Direct Laser Processing of Two-Scale Periodic Structures for Superhydrophobic Surfaces Using a Nanosecond Pulsed Laser

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Abstract

Hierarchical structures are promising geometries for superhydrophobic surfaces, however a processing method with a single laser light source that is capable of both one-pass and rapid processing has not been established. The purpose of this study was to propose a concept of direct laser processing of two-scale periodic structures exhibiting superhydrophobicity. We hypothesized that the molten material that occurs due to the expanding plasma and that is squeezed around the micro-holes could play an active role in the processing of two-scale periodic structures. Percussion drilling using a nanosecond pulsed laser (532 nm wavelength) was performed on a steel surface. Twenty four different test-pieces were prepared using pitch (16–120 μm), number of repetition shots (1–120), and fluence (2.49–20 J/cm^2), as the parameters. As the results, micro-holes with bank-shaped outer rims were formed. The maximum apparent contact angle was 161.4° and the contact angle hysteresis was 4.2° for a pitch of 80 μm and 20 repetition shots. The calculated results for the apparent contact angles were consistent with the measured results. Finally, an equation for estimating the processing rate was proposed. We demonstrated that this direct processing method can achieve a maximum processing rate of 823 mm^2/min .

Keywords Direct laser processing · Hydrophobicity · Two-scale periodic structure · Nanosecond pulsed laser · Steel

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Introduction

Nature-inspired surface engineering has flourished over the past two decades. Novel biomimetic surfaces similar to those found in nature have been developed to realize improved physical properties of wettability for applications such as liquid repellency, low adhesion, self-cleaning, and drag reduction [1–5]. A surface structure that has two different-scales and exhibits such physical functions is known as a functional texture. A surface is categorized as being hydrophobic if its apparent contact angle, θ' , of water is greater than 90° [6] and superhydrophobic if θ' of water is greater than $>150^\circ$ and the contact angle hysteresis, *CAH*, of water is less than 10° [7] or 5° [8]. Superhydrophobic surfaces can be produced by mimicking lotus leaves, which possess hierarchical structures with two-scales [9]. Several fabrication methods based on lithographic techniques have been proposed for producing two-scale periodic structures [4, 10, 11]. However, a fabrication method that can process two-scale periodic structures simultaneously, one-pass processing, is yet to be established using a lithography-based approach.

In terms of drilling micro-holes, lasers have shown excellent performance, and commonly used drilling techniques are percussion drilling [12], trepanning [13], and laser helical drilling [14]. Pulsed laser sources such as nanosecond [15], picosecond [16], and femtosecond pulsed lasers [17] can be used to create various structures in an open environment and in an acceptable time. Interference patterning has been proposed for fabricating two-scale periodic structures simultaneously on industrial materials such as metals and resins. However, laser-induced periodic structures, LIPSS, are sometimes limited regarding small-scale structures with no periodicity [18, 19]. Also, direct laser interface patterning, DLIP, with two or more laser beams [20, 21] is limited for structures, especially given that the pitch cannot be set arbitrarily. Therefore, one-pass processing to create any periodic structures with a single laser light source is needed. This is a barrier to fast laboratory-to-fabrication transfer of two-scale periodic structures, especially in the industrial field of processing.

The main feature of femtosecond pulsed lasers is a clear ablation threshold. Compared with nanosecond pulsed lasers, femtosecond pulsed lasers minimize the thermal damage [22]. In contrast, a micro-hole formed by a nanosecond pulsed laser is surrounded by an outer rim comprising molten material squeezed out of the hole by the expanding plasma [23]. The processing of materials by means of short pulsed lasers has evolved significantly and is starting to show its industrial potential for creating regions smaller than $1\text{ }\mu\text{m}$ in size [19, 24]. The possibility of introducing micro-patterns directly using short pulsed lasers has been demonstrated on the surfaces of metals [25] and resins [26]. Realizing direct laser processing would improve the wetting properties that can be achieved with one-pass processing [27, 28]. An optical method using a cylindrical lens has been proposed [29], however the inertial mass of the component parts limits the extent to which the processing rate can be improved. For functional textures, a strategy is required for processing two-scale periodic structures satisfying both one-pass and rapid processing.

