Micro-grooving of brittle materials using textured diamond grinding wheels shaped by an integrated nanosecond laser system

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Abstract

Freeform surfaces including both the aspherical and prismatic concave/convex have been widely utilized in optical, electrical, and biomedical areas. Most recently, it is reported that grinding with structured wheels provides new possibility to generate patterns on hard and brittle materials. This paper reports the latest research progress on micro-grooving glass ceramic using laser structured diamond grinding wheels. A nanosecond pulse laser is firstly integrated into an ultra-precision machine tool and used for the in-line conditioning of super abrasive grinding wheels, i.e., truing, dressing, and profiling/texturing. Meanwhile, an offset compensation method, considering the shifting depth of focus (DoF) at different laser irradiation positions, is proposed to accurately generate various profiles on the periphery of the grinding wheels. Three types of patterns (riblets, grooves, and pillars) are successfully fabricated on the ceramic substrate using the laser textured grinding wheels. The results indicate that the integrated laser system offers high flexibility and accuracy in shaping super abrasive grinding wheels, and the grinding using textured grinding wheels provides a promising solution to generate functional microstructures on hard and brittle materials.

Keywords Laser processing · Diamond grinding wheels · Functional surfaces · Micro-machining

1 Introduction

Recently, there are increasing applications of functional micro-/nanostructured surfaces in optical, electrical and biomedical areas. For example, compressor blades of a gas turbine with riblets in 20–120 μm width and 0.5 aspect ratio can reduce friction and avoid turbulences. The micro-holes and pillars can change the wet properties of surfaces. Various physical- and chemical-based methods have been developed to fabricate functional microstructures [1, 2]. Several pioneering works have also demonstrated the feasibility on micro-/nano-machining using facet, sharp point (S-point) and structured cutting tools to generate surface structures/patterns [3]. With the advance of FIB/laser-assisted shaping of cutting tools, micro-/nano-structures can be generated on

cutting tool tips [4] and grinding wheels [5] and then be replicated on material surfaces through cutting. The grinding harden was observed, and its effects on the grinding process have been reported in [6]. For hard and brittle materials, grinding is regarded as the only effective method for massive surface structuring [7].

Indeed, the achievable machining accuracy of surface structures significantly relies on the shape/profile of the structures generated on grinding wheels. The traditionally utilized mechanical conditioning tools such as diamond nibs, rollers, or dressing wheels are prone to serious wear after a period of working [8–10] because the mechanical conditioning process is a hard to hard contact with large force engaged between grinding wheels and conditioning tools. This will eventually result in form deviation of structures generated on tools. It is also noticed that grinding with micro-abrasive tools (also called micro-abrasive pencils or micro-pencil grinding tools) can produce small feather size on samples through depositing or coating grits on the base substrate such as cemented carbide [11]. However, the non-uniform protrusion height, clogging, and breakage hinder its application from machining with large allowance. It remains a challenging task to prepare the structured grinding wheels with super abrasive grains.

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With the development of laser machining, it is reported that a laser beam is capable of shaping the grinding wheel with higher efficiency and less pollution [12, 13]. There have been continuous efforts to investigate the effects of laser beam output (continuous or pulsed), wavelength, power, and polarization on the quality of laser conditioned grinding wheels [14]. For example, Wu et al. [15] fabricated a series of grooves ($\sim 300 \mu\text{m}$ in width and $\sim 70 \mu\text{m}$ in depth) on a coarse grain ($213 \mu\text{m}$) diamond grinding wheel using a nanosecond pulse laser. Then linear and square microstructures were replicated on tungsten carbide and BK7 glasses by ultraprecision grinding. Deng et al. [16] investigated the influence of the spot overlap, line overlap, power, and scan cycles on bond smoothness of the grinding wheel and found that the laser scan cycle should be carefully controlled to obtain well-controlled grain protrusion height. Furthermore, Ackerl et al. [17, 18] developed a multi-axis synchronized motion platform to improve the profile accuracy of shaped wheels. Various cross-sectional shapes of grooves fabricated by laser have been reported in [19, 20].

