Surface Periodicity Index (S_{PI}): A Measure of Periodicity of Surface Topography

WCMNM 2021

Rohit Gupta[1] and Madhu Vadali[1*]

[1]*SMART Lab, Mechanical Engineering Discipline, Indian Institute of Technology Gandhinagar, INDIA*
[*]*Corresponding author*

Abstract

The periodicity of micro and nanoscale surface features generated by various manufacturing processes plays a vital role in the functional behavior of the parts. The periodicity, usually a function of process parameters, is not effectively captured by the existing surface topography characterization parameter. In this work, a new characterization parameter called *surface periodicity index*, S_{PI}, is defined to indicate the significance of periodic spatial features on a surface. S_{PI}, a measure of the energy of the periodic features, is shown to effectively capture the significance of patterned surfaces with repetitive features with the help of artificial surfaces. Further, a case study on pulsed laser micro polishing is presented that demonstrates the utility of the surface periodicity index.

Keywords: Surface topography, texture, periodicity, power spectral density.

1. Introduction

The periodicity of surface features strongly affects the functional properties and the mechanical properties of the machined components [1,2]. These are especially important at micro and nanoscale features. For example, periodicity can control the contact angle of the surface for wetting application [3]. It also helps to increase wear and corrosion resistance and biocompatibility of any surface [4]. Therefore, quantifying the significance of the periodicity is important for the functional behaviour of the component and manufacturing process. The frequency of the periodic feature induced on the surface, either intentional or consequential, is a function of process parameters such as translation speed, depth of cut, and feed.

Several parameters are defined to characterize the topography of the surface, such as amplitude parameters, spatial parameters, hybrid parameters and functional parameters [7,8]. While these quantify and characterize the topography, these parameters do not capture the significance of the periodicity of any surface [9]. Therefore, a new metrological parameter called as *surface periodicity index* (S_{PI}) is defined in paper, which can be used to indicate the significance of a periodic feature.

The surface periodicity index, S_{PI}, is derived from the power spectral density (PSD) of the surface features. Zeng et al. [1] have shown that PSD is a better indicator to capture the strength of a periodic feature than the amplitude-frequency spectrum. However, PSD does not capture the significance of the frequency on the surface. S_{PI} overcomes this limitation by quantifying the significance of a spatial frequency component in among other features on the surface.

In the following sections, a detailed description of how to calculate S_{PI} is given, followed by a case study to show the utility of this parameter. For the case study, feature marks resulting from pulsed laser micro polishing (PLμP) are chosen to calculate S_{PI}, that shows capillary regime and thermocapillary regime polished surface. A smaller value of S_{PI} indicates the thermocapillary regime polished surfaces due to the periodic feature and a larger value of S_{PI} indicates capillary regime polishing due to the absence of these polishing marks.

2. Calculating S_{PI}

S_{PI} is a measure of the *energy* of a periodic feature in the context of the surface. It is defined as the area under a uniform PSD spectrum as a percentage of the area for a purely random surface with no periodicity. Therefore, a surface with distinct periodic features will have a sharp PSD at the corresponding spatial frequency, and thus the area under it will be close to zero. On the other hand, a surface with no periodicity will have a nearly 100% S_{PI}. The algorithm to calculate S_{PI}, as shown in Fig. 1, is described in the following:

Step 1: Obtain surface height measurements of the processed part with periodic features.
Step 2: Theoretically estimate the spatial frequency of the periodic features. The frequency is typically a function of the process parameters.
Step 3: Compute the power spectral density of the measured surface [1]. It is to be noted that zero padding may be necessary to ensure sufficient resolution of the spectrum [10].
Step 4: Filter the PSD in Step 3 through bandpass filter, such that the central frequency of the filter is equal to theoretically estimated feature frequency in Step 2. In the current work, a fifth order Butterworth filter is applied on the PSD frequency spectrum.
Step 5: In this step, the filtered PSD is normalized with the highest peak in spectrum. For a periodic feature, the highest peak would be at the estimated spatial frequency of the periodic feature.
Step 6: In the last step, the ratio of area under the filtered and normalized PSD spectrum to the area of the bandpass filter is calculated that results in S_{PI}. This can be given as:

$$S_{PI} = \left(\frac{A_{PSD}}{A_f}\right)100 \quad (1)$$

where, A_{PSD} is the area of filtered and normalized PSD spectrum and A_f is the area under the bandpass filter.

