Supporting Information

Surface functionalization by nanosecond-laser texturing for controlling hydrodynamic cavitation dynamics

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1 Texturing of stainless steel cylinders by laser pulses

The stainless steel cylinders were mounted on the rotational stage with an angular resolution of 0.005° in a way that their symmetrical axis was aligned with the stage axis of the rotation. The top part of the cylinder surface was placed into the focus of an F-theta lens with a focal length of $f_L = 163$ mm. The beam diameter on the lens equaled $D = 7.5$ mm, while the beam quality was $M^2 = 1.3$. Thus, the beam waist radius $w_0$ for the wavelength of our laser source ($\lambda = 1060$ nm) can be estimated as:

$$w_0 = \frac{2M^2 \lambda f_L}{\pi D} = 19 \, \mu m$$  \hspace{1cm} (S1)

![Figure S1. Presentation of the laser system for texturing cylinders.](image)
2 Laser processing parameters

The processing parameters that were used to texture the surfaces of the cylinders (the pulse duration $t_{\text{FWHM}}$, pulse frequency $f_p$, average power $P$, scanning velocity $v$, scanning line separation $\Delta y$, and number of passes over the same line $N$) are presented in Table S1. Additionally, the pulse energy $E_p$ was calculated as a ratio between the average power $P$ and the pulse frequency $f_p$

$$E_p = \frac{P}{f_p} \quad \text{(S2)}$$

and the pulse fluence $F_p$ was calculated as pulse energy $E_p$ per area within a beam waist radius $w_0$

$$F_p = \frac{E_p}{\pi w_0^2} \quad \text{(S3)}$$

The pulse separation $\Delta x$ can be obtained as a ratio between the scanning velocity $v$ and the pulse frequency $f_p$

$$\Delta x = \frac{v}{f_p} \quad \text{(S4)}$$

while the pulse overlapping $\delta$ equals to:

$$\delta = 1 - \frac{\Delta x}{2w_0} \quad \text{(S5)}$$

The energy per length is calculated as

$$E / L = N \frac{P}{v} \quad \text{(S6)}$$

In case of drilling, the total energy per spot is calculated instead the energy per length.

Table S1. Laser processing parameters.

| Sample        | $t_{\text{FWHM}}$ [ns] | $f_p$ [kHz] | $P$ [W] | $v$ [mm/s] | $\Delta y$ [µm] | $N$ | $E_p$ [μJ] | $F_p$ [J cm$^{-2}$] | $\delta$ | Energy per length |
|---------------|------------------------|-------------|---------|-------------|-----------------|-----|------------|---------------------|---------|-------------------|
| Dimpled (S2)  | 10                     | 900         | 19      | /           | /              | 27000 | 21         | 1.9                 | 100%    | 0.57 J per spot    |
| Velvet (S3)   | 28                     | 90          | 19      | 540         | 11             | 1    | 211        | 18.6                | 84%     | 0.35 J cm$^{-1}$   |
| Oxidized (S4) | 10                     | 100         | 3.7     | 300         | 0.9            | 1    | 37         | 3.3                 | 92%     | 0.12 J cm$^{-1}$   |
| Waved (S5)    | 28                     | 90          | 19      | 540         | 67             | 1    | 211        | 18.6                | 84%     | 0.35 J cm$^{-1}$   |
| Grooved (S6)  | 28                     | 90          | 19      | 540         | 130            | 10   | 211        | 18.6                | 84%     | 3.5 J cm$^{-1}$    |
3 SEM images of the laser-textured surfaces

SEM images of surfaces are shown in Figures S2 – S10. Images were recorded using a JEOL JSM-6500F scanning electron microscope, in some of them the electron beam was tilted by ~65° regarding the surface normal.

Figure S2. SEM image of the laser-textured dimpled surface (S2).
Figure S3. SEM image of the laser-textured dimpled surface (S2) in a tilted mode.

Figure S4. SEM image of the laser-textured velvet surface (S3).
Figure S5. SEM image of the laser-textured velvet surface (S3) in a tilted mode.