Nevertheless, the laser processing of grinding wheels is a complex interaction between the laser beam and grinding wheels. The thermal conditioning process is affected by the absorption mechanism of laser beam, material properties of the irradiated sample, and surface morphology [21, 22]. It is generally acknowledged that the irradiated material can be ablated if the threshold fluence F (absorbed energy on unit area) is reached. However, the threshold for same material does not correspond from different works because of the incubation effect [23–25]. In practice, the guideline for selecting laser machining parameters relies greatly on users' experience. Large fluence is usually set to remove both the bonding material and grains in truing, whereas small fluence is assigned to selectively ablate the bonding materials and preserve the abrasive grains in dressing and cleaning. For laser conditioning of wheels, the tangential irradiation and the radial irradiation are two typical configurations. Research from Wang et al. [19, 26] showed that the absorbed energy of grinding wheels changed significantly at different radial positions and incident angles, because the space distribution of absorbed and scattered energy was far more

Table 1 Parameters of the laser source

Parameters	Value	Parameters	Value
Power, p	3–30 W	Wavelength, λ	1064 nm
Frequency, f_p	2–200 kHz	Beam quality, M^2	2
Pulse duration, $\Delta\tau$	100 ns	Spot size, r	$\sim 50 \mu\text{m}$
Machining area	$60 \times 60 \text{ mm}^2$	Focal length (working distance)	100 mm

different during laser irradiation. Therefore, the laser head should move along with the grinding wheel axis in order to keep the focus offset constant.

In this paper, a novel conditioning strategy using nanosecond pulse laser was developed for metal bond diamond grinding wheels. The whole conditioning chain, including the truing, dressing, and texturing/profiling of the grinding wheel, was achieved using the same laser source. A preliminary test was performed to quickly determine proper processing parameters for different laser processing. An offset compensation value was calculated and used in laser profiling. The grinding capability of laser conditioned tools was demonstrated by generating riblets, grooves, and pillars on ceramic samples.

2 Methodology

2.1 Experimental platform

Figure 1a shows the laser conditioning configuration. A nanosecond pulse laser marking head (YLP-V2-1-100-30–30, IPG) was integrated on Z slide of an ultraprecision machine tool (Nanoform 250 Ultragrinder, Precitech). Two galvo motors in the marking head can adjust the laser machining area. The minimum spot size was about $\varnothing 50 \mu\text{m}$ in the focus plane, and the beam quality M^2 is 2. The beam quality is defined as a beam parameter to reflect how tightly a laser beam can be focused under certain conditions and it can be calculated by dividing the corresponding product for a diffraction limited Gaussian beam with same

Fig. 1 Configuration for (a) the laser conditioning grinding wheel and (b) grinding microstructures on sample

Table 2 Parameters of the grinding wheel and workpiece

Grinding wheel		Workpiece	
Grain size	#1200	Young's Modulus	66.9 GPa
Tool size	Ø8 × 10 mm	Poisson's Ratio	0.29
Bonding	Bronze	Knoop Hardness	250 kg/mm ²
Concentration	125%	Density	2.52 g/cm ³

wavelength. More details about the laser beam are listed in Table 1. As shown in Fig. 1a, for laser dressing the grinding wheel (#1200 diamond grinding Ø 8 × 10 mm) was fixed on a tool holder which was then vacuum chucked on the machine spindle. The grinding wheel can move with the machine X slide for the fine adjustment to the laser marking head. A chromatic confocal probe (CHRocodile S, Precitec), which had 100 µm working range and 2 kHz sampling rate, was integrated into the ultra-precision grinding environment for on-machine surface measurement [27]. The integrated confocal probe was used for on-machine measuring the radial runout of wheels before and after laser truing. A USB microscopy (AM4815ZTL, Dino-Lite) was used for alignment and in-process monitoring laser conditioning and microstructure grinding process.

The grinding configuration is shown in Fig. 1b. A 25 × 25 × 5 mm glass ceramic substrate (Corning Macor) was vacuum-chucked on the spindle by a specially designed holder. The laser conditioned grinding wheel was clamped on an electro-spindle assembly (NR-3060S, Nakanishi). The rough and fine alignments were achieved by the USB microscopy and feeler gauges, respectively. The Clairsol 330™ coolant mist was used throughout the grinding process. The laser conditioned wheels and ground samples were ultrasonic-cleaned and then measured using a non-contact optical 3D microscopy (Alicona G4 InfiniteFocus). More parameters about the grinding wheel and the sample are listed in Table 2.

