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FOURIER ANALYSES OF OPTICAL PROFILOMETRY AS AN INFERENTIAL MEASUREMENT FOR IMPACT COVERAGE.

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Abstract

A critical consideration in peening process design is achieving sufficient impact coverage. Conventional methods for assessing coverage rely on manual inspection, which is time-consuming and poorly suited for automated control. In this work, we investigate the use of frequency-domain analysis to quantify surface modification in peened samples using optical profilometry (OP) data. Three-dimensional surface maps of Almen strips were acquired using a high-resolution OP system and analyzed via fast Fourier transform (FFT) to compute spatial power spectral densities (PSDs). PSD maps and radially averaged profiles reveal consistent amplification of harmonic components similar to the nominal particle size, with increasing intensity and frequency shift as a function of impact velocity and coverage. A normalized PSD metric was introduced to highlight frequency bands most affected by peening, and the peak amplification was shown to correlate with process parameters. These results suggest that spectral decomposition of OP measurements offers a rapid, interpretable, and scalable method for characterizing peened surfaces and could support future closed-loop process control in manufacturing environments.

Keywords: Optical Profilometry, Impact Coverage, Surface Roughness.

Introduction

Achieving sufficient impact coverage is a key consideration in peening process design, as it directly influences fatigue life[1]. Standard methods for characterizing surface impact density are often experimentally cumbersome, typically requiring direct inspection with optical microscopy[2].

Manual inspection techniques are poorly suited for process control applications, where rapid feedback is essential for corrective adjustments. Modern optical profilometry (OP) systems, by contrast, are designed for automation and can rapidly acquire high-resolution measurements of critical regions of a component.

These OP systems generate three-dimensional point clouds, enabling detailed analysis of the integrity of treated surfaces. In this work, we investigate the use of the Fast Fourier Transform (FFT) to analyze the spectral structure of shot-peened surfaces across varying coverage levels, evaluating whether a surface's characteristic spectral pattern can serve as a reliable indicator of impact coverage.

Experimental Procedures or Computational Methods

The Fast Fourier Transform (FFT) is a fundamental algorithm in signal processing that decomposes a complex waveform into a sum of sine and cosine functions[3]. The SciPy [4] implementation of the 1-D FFT is shown in Equation 1. Using Euler's formula, $\exp\left(-2\pi i \frac{kn}{N}\right)$ can be expressed as $\cos(-2\pi kn/N) + i \sin(-2\pi kn/N)$, representing the sum of sine and cosine waves corresponding to a frequency of $-2\pi k/N$, also known as the k-th harmonic.

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For a discrete signal $x[n]$ of length N , the FFT produces $y[k]$, known as a Fourier coefficient, a complex number of the form $a + bi$. The real part a and the imaginary part b scale the contributions of the cosine and sine components, respectively. The magnitude of the Fourier coefficient determines the prominence of the corresponding harmonic, while the relative values of a and b determine its phase (orientation). Power spectral density (PSD) is the squared magnitude of a Fourier coefficient $a^2 + b^2$, and describes the distribution of signal power across frequency components. In other words, it quantifies how much of the signal's variance or energy is associated with each frequency band. When computed over spatial fields, the PSD reveals dominant length scales and texture features by capturing the intensity of periodic or quasi-periodic structures.

$$y[k] = \sum_{n=0}^{N-1} e^{-2\pi i \frac{kn}{N}} x[n] \quad (1)$$

In one dimension, the FFT produces a vector of Fourier coefficients that describe the relative contribution of each harmonic to the original waveform. Analogously, for a two-dimensional field of size $N \times N \text{ pixels}^2$, the FFT produces a 2-D array of Fourier coefficients, where the $[u, v]$ -th entry represents the contribution of the 2-D harmonic with frequencies u/N in the x-direction and v/N in the y-direction. In this case, $[u, v]$ is known as a wavevector, often denoted $\mathbf{k} = [k_x, k_y]$.

