Toward Fully Automated Smart Factory Using Ultrashort-Pulsed Laser Processing

Ren Goto
Graduate School of Medicine,
Science & Technology
Shinshu University
Ueda, Japan
24hb201h@shinshu-u.ac.jp

Hiromu Ishimura
Graduate School of Science & Technology

Shinshu University
Ueda, Japan
25bs202e@shinshu-u.ac.jp

Masaki Yamaguchi*
Graduate School of Medicine,
Science & Technology
Shinshu University
Ueda, Japan
masakiy@shinshu-u.ac.jp
*Corresponding author

Abstract— **The purpose of this study was to propose a data-driven approach to ultrashort-pulsed laser microfabrication of functional textures inspired by biological surfaces. A fully automated system that integrated a femtosecond-pulsed laser, laser microscope, and industrial robot enabled continuous unmanned operation and a acquisition of 6,750 three-dimensional surface geometry datasets within five days. A deep learning model, constructed using TensorFlow and Keras, was trained with four processing parameters: fluence, overlap ratio, number of spiral turns, and number of repetitions. Because geometric parameters such as groove width and depth are crucial for designing functional textures, the model was evaluated with high predictive performance, achieving more than 95% accuracy for groove width. The relatively low depth accuracy was attributed to redeposition randomness following ablation, which resembles quantum probabilistic processes. This approach shows that machine learning combined with large-scale experimental data could support practical adoption of laser processing. Furthermore, ultrashort-pulsed laser fabrication provided environmentally benign processing, contributing to at least nine sustainable development goals. These findings positioned ultrashort-pulsed lasers as a key enabler of sustainable, data-driven manufacturing aligned with Industry 4.0 and Society 5.0 visions.**

Keywords— laser processing, biomimetics, functional texture, machine learning, SDGs

I. INTRODUCTION

Initiatives that leverage advanced technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) to enhance efficiency, promote optimization, create human-centered value, and realize sustainability have been attracting considerable attention. As national visions for society and industry, Industry 4.0 has been proposed in Germany, originating from innovation in manufacturing, while Society 5.0 has been advanced in Japan, with the overarching aim of addressing societal challenges in their entirety (Table 1) [1 – 4]. Although the starting points and contexts of these two visions differ, they share common objectives, which include the “maximal utilization of digital technologies”, “efficiency and optimization”, “human-centered value creation ” , and “sustainability and competitiveness”.

Nevertheless, Society 5.0, precisely because it aspires to solve a wide array of societal issues, encompasses an overly broad scope. As a result, its concrete strategies tend to become diffuse, and ensuring feasibility remains a significant challenge. By contrast, Industry 4.0 provides a more clearly defined framework that directly links technological innovation to productivity improvements and industrial competitiveness. From the perspective of strengthening competitiveness, Industry 4.0 can therefore be regarded as offering a more effective and practical approach than the more expansive, albeit less actionable, agenda of Society 5.0.

TABLE 1. Comparison between Industry 4.0 and Society 5.0

Item	Industry 4.0	Society 5.0
Origin	Proposed by the German government in 2011〔[1]〕	Proposed by the Japanese government in 2016〔[2]〕
Main Focus	Manufacturing sector (smart factory)〔[1]〕	Society as a whole (industry, healthcare, administration, daily life)〔[2]〕
Basic Concept	Integration and autonomous control of production systems through IoT/CPS〔[3]〕	Human-centered approach to solving social challenges using digital technologies〔[4]〕
Representative Technologies	Smart sensors, Industrial IoT, Digital Twin, Robotics	AI, IoT, Robotics, Big Data, Autonomous Driving, Digital Government
Ultimate Objective	Maximization of productivity and efficiency〔[3]〕	Creation of social value and improvement of well-being〔[4]〕
Regional Background	Enhancement of competitiveness of German manufacturing sector〔[1]〕	Response to Japan’s issues such as aging society and labor shortage〔[2]〕

However, Industry 4.0 is not without its own challenges. The creation of new industries requires the rapid and efficient adoption of cutting-edge technologies developed in academia. This translation process remains far from straightforward. The primary reason lies in the persistent gap between academia and industry in terms of objectives and evaluation criteria (Table 2) [5]. Academia tends to prioritize publications, academic originality, and novelty, whereas industry places emphasis on business profits, market potential, and feasibility of implementation. Moreover, decision-making criteria also diverge: academia often privileges frontier and theoretically innovative topics, while industry focuses on market compatibility and the minimization of risk.

We maintain that the key to bridging this gap lies in data-driven science. If technologies for the automated acquisition of high-quality, large-scale datasets can be established, and if these data can be efficiently analyzed through machine learning, the risks perceived by industry could be substantially reduced, thereby facilitating greater alignment with academic approaches. Furthermore, in academia, empirical findings supported by vast datasets cannot be disregarded, thus fostering a shared foundation for mutual understanding.

