresholds for multiple slot widths. It is found that both experimental and simulated cleaning thresholds increase with the growth of slot widths, \( d \), and form an approximately quadratic dependence. The experimental cleaning threshold

![Figure 2. Geometric sketch of CST modelling.](image)
Table 1. Optical and thermal properties of fused silica and silicon [17–20].

<table>
<thead>
<tr>
<th>Materials</th>
<th>Density, ρ (kg m⁻³)</th>
<th>Thermal conductivity, k (W m⁻¹ K⁻¹)</th>
<th>Specific heat, C(J kg⁻¹ K⁻¹)</th>
<th>Refractive index, n</th>
<th>Extinction coefficient, k</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1.3</td>
<td>700</td>
<td>1.51</td>
<td>0.00</td>
</tr>
<tr>
<td>fused silica</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substrate:</td>
<td>2329</td>
<td>130</td>
<td>860</td>
<td>1.57</td>
<td>3.56</td>
</tr>
<tr>
<td>silicon</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Figure 3. (a) Experimental and simulated cleaning thresholds for multiple slot widths. The surface morphologies at the edge of the cleaned area for a 60 mJ laser on a 6 mm wide slot sidewall with magnifications of (b) 250× and (c) 500×.

for the 3.5 mm wide slot was approximately 21 mJ. However, when the slot width enlarges to 13 mm, it increases to about 330 mJ. The simulated curve fits well the experimental results for the slot whose width is smaller than 9 mm. When slot width is larger than 9 mm, it is observed that the experimental thresholds are 10% higher than the simulated values. The calculation procedure of the simulated threshold is clarified in the discussion.

To illustrate the cleaning effect figures 3(b) and (c) show the surface morphologies at the edge of the cleaned area for a 60 mJ laser on a 6 mm wide slot sidewall with magnifications of 250× and 500×. It is seen that there is no particle left in the laser-cleaned area (left-hand side in the pictures). Contrarily, the particles with high density locate in the area which is without laser irradiation (right-hand side in the pictures), as shown in figures 3(b) and (c).

4.2. Cleaning efficiencies

Figure 4(a) presents the cleaning efficiencies of multiple laser pulse numbers for 60 mJ output energy on the sidewall of 4, 5 and 6 mm wide slots. It is obvious that the laser cleaning efficiency increases with the growth of pulse number for all the three slot widths. Under the same laser output energy and pulse number, the slot width plays an important role in axial laser cleaning. For the same pulse number the cleaning efficiency of 4 mm slot width is much higher than those for the other two dimensions, and achieves 100% after the shooting of 15 pulses. The pulse numbers that clean 100% particles for the 5 mm and 6 mm wide slots approximate to 30 and 40, respectively. The surface morphology of the sidewall layered particles for the 5 mm wide slot is illustrated in figure 4(b).

Under the same conditions, the morphologies of the sidewall
Figure 4. (a) Cleaning efficiencies of multiple laser pulse numbers for 60 mJ output energy on the sidewall of 4, 5 and 6 mm wide slots. (b) Surface morphology of the sidewall layered particles for a 5 mm wide slot. (c)-(f) Surface morphologies of the sidewall after 5, 10, 20 and 30 pulses.
Figure 5. (a) Simulated electromagnetic distribution of single particle sitting on the silicon sidewall. (b) Temporal temperature rises for the 4, 5 and 6 mm wide slots at the contact point between the particle and the sidewall substrate.

4.3. Simulation results

Figure 5(a) shows the electromagnetic distribution of single particles sitting on the silicon sidewall. The electromagnetic module of CST uses the normalized units. The magnitude of input light is set up to 1 unit. The distribution of electric field is normatively mapped in the whole modelling space. It is found that the highest magnitude of electric field intensity is observed at the rear end of the particle along the direction of laser propagation, and the largest value achieves 448 units (not the particle-substrate contact point), as shown in figure 5(a). The intensity around the silicon sidewall substrate and contact point maintains almost the same level as that for the input laser light. Outstanding enhancement of intensity is not found in this area.