The inverse Fourier transform allows the original field to be reconstructed by summing the scaled contributions of these harmonics. By discarding harmonics with small Fourier coefficients, often associated with noise, one obtains a smoothed approximation of the original measurement[5]. Figure 1 illustrates this concept, showing a reconstructed surface obtained using only the 20 largest-magnitude harmonics.

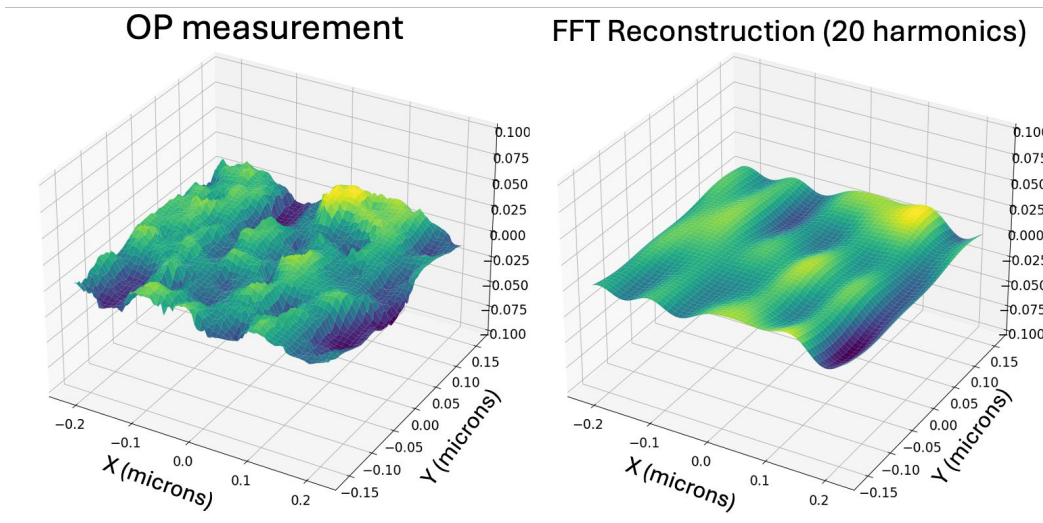


Figure 1. Point cloud of a shot-peened surface and smoothed representation obtained via filtering of low magnitude Fourier coefficients.

This analysis centers on a comparison of the surface finishes of nine Almen strip samples encompassing a full factorial of cycle times and impact velocities. Samples were treated using a laboratory-scale shot peening test stand (Sentenso GmbH, Datteln, Germany) with G1 grade

conditioned cut wire 32 media. Process parameters are summarized in Table 1. Media velocity was measured using the *Sentenso VelocityEasy* high-speed camera system for particle trajectory tracking[6].

Table 1. Peening process parameters used with *Sentenso ProcessMaster*, laboratory scale shot peening test stand.

Media Type	Velocity	Cycle Time	Angle	Mass Flow Rate
CCW32	42, 62, 82 m/s	1, 10, 100 s	76°	2 kg/min

A *Keyence VR-6000* series optical profilometer was then used to acquire high-resolution point cloud representations of the treated surfaces[7]. The Keyence system concentrates sampling points around irregular features. Regular rectilinear grids, a requirement of the FFT algorithm, were obtained via linear spline interpolation with a pixel size of 40 μm . Each rectilinear grid was split into patches of size 2 mm \times 2 mm, and the power spectral density of each harmonic was analyzed.

Results

Figure 2 is a visual comparison of surface finish across the three cycle times with 62 m/s impact velocity. A significant portion of the 1-second trial's surface is uncovered. Impact dimples appear largely discrete with rare overlaps. The 10s and 100s cases are difficult to distinguish. Neither exhibits significant regions unaffected by impacts, though there is an order of magnitude difference in cycle time.