We hypothesized that the molten material that is squeezed out of the micro-holes could play an active role in processing two-scale periodic structures. This nanosecond pulsed laser processing is dominated by the melt-pool dynamics due to Marangoni stress, which lead to the formation of bank-shaped outer rims [30]. The purpose of this

study was to propose a concept that enables both one-pass and rapid laser processing of two-scale periodic structures simultaneously with arbitrarily pitch on the surface of a material by percussion drilling using a nanosecond pulsed laser. To explore this, we performed percussion drilling to fabricate two-scale periodic structures on test-pieces of steel. The wetting behavior in the form of contact angles and contact angle hysteresis were measured after annealing. The optimum conditions for direct processing leading to superhydrophobicity were shown both experimentally and theoretically. To reveal the processing efficiency, the area processed per unit time, i.e. processing rate, of the two-scale periodic structures processed using a nanosecond pulsed laser was estimated.

Materials and Methods

Direct Laser Processing

A steel (PSL, $R_a = 0.26$ ($n = 24$) of surface roughness, 33–37 HRC of hardness, Hitachi Metals Tool Steel Ltd., Tokyo, Japan) was used as the material fabricating a square-shaped test-piece (test-piece for wettability evaluation, 20 mm length $\times$ 20 mm width $\times$ 5 mm thickness) to produce two-scale periodic structures on the surfaces. Because of the difficulty of cutting a thin rod, a pin-shaped steel (SKD-11, 58.0 HRC of hardness, Hitachi Metals Tool Steel, Ltd.) was instead used for a pin-shaped test-piece (test-piece for depth evaluation, 1.5 mm diameter) to estimate the depth of the percussion drilling. Table 1 shows element compositions of steels used for fabricating test-pieces.

The processing of a two-scale periodic structure using a nanosecond pulsed laser is shown schematically in Fig. 1. The two-scale periodic structure consist from (i) a basically periodic surface structure formed by the pitch of the percussion drilling and (ii) a small-scale periodic surface structure formed by the molten material around the micro-holes. A commercial nanosecond pulsed laser system (ML-9011A, 10 W, YVO₄ solid-state laser, Amada Miyachi Co., Ltd., Isehara, Japan) that provides an oscillation wavelength of 532 nm, a pulse width of 11 ns, and a repetition rate of 20 kHz was used for the experiment (Fig. 1a). The laser beam with a Gaussian profile was focused perpendicularly on the test-piece using a beam expander ($\times 8$, Geomatec Co. Ltd., Kanagawa, Japan), using an f θ lens (focal length: $f = 160$ mm, Geomatec Co. Ltd., Kanagawa, Japan) and two-dimensional galvanometric mirrors. The spot diameter at the focal point on the test-piece surface was calculated as 16 μm by $1/e^2$ using a laser beam quality factor of $M^2 = 1.2$ and an expanded laser beam diameter of 8 mm [31].

The laser scanning route consisted of parallel beam lines, the distance (pitch) between which was used as a parameter, τ ($\tau_x = \tau_y$, Fig. 1b). The laser scanning velocity, v_s , was set to 1500 mm/s for both directions, achieved using the two-

Table 1 Element compositions of steels used for fabricating test-pieces

Test-piece	Model number	Fe	C	Si	Mn	Ni	Cr	Mo	V	Cu
Wettability evaluation	PSL	75.06	0.04	0.4	0.8	4.5	15.5	0.7	0	3.0
Depth evaluation	SKD-11	84.60	1.5	0.3	0.4	0	12.0	0.9	0.3	0

Fig. 1 Machining process of two-scale periodic structures on a metal surface by percussion drilling using a nanosecond pulsed laser

dimensional galvanometric mirrors. The nanosecond pulsed laser was used for percussion drilling so that both thermal and ablation processes would occur (Fig. 1c). Consequently, a two-scale periodic structure is formed by processing two periodic structures simultaneously (Fig. 1d).