From a related perspective, biomimetics, which involves the artificial imitation of various functions that living organisms have acquired through evolution to adapt to the global environment, has been attracting attention from the manufacturing sector [6–8]. Nanometer- and micrometer-scale surface microstructures exhibiting physical functionalities, such as hydrophobicity, hydrophilicity, slippage, anti-fouling, anti-reflection, optical transparency, structural coloration, reduced friction and flow resistance, and noise reduction, are collectively referred to as functional textures. An illustrative case is surface slippage, which constitutes a critical function for organisms inhabiting a water planet, such as Earth. The hierarchical nanometer- and micrometer-scale structures on lotus leaves, which exhibit remarkable hydrophobicity and slippage, are well known as the lotus effect [9]. In this hydrophobic texture, hydrophobic air is exploited, whereby the surface topography creates minute air pockets, thereby leading to an apparent enhancement of liquid repellency [10]. To achieve industrial implementation of such functionalities, manufacturing technologies capable of fabricating nanometer- and micrometer-scale structures on surfaces are required, without being constrained by material type, including inorganic substances such as steel, ceramics, and glass, as well as organic materials such as polymers and proteins. Among the most promising candidates for such processing technologies is an ultrashort-pulsed laser processing [11–12]. Although many studies have demonstrated biomimetic textures using ultrashort-pulsed lasers, most existing systems rely on manual or semi-automated operation, limiting dataset size and reproducibility [13–15].

Building on the perspective of Industry 4.0, the authors focus on the utilization of automation technologies and machine learning as a means to advance manufacturing and enhance industrial competitiveness, and are pursuing the industrial implementation of data-driven science. This paper proposes a fully automated ultrashort-pulsed laser processing system, presenting a valuable practical work. In this paper, we aim to apply one of the most advanced processing technologies, ultrashort-pulsed laser processing, to surface microfabrication, and report on its fundamental technologies, system architecture, and the competitiveness of the resulting products and services in the market. In addition, we discuss the alignment of this approach with the sustainable vision articulated in Society 5.0, particularly in relation to the sustainable development goals (SDGs).

II. LASER PROCESSING OF FUNCTIONAL TEXTURE

Engineering may be regarded as a discipline oriented toward practical implementation in society, and from this perspective its fundamental stance can be considered as a mimetic approach. Humanoid robots are designed on the basis of human mimicry, while the aerodynamic design of automobiles draws inspiration from the streamlined forms of birds and fish. From this standpoint, living organisms constitute a treasure trove that provides inexhaustible ideas for material and structural design, and engineering itself may thus be considered to be, in essence, biomimetics.

In plants, a wide variety of wettability-related functions such as hydrophobicity, slippage, hydrophilicity, and water retention are observed, which are thought to contribute to enhanced photosynthetic efficiency and secure water uptake [16]. The surface of lotus leaves exhibits a hierarchical texture, in which convex structures on the order of several tens of micrometers (long-period structures) are overlaid with wax nanocrystals on the order of several hundred nanometers (short-period structures) [9]. Consequently, the artificial reproduction of such functional textures requires surface-processing techniques capable of addressing structures across both nanometer and micrometer scales. Conventional cutting processes can readily produce micrometer scale structures; however, the minimum feature size is limited to approximately 10 µm. Photolithography enables extremely fine patterning down to the 10-nm scale; however, its applicability is largely restricted to planar silicon wafers. In contrast, ultrashort-pulsed laser processing can directly fabricate structures ranging from several hundred nanometers to several hundred micrometers, with minimal restrictions on target material. Moreover, as a non-contact technique, it is suitable for producing curved and even inverse-tapered geometries [17].

Despite these advantages, ultrashort-pulsed laser processing also presents inherent challenges. Femtosecond-pulsed laser

TABLE 2. Gap between academic research and industrial implementation in industrial sector

Domain	Main Incentive	Outcome-oriented indicators
Academia	Number of publications, Academic originality, Novelty	Frontier research, Theoretical novelty
Industry	Business profits, Marketability, Implementability	Market compatibility, Minimization of risk

processing involves multiple nonlinear phenomena, including (i) laser energy absorption, (ii) thermal conduction within the substrate, (iii) ablation (sublimation), (iv) laser intensity distribution, and (v) optical properties of the elements constituting along the beam path (Fig. 1). These factors lead to considerable difficulty in precisely predicting the resulting surface geometries. To address such nonlinearity and complexity, which are beyond the reach of conventional theoretical models, this study introduces data-driven scientific approach, wherein large volumes of experimental data are analyzed through machine learning to construct predictive models [18]. Specifically, extensive datasets of laser processing parameters and measured surface geometries were compiled, which enabled machine learning algorithms to learn and predict the relationship between laser processing conditions and the final three-dimensional (3D) surface geometries.