Figure S6. SEM image of the laser-textured oxidized surface (S4).
Figure S7. SEM image of the laser-textured waved surface (S5).

Figure S8. SEM image of the laser-textured waved surface (S5) in a tilted mode.
Figure S9. SEM image of the laser-textured grooved surface (S6).

Figure S10. SEM image of the laser-textured grooved surface (S6) in a tilted mode.
4 Surface parameters

The average height of the selected area ($S_a$ parameter)

Optical 3D metrology system, model Alicona Infinite Focus (Alicona Imaging GmbH), and IF-MeasureSuite (Version 5.1) were used to evaluate the average height of the selected area $S_a$ parameter, defined as:

$$S_a = \frac{1}{L_x L_y} \int_{0}^{L_x} \int_{0}^{L_y} |z(x,y)| \, dx \, dy,$$

where $L_x$ and $L_y$ stand for the acquisition lengths of the selected surface in the $x$ and $y$ directions, respectively and $|z(x,y)|$ is the absolute value of the height.

The roughness of a profile ($R_a$ parameter)

To enable better comparison with other (existing and future) similar studies, the roughness of a profile $R_a$ was also evaluated, although in some samples, like reference (S1), dimpled (S2), and oxidized (S4) it is not a good measure of roughness. The $R_a$ is defined as:

$$R_a = \frac{1}{L_x} \int_{0}^{L_x} |z(x)| \, dx,$$

were $L_x$ stands for the acquisition length and $|z(x)|$ is the absolute value of the height. The parameter $R_a$ was measured in the following way:

- for the reference sample (S1) it was measured parallel to the cylinder axis (since this sample was polished during the rotation and the abrasion occurs in the direction, perpendicular to the cylinder axis;
- for the dimpled sample (S2) it was measured across the centers of the laser-drilled holes;
- for the oxidized sample (S4) it was measured along the cylinder axis and in the perpendicular direction;
- for other samples [velvet (S3); waved (S5); and grooved (S6)] it was measured perpendicular to the laser scanning lines.

In all cases, the $R_a$ parameter was measured on the length of $L_x > 14$ mm. Since enough long $L_x$ was used, the measured $R_a$ parameter is very similar to the $S_a$ parameter.
The peak-to-peak amplitudes
Profile curves of all the tested samples are revealed on Figures S11–S16. In the case of the dimpled (S2) surface, the profile curve is measured along the centers of the holes, while in the case of the velvet (S3), waved (S5) and grooved (S6) surfaces, the profile curve is measured perpendicular to the laser scanning lines. The presented results reveal that reference (S1) and oxidized (S4) surfaces do not express any periodicity in the profile curve, while the periodicity of the profile curve decreases by decreasing the scanning line separation [e.g., for the velvet surface (S3)].

The peak-to-peak amplitude was measured as schematically shown in Figure S12. It presents an average height between the valley and the peak marked by the circles (for the valleys) and the squares (for the peaks) of the same color in Figure S12.

Figure S11. Profile curve of the polished (S1), reference surface.
Figure S12. Profile curve of the dimpled (S2) surface. The peak-to-peak amplitude is also presented.

Figure S13. Profile curve of the velvet (S3) surface.
Figure S14. Profile curve of the oxidized (S4) surface.

Figure S15. Profile curve of the waved (S5) surface.
Figure S16. Profile curve of the grooved (S6) surface.
5 High-speed visualization of cavitation behind the specimens

Image time sequences of cavitation behind various specimens are presented on Figures S17-S21. The time step between two images equals 0.5 ms. Red circles present specimen position and the fluid flow is from right to left.

On Figure S17 at $\sigma = 2.3$, almost no cavitation can be noticed, since this operating point was chosen at the point of cavitation incipient on a reference, i.e., highly polished specimen.

On Figure S18 at $\sigma = 1.8$ the initial cavitation can be seen on the grooved, waved, oxidized, polished and velvet specimens, but no cavitation can be noticed on the dimpled specimen.

Developed cavitation behind all the specimens at $\sigma = 1.4$ can be observed on Figure S19, where the dimpled, velvet and oxidized sample do not form typical von Karman cavitation shape, as it can be seen on the polished, waved and grooved specimens.