Twenty four test-pieces for wettability evaluation were prepared using the pitch (16–120 μm), number of repetition shots, s (1–120), and fluence, F (2.49–20 J/cm^2), as the parameters (Table 2).

Measurement of Two-Scale Periodic Structure

The various surface geometries of the test-pieces for wettability evaluation were compared using experimental observations made perpendicularly with a non-contact laser confocal microscope (1 nm resolution for depth, OLS4100, Olympus Co., Tokyo, Japan) for all the test-piece for wettability evaluation. However, it was difficult to use the laser confocal microscope to measure the depth of the percussion drilling because of the high (>1) aspect ratio (depth-to-diameter ratio) of the holes. Instead, we used a high-resolution three-dimensional X-ray microscopy (micro-CT, 2 μm resolution, SKYSCAN 1272, Bruker Japan K.K., Tokyo, Japan) to measure the depth nondestructively in the test-pieces for depth evaluation. Metal suffers from low X-ray

Table 2 Fabricated test-pieces for wettability evaluation used for direct laser processing of two-scale periodic structures

Sample no.	Pitch τ (μm)	Number of repetition shots s	Fluence F (J/cm^2)	Pulse width t (ns)	Spot diameter d (μm)
1	16	1	20.0	11	16
2		20			
3		40			
4		80			
5		120			
6	40	1			
7		20			
8		40			
9		80			
10		120			
11	80	1			
12		20			
13		40			
14		80			
15		120			
16	120	1			
17		20			
18		40			
19		80			
20		120			
21	40	80	2.49		
22			4.98		
23			7.46		
24			9.95		

transmittance, therefore we used thin test-pieces for depth evaluation (1.5 mm diameter) for cross-sectional observation under the same processing conditions as those used for the test-pieces for wettability evaluation. The measurements were repeated for five times ($n = 5$), and the mean values were used.

Apparent Contact Angle and Contact Angle Hysteresis

The equilibrium contact angle, θ , apparent contact angle, θ' , and contact angle hysteresis ($CAH = \theta_{\text{rec}} - \theta_{\text{adv}}$) of the test-pieces for wettability evaluation were measured using a commercial contact angle analyzer (DM-701, Kyowa Interface Science Co. Ltd., Niiza, Japan) by dropping a droplet of distilled water from a microsyringe. The volume of droplet was 2 μL for measuring θ and θ' . The volume of droplet was 30 μL for measuring CAH . The measurements of θ and θ' were repeated for five times ($n = 5$), and the mean values were used. For CAH , time-course changes of CAH s were measured, and the mean values of five data points ($n = 5$) were used.

It has been reported that wetting behavior is related to the amount of organic compounds on the surface with time [32–34]. Therefore, the time-course changes of the apparent contact angles were measured for a month and a half period to capture any changes. Immediately after the laser processing, the test-pieces were kept at 48 °C in an incubator (MIR-153, PHC Holdings Co., Tokyo, Japan) during this evaluation to accelerate the oxidation aging.

Estimation of Processing Rate

Figure 2 shows a time chart of the nanosecond pulsed laser used for this laser processing. The processing time per shot, t , is shown by the sum of (i) the percussion drilling time, t_p , (ii) the time taken to move the scanner to the next position, t_m , and (iii) the scanner settling time, t_s , as follows:

$$t = t_p + t_m + t_s \quad (\text{s}) \quad (1)$$

The percussion drilling time, t_p , is given as follows:

$$t_p = \frac{s}{f} = \frac{s}{20} \times 10^{-3} \quad (\text{s}) \quad (2)$$

where, s : Number of irradiations (= 1–120),
 f : repetition rate, = 20 kHz.