In this work, the data of electromagnetic field would couple to the thermal module of CST for the analysis of temperature distributions on the sidewall surface. The laser fluences at the output pulse energy of 50 mJ laser irradiating on the sidewalls of the 4, 5 and 6 mm wide slots are loaded in the thermal module through the corresponding calculated power scaling factors [24]. The equivalent laser fluences under the above conditions are 625 mJ cm$^{-2}$, 400 mJ cm$^{-2}$ and 278 mJ cm$^{-2}$ for the 4 mm, 5 mm and 6 mm wide slots, respectively. The related equations and the calculation procedure are indicated in the discussion. Figure 5(b) shows the temporal temperature rise for three dimensions at the contact point between the particle and the sidewall substrate. From figure 5(b), it is found that the temperature rise of the contact point is significantly related to the slot widths. Using the same output laser energy, the peak temperatures for the slots with 4 mm, 5 mm and 6 mm widths achieve 1080 K, 790 K and 630 K, respectively. All of them are obtained at 12 ns and the temperature returns to room temperature after 30 ns. Also, a theoretically calculated temperature, $T_c$, which could generate the minimum temperature rise to get enough cleaning force for a 5 µm diameter particle is marked in figure 5(b).

5. Discussion

5.1. Effect of slot widths and sidewall

It is emphasized that the slot width is an important process condition in axial laser beam cleaning of sidewalls. The size of the cleaning area is significantly affected by the slot widths. Wide slots always provide a wider and shorter projection on the sidewall compared with relatively narrow slots, which means that the cleaning area on the sidewall of a wide slot would not follow the same characters. However, the general shape of the cleaning area may not be changed. If the focusing position of the lens is fixed, it is observed that the front end of the cleaning area would gradually fall with the increase in slot width. A vertical view schematic of this phenomenon is illustrated in figure 6(a), and the corresponding experimental effect is shown in figure 6(b) (slot widths 3.5 and 4 mm, paint background). It is known that the axial spot sizes of the laser beam are different for various slot widths and grow with the increase in slot widths. For this reason, the beam needs longer distance to reach the sidewall of the slot with large width, which is treated as the main reason that caused the shift of the front ends of the cleaning areas.

This phenomenon also results in a difference in the cleaning thresholds for multiple slot widths. From figure 3(a),
it is known that the cleaning thresholds increase with the growth of slot widths. The particles on the sidewall of a wide slot require much higher laser energy to be cleaned. In fact, if the output laser energy is constant, the laser fluence at that particular plane would decline gradually with the enlargement of the axial spot size of the beam, and would be angularly loaded on the particles on the slot sidewall. This could be the reason that the cleaning thresholds for wide slots are much higher than those for relatively narrow slots. For our current laser source (GSI Lumonics IPEX 848 excimer laser), the extreme cleaning slot width is experimentally about 13 mm. Laser fluence in that extreme circumstance could achieve enormous heights. The common protective method is using an object to block the laser beam from reaching the slot bottom. If the damage threshold is unknown, some protective methods should be adopted first on the slot bottom to avoid its damage due to a very high laser energy. The common protective method is using an object to block the laser beam from reaching the slot bottom. After the cleaning of the slot sidewalls, that object could be removed to make the slot bottom clean by the low laser energy.

Meanwhile, from the established literature, it is well known that the laser cleaning of tiny transparent particles is different from that of film contaminants, because the particles interact with laser light and manifest unique near-field effects, such as lens focusing [25–27]. Based on this theory, the concentration of laser energy via the particle would accelerate the ejection of the particle from the substrate and enormously enhance the cleaning force [28, 29]. However, from figure 5(a), it is found that the high-magnitude area of the electric field is along the direction of laser propagation after the focusing of the convex lens and far from the substrate. The magnitude of electric field around the substrate is still about 1 unit (normalized unit), which is the same as the input laser light. Therefore, it is shown that the near-field focusing effect could not provide an enhancement for the sidewall cleaning process in this case because of its extreme angular irradiation.