Fig. 2(a) and (b) shows filtered and normalized PSD spectrum for artificially generated periodic and

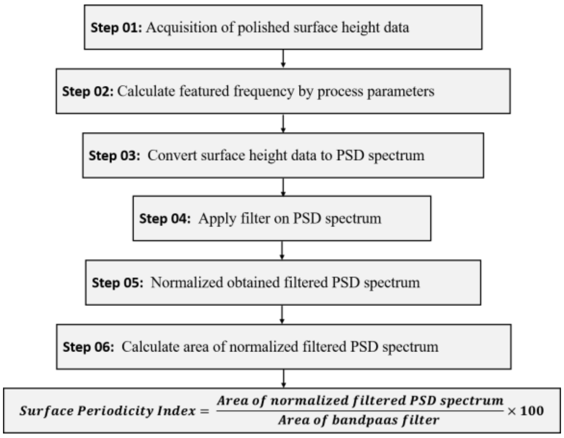

Fig. 1. Steps involved for the calculation of Periodicity Index ($\boldsymbol{S_{PI}}$).

aperiodic surface, respectively. Large number of spatial frequency components in the filtered and normalized PSD spectrum shows random noise surface. Whereas single spatial frequency components in the filtered and normalized PSD spectrum represent periodic features on the surface.

Areas under the filtered and normalized PSD spectrum for periodic and aperiodic surface are calculated as 3.77 µm^2 and 16.82 µm^2 respectively. Smaller areas indicate significant periodicity on the surface (see Fig. 2a). whereas larger areas indicate aperiodicity on the surface (see Fig. 2b). In the current work, a fifth order Butterworth filter is used as a bandpass filter with a bandpass of 40 mm^{-1} and an area of 47.55 µm^2. Correspondingly, the S_{PI} for periodic and aperiodic surfaces are 7.9% and 35.37% respectively.

Surface periodicity index, S_{PI} is sensitive to periodic spatial frequency and the passband of the filer. The passband is decided based on the theoretical periodicity. If the actual frequency is beyond the passband, then the value of S_{PI} will be significantly different. Therefore, a detailed sensitivity analysis is warranted and becomes part of future work.

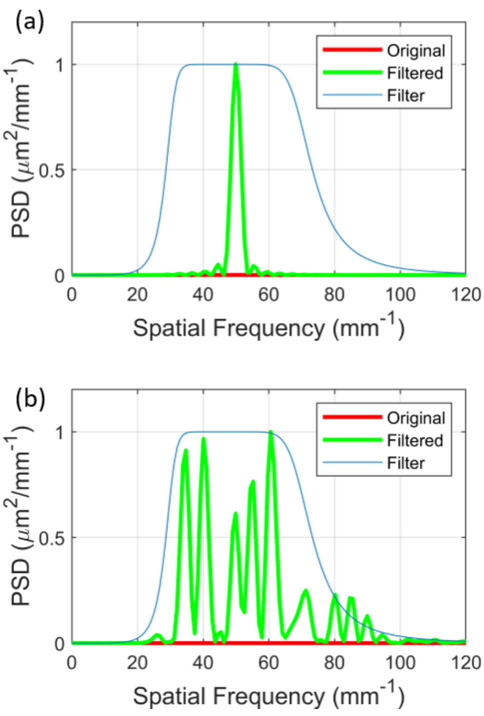

Fig. 2. Filtered and normalized PSD frequency spectrum of (a) periodic surface and (b) aperiodic surface.

3. A case study: pulsed laser micro polishing

Pulsed laser micro polishing (PLµP) is a thermal non-contact surface smoothening process for metallic parts of micro/meso scales [11]. In PLµP, it is common to use zigzag (or raster) motion for the laser beam to cover the entire sample surface (see Fig. 3a). Two regimes exist in PLµP, namely the capillary regime and the thermocapillary regime [12,13]. In capillary regime, usually at sub-µs laser pulse durations, no process induce periodicity is observed. In thermocapillary regime, usually longer µs pulse durations, periodic features corresponding to overlapping of laser spots and step over of the zigzag path are observed, as shown in Fig. 3. While the stepover along the y axis is a direct process parameter, the spot overlap can be calculated using the scan speed and laser pulse frequency [12,13] and area given as follows:

$$f_{spot} = f_{pulse} \, / \, V_{scan}, \; f_{step} = 1 \, / \, stepover \qquad (2)$$

where, f_{spot} is the spot overlap spatial frequency (mm^{-1}), f_{step} is the stepover spatial frequency (mm^{-1}), f_{pulse} is the laser pulse ($\#pulses/s$), V_{scan} is the laser scan speed (mm/s).