(a) Moving of scanner

(b) Percussion drilling

Fig. 2 Time chart of nanosecond pulsed laser (t_m : moving time of scanner, t_s : settling time of scanner, t_p : percussion drilling time)

In this experiment, t_p was between 0.05 and 6 ms. The maximum value of $t_m (= \tau/v_s)$ was estimated as 0.08 ms from the laser scanning velocity ($v_s = 1500$ mm/s) and the maximum pitch ($\tau = 120$ μm). For the present nanosecond pulsed laser system, t_s was 1 ms, in which case t_m is negligible. Thus, the total processing time, T , is expressed in terms of the number of holes, N , as follows:

$$T = \left(\frac{s}{f} + 1 \right) \times N \times 10^{-3} \quad (\text{s}) \quad (3)$$

When both the pitch ($\tau_x = \tau_y$) and the length of the processed area ($l_x = l_y = l$) are the same in both directions, the number of holes per unit area, N , is given as follows:

$$N = \frac{l_x}{\tau} \times \frac{l_y}{\tau} = \left(\frac{l}{\tau} \right)^2 = \frac{1}{\tau^2} \quad (1/\text{m}^2) \quad (4)$$

Thus, the processing rate, v , is given as follows:

$$v = \frac{1}{T} = \frac{\tau^2 \times 10^3}{\frac{s}{f} + 1} \quad (\text{m}^2/\text{s}) = \frac{6 \times 10^{10} \times \tau^2}{\frac{s}{f} + 1} \quad (\text{mm}^2/\text{min}) \quad (5)$$

Results and Discussion

Measurement of Periodic Structure

Figure 3 shows a sequence of laser confocal microscope micrographs of the test-pieces for wettability evaluation for various laser fluences (samples no. 21–24 in Table 2). As expected, crater-shaped holes were observed in the direction of the laser beam. It was considered that the bank-shaped outer rim around each micro-hole was formed by the molten material which was squeezed out of the micro-hole by the expanding plasma. Mirza et al. reported that craters could be processed by using a femtosecond pulsed laser, however the heights of the outer rim did not change significantly [23]. In Fig. 4, the structure processed on steel by percussion drilling is illustrated schematically as a two-scale periodic structure, where f_1 is the width of the solid–liquid interface, f_2 is the width of the liquid–air interface, h_1 is the depth of the basically periodic surface structure, f_{s1} is the width of the small-scale periodic surface structure, and h_2 is the bank height of the small-scale periodic surface structure. The values of f_{s1} could not be determined under the condition of 16 μm pitch due to the overlap of two-scale periodic structures. The value of f_{s1} was in the range of 2.9–10.2 μm . The values of the bank height, h_2 , for fluence values of 2.94, 4.98, 7.46, and 9.95 J/cm² were 0.7, 2.8, 6.0, and 8.2 μm , respectively. Therefore, we reason that the bank-shaped outer rim was caused by the molten material generated by the expanding plasma of the nanosecond pulsed

Fig. 3 Three-dimensional images of surface morphology for fluences of 2.49 J/cm² (no. 21), 4.98 J/cm² (no. 22), 7.46 J/cm² (no. 23), and 9.95 J/cm² (no. 24)

laser, meaning that the bank height could be controlled when using a nanosecond pulsed laser.

The results for the geometrical parameters of the two-scale periodic structures measured using the non-contact laser confocal microscope are shown in Table 3. The value of h_1 at $\tau = 16 \mu\text{m}$ could not be measured because adjacent processing areas interfered. For sufficient pitch length, h_1 was considered to be almost constant and

Fig. 4 Schematic depiction of laser processed two-scale periodic structures on steel by percussion drilling

Table 3 Measured results for the two-scale periodic structures and the contact angles ($F = 20 \text{ J/cm}^2$)