5.2. Cleaning force

In a dry laser cleaning system, van der Waals force is thought to be the dominant adhesion force for tiny particles with diameters less than a few micrometres [2, 5]. The attractive van der Waals force between an ideal spherical particle and a flat solid surface, \( F_v \), is given by [5]

\[
F_v = \frac{hr}{8\pi z^2},
\]

where \( r, h \) and \( z \) are the particle radius, the material-dependent Lifshitz–van der Waals constant, and the atomic separation between the particle and the surface, respectively. As it is the main adhesion force between the particle and the substrate, the radius of contact area, \( a \), and elastic depth, \( d \), could be deduced by the following equations [1]:

\[
F_v = \frac{1}{2} E^* r^{1/2} d^{3/2}
\]

where \( E^* \) is the elastic modulus of two bodies, which is given by

\[
\frac{1}{E^*} = \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2},
\]

\( E_1, E_2 \) and \( v_1, v_2 \) are the elastic modulus and Poisson’s ratio associated with each part, respectively.

Due to the short pulse laser irradiation (15 ns), there is a rapidly increasing temperature gradient on the substrate, which generates a cleaning force that ejects particles from the substrate surface. Based on the established literature, the equations of dry laser cleaning force per unit area, \( f_i \), and cleaning force, \( F_c \), are given by [5]

\[
f_1 = \gamma E_v \Delta T(0, t)
\]

\[
F_c = \frac{f_1 \pi a^2}{2}
\]

where \( \gamma \) and \( E_v \) are the linear thermal expansion coefficient and the elastic modulus of the substrate, respectively. \( \Delta T(0, t) \) is the temperature rise at the substrate surface and time \( t \), which is given by \( \Delta T(0, t) = T(0, t) - T_0 \), where \( T_0 \) is the initial temperature at the substrate surface. For removal of tiny particles on the sidewall surface the cleaning force, \( F_c \), must be larger than the main adhesion force—van der Waals force, \( F_v \), which is millions times larger than the gravity of particle by calculation [30]. In this work, the radius of particle, \( r \), is 2.5 mm (5 mm diameter particle). Regarding the aforementioned equation (3), the van der Waals force, \( F_v \), is calculated as \( 0.498 \times 10^{-6} \) N, and for obtaining preconditions of cleaning, \( F_c > F_v \), \( \Delta T(0, t) \) should theoretically achieve 450 K. The temperature, \( T_c \), as shown in figure 5(b), is observed that the peak temperature for the output laser energy 50 mJ is not above \( T_c \), which means the corresponding temperature rise cannot generate enough cleaning force and it is impossible to clean the particles. The experimental cleaning thresholds, as shown in figure 3(a), correspond well with this numerical thermal result.

5.3. Prediction of cleaning thresholds

With the help of coupling of CST electromagnetic and thermal modules, the simulation predicted cleaning thresholds for multiple slot widths are calculated in this study based on theoretically deduced \( \Delta T(0, t) \), and \( T_c \), as shown in figure 5(b). The CST model could provide the corresponding minimum fluence (mJ cm\(^{-2}\)), \( J_c \), to achieve the known \( T_c \). The predicted cleaning threshold of output laser energy (mJ), \( P_i \), is expressed by [31]

\[
P_i = J_c S,
\]

where \( S \) is the laser beam size. In fact, due to the fact that the laser beam is restricted in the narrow slot, beam size, \( S \), is decided by the slot width. According to the aspect ratio of the original output beam (2 : 1, 26 mm), \( S \), is always presented in the form of

\[
S = \text{Slot width} \times \frac{\text{Slot width}}{2}.
\]
In this case, the minimum cleaning fluence, $J_c$, is 347 mJ cm$^{-2}$. And the $P_c$ values for slot widths larger than 9 mm are about 10% lower than the experimental thresholds, which could be explained by the fluctuation of the output energy of the excimer laser between pulses in the experiment and the errors in material properties in the modelling [32].

6. Conclusion

This work demonstrates a novel laser cleaning method that successfully removes tiny particles from the sidewalls of a slot using an axial beam. The corresponding experimental cleaning thresholds and efficiencies for multiple slot widths are presented, and supported well by an electromagnetic–thermal–mechanical coupled multi-physics model. The cleaning thresholds are found to generally increase with slot widths. This work could be applied to laser cleaning of other complex 3D industrial components.

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