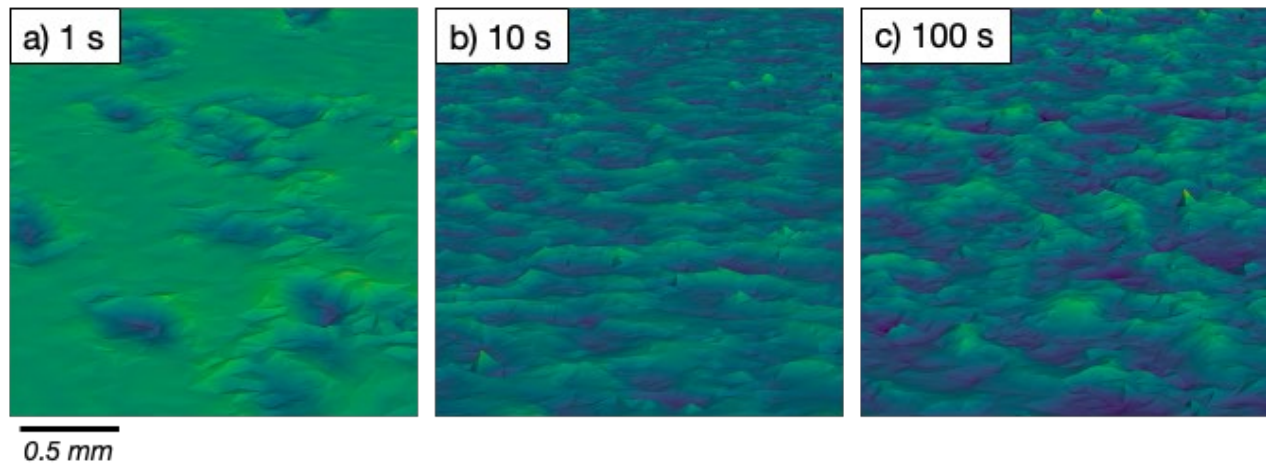


Figure 2. Surface finishes for a) 1 second, b) 10 seconds, and c) 100-second peening cycle time samples at 62 m/s impact velocity.

PSD maps for the three surfaces are shown in Figure 3. k_x and k_y represent the frequency of the harmonic components in the x - and y -directions, respectively. The colormap corresponds to $\log(1 + \text{PSD})$, which compresses the dynamic range so that high-frequency harmonics (typically associated with very small magnitudes) do not dominate the visualization scale. Fourier coefficients corresponding to opposite harmonics (e.g., $[k_x = 1, k_y = 2]$ and $[k_x = -1, k_y = -2]$) are complex conjugates and have identical magnitudes. While the 10- and 100-second trials appear visually similar, the power spectrum maps for all three surfaces exhibit distinct frequency characteristics. In particular, the magnitude of PSDs increase across low, medium, and high frequency harmonics with increasing cycle time.

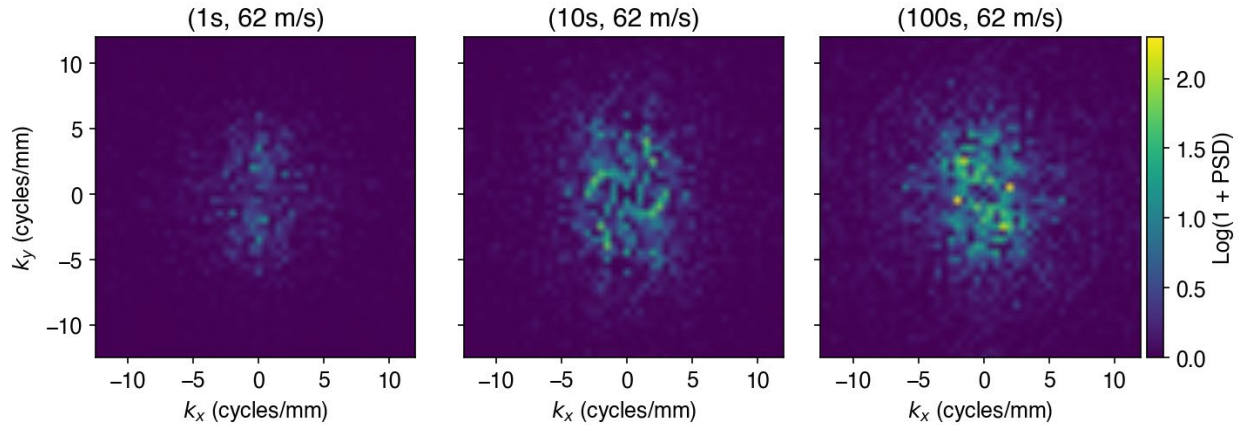


Figure 3. PSD maps for 1, 10, and 100 second peening cycle time, 62 m/s impact velocity. Log scaling used on color axis.