2.2 Laser conditioning of grinding wheels

A preliminary was planned to explore the laser machining ability and find the laser processing parameters for truing, dressing, and profiling the grinding wheel. The four evaluated factors were pulse power e , pulse overlap U_p , line overlap U_l , and loops, and the two responses were degree of graphitization and material removal volume. Three levels for each factor are estimated. An orthogonal test was designed according to [28] with four three-level factors L_9 (3^4) as listed in Table 3. Totally nine groups of tests are performed. To exclude the environment disturbance, the experiment was performed at random order. The pulse overlap and line overlap were calculated by Eqs. (1) and (2). The material removal volume of each 2 × 2 mm square was measured by Alicona. The degree of graphitization was evaluated by observing the optical image of laser irradiated surfaces, where black surface represents serious graphitization of diamond grits.

$$U_p = 1 - \frac{\pi \times D \times S}{d \times f} \quad (1)$$

$$U_l = 1 - \frac{pitch \times f}{d \times S} \quad (2)$$

where the D , S , d , f , and $pitch$ represent the wheel diameter, wheel rotation speed, spot diameter, pulse frequency, and spot interval, respectively.

Figure 2 shows images of laser ablated nine pockets according to machining parameters in Table 3. It is found that the laser irradiated surfaces in the 2nd, 4th, 5th, and 9th run were darker in color, indicating severe graphitization of the diamond abrasive grits. On the contrary, the laser machined surfaces in the 1st and 3rd run were bright, indicating less graphitization transition with small pulse energy (0.2 mJ) and low pulse overlap (20%). The range analysis was performed for both the material volume and

Table 3 Preliminary on laser ablation test

Standard order	Run order	Pulse energy mJ	Pulse overlap	Line overlap	Loops	Graphitization degree (Level 1–4)	Removal volume mm ³
1	1st	0.2	20%	20%	5	1	0.048
2	3rd	0.2	35%	35%	10	2	0.148
3	2nd	0.2	50%	50%	15	3	0.176
4	7th	0.4	20%	35%	15	2	0.12
5	9th	0.4	35%	50%	5	3	0.344
6	8th	0.4	50%	20%	10	2	0.216
7	4th	0.6	20%	50%	10	3	0.648
8	6th	0.6	35%	20%	15	2	0.48
9	5th	0.6	50%	35%	5	4	0.456

Fig. 2 The laser ablated pockets

graphitization. To quantitatively evaluate the influence of different factors on the graphitization, the index 1–4 is assigned to each pocket according to the burn degree. Range value R , which can reflect the effect of estimated factors, was calculated by

$$K_i = \sum_{i=1}^3 y_i \quad (3)$$

$$\overline{K_i} = \frac{K_i}{3} \quad (4)$$

$$R_i = \max \overline{K_i} - \min \overline{K_i} \quad (5)$$

where i represents low, medium, and high level, y_i is the output of each test from graphitization degree and material removal volume, and K_i and $\overline{K_i}$ are the sum and mean value of output at each level, respectively.

The impact of each factor is evaluated and ranked as shown in Table 4. It was found that the pulse energy dominates the material removal volume, and the pulse energy and pulse overlap are the two most important factors affecting the phase transition from diamond to graphite. To balance the material removal volume and degree of

graphitization, the maximum pulse energy (i.e., $e = 1$ mJ) was chosen in laser truing for fast material removal, while small pulse energy (i.e., $e = 0.2$ mJ) was used in fine dressing to remove the graphitization layer and protrude the diamond grains.

The whole laser conditioning chain is schematically shown in Fig. 3. Firstly, the radial runout of the grinding wheel was controlled within ± 1.25 μm by the integrated gage. Then laser truing with $e = 1$ mJ, $f = 30$ kHz, $S = 1000$ RPM, and $t = 5$ min was performed to reduce the wheel radial offset and create the straight base line by repetitively scanning along the axial direction, as shown in Fig. 3a. The total removal depth was 100 μm with twice 50 μm radial infeed. After tangential truing, the laser dressing with low fluence ($e = 0.2$ mJ, $f = 30$ kHz, $S = 1000$ RPM, and $t = 3$ min) was carried out to remove only the metal bonding and protrude diamond grains in Fig. 3b. The desired pattern was then produced through the layer-by-layer irradiating mode as shown in Fig. 3c.