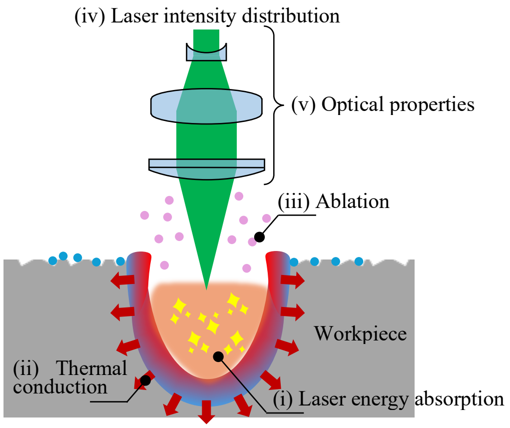


Fig. 1. Schematic diagram of nonlinear physical phenomena induced by ultrashort-pulsed laser processing.

III. INTRODUCTION OF DATA-DRIVEN SCIENCE

A. *Fully automated data collection system*

To automate laser processing and surface geometry data acquisition, a fully automated ultrashort-pulsed laser processing system was constructed. Fig. 2 and 3 show the external appearance and the configuration of the system, respectively (video: https://fiber.shinshu-u.ac.jp/yamaguchi/flat-innovation-studio/facility.html). The system consists of a femtosecond-pulsed laser (CARBIDE CB5, Light Conversion UAB, Vilnius, Republic of Lithuania) and a scanner (CUA32-MST-AC, Newson NV, Dendermonde, Belgium) for processing, a laser microscope for 3D surface geometry measurements (VK-X3000/3050, Keyence Co., Tokyo, Japan), and an industrial robot (RV2-FR-Q, Mitsubishi Electric Co., Tokyo, Japan) that transfers samples among these devices.

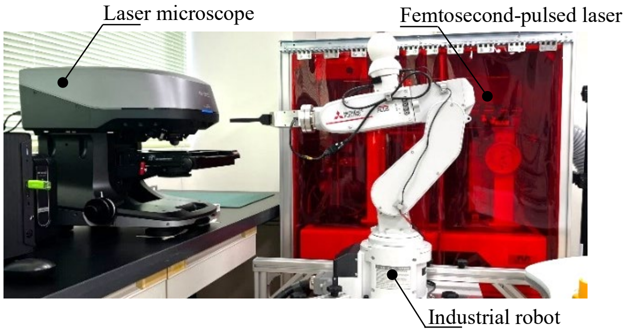


Fig. 2. Fabricated fully automated data collection system for laser surface processing.

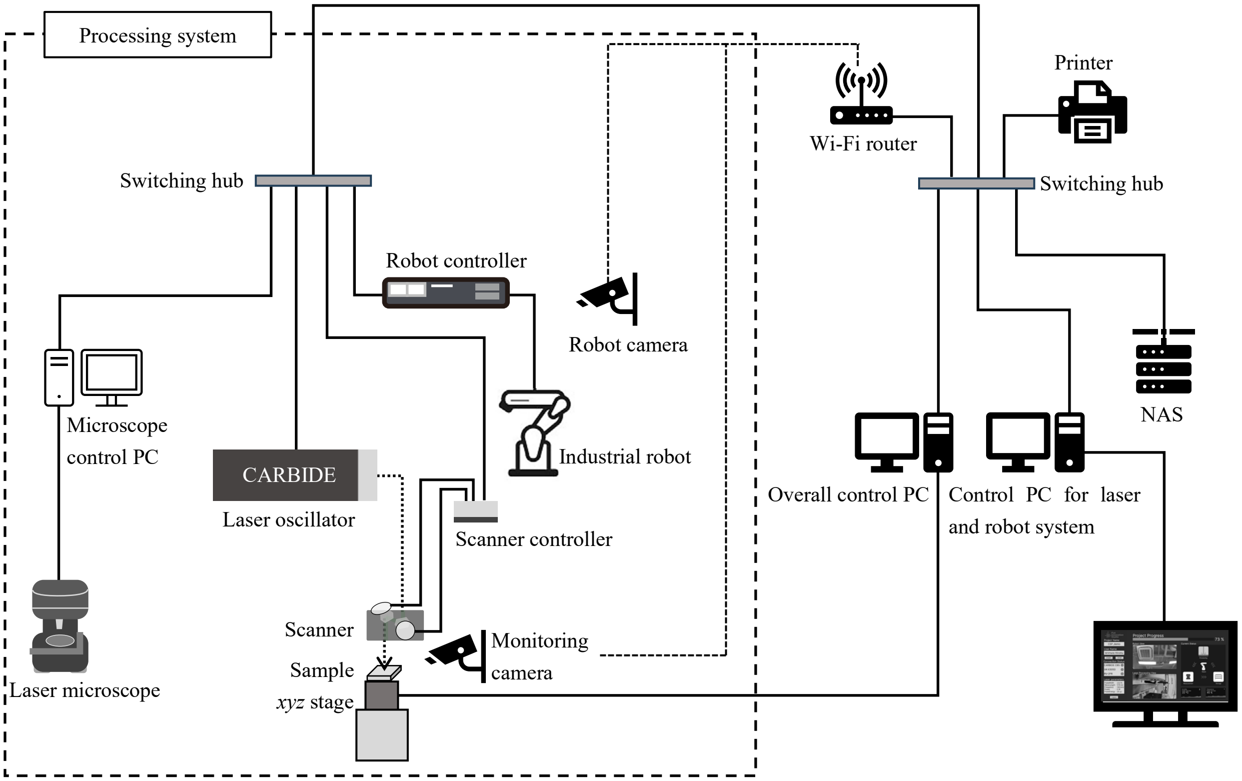


Fig. 3. Configuration of the constructed fully automated ultrashort-pulsed laser processing system.