Pitch (μm)	τ shots, s	Measured results									
		τ (μm)	f_1 (μm)	f_2 (μm)	$^*1 f s_1$ (μm)	$^*2 h_1$ (μm)	h_2 (μm)	f_1/τ	f_2/f_1	$^*3 \theta'$ ($^\circ$)	CAH ($^\circ$)
16	1	16.1	6.3	9.8	—	*4—	2.3	0.39	1.56	146.0	81.9
	20	16.2	7.2	9.0	—	—	12.5	0.44	1.25	148.8	24.5
	40	16.1	7.3	8.8	—	—	21.6	0.45	1.21	155.9	11.0
	80	16.4	8.5	7.9	—	—	19.0	0.52	0.93	154.1	10.5
	120	16.6	8.3	8.3	—	—	17.3	0.50	1.00	153.7	20.5
40	1	40.7	17.5	23.2	2.9	1.6	1.0	0.43	1.32	141.7	59.0
	20	40.9	21.9	18.9	6.9	30.6	10.1	0.54	0.86	157.6	12.3
	40	40.3	22.8	17.5	9.4	—	11.7	0.57	0.77	158.9	17.3
	80	40.5	25.4	15.1	10.1	—	12.5	0.63	0.60	158.2	9.9
	120	40.4	23.6	16.7	10.0	—	11.4	0.59	0.71	157.7	7.4
80	1	79.5	53.1	26.4	3.1	2.0	1.5	0.67	0.50	143.4	78.0
	20	79.6	59.1	20.5	6.5	30.5	8.6	0.74	0.35	161.4	4.2
	40	79.7	65.9	13.8	9.3	—	13.1	0.83	0.21	160.8	14.6
	80	79.3	64.4	14.9	10.0	—	13.4	0.81	0.23	160.3	18.9
	120	79.9	65.1	14.9	10.2	—	11.8	0.81	0.23	158.9	20.6
120	1	119.3	93.0	26.3	3.6	1.9	1.4	0.78	0.28	134.8	52.6
	20	121.2	101.2	20.1	6.2	32.2	10.0	0.83	0.20	139.7	75.4
	40	120.5	103.9	16.6	9.3	—	11.9	0.86	0.16	140.6	87.5
	80	121.2	103.8	17.3	10.0	—	11.9	0.86	0.17	141.9	91.1
	120	120.9	103.6	17.4	9.9	—	13.1	0.86	0.17	141.7	98.7

*1: Width of the small-scale periodic structure, $f s_1$, could not be determined due to the overlap of the two-scale periodic structures

*2: Depth of hole, h_1 , could not be measured by the laser confocal microscope because the aspect ratio

*3: Equilibrium contact angle was $\theta = 97.3^\circ \pm 3.2^\circ$ (mean $\pm$ SD)

*4: — shows the data which cannot be measured. $n = 5$

independent of the pitch. The f_1/τ ratio was in the range of 0.37–0.87, increasing in proportion to the pitch. Thus, the f_2/f_1 ratio was in the range of 0.15–1.69, decreasing in proportion to the pitch. The diameter, f_2 , changed with the pitch distance and the number of laser pulses. It was considered that the molten material was squeezed around the micro-holes in proportion to the number of laser pulses, whereupon f_2 decreased.

Figure 5 shows the results for the hole depth, h_1 , measured using the test-pieces for depth evaluation and three-dimensional X-ray microscopy because the aspect ratio of the holes prevented them from being measured fully using the laser confocal microscope. Figure 5a and b show how h_1 varied with the fluence, F , and the number of repetition shots, s , respectively. The value of h_1 increased linearly in proportion to the fluence (Fig. 5a). The absolute values of h_1 for the SKD-11 steel were similar to those of the PSL steel for $s = 1$ and 20 (Table 3). The compositional differences between the two steels were those regarding C, Ni, V, and Cu, clarified as being a few percent.