In order to improve the accuracy of profiling, a radial compensation strategy was adopted and schematically described in Fig. 3d. Along the laser beam propagation direction, most energy was focused within a narrow depth of focus (DoF). The energy transferred to the grinding wheel will induce

Table 4 Range analysis of orthogonal test

	Material removal volume				Graphitization degree			
	Pulse energy	Pulse overlap	Line overlap	Loops	Pulse energy	Pulse overlap	Line overlap	Loops
K_1	0.372	0.816	0.744	0.848	6	6	5	8
K_2	1.584	0.972	0.724	1.012	9	7	8	7
K_3	0.68	0.848	1.168	0.776	7	9	9	7
$\overline{K_1}$	0.124	0.272	0.248	0.283	2	2	1.7	2.7
$\overline{K_2}$	0.528	0.324	0.241	0.337	3	2.3	2.7	2.3
$\overline{K_3}$	0.227	0.283	0.389	0.259	2.3	3	3	2.3
R	0.404	0.052	0.148	0.078	1	1	1.3	0.4
Pulse energy > Line overlap > Loops > Pulse overlap					Line overlap > Pulse energy = Pulse overlap > Loops

Fig. 3 (a) Laser truing (b) dressing (c) profiling, and (d) offset compensation

heat-affected zone (HAZ) where the metal bonding material or diamond grains will be ablated if their fluence threshold is reached. However, when the truing line fed along radial direction, the laser should retreat a distance AB to place the DoF on the new exposed area of the grinding wheel. In this case, the DoF was evaluated to be $\sim 850 \mu\text{m}$ by Eq. (6). The radial compensation distance AB for each laser scanning was calculated according to Eq. (7). The radius of the grinding wheel was 4 mm. For example, if the profiling infeed a is set as $30 \mu\text{m}$ for the 1st laser beam scan, the grinding wheel should move away $489 \mu\text{m}$ along the X slide.

$$DoF = 2 \times Z_R = \frac{2\pi r^2}{\lambda M^2} \quad (6)$$

$$AB = \sqrt{(R - a \times (n - 1))^2 - (R - n \times a)^2} \quad (7)$$

where R , λ , M^2 , r , a , and n are the wheel radius, laser wavelength, beam quality, spot radius, profiling infeed value, and radial infeed times, respectively.

3 Results and discussion

3.1 Truing, dressing, and profiling

Figures 4a–c shows the surface characteristics of the metal bond diamond grinding wheel at different laser conditioning phases, and the radial runout measured by the confocal probe is plotted in Figs. 4d–f. The surface of an as-received new grinding wheel (Fig. 4a) is very rough with some contaminants/bonding material left on it. Large co-axiality and radial runout were observed after mounting the wheel in the spindle which are resulted from the mounting error and the surface unevenness of the grinding wheel (Fig. 4d). After

Fig. 4 The surface topography (a) before truing, (b) 5-min truing, (c) 10-min truing, and the radial runout (d) before truing, (e) 5-min truing, and (f) 10-min truing

5-min laser truing, redundant bonding and abrasive materials were ablated by the high fluence laser and a precise concentricity of the grinding and spindle axis was achieved. The measured radial runout was reduced to $\sim 20\text{ }\mu\text{m}$ as shown in Fig. 4e. Followed by another 10-min laser fine truing (as illustrated in Fig. 3d), the outer layer material of the grinding wheel was fully ablated. Since only a small part of the laser was projected to the wheel surface, the absorbed and accumulated energy was small, and the material removal volume was slow. The grinding wheel surface after fine laser truing is shown in Fig. 4c and less than $\sim 10\text{ }\mu\text{m}$ radial runout was achieved (Fig. 4f).

Figure 5 shows the surface topography and the statistical texture parametric analysis results of grinding wheels processed under different laser conditioning stages. The root mean square height S_q and arithmetical mean height S_a were selected as indicators to surface smoothness, and the peak height S_{pk} value was used to describe the grain protrusion. As shown in Fig. 5a, the as-received grinding wheel had irregular surface ($S_a\ 16.3\text{ }\mu\text{m}$ and $S_q\ 22.8\text{ }\mu\text{m}$) and abrasive grains were fully covered by bronze bonding. After 10-min laser fine truing, most diamond grains were pulled off which led to massive pits and converted graphite in situ as shown in Fig. 5b. The surface of grinding wheel was smooth with reduced surface roughness ($S_a = 1.4\text{ }\mu\text{m}$ and $S_q = 1.9\text{ }\mu\text{m}$). To ensure good grinding performance, the protrusion height of grit after dressing should be within $1/3 \sim 1/2$ of the grit size [18]. Therefore, another 5-min laser tangential dressing with low fluence was conducted and the bronze bonding materials were melted and then blown away by the compressed air. A large number of diamond grains were disclosed again as shown in Fig. 5c. The surface roughness of grinding wheels is $S_a\ 9.9\text{ }\mu\text{m}$ and $S_q\ 14.2\text{ }\mu\text{m}$, and the grain protrusion height was approximately $5.3\text{ }\mu\text{m}$ as indicated by S_{pk} .