For system control, two personal computers were employed: one dedicated to operating the femtosecond-pulsed laser and the industrial robot via specialized programs, and another responsible for feedback control of the entire system using an in-house Python program. In addition, a camera mounted on the industrial robot enables observation of the processed samples, while a separate camera monitors laser irradiation, allowing remote confirmation of system operation.

The system is capable of unmanned continuous operation, including during nighttime, and, depending on the processed area, can perform laser processing and 3D surface geometry measurements for approximately 1,000 samples per day. All acquired data are sequentially stored on a network-attached storage device (NAS, TS-932PX, QNAP Systems Inc., New Taipei, Taiwan).

B. *Machine learning-based modeling*

The lotus effect can be explained by the Cassie–Baxter model, in which the primary geometrical parameters governing hydrophobicity are tooth width, f_1, groove width, f_2, and depth, h [19]. The pitch of the hydrophobic texture is defined as $\tau = f_1 + f_2$. Although pillar-shaped structures are commonly employed as the basis for fundamental studies, our study employed the inverted configuration, specifically a waffle-shaped structure, which offers enhanced durability [20].

Constructing an algorithm for fabricating functional textures corresponds to designing a drawing program for the geometrical structures. In this study, a square-spiral drilling method was employed for the fabrication of waffle-shaped structures (Fig. 4A). The process begins with a forward movement by one unit distance (4 µm in this study) along the +*x* direction from the machining center. The scanning direction is subsequently rotated by 90° after each move, and the side length is increased by one unit after every odd-numbered step. The number of side-length increments is defined as the number of spiral turns, n_l. This operation is repeated until the machining width reaches the groove width, f_2, yielding a square-spiral approximated by piecewise linear segments aligned with the Cartesian coordinates.

Here, the laser spot diameter is denoted as d, and the degree of overlap between adjacent laser spots is defined as the overlap ratio, OR %. The depth can be increased by repeating the square-spiral drilling, and the number of repetitions is defined as n_o. In this study, τ = 120 µm and d = 20 µm were fixed, thereby establishing the relationships between the geometrical parameters determining hydrophobicity and the laser processing parameters, as shown in Fig. 4B. It is evident that all geometrical parameters are influenced by multiple processing conditions, resulting in considerable complexity. In particular, the parameters associated with depth are the most numerous, which leads to relatively difficult in its prediction. Stainless steel (SUS304) flat plates were used as the substrates.

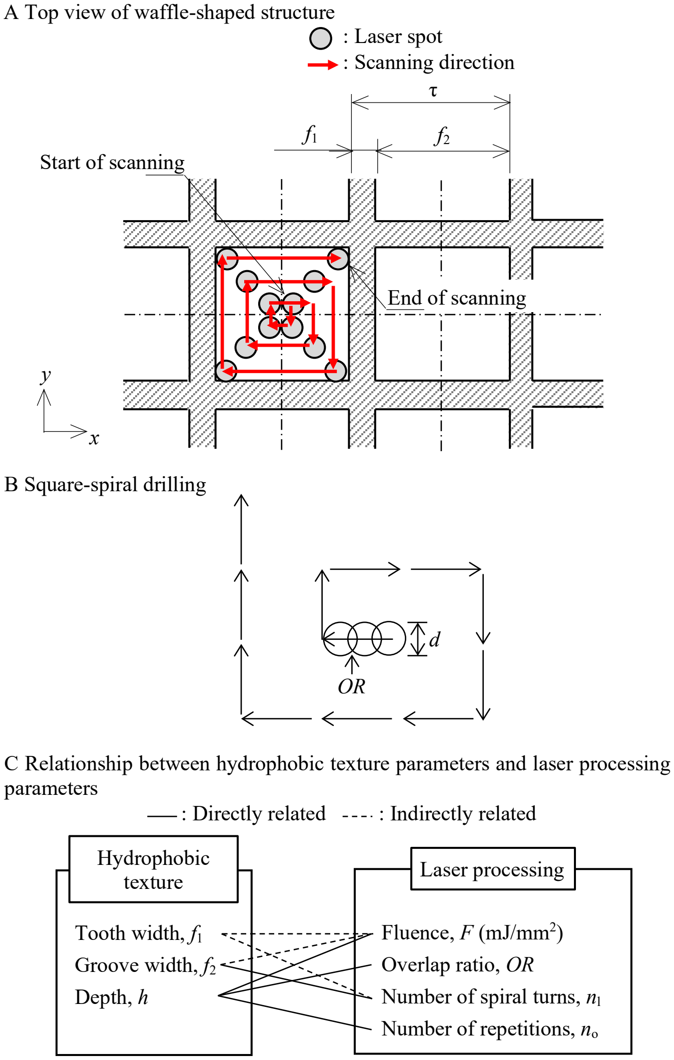


Fig. 4. Waffle-shaped structuring fabricated by using square-spiral drilling method (Since the pitch is predefined, once the groove width is specified, the tooth width is uniquely determined; therefore, solid lines are not shown.).