On Figure S20 at $\sigma = 1.2$ fully developed cavitation is visible behind all the specimens, but one can distinct different dynamic nature of cavitation behavior between various specimens. Once again, cavitation behind the dimpled and the velvet specimens does not form a distinct von Karman shape as it can be seen, e.g., behind the polished specimen. The polished, oxidized, waved and grooved specimens also form strong cavitation shedding, which is in case of the dimpled and the velvet specimen diminished.

On Figure S21 at $\sigma = 1.0$ cavitation is on the boundary between fully developed and supercavitation. At this cavitation number, distinct differences are visible between cavitation dynamics behind various specimens. While cavitation behind the polished specimen still preserves von Karman dynamic behavior, cavitation behind the dimpled specimen acts much less dynamic and more stable without shedding.
Figure S17. Visualization images of cavitation behind the specimens at $\sigma = 2.3$. Time step between two images equals 0.5 ms.
Figure S18. Visualization images of cavitation behind the specimens at $\sigma = 1.8$. Time step between two images equals 0.5 ms.
Figure S19. Visualization images of cavitation behind the specimens at $\sigma = 1.4$. Time step between two images equals 0.5 ms.
Figure S20. Visualization images of cavitation behind the specimens at $\sigma = 1.2$. Time step between two images equals 0.5 ms.
Figure S21. Visualization images of cavitation behind the specimens at $\sigma = 1.0$. Time step between two images equals 0.5 ms.
6 Determination of the cavitation length

The heights of the acquired images (an example is shown on the bottom of Figure S22) equal \( H = 256 \) px, while their widths equal \( W = 640 \) px. Thus, each \((i\text{-th})\) acquired image can be presented as the following matrix:

\[
I_i(m,n) = \begin{bmatrix}
(1,1) & \ldots & (1,W) \\
\vdots & \ddots & \vdots \\
(H,1) & \ldots & (H,W)
\end{bmatrix}.
\] \hspace{1cm} (S9)

In Equation (S9), each pixel at \((m,n)\) position can take an integer value between 0 and 255, since 8-bit monochrome images were used for the image processing.

For each tested sample at each flow rate, we acquired \( N = 10,000 \) frames. We have divided the whole image sequence into 25 sequences, each containing \( N_p = 400 \) frames. This allowed us to calculate the average length (as an arithmetic mean) as well as the length variations (as a standard deviation).

Partial sequence of \( N_p = 400 \) frames was chosen according to the main distinct shedding frequency of the cavitation, which in our case equals approximately 500 Hz. For the visualization we used framerate of 20,000 fps. To process approximately 10 cycles of the cavitation shedding within a single partial sequence, this partial sequence should contain \( N_p = 20,000/500 \times 10 = 400 \) frames.

For each sequence \((p = 1, \ldots, 25)\), the sum value of the gray level distribution is calculated as:

\[
I_{\text{tot}}^p(m,n) = \sum_{i=1}^{N_p} I_i(m,n)
\] \hspace{1cm} (S10)

To determine the length of the cavitation, the sum value of the gray level distribution for a partial sequence was converted into the vector (with length of \( W \) elements), as:

\[
G^p(m) = \sum_{n=1}^{H} I_{\text{tot}}^p(m,n) = [g_{1}, g_{2}, \ldots, g_{W}].
\] \hspace{1cm} (S11)

Each \( g_m \) element in Equation (S11) equals the sum of the values in the \( m\)-th column of the \( I_{\text{tot}}^p \).

The vector of the gray level distribution \( G^p(m) \) was further normalized as:
Here, the maximum value $G_{\text{max}}$ was chosen as the average of maxima of $G^{\rho}(m)$ for the reference, polished (S1) sample at each flow rate. The maximum values used for the normalization as a function of the Reynolds numbers are shown in Figure S23. The increase of the normalization value $G_{\text{max}}$ by the Reynolds number indicates the increase of the cavitation intensity.