To demonstrate the effectiveness of the S_{PI}, experimental data from the PLµP work at University of Wisconsin Madison is used [13–15]. The experimental and measurement information can be found in [13–15]. In these experiments, PLµP is performed on initially

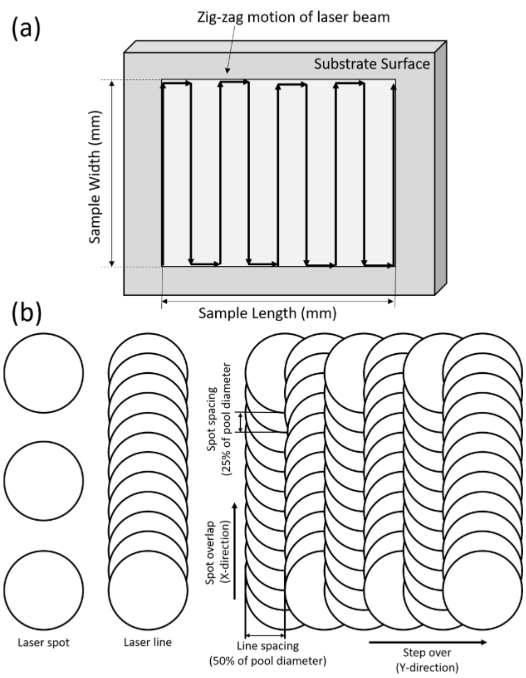

Fig. 3. (a) Zig zag motion of PLµP laser beam over the sample (b) Featured marks on the polished surface due to zig zag motion of laser beam.

micro-milled surfaces. Therefore, only PLμP induced periodicity is considered and periodicity due to micro-milling is ignored. Here, the capillary regime with no periodic features and the thermocapillary regime with periodic features are chosen based on visual inspection. It will be shown in the following that visual inspection can be replaced by surface periodicity index, S_{PI}.

Capillary regime polished surface height profile (see Fig. 4a) represents lower spatial frequency unpolished milling marks on the polished surface. S_{PI} analysis of the surface (f_{spot} and f_{step} are 357.14 mm^{-1} and 142.85 mm^{-1}, respectively) along the width and length of the sample has been performed and named as S_{PI}^{spot} and S_{PI}^{step} respectively, calculate using filtered and normalized PSD spectrum of spot and step spatial frequency spectrum (see Fig. 4b, Fig. 4c). Calculated S_{PI}^{spot} and S_{PI}^{step} values are 50.1% and 43.3% respectively. Large number of spatial frequency components in the neighbouring region of featured frequency and higher S_{PI} value shows aperiodic feature at featured frequency, confirms the capillary regime of the polished surface.

Similarly, the thermocapillary regime polished surface height profile (see Fig. 5a), represents spot overlap marks in the x-direction and step over marks in the y-direction on the laser polished surface (f_{spot} and f_{step} are 147.05 mm^{-1} and 58.82 mm^{-1} respectively). Analysis shows S_{PI}^{spot} and S_{PI}^{step} values are 10.9% and 7.3% respectively, calculate using filtered normalised PSD spectrum of spot and step spatial frequency spectrum (see Fig. 5b, Fig. 5c). Smaller number of spatial frequency components in the neighbouring region of featured frequency and lower S_{PI} value shows periodic feature at featured frequency, confirms the thermocapillary regime of polished surface.

Similarly, different thermocapillary regime polished surface experimental data (f_{spot} and f_{step} are 178.57 mm^{-1} and 71.42 mm^{-1} respectively) analyse to get S_{PI}^{spot} and S_{PI}^{step} values, calculated as 13.9% and 9.8% respectively (see Fig. 6). Periodicity index analysis has been done with the bulk of the experiments, shows similar results and distinguish between capillary and thermocapillary polished regime.