Fig. 5 shows the deep learning algorithm used for constructing a prediction model, in which laser processing parameters serve as input variables and the processed 3D

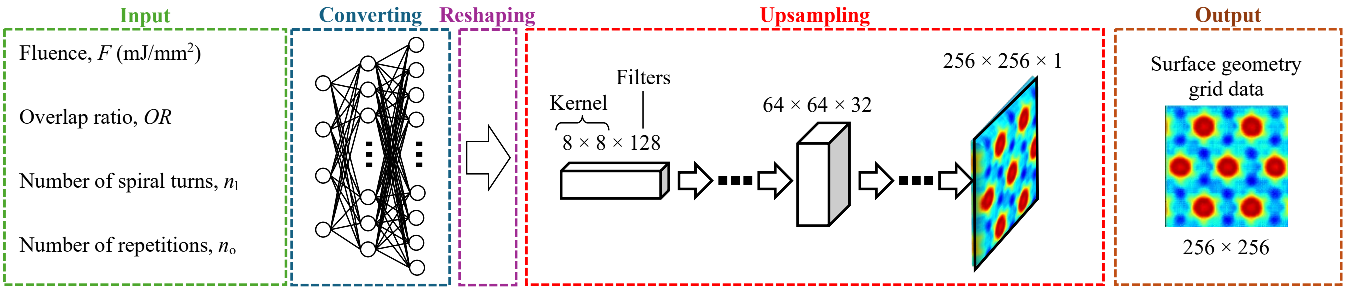


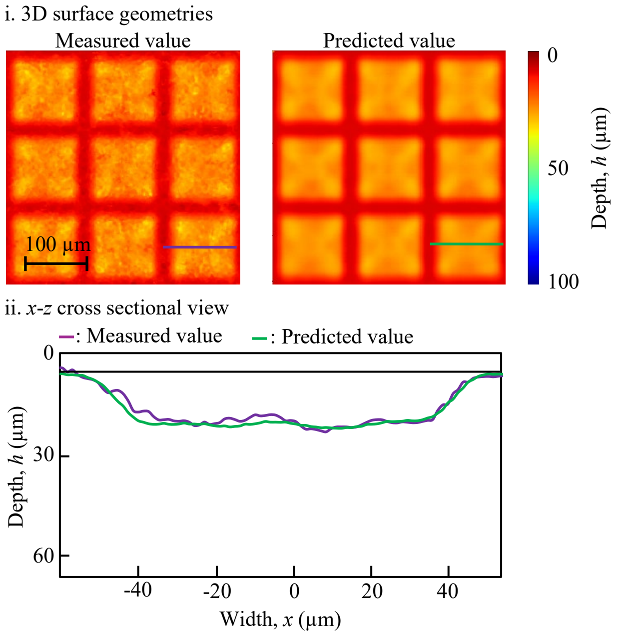
Fig. 5. Deep learning architecture for creation of predictive model based on open-source libraries TensorFlow and Keras.

geometries serve as output variables [21]. The model was implemented using the libraries provided by TensorFlow (https://www.tensorflow.org/) and Keras (https://keras.io/). The algorithm consisted of three fully connected layers and ten transposed convolutional layers. The input variables comprised four laser processing parameters: fluence, F (energy per unit area), overlap ratio, OR, number of spiral turns, n_l, and number of repetitions, n_o. These four scalar variables were transformed into a 3D tensor through the transposed convolutional layers, ultimately yielding a prediction model that outputs the 3D surface geometry.