As an example, all 25 normalized gray level lines $G_{\text{norm}}^{\rho}(m)$ for the polished sample (S1) at $\sigma = 1.4$ are shown in Figure S22.

In all the images, the center of the cylinder (see the bottom of Figure S22) was positioned as $m_c = 575$ px. The position $m_l\rho$, defined as the end of the cavitation, was determined as $m$, where the normalized gray level line equals $G_{\text{norm}}^{\rho}(m_l) = 0.5$ (these positions are marked by the circles in Figure S22). The cavitation length within each partial sequence was further calculated as:

$$L_{\rho} = \kappa |m_{l\rho}^{\rho} - m_l|, \quad \text{(S13)}$$

where $\kappa = 92.6 \, \mu\text{m}/\text{px}$ is the magnification of our optical system and was determined by appropriate calibration.

By using Equation (S13), 25 different values of $L_{\rho}$ (for $\rho = 1, \ldots, 25$) were determined for each testing parameter. From them, we have calculated the cavitation length as an arithmetic mean and corresponding standard deviation. They are listed in Table S2.
Table S2. Cavitation characteristics for tested samples at various flow conditions.

| Specimen     | $\sigma$ (-) | Re (-) | $L$ (mm) | $St$ (-) |
|--------------|--------------|--------|----------|----------|
| Polished (S1)| 2.6          | 83,000 | -        | 1.09 ± 0.2 |
|              | 2.3          | 89,000 | -        | 0.95 ± 0.1 |
|              | 1.8          | 100,000| 11.4 ± 0.9 | 0.74 ± 0.1 |
|              | 1.4          | 111,000| 12.3 ± 0.3 | 0.60 ± 0.2 |
|              | 1.2          | 122,000| 15.7 ± 0.8 | 0.49 ± 0.1 |
|              | 1.0          | 133,000| 24.2 ± 1.1 | 0.48 ± 0.1 |
| Dimpled (S2) | 2.6          | 83,000 | -        | -        |
|              | 2.3          | 89,000 | -        | 0.87 ± 0.2 |
|              | 1.8          | 100,000| -        | 0.75 ± 0.3 |
|              | 1.4          | 111,000| 9.8 ± 0.5 | 0.73 ± 0.1 |
|              | 1.2          | 122,000| 14.1 ± 0.7 | 0.47 ± 0.4 |
|              | 1.0          | 133,000| 22.6 ± 1.6 | 0.96 ± 0.4 |
| Velvet (S3)  | 2.6          | 83,000 | -        | -        |
|              | 2.3          | 89,000 | -        | 0.82 ± 0.6 |
|              | 1.8          | 100,000| 3.0 ± 0.7 | 0.80 ± 0.4 |
|              | 1.4          | 111,000| 7.8 ± 0.7 | 0.76 ± 0.2 |
|              | 1.2          | 122,000| 13.2 ± 0.7 | 0.49 ± 0.1 |
|              | 1.0          | 133,000| 21.0 ± 1.2 | 0.86 ± 0.2 |
| Oxidized (S4)| 2.6          | 83,000 | -        | -        |
|              | 2.3          | 89,000 | -        | 0.91 ± 0.3 |
|              | 1.8          | 100,000| 3.2 ± 1.0 | 0.84 ± 0.7 |
|              | 1.4          | 111,000| 10.7 ± 0.6 | 0.79 ± 0.2 |
|              | 1.2          | 122,000| 15.9 ± 1.0 | 0.48 ± 0.1 |
|              | 1.0          | 133,000| 22.9 ± 1.1 | 0.80 ± 0.2 |
| Waved (S5)   | 2.6          | 83,000 | -        | 1.02 ± 0.0 |
|              | 2.3          | 89,000 | -        | 0.95 ± 0.0 |
|              | 1.8          | 100,000| -        | 0.88 ± 0.3 |
|              | 1.4          | 111,000| 13.0 ± 0.6 | 0.73 ± 0.1 |
|              | 1.2          | 122,000| 16.8 ± 0.9 | 0.52 ± 0.1 |
|              | 1.0          | 133,000| 25.7 ± 1.1 | 0.55 ± 0.2 |
| Grooved (S6) | 2.6          | 83,000 | -        | 1.35 ± 0.2 |
|              | 2.3          | 89,000 | -        | 1.19 ± 0.2 |
|              | 1.8          | 100,000| 12.8 ± 0.8 | 0.93 ± 0.2 |
|              | 1.4          | 111,000| 12.5 ± 0.5 | 0.84 ± 0.2 |
|              | 1.2          | 122,000| 17.6 ± 0.5 | 0.48 ± 0.1 |
|              | 1.0          | 133,000| 32.3 ± 2.0 | 0.48 ± 0.1 |
Figure S22. Determination of the cavitation length – an example for polished sample S1 at $\sigma = 1.4$. 
Figure S23. Normalization values $G_{\text{max}}$ in dependence of Reynolds number.

