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EXPLORING SURFACE TEXTURE QUANTIFICATION IN PIEZO VIBRATION STRIKING TREATMENT (PVST) USING TOPOLOGICAL MEASURES

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ABSTRACT

Surface texture influences wear and tribological properties of manufactured parts, and it plays a critical role in end-user products. Therefore, quantifying the order or structure of a manufactured surface provides important information on the quality and life expectancy of the product. Although texture can be intentionally introduced to enhance aesthetics or to satisfy a design function, sometimes it is an inevitable byproduct of surface treatment processes such as Piezo Vibration Striking Treatment (PVST). Measures of order for surfaces have been characterized using statistical, spectral, and geometric approaches. For nearly hexagonal lattices, topological tools have also been used to measure the surface order. This paper explores utilizing tools from Topological Data Analysis for measuring surface texture. We compute measures of order based on optical digital microscope images of surfaces treated using PVST. These measures are applied to the grid obtained from estimating the centers of tool impacts, and they quantify the grid's deviations from the nominal one. Our results show that TDA provides a convenient framework for characterization of pattern type that bypasses some limitations of existing tools such as difficult manual processing of the data and the need for an expert user to analyze and interpret the surface images.

Keywords: Piezo Vibration Striking, surface texture, topological data analysis

1 Introduction

One of the main objectives of the manufacturing enterprise is to achieve products that satisfy a preset quality under the constraints of time, cost, and available machines [1]. A key quality in manufacturing is the surface texture which is directly related to surface roughness [2–4] and to the tactile feel of the resulting products which is quantified by tactile roughness [5, 6]. Surface texture can be either intentionally introduced to satisfy functional or aesthetic surface properties, or it can be a byproduct of a specific manufacturing setting. However, the importance of surface texture goes beyond merely the aesthetics since the resulting surface properties have a strong influence on ease of assembly, wear, lubrication, corrosion [7], and fatigue resistance [8–10].

An example of a process where surface texture is introduced in order to both enhance the mechanical properties of the part and

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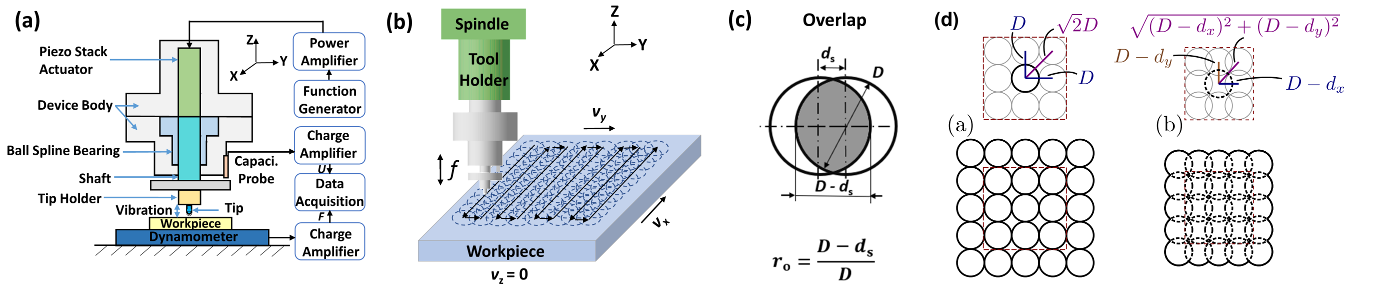

FIGURE 1: Schematics of PVST: (a) PVST; (b) Striking process in PVST; (c) Overlap of indentations; (d) Grid geometry. PVST nominal grid for (d1) x and y overlap $d_x = d_y = 0$, and d2) for x overlap $d_x \geq 0$ and y overlap $d_y \geq 0$. The striking tool diameter is D, and the figure shows a scanning strategy where the x and y scanning speeds are set to obtain a certain overlap ratio. When the overlap in x and y is the same, we write $d_x = d_y = d_s$.