4. Conclusions

In this work, a new surface topography

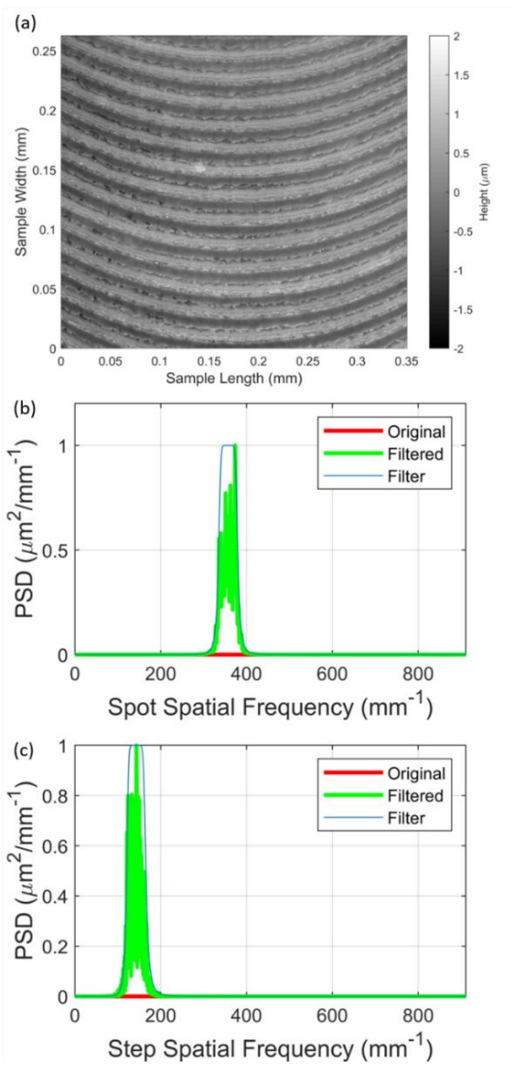

Fig. 4. (a) Capillary regime height profile of a surface with no periodicity, (b) spot spatial frequency and (c) step spatial frequency filtered and normalized PSD spectrum

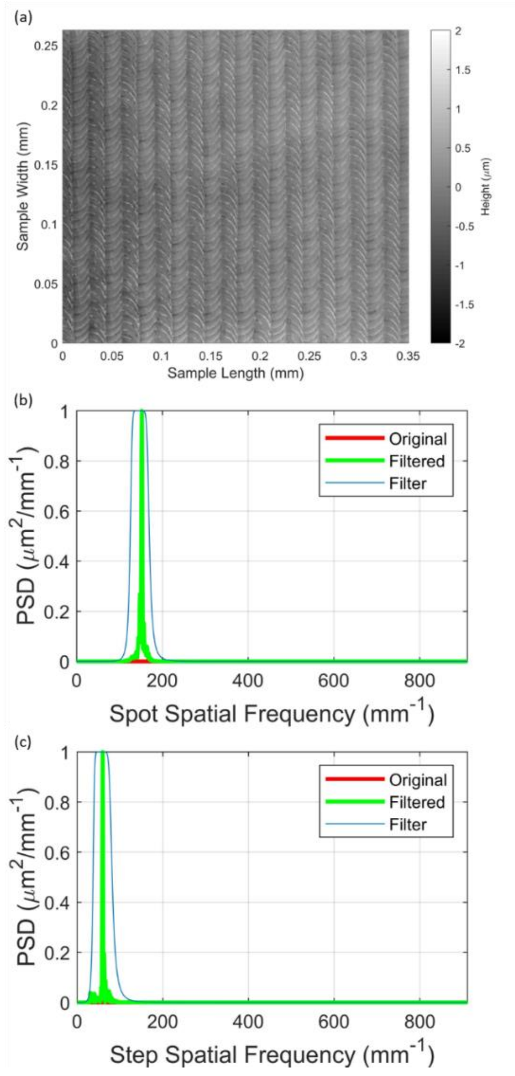

Fig. 5. (a) Thermocapillary regime height profile of a surface with periodic features (b) spot spatial frequency and (c) step spatial frequency filtered and normalized PSD

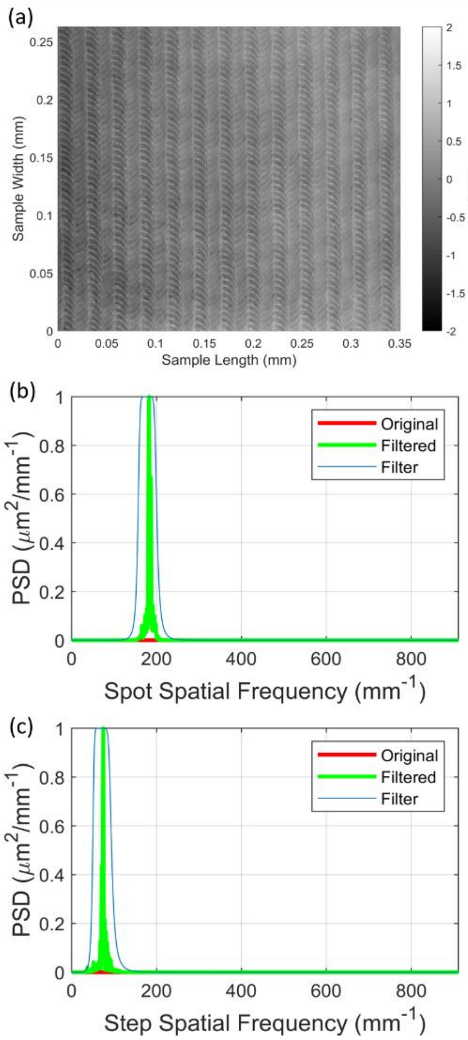

Fig. 6. (a) Surface height profile a surface with periodic features, (b) spot spatial frequency and (c) step spatial frequency filtered and normalized PSD spectrum