7 Validation of the frequency response

The validation of the frequency response was performed by comparison between:

- the frequency spectra, measured by the hydrophone RESON TC4013 (the violet curve in Figure S24);
- the frequency spectra, measured by the high frequency pressure transducer PCB 113B28 (the green curve in Figure S24);
- and the frequency spectra, calculated from the high-speed visualization (the red and the blue curves in Figure S24).

Figure S24 shows an example of frequency validation for the polished specimen (S1) at cavitation number 1.2. Typical signals (i.e., pressure as a function of time), measured by the hydrophone and PCB are shown in Figure S25. From this signal, the frequency spectra (the green and the violet curves) in Figure S24 were obtained by using the Fast Fourier Transformation (FFT).

The frequency response from visualization was calculated at two different regions of interest (ROI), marked as ROI-1 and ROI-2 in images in Figure S24. At each image, all the pixel values within each ROI were summed. The sum of the ROI pixels as a function of time was further transformed into the frequency domain by FFT. In this way, the blue curve for ROI-1 and the red curve for ROI-2 were calculated.

A typical shedding frequency of the cavitation behind the selected specimen is clearly visible as a frequency peak at 530 Hz in the PCB, hydrophone and ROI-1 spectra. This peak at ROI-1 spectrum
perfectly correlates by the frequency response measured by the hydrophone and the PCB, since ROI-1 was chosen at the same position as the PCB and the hydrophone were mounted.

When the frequency response from the visualization is calculated from the ROI-2, the peak corresponding to the shedding frequency appears at \( \frac{530 \text{ Hz}}{2} = 265 \text{ Hz} \). This happens, since the cavitation alternates between the upper and the bottom side of the cylinder. Thus, at ROI-2, only the half of the shedding frequency is measured.

Comparing the frequency spectra from the hydrophone and PCB, one can notice that PCB sensor amplifies frequencies (300 Hz – 350 Hz) that are approximately half of the amplified hydrophone frequencies (600 Hz – 700 Hz). Since the PCB pressure sensor is mounted 30 mm downstream from the specimen, it may sense predominately pressure oscillations caused by cavitation growth. On the other hand, the hydrophone is located 90 mm downstream. Thus, it sense predominately pressure oscillations connected with cavitation cloud collapses, which appear in its vicinity.

Figure S24. Frequency response, measured by different techniques for the polished sample S1 at \( \sigma = 1.4 \).
Figure S25. The pressure as a function of time, measured by hydrophone RESON (left) and PCB pressure transducer (right) for the polished sample S1 at $\sigma = 1.4$.

8 Evaluation of the frequency response

In order to compare the individual spectra between all the samples tested under different flow conditions, we have fitted the Gaussian function to the secondary peaks (as shown by the green line in Figure S26):

$$Y(f) = ae^{-\frac{[(f-f_0)]^2}{2\sigma_f^2}}$$  \hspace{1cm} \text{(S14)}

where $\sigma_f$ stands for the standard deviation of the frequency distribution. It was used to calculate the standard deviation of the Strouhal numbers (the error bars in Figure 9 in the manuscript).
Figure S26. Fitting the Gaussian function on the FFT frequency spectrum, acquired by hydrophone RESON for polished sample S1 at $\sigma = 1.4$. 