Deep Learning-Based Optimization of Spiral Scan Processing for Hydrophobic Waffle Structures

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Objectives: Micrometer-scale surface texturing can enhance liquid repellency across a variety of materials. Among such textures, the waffle structure is known to exhibit excellent hydrophobic properties due to its high groove width/tooth width ratio. Ultrashort-pulsed lasers are suitable for fabricating these microstructures; however, maintaining hydrophobicity under environmental disturbances requires a high depth/pitch (d/τ) ratio. We propose a spiral scan processing for realizing the waffle structure, and present the results of optimization of laser processing conditions using deep learning to satisfy the required aspect ratio.
Methods: Spiral scan processing is a laser texturing method in which the laser beam is scanned concentrically in two dimensions (2Ds) from the center of the intended waffle structure to excavate a square area (Fig. 1). A limitation of this method is that the center region tends to be shallower under suboptimal conditions. Multiple samples with waffle structures were fabricated on Type 304 stainless steel using a femtosecond-pulsed laser (Carbide CB5, Light Conversion) and an *f*67 focusing lens. The processing parameters included fluence (F), shot pitch (τ_s), overlap ratio (OR), and number of passes (n), and a total of 3,000 data points were collected. A deep learning model was constructed using TensorFlow (https://www.tensorflow.org/) and Keras (https://keras.io/). The model for predicting 3D surface geometries was built as follows: (i) the four input parameters were converted into a multidimensional vector via fully connected layers, (ii) reshaped into an 8 × 8 spatial tensor, and (iii) upsampled to a 256 × 256 resolution via transposed convolution layers (Fig. 2).
Results and Discussion: The trained deep learning model yielded 3D surface predictions with a depth error of 2.5% and groove width error of 4.9%, showing good agreement with the measured results (Fig. 2). Based on the model, we successfully identified laser processing conditions satisfying the requirement of $d/\tau \geq 0.5$ in spiral scan processing (F = 30 mJ/mm², τ_s = 0.5 µm, OR = 97.5%, n = 4).
Conclusion: The proposed spiral scan processing method, in conjunction with optimized laser parameters, enables the fabrication of hydrophobic waffle structures using ultrashort-pulsed laser texturing.

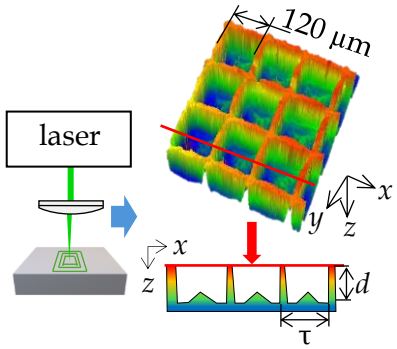

Fig. 1 Spiral scan processing using femtosecond-pulsed laser.

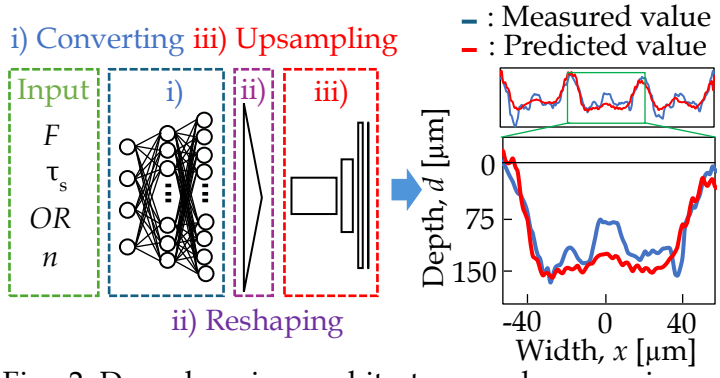

Fig. 2 Deep learning architecture and comparison between measured and predicted surface geometries.