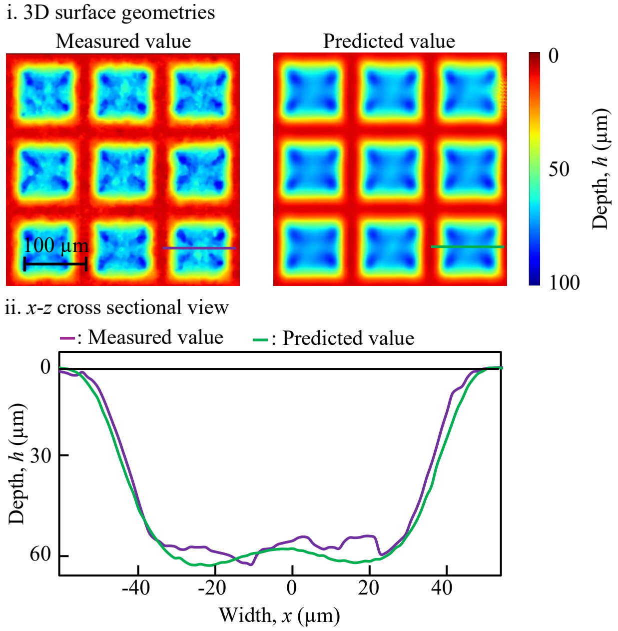
The loss function was set to mean squared error (MSE), which was relatively robust to noise. To minimize the loss function, model parameters such as weights and biases were optimized using adaptive moment estimation (Adam) algorithm. To stabilize training and improve generalization performance, dropout (disabling a fraction of neurons), batch normalization, and L2 regularization were incorporated. In addition, a learning rate scheduler was employed to adjust the training speed dynamically, enabling stable convergence toward the optimal solution. Hyperparameter tuning was performed using Bayesian optimization, an efficient search strategy for high-dimensional parameter space.

To construct a prediction model, 6,750 datasets of surface geometries were acquired over five days using the fully automated data collection system. The dataset was divided into training, validation, and test sets in a ratio of 7:1.5:1.5, respectively, for model training and performance evaluation.

Fig. 6 shows the comparison between the measured and predicted values obtained using the deep learning-based prediction model. In the x–z cross-sectional profiles, the measured values are shown as solid lines and the predicted values as dashed lines. The x–y plane geometries were reproduced with high fidelity, and the prediction accuracy for groove width exceeded 95%. In contrast, the prediction accuracy for groove depth was limited to slightly over 80%. This limitation may be attributed to two possible factors. The first is the high complexity arising from the large number of laser processing parameters that influence depth. The second factor can be attributed to the randomness of redeposited material following laser ablation. The trajectories of sublimated metal atoms are thought to exhibit behavior analogous to a quantum probabilistic process, being influenced by thermal motion and collision probabilities. Such random phenomena are fundamentally difficult to predict. Addressing this complexity requires further expansion of the dataset. Addressing the randomness may be achieved by incorporating statistical regularities at the macroscopic scale into the prediction model.



A. F = 30 mJ/mm^2, OR = 95%, n_l = 11, n_o = 3



B. F = 30 mJ/mm^2, OR = 95%, n_l = 11, n_o = 9

Fig. 6. Comparison between measured and predicted values for waffle-shaped structure.

IV. FUNCTIONAL TEXTURES AND SDGS

Ultrashort-pulsed lasers enable material processing with low power consumption, free from noise, heat, and oil, thereby resulting in an extremely low environmental impact compared with conventional manufacturing technologies. By applying functional textures fabricated using ultrashort-pulsed lasers to housing and architectural materials, solar cells, and other applications, it can be possible to complement the drawbacks of traditional chemical coatings and mold-based processing, thereby providing an alternative pathway toward an environmentally benign fabrication technology.

Table 3 summarizes the potential applicability of functional textures, as assessed by the authors from the functionalities that can be imparted through surface microstructures. By designing functional textures optimized for each functionality, significant contributions to the SDGs can be anticipated across a wide range of fields, including agriculture, medicine, energy, housing and building, and water and marine resource conservation. For example, antifouling and anti-fogging functionalities inspired by