as an inevitable byproduct is the Piezo Vibration Striking Treatment (PVST) [11]. In PVST, a tool is used to impact the surface and a scanning strategy is applied to treat the whole surface, see Fig. 1. Depending on the impact depth and speeds set for the process, various grid sizes and diameters can be obtained. By varying parameters such as the scanning speed and the overlap of the impacts, a texture inevitably is left behind on the surface. While this can be leveraged to both treat and texture the surface, the resulting pattern can also provide invaluable information about the success of the treatment such as quantifying missed or misplaced impact events. Further, the texture can also be utilized to assess the quality of the machined surface through comparing the resulting pattern with the nominal or desired pattern. Specifically, if the resulting pattern is missing too many features (indentations), this can be an indication of large deviation of material distribution on the surface. Detecting such events can signal the need for further finishing, or for adjusting the manufacturing process to enhance the resulting surfaces.

While there are several classical tools for quantifying surface texture [12], one limitation of these methods is their strong reliance on the user for tuning the needed parameters. For example, a common pre-requisite for these tools is knowing the relative pixel intensity in the image and which threshold size for removing objects from the image will result in a successful texture segmentation. An emerging tool that has shown promise for quantifying texture is from the field of Topological Data Analysis (TDA). More specifically, topological measures were used to quantify order of nearly hexagonal lattices [13] which represent nanoscale pattern formation on a solid surface that can result from broad ion beam erosion [14]. The input data in [13] was the location of the nanodots on the surface, which is an input data type often referred to as a point cloud. Topological measures were shown to be more sensitive than traditional tools, and they can provide insight into the generating manufacturing process by examining the resulting surfaces.

This paper explores utilizing topological measures for quantifying the surface texture produced by PVST. Specifically, the goal of this paper is to use topological methods to quantify lattice types in a PVST image, which can provide insight into the effectiveness of the PVST process. While we use measures inspired by those utilized on point clouds, i.e., point locations in the plane, in [13], the data in our work are images of the resulting surface obtained using KEYENCE Digital Microscope. Therefore, in our setting we need to process the data to extract the PVST indentation centers in order to quantify the resulting pattern. Our exploratory results show possible advantages to our approach including automation potential in contrast to standard tools where intensive user-input is required.

The paper is organized as follows. Section 2 provides background for PVST. Section 3 explains the experimental setup and how the experimental data is collected. Section 4 outlines the processing performed on each image to obtain the point cloud data. Section 5 discusses the TDA-based approach proposed in this study. Section 6 compares the results of the analysis to a perfect square lattice. Section 7 includes the concluding remarks.

2 Piezo Vibration Striking Treatment

Mechanical surface treatment uses plastic deformation to improve surface attributes of metal components, such as surface finish, hardness, and residual stress, which is an effective and economical way of enhancing the mechanical properties of engineering components. Among various mechanical surface treatment processes, i.e., Shot Peening [15], Surface Mechanical Attrition Treatment [16], High-frequency Mechanical Impact Treatment [17], and Ultrasonic Nanocrystal Surface Modification [18], PVST is a novel mechanical surface treatment process that is realized by a piezo stack actuated vibration device integrated onto a computer numerical control (CNC) machine to impose tool strikes on the surface. Different from those processes, the non-resonant mode piezo vibration in PVST and the integration with CNC machine enable PVST to control the process more conveniently and precisely as demonstrated in previous applications in modulation-assisted turning and drilling processes [19, 20]. The schematics of PVST are shown in Fig. 1. The device is connected to the spindle of a CNC mill through a tool holder. The spindle can only move along the Z direction to control the distance between striking tool and workpiece surface. The motion of the machine table along the X or Y directions defines specific striking locations on the workpiece mounted on the table. As shown in Fig. 1a, the piezo stack actuator is connected with a spline shaft that is part of the ball spline bearing, both of which are fixed in the device body. The actuator drives the shaft to move along the Z direction, but no bending or rotation is allowed. The striking tool is rigidly connected to the shaft through a holder. The power generator and amplifier produce amplified driving voltage to extend and contract the actuator and hence actuate the tool to oscillate along the axial direction. A capacitance probe clamped onto the device body and a dynamometer plate mounted on the machine table are used to measure the displacement of the tool and the force during the treatment. Both the force and displacement are recorded synchronously in a data acquisition system. The lower bound and upper bound of the driving voltage are set as zero and peak-to-peak amplitude V_{pp} of the voltage oscillation, which can control the frequency and amplitude of the tool vibration to generate different surface textures. The initial position of the tool Z can be used to control the distance between the tool and the workpiece surface and hence change the striking depth to produce different surface textures as well. As shown in Fig. 1b-d, the successive strikes controlled by scan speed v_s will be imposed on different locations of the surface along the tool scan path. The offset distance d_s between two successive strikes and the diameter of the indentation can be utilized to compute the overlap ratio. Different overlap ratios can generate various surface textures, namely higher overlap ratio leads to a denser distribution of the indentations. This paper focuses on the low overlap ratio images produced using PVST to detect the center points of the circles in the image and quantitatively determine the lattice type present in the texture with minimal user input.