Figure 6 shows the textures and cross-sectional profiles of diamond grinding wheels shaped by laser and mechanical dressing tip, respectively. As shown in Fig. 6a, b, riblet structures with different dimensions were designed and well shaped by the integrated laser beam. The laser structured grinding wheel has better form uniformity, and the shape

and dimensions of structures can be flexibly controlled. In contrast, the mechanically profiled grinding wheel using diamond nib had large form deviation due to the diamond tip wear and elastic back-off of the grinding wheel (Fig. 6c, d). An important notice is that the laser profiling accuracy depends on the stability and energy distribution of laser pulse. The actual dimension of the laser processed structures was slightly larger than the designed dimensions. This is mainly caused by the overlapping of laser spot at the corners. The positioning error of the galvo motors, the loosening and pull-out of grains near the irradiated surface, and the re-deposition of melted bronze bonding materials on the top of wheel can also reduce form accuracy of shaped surface structures. The re-deposition layer has less strength than diamond grains and will be removed shortly in grinding process.

3.2 Grinding with textured wheels

To demonstrate the grinding performance of laser conditioned diamond grinding wheels, three typical microstructures (riblet grooves, rectangle grooves, and pillar array) were machined. The riblets and rectangle grooves were processed with plunge grinding mode, while the pillar array was fabricated by twice plunge grinding with the workpiece 90° apart. The structure height was designed as $150\text{ }\mu\text{m}$ for riblets (textured grinding wheel shown in Fig. 6a) and $100\text{ }\mu\text{m}$ for rectangle grooves and pillar array (textured grinding wheel shown in Fig. 6b). Other parameters were set as $S = 40\ 000\text{ rpm}$, $DoC = 10\text{ }\mu\text{m/pass}$, $feedrate = 5\text{ mm/min}$, and $v = 16.7\text{ m/s}$, respectively.

Figure 7 shows the overview and close-up of the ground riblets on ceramic glass. Two groups of riblets with different periods and depths were machined on the ceramic glass. The ground structure has uniform profile accuracy along the 14 mm length, and the surface roughness S_a was measured to be $1.6\text{ }\mu\text{m}$. It is found that the period of riblet structure on the ground sample was $450\text{ }\mu\text{m}$ and $300\text{ }\mu\text{m}$, respectively, which match the period of structure on the laser profiled grinding wheel (Fig. 6a). The measured depths of riblet structures were $120\text{ }\mu\text{m}$ for Group 1 and $140\text{ }\mu\text{m}$ for

Fig. 5 The surface topography of grinding wheels (a) as received (b) truing and (c) dressing

Fig. 6 (a) (b) The laser profiled metal bond grinding wheels, (c) the diamond dressing nib and (d) conditioned grooves on resin bond grinding wheel (image (c) and (d) are reproduced from [9])

Fig. 7 (a) Overview, (b) local and (c) 2D profile of the riblet structures

Group 2, which are slightly smaller than the designed grinding depth (150 μm) due to the macro-wear of the grinding wheel. Some cracks and fractures were observed on the ground surface by optical microscopy, indicating that the ceramic glass was removed under brittle removal method. During the grinding, the normal and tangential load between abrasive grains and workpiece accelerates the generation of lateral, median, and radial cracks. These cracks grow along different directions and intersect with each other to achieve the material removal. The brittle fracture leads to uncontrollable and larger material removal volume in machining hard and brittle materials; thus, the machined structure had larger dimension than the laser profiled structure on grinding wheel. Besides, the macro-wear along radial direction of the wheel can also deteriorate the form accuracy.

Figure 8 shows the overview and close-up of the ground rectangular grooves (14 mm $\times$ 4 mm) on the ceramic glass. The period of ground structures was 400 μm and 600 μm , which also match very well with the pitch of structure on

Fig. 8 (a) Overview, (b) local and (c) 2D profile of the rectangle structures

wheel. The ground surface was rougher (S_a 2.1 μm), and structure height was 20 μm shorter than design because of the serious wheel wear. Compared to the riblet structures in Fig. 7, the machined rectangular grooves have better form accuracy, indicating that the shaper transferability of rectangular texture on wheels is better. The reason might be that the grinding wheel wear is more stable for wheel with rectangular texture.