Fig. 5 Variation of hole depth, h_1 , with fluence, F , and number of repetition shots, s

Thus, it was considered that the ablation thresholds of the two used steels comparable to lead to the same surface features. A limitation was that the single pulse results should be excluded because of the resolution of the micro-CT. The hole depth could potentially increase exponentially because reflectivity decreases with increasing temperature [35]. However, the value of h_1 also increased linearly in proportion to the number of repetition shots (Fig. 5b). Therefore, we assumed our conditions limited the increase in surface temperature sufficiently so that we can use both the fluence and the number of repetition shots to estimate the hole depth in a linear manner. These data were used to estimate the processing rate for the two-scale periodic structures.

Apparent Contact Angle and Contact Angle Hysteresis

Figure 6 shows the time-course changes of the apparent contact angles immediately after the laser processing of the test-pieces for wettability evaluation (samples no. 1–20 in Table 2). The apparent contact angles of the steel surfaces increased over time, and the surfaces became nearly superhydrophobic. Jagdheesh et al. reported that laser processing of metal surfaces creates preferential sites for the adsorption of organic compounds from the air [26]. The change in wetting behavior was correlated with the amount of carbon on the structured surfaces [33]. It was considered that the apparent contact angles to have stabilized after 4 weeks and we used those values to evaluate the hydrophobicity.

The maximum contact angles after aging for each test-piece for wettability evaluation are shown in Table 3. The measured apparent contact angle increased as the pitch increases from 16 to 80 μm , after which it decreased. The maximum apparent contact angle of 161.4° was associated with a pitch of 80 μm and 20 repetition shots. This condition might be the optimum condition based on the Cassie-Baxter equation. This superhydrophobicity was equal to or above with the previous report of the hierarchical structure [36]. Also, the same conditions are associated with the minimum contact angle hysteresis of 4.2° . These results agreed well with those in a previous report that found the hysteresis values to be less than 10° when the apparent contact angle exceeded 150° [37].

It seems that the contact angle did not change much after a few pulses (Table 3). In particular, the contact angle for $s \geq 20$ remained almost constant for pitch values of 40

Fig. 6 Time-course changes of apparent contact angles

and 80 μm . These findings suggested that we could focus on using low pulse numbers. Reducing pulse numbers contribute to reduce processing time and heat affected zone. If the number of repetition shots increases, unstable morphology may appear in the pores, which may not be conducive to obtaining a stable superhydrophobic structure.

Table 4 shows the relationship between geometrical parameters and wettability of the two-scale periodic structures. In this table, the depth of the basically periodic surface structure, h_1 , was estimated by using the linear regression analysis between the hole depth and the fluence (Fig. 5a). The h_1 saturated when fluence exceeded 80 J/cm². It was considered that the increase in the hole depth slowed down by the plasma shielding effect [38]. The apparent contact angle showed hydrophobicity when the basically periodic surface structure, h_1 , and the bank height, h_2 , exceeded a threshold level. The absolute values of each threshold level will be changed by geometrical parameters such as pitch.

The values of the apparent contact angle, θ' , were calculated based on the Cassie-Baxter equation and introducing a non-dimensional roughness factor $R_f (\geq 1)$ on surface f_1 as follows [39, 40]:

Table 4 Relationship between geometrical parameters and wettability of the two-scale periodic structures

Pitch τ (μm)	Number of repetition shots, s	Measured results			
		h_1^* (μm)	h_2 (μm)	f_1 / τ	θ' ($^\circ$)
16	1	2.7	2.3	0.39	146.0
	20	38.5	12.5	0.44	148.8
	40	63.7	21.6	0.45	155.9
	80	127.1	19.0	0.52	154.1
	120	125.5	17.3	0.50	153.7
40	1	2.7	1.0	0.43	141.7
	20	38.5	10.1	0.54	157.6
	40	63.7	11.7	0.57	158.9
	80	127.1	12.5	0.63	158.2
	120	125.5	11.4	0.59	157.7
80	1	2.7	1.5	0.67	143.4
	20	38.5	8.6	0.74	161.4
	40	63.7	13.1	0.83	160.8
	80	127.1	13.4	0.81	160.3
	120	125.5	11.8	0.81	158.9
120	1	2.7	1.4	0.78	134.8
	20	38.5	10.0	0.83	139.7
	40	63.7	11.9	0.86	140.6
	80	127.1	11.9	0.86	141.9
	120	125.5	13.1	0.86	141.7