As a result of the high impact angle, deformation was not strongly anisotropic, and the corresponding PSD maps are largely symmetric about the origin. To further investigate the effect of peening cycle time on surface finish, we computed the average PSD as a function of wavevector magnitude, $|k| = \sqrt{k_x^2 + k_y^2}$, as shown in Figure 4. Trials are grouped by impact velocity and stratified by peening cycle time. A power spectrum profile for an unpeened Almen strip is included in each plot as a baseline reference. Average PSD increases across all spatial frequencies with both increasing impact coverage and impact velocity.

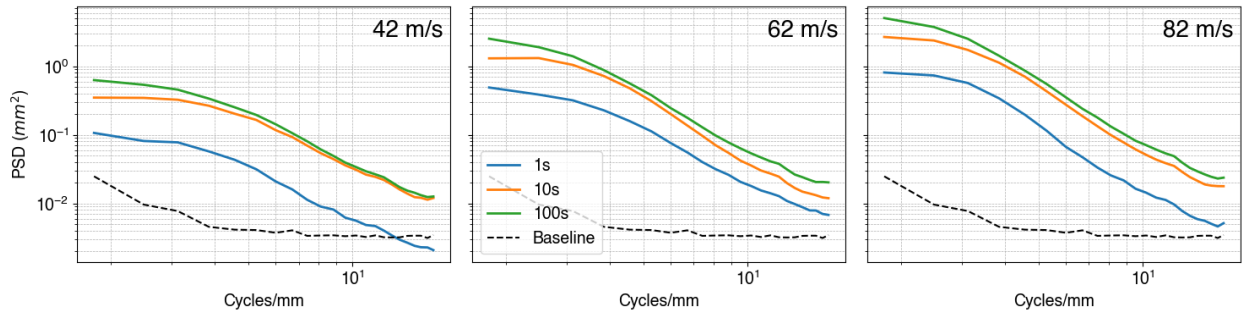


Figure 4. Radially averaged power spectral density (PSD) as a function of wavevector for all peening trials.

Figure 5 presents the average PSD of each peened sample normalized by that of the unpeened Almen strip. This normalization highlights the relative amplification of spatial frequencies introduced by shot peening. The process most strongly amplifies frequencies in the range of 2.5 to 4 mm^{-1} , corresponding to spatial wavelengths between approximately 0.25 and 0.4 mm . Given a nominal particle diameter of 0.88 mm , these harmonics align closely with the characteristic size of individual impact dimples. The localized amplification in this frequency band suggests that the dominant surface features introduced by peening are directly linked to the plastic imprint left by single-particle impacts. The most amplified frequency appears to shift to the left with increased impact velocity, consistent with larger dimples induced by faster impacts. Additionally, increased coverage time results in further amplification of all frequencies.