Figure 9a shows the measurement results of ground pillar array in a 5 mm $\times$ 6 mm square area. A variety of pillars with different dimensions were generated by the proposed crossing plunge grinding. Three groups of pillars, as indicated by red, black, and yellow squares, were extracted for detailed analysis (Fig. 9b–d). An important notice is that the depth of ground pillar array decreased gradually from the left bottom corner (~ 80 μm) to the top right corner (~ 50 μm) because of mounting unevenness of the sample. The height consistency can be improved by flat grinding the sample before fabricating microstructures.

Fig. 9 (a) Overview and (b)–(d) close-up of the pillar array

Fig. 10 The geometry topography of the grinding wheel after machining pillar array

3.3 Grinding wheel wear

The surface topography of the grinding wheel after machining is shown in Fig. 10. Macro-wear and micro-wear were observed, and the average height of structure left on the grinding wheel was reduced to around 70 μm after the grinding, indicating ~ 40 μm wear in height as compared with profile height being 110 μm (Fig. 6b). During the grinding process, mechanical and thermal loads are applied to the textured grinding wheel. Grains and bonding material are broken and pulled out under the intermittent normal and tangential force. Therefore, macro-wear happens along the radial direction of the grinding wheel. To quantitatively depict the wear condition of the textured grinding wheel, the grinding ratio, defined as the material removal volume divided by the volume of wheel wear, was estimated to be 6.3–6.5 in machining riblets and rectangle grooves. Moreover, the micro-worn of the texture of the grinding wheel was assessed by surface roughness parameters. It is found that the areal roughness reduced to S_a 1.5 μm and S_q 1.9 μm and the abrasive protrusion decreased from S_{pk} 5.3 μm to S_{pk} 1.4 μm . A possible reason for the micro-wear of the grits is that during the contact between grains and workpiece, the grinding force was gradually accumulated and led to grain fracture and bond breakage once the local load was unendurable. New grains were exposed but usually with blunt and negative cutting edges, thus inducing larger grinding force and smaller protrusion height.

4 Conclusion and future work

This paper proposed a functional surface grinding method using the laser conditioned diamond grinding wheels. The on-machine truing, dressing, and profiling of the metal bond diamond grinding wheels were achieved using the integrated nanosecond pulse laser beam. Three typical structures were machined using the laser textured diamond grinding wheels. Main conclusions and outlook for future work are summarized as follows:

- The integrated nanosecond pulse laser beam provides an effective tool for on-machine conditioning of super abrasive grinding wheels, i.e., truing, dressing, and profiling/texturing. The radial runout less than 10 μm has been achieved. Laser tangential dressing with low energy fluence can ensure the textured grinding wheel with a proper grain protrusion height (approximately 5.3 μm) for grinding.
- The surface structuring using laser conditioned grinding wheels has significant potential to generate microstructures on hard and brittle workpiece. Riblets, rectangle grooves, and pillar array have been successfully fabricated with different widths, heights, and periods.
- Macro-wear and micro-wear are the wear failure forms of the structured diamond grinding wheels during the surface structuring of ceramics. The grinding ratio of wheel was about 6.3–6.5, and a 40 μm wear of laser-shaped texture was found for the tested grinding wheels.
- The proposed methodology extends the range of application of laser beam on surface structuring. The laser machining model proposed in the present work provides a promising solution to condition the super abrasive grinding wheel with higher efficiency and flexibility in engineering practice. The laser conditioning accuracy can be further improved by optimizing the laser machining parameters and scanning path, using ultrashort pulse laser beam (less thermal damage) and a real-time synchronization of motion stage with the laser source. More patterns will be further explored on the grinding wheels according to specific requirements on surface structuring.

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Code availability The paper has no associated code.

Declarations

Ethics approval and consent to participate Research participants were not subjected to harm in any ways whatsoever. The respect for the dignity of all the research participants had been prioritized, and full consent was obtained from the participants prior to the research study.

Consent for publication The authors consent to Springer the non-exclusive publication rights and warrant that their contribution is original and that they have full power to make this grant.

Competing interests The authors declare no competing interests.

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