*: Depth of the basically periodic structure, h_1 , was estimated by using the linear regression analysis between the hole depth and the fluence (Fig. 5a, $F = 20 \text{ J/cm}^2$)

$$\cos\theta' = -1 + \frac{f_1}{\tau} (R_f \cos\theta + 1) \quad (6)$$

where θ is the equilibrium contact angle, and is equal to $97.3 \pm 3.2^\circ$ (mean $\pm$ standard deviation, the mean value was calculated using 24 test-pieces for wettability evaluation). This theoretical model adapts the hypothesis that the water is under zero hydrostatic pressure. This model approximates the two structures as a basically periodic surface structure and a small scale structure on surface f_1 . Figure 7 shows the relationship between the apparent contact angle and f_1/τ ratio for these structures. The measured apparent contact angle decreased with increasing f_1/τ ratio. The calculated results agreed well with the measured results when $R_f = 1-7$ were used. These results confirmed that the present theoretical model pertains to the two-scale periodic structures.

Estimation of Processing Rate

Figure 8 shows the processing rate of the two-scale periodic structures calculated using Eq. (5). Under the present conditions, the processing rate ranged between 2 and 823 mm²/min, increasing with the pitch and decreasing with the number of repetition shots. In this method, the number of repetition shots can be reduced by increasing the fluence. Eq. (5) showed that increasing the repetition rate, f , was an effective way to increase the processing rate. Consequently, a maximum processing rate of 823 mm²/min was achieved with $\tau = 120 \mu\text{m}$ and $s = 1$. This processing rate equivalent to 28.7 mm square per min and/or 222 mm square per hour. In previous research involving percussion drilling using a nanosecond pulsed laser, Cai et al. used an area

Fig. 7 Relationship between apparent contact angle and f_1/τ ratio of two-scale periodic structures

Fig. 8 Estimated processing rate of two-scale periodic structures using nanosecond pulsed laser

of 10 mm square area, 110.9 μm pitch, 1 shot/hole, and 0.4 s duration time on stainless steel [41]. Yang et al. used a condition of 20 mm diameter area, 100 μm pitch, 24 shots/hole, and 50 mm/s scanning speed on nickel-chromium-based superalloy [42]. Although neither report states the processing rate clearly, we estimated that it was in the range of 1–100 mm^2/min . Therefore, the present results supported the assertion that a rapid fabrication method has been obtained, leading to fast laboratory-to-fabrication transfer. With superhydrophobicity, we can use $s \geq 20$, in which case the processing rate will be 432 mm^2/min with $\tau = 120 \mu\text{m}$. A stop-and-go action is necessary to increase the roundness of the work marks on the workpiece. However, if such stop-and-go action can be avoided and the pulsed laser source moved continuously, then the throughput can be increased substantially.

Conclusion

We have purposed a concept for the one-pass and rapid laser processing of two-scale periodic structures with arbitrarily set pitch, lead to superhydrophobicity on steel by percussion drilling using a nanosecond pulsed laser with a single laser light source. The molten material due to the expanding plasma squeezed around the micro-holes could play an active role in processing two-scale periodic structures. A maximum apparent contact angle of 161.4° was achieved with a contact angle hysteresis of less than 5° . The proposed method was shown to be capable of a maximum processing rate of 823 mm^2/min and of being useful as a direct processing method.

By creating a replica mold, it might be possible to apply this novel laser processing method to conventional injection molding. Additional evaluation may be required for the hole diameter that also affects the hole depth.

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Compliance with Ethical Standards

Declaration of Competing Interest The authors declare that they have no known competing financial interests or personal relationship that could have appeared to influence the work reported in this paper.

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