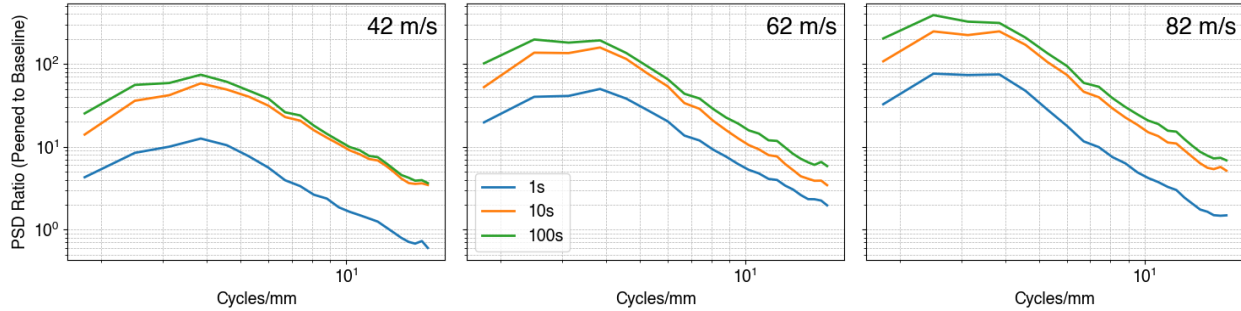


Figure 5. PSD normalized to unpeened Almen strip, highlighting amplification of frequencies related to particle diameter.

Figure 6 summarizes the maximum value of normalized PSD as a function of impact count, grouped by impact velocity. These results suggest that spectral decomposition of optical profilometry measurements can serve as a sensitive diagnostic tool for quantifying the extent and characteristics of surface modification due to peening. In particular, the peak amplification metric captures both the intensity and dominant spatial scale of surface deformation, enabling differentiation between peening regimes based on process.

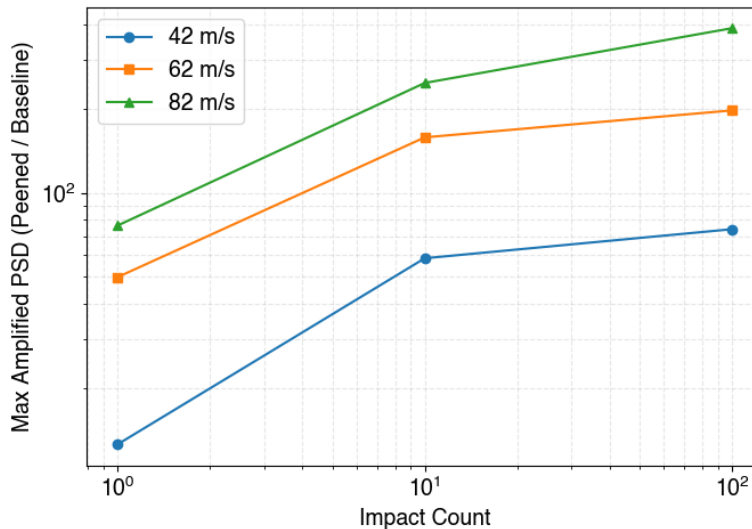


Figure 6. Maximum value of PSD amplification metric with respect to unpeened baseline.

Discussion and Conclusions

This study demonstrates the potential of frequency-domain analysis for quantifying shot peening coverage using optical profilometry (OP) data. Traditional methods for assessing impact coverage rely on manual surface inspection, which can be slow, subjective, and impractical for real-time process monitoring. By contrast, the approach presented here leverages data-rich surface point clouds and fast Fourier transform (FFT)-based spectral analysis to extract quantitative, interpretable features of surface modification.

Our results show that the power spectral density (PSD) of a shot-peened surface increases systematically with both impact coverage and impact velocity. Radially averaged PSD curves revealed consistent amplification across all spatial frequencies, while normalized spectra showed that peak amplification occurs in the frequency range corresponding to the nominal particle size. This spectral signature serves as a reliable indicator of surface impact density. Additionally, the frequency of maximum amplification was observed to shift toward lower spatial frequencies with increasing impact velocity, consistent with larger impact dimples resulting from

higher kinetic energy. Increased coverage time further amplified these features across all frequencies, reflecting the cumulative nature of surface deformation during extended peening.

PSD amplification metrics, such as the peak value or dominant frequency, have the potential to distinguish between peening regimes and infer both the extent and character of surface modification. These findings support the use of spectral analysis as a fast, scalable, and physically interpretable method for process monitoring in shot peening and potentially other surface treatment applications. Future work may focus on correlating spectral metrics with fatigue performance, expanding this methodology to more complex geometries, and integrating it into feedback-controlled manufacturing systems.

Acknowledgement

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