characterization parameter, called *surface periodicity index* (S_{PI}) is proposed to indicate the significance of periodicity of the surface feature in the context of the surface. It is defined as the percentage ratio of area of filtered and normalized power spectral density of a surface to the area under a bandpass filter, with a central frequency being the periodicity of interest. Surfaces with only a periodic feature have a sharp peak in its power spectral density plot, and therefore having a near zero area under it. On the other hand, surfaces with no periodicity (ideally a random surface) will have no unique peak on the power spectral density plot, therefore having a significantly larger area. S_{PI} takes advantage of this nature of periodic surfaces.
The utility and the intuition of the parameter is demonstrated using artificial surfaces with and without periodicity. In addition, a care study with surfaces generated through pulsed laser micro polishing are shown wherein polishing under capillary regime do not generate periodic features while those polished under thermocapillary regime generate features with a periodicity that is a function of process parameters. It was shown that S_{PI} can be used to differential between the two regimes instead of relying on subjective visual inspection.

Acknowledgments

The authors thank the University of Wisconsin, Madison for the permission to use the experimental data used in this paper, that was generated under NSF supported project (Grant No. CMMI-0900044). The authors also acknowledge the support of Indian Institute of Technology Gandhinagar in accomplishing this work.

References

[1] Q. Zeng et al., “Correlating and Evaluating the Functionality-Related Properties with Surface Texture Parameters and Specific Characteristics of Machined Components,” Int. J. Mech. Sci., 2018; 149: 62–72.
[2] D. Ulutan et al., “Machining Induced Surface Integrity in Titanium and Nickel Alloys: A Review,” Int. J. Mach. Tools Manuf., 2011; 51(3): 250–280.
[3] A. M. Kietzig et al., “Patterned Superhydrophobic Metallic Surfaces,” Langmuir, 2009; 25(8): 4821–4827.
[4] J. Bonse et al., “Applications of Laser-Induced Periodic Surface Structures (LIPSS),” Laser-Based Micro- and Nanoprocessing XI, International Society for Optics and Photonics, 2017; p. 100920N.
[5] S. lou et al., “Material Ratio Curve of 3D Surface Topography of Additively Manufactured Parts: An Attempt to Characterise Open Surface Pores,” Surface Topography: Metrology and Properties, 2021; 9(1), p. 015029.
[6] S. lou et al., “Application of Clustering Filter for Noise and Outlier Suppression in Optical Measurement of Structured Surfaces,” Conf on Precis Electromagn Meas (CPEM), 2020; Pap, 69(9), pp. 6509–6517.
[7] IS0 4287:1997 Geometrical product specifications (GPS) - Surface texture: Profile method - Terms, definitions and surface texture parameters.
[8] L. Pagani et. al., “Towards a New Definition of Areal Surface Texture Parameters on Freeform Surface: Re-Entrant Features and Functional Parameters,” Industrial metrology, 2019, 141, pp. 442–459
[9] D. Chiffre et. al., “Quantitative Characterisation of Surface Texture,” CIRP Annals, 2000; 49(2): 635–652.
[10] R. G. Lyons “Understanding Digital Signal Processing,” Pearson Education India, 2004, 3/E.
[11] T. L. Perry et al., “Micromelting for Laser Micro Polishing of Meso/Micro Metallic Components,” ASME 2007 International Manufacturing Science and Engineering Conference, ASMEDC, Atlanta, Georgia, USA, 2007; pp. 363–369.
[12] Q. Wang et al., “Surface Prediction Model for Thermocapillary Regime Pulsed Laser Micro Polishing of Metals,” J. Manuf. Process., 2015; 20:340–348.
[13] F. E., Pfefferkorn, Duffie et al., “Improving Surface Finish in Pulsed Laser Micro Polishing Using Thermocapillary Flow,” CIRP Annals, 2013; 62(1):203–206.
[14] M. Vadali et al., “Effects of Pulse Duration on Laser Micro Polishing,” J. Micro Nanomanuf., 2013; 1(1):011006.
[15] M. Vadali et al., “Pulsed Laser Micro Polishing: Surface Prediction Model,” J. Manuf. Process., 2012; 14(3): 307–315.