TABLE 3. Potential contribution of functional textures to SDGs

Goal	Measures	Methods	Surface functionality
2 ZERO HUNGER Zero hunger	- Improvement of energy efficiency in plant factories	- Prevention of stray light by anti-reflective structures	Anti-reflection, decorative
	- Improvement of ventilation efficiency in poultry houses	- Flow resistance reduction through riblet structures	Fluid resistance reduction
3 GOOD HEALTH AND WELL-BEING Good health and well-being	- Prevention of thrombosis in medical devices	- Friction reduction of device surfaces via riblet structures	Fluid resistance reduction
	- Prevention of falls among the elderly	- Anti-slip properties for footwear	Hydrophobicity
	- Prevention of infectious diseases	- Antibacterial/viral functionality for clothing	Antibacterial/viral, anti-fouling
	- Reduction of traffic accidents by visible signage	- Prevention of stray light and contamination by moth-eye structures	Hydrophobicity, hydrophilicity, sliding, anti-fouling
	- Reduction of traffic accidents in winter	- Prevention of road surface freezing	Hydrophobicity and sliding
	- Anti-fouling for in-vehicle sensors	- Contamination prevention by nanometer-scale surface structures	Hydrophobicity, sliding, and optical transparency
6 CLEAN WATER AND SANITATION Clean water and sanitation	- Prevention of bacterial/viral growth and diffusion	- Anti-fouling of sanitary ceramics through lotus-inspired structures	Hydrophobicity, hydrophilicity, sliding, anti-fouling
	- Prevention of mold by antibacterial effect	- Sterilization effects by dragonfly wing-inspired structures	Antibacterial/viral
	- Harvesting of water resources	- Water harvesting systems by beetle surface structures	Hydrophobicity + hydrophilicity
7 AFFORDABLE AND CLEAN ENERGY Affordable and clean energy	- Improvement of power generation efficiency in solar panels	- Anti-fouling of surfaces	Anti-fouling
	- Improvement of wind power efficiency	- Reduction of energy loss through turbulence suppression	Fluid resistance reduction
	- Prevention of fuel cell failures	- Prevention of liquid clogging by bubbles	Hydrophilicity
	- Efficiency enhancement of internal combustion engines	- Oil retention by microstructures	Hydrophilicity
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE Industry, innovation and infrastructure	- Achievement of carbon neutrality (mitigation)	- Low power consumption through ultrashort-pulsed laser processing	Not limited
11 SUSTAINABLE CITIES AND COMMUNITIES Sustainable cities and communities	- Reduction of noise from transportation systems	- Frequency modulation by serration structures	Low noise
	- Improvement of heat dissipation and air-conditioning efficiency in buildings	- Control of airflow	Heat dissipation
	- Disaster-resilient architecture	- Prevention of rebar corrosion with hydrophobic concrete formworks	Hydrophobicity
	- Prevention of condensation in buildings	- Water repellency by lotus-inspired structures	Hydrophobicity
	- Improvement of soundproofing performance in housing	- Quiet structures of owl feather	Frequency modulation
12 RESPONSIBLE CONSUMPTION AND PRODUCTION Responsible consumption and production	- Elimination of chemical materials	- Addition of surface functions	Not limited
	- Elimination of paint	- Addition of structural color	Structural color (decorative)
14 LIFE BELOW WATER Life below water	- Recovery of marine oil	- Efficient oil recovery by microstructures	Oil repellency, oleophilicity
	- Reduction of wastewater/discharge	- Oil-water separation or Anti-fouling treatment for tableware	Hydrophobicity, oil repellency
15 LIFE ON LAND Life on land	- Forest conservation	- Prevention of soil erosion by hydrophobic/hydrophilic layers	Hydrophobicity, hydrophilicity
	- Countermeasures against desertification	- Protection against salt damage and rainwater retention by hydrophilic sands	Hydrophobicity, hydrophilicity
	- Water collection	- Harvesting of atmospheric water vapor	Hydrophobicity, hydrophilicity

Icons of SDGs reproduced from United Nations, Guidelines for the use of 17 Icons (2019). Use permitted without prior permission for informational, non-commercial purposes.

lotus-leaf structures not only contribute to safe water supply and infection prevention but also directly support the performance retention of solar cells and automotive sensors. Furthermore, fluid resistance reduction and noise suppression based on serration structures contribute to the realization of sustainable urban environments through improved transportation systems and enhanced energy efficiency. In addition, textures with antibacterial activity and water- and oil-repellent properties can contribute to the improvement of the medical environments, the reduction of wastewater discharge, and the conservation of forests and marine ecosystems. Thus, the combination of ultrashort-pulsed laser processing and functional textures can contribute substantively to nine of the seventeen SDGs, with mutually reinforcing effects across different goals.

V. CONCLUSION

In this study, we demonstrated that the introduction of data-driven science can provide a potential design methodology with superior predictive capability, even though ultrashort-pulsed laser surface microfabrication exhibits inherent complexity and nonlinearity. Specifically, high prediction accuracy was achieved by constructing a methodology for collecting large datasets of processing parameters and surface geometry measurements, and by modeling the relationship between laser processing conditions and the resulting 3D geometries using machine learning.

Surface treatment technologies are still predominantly based on chemical processes in terms of cost and speed. However, the introduction of ultrashort-pulsed lasers is creating the conditions necessary for physical processes to become industrially feasible. The global market for laser-processed products continues to expand, having reached 17.8 billion U.S. dollars in 2022 and estimated to grow to 32.7 billion U.S. dollars by 2030 [22]. Within this trend, ultrashort-pulsed lasers are positioned as a novel manufacturing technology that supports the SDGs and carbon neutrality. It is expected that this innovative laser processing technology will be realized as an environmentally sustainable manufacturing method.

The economist E. F. Schumacher, in his 1973 book "Small is Beautiful", advocated for technologies of an appropriate scale tailored to human needs, in contrast to the prevailing value system of "bigger is better," which still persists today [23]. Inspired by this philosophy, we have articulated the vision of "constructing an ecosystem based on biomimetics".

ACKNOWLEDGMENT

A part of this research was supported by the Advanced Technology Education Program of Ueda City, Japan.

REFERENCES

[1] H. Kagermann, W. Wahlster, and J. Helbig, "Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Final report of the Industrie 4.0 Working Group," German National Academy of Science and Engineering, 2013.

[2] Government of Japan, "The 5th Science and Technology Basic Plan," Cabinet Office, Government of Japan, 2016.