3 Experimental Procedure

A mild steel ASTM A572GR50 workpiece with a dimension of 120 mm × 40 mm × 20 mm is used for surface texture data collection under various PVST conditions (see Tab. 1).

The treated area for each condition is 5 mm × 5 mm. Only a size of 2.5 mm × 2.5 mm is used for surface texture data collection due to the duplicate characteristic of the surface texture throughout the treated area and the computation efficiency for data processing. The selected area is fixed at the upper left corner of the treated area for consistent data collection. The workpiece is placed on a free-angle XYZ motorized observation system (VHX-S650E), and 3D surface profiles are characterized using KEYENCE Digital Microscope (VHX6000), as shown in Fig. 3a. A real zoom lens (KEYENCE VH-Z500R, RZ x500 - x5000) and x1000 magnification are utilized to achieve sufficient spatial resolution (0.21 μm). Since each capture under this magnification can only cover a small area, the stitching technique (22 × 22 scans in horizontal and vertical directions) is employed to achieve sufficient capture field. Fig. 3b shows one of the captured 3D profiles under two different types of illustrations (texture and surface height map). The scanned surface textures after different PVST conditions are shown in Fig. 2. Note that for this paper, images e, f, and g were the main focus because they allow extracting the indentation centers. The centers in the remaining images are not easily identifiable, and they require tools from image analysis that are beyond the scope of this paper.

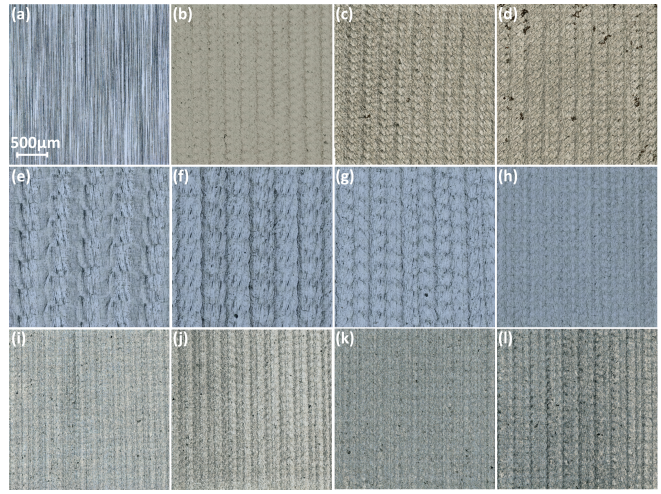

FIGURE 2: Various surface textures under different PVST conditions: (a) initial workpiece surface; (b) – (d) different Z values; (e) – (h) different overlap ratios; (i) – (l) different driving voltages.

TABLE 1: Various PVST conditions. The first column represents the samples in Fig. 2.

No.	f (Hz)	V_{pp} (V)	d (mm)	r_o	Z (μm)
b-d	100	120	3	0.75	0,10,20
e-h	100	120	3	0, 0.25, 0.5, 0.75	0
i-l	100	60, 90, 120, 150	3	0.75	0