[3] Y. Liao, F. Deschamps, E. de F. R. Loures, and L. F. P. Ramos, "Past, present and future of Industry 4.0 – A systematic literature review and research agenda proposal," Int. J. Prod. Res, vol. 55, pp. 3609–3629, 2017.

[4] A. Deguchi, C. Hirai, H. Matsuoka, T. Nakano, K. Oshima, M. Tai, and S. Tani, "Society 5.0 A People-centric Super-smart Society, What Is Society 5.0?," Singapore: Springer Nature Singapore Pte Ltd., 2018, pp. 1–23.

[5] A. Windmann, P. Wittenberg, M. Schieseck, and O. Niggemann, "Artificial Intelligence in Industry 4.0: A Review of Integration Challenges for Industrial Systems," IEEE 22nd Int. Conf. Ind. Informatics (INDIN), 2024.

[6] S. Mzali, F. Elwasli, S. Mezlini, K. Hajlaoui, and N. H. Alrasheedi, "Tribological behavior of 3D printed biomimetic surfaces," Tribol. Int., vol. 193, 109352, 2024.

[7] J. Luo and Z. Guo, "Recent advances in biomimetic superhydrophobic surfaces: focusing on abrasion resistance, self-healing and anti-icing," Nanoscale, vol. 16, pp. 16404–16419, 2024.

[8] K. Yang, C. Wu, H. Chen, and J. Tang, "Recent progress in hydrophobic interfaces: Design, preparation, properties, and applications," Mater. Today Chem., vol. 45, 102621, 2025.

[9] W. Barthlott and C. Neinhuis, "Purity of the sacred lotus, or escape from contamination in biological surfaces," Planta, vol. 202, pp. 1–8, 1997.

[10] D. Zhang, J. Ji, C. Yan, J. Zhang, Z. An, and Y. Shen, "Research advances in bio-inspired superhydrophobic surface: Bridging nature to practical applications," J. Ind. Eng. Chem., vol. 140, pp. 20–46, 2024.

[11] H. Guo, J. Xie. J. Yu, J. Li, Y. Zhao, M. Luo, and H. Han, "A review of ultrafast laser micro/nano fabrication: Material processing, surface/interface controlling, and devices fabrication," Nano Res., vol. 17, pp. 6212–6230, 2024.

[12] L. Gao, Q. Zhang, and M. Gu, "Femtosecond laser micro/nano processing: from fundamental to applications," Int. J. Extrem. Manuf., vol. 7, 022010, 2025.

[13] R. Sharma, M. Raissi, Y. B. Guo, "Physics-informed machine learning for smart additive manufacturing," arXiv preprint, arXiv:2407.10761, 2024.

[14] C. Petit, N. Mariaule, S. Wauters, A. de Decker, D. Bruneel, "AI-Supported Prediction of Femtosecond Laser Micromachining Parameters," Proc. LPM2024, 11p., 2024.

[15] A. Wienke, S. Shareef, J. Koch, P. Jaschke, and S. Kaierle, "Surface functionalization without knowledge of surface topography and chemistry – a versatile approach," Proc. LPM2024, 6p., 2024.

[16] W. Barthlott, M. Mail, B. Bhushan, "Plant surfaces: structures and functions for biomimetic innovations," Nano-Micro Lett., vol. 9(23), pp. 20–46, 2017.

[17] C. Yang, C. Ji, S.e Feng, Y. Liu, W. Wei, Y. Long, "Ultrafast laser-matter interaction mechanisms and applications in functional device fabrication: Recent advances and perspectives," Appl. Phys. Rev., vol. 12, 031325, 2025.

[18] S. von Enzberg, J. Weller, J. Brock, S. Merkelbach, M. Panzner, J. Lick, A. Kühn, R. Dumitrescu, "On the Current State of Industrial Data Science: Challenges, Best Practices, and Future Directions," Procedia CIRP, vol. 130, pp. 1454–1461, 2024.

[19] T. Sherin, M. R. Motapothula, G. K. Dalapati, S. Ramakrishna, S. Sangaraju, S.i Chakrabortty, S. Krishnamurthy, S. Ghosh, "A comprehensive review on realization of self-cleaning surfaces by additive manufacturing," Prog. Addit. Manuf., vol. 10, pp. 1785–1808, 2025.

[20] R. Goto, Y. Oshima, M. Yamaguchi, "Hydrophobicity of Periodic Structure with Taper Angle under Pressure Impact," Sci. Rep., vol. 14, 30228, 2024.

[21] H. Ishimura, R. Goto, M. Yamaguchi, "Deep Learning-Based Optimization of Spiral Scan Processing for Hydrophobic Waffle Structures," 13th International Conference on Photo-Excited Processes and Applications (ICPEPA-13), 2025.

[22] Grand View Research, Inc., "Global Laser Technology Market Size, Share & Trends Analysis Report, 2023 – 2030", Grand View Research, Inc. eds., 2023, p.100.

[23] E. F. Schumacher, "Small Is Beautiful: A Study of Economics As If People Mattered," Blond & Briggs Ltd., 1973, pp. 1–23.