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Extending ultra-short pulse laser texturing over large area

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ABSTRACT

Surface texturing by Ultra-Short Pulses Laser (UPL) for industrial applications passes through the use of both fast beam scanning systems and high repetition rate, high average power P, UPL. Nevertheless unwanted thermal effects are expected when P exceeds some tens of W. An interesting strategy for a reliable heat management would consists in texturing with a low fluence values (slightly higher than the ablation threshold) and utilising a Polygon Scanner Heads delivering laser pulses with unrepeated speed.

Here we show for the first time that with relatively low fluence it is possible over stainless steel, to obtain surface texturing by utilising a 2 MHz femtosecond laser jointly with a polygonal scanner head in a relatively low fluence regime (0.11 J cm^{-2}). Different surface textures (Ripples, micro grooves and spikes) can be obtained varying the scan speed from 90 m s^{-1} to 25 m s^{-1}. In particular, spikes formation process has been shown and optimised at 25 m s^{-1} and a full morphology characterization by SEM has been carried out. Reflectance measurements with integrating sphere are presented to compare reference surface with high scan rate textures. In the best case we show a black surface with reflectance value < 5%.

1. Introduction

Surface engineering and functionalization by nano and micro structures generated upon short [1–3] and ultrashort pulse (USP) lasers irradiation, has been reported for a wide variety of materials like metals [1–6], semiconductors [7–9], polymers [10–12] and dielectrics [13,14]. In this context, Laser Induced Periodic Surface Structures (LIPSS or ripples), micro-grooves and spikes formation has been intensively studied [15–23] as it allows for tailoring some key surface properties like wettability, tribology and colour [16–18].

It has been observed that for a fixed fluence value Φ of the laser pulse, the integrated laser fluence, or surface energy dose ξ, has a crucial relevance in determining the final LIPSS morphology [10,11]. ξ depends on several parameters including the inter-pulses distance d, the offset δ between successive scan lines and the number N of successive scans over a given surface area. For instance, for a relatively low number of N, ripples characterized by a spatial periodicity smaller than the laser wavelength, are formed. Increasing N, micro-grooves appear. Finally, for a relatively large number of N, micro-spikes are uniformly induced on the surface.

Nevertheless, for the USP surface texturing process to gain an actual foothold into the industrial scene, it is crucial to increase the process throughput in order to reach a takt-time compatible with commercial purposes. A promising strategy would be to keep the values of ξ and Φ unmodified whilst increasing the scanning speed (up to several tens of m/s) and the repetition rate (in the range of MHz).

This issue may be addressed by the use of polygon scanning systems (PSS) which have been proved to be an effective tool to reliably position laser pulses with scanning speeds up to few hundreds of m/s [25,26]. Jointly with high power, high repetition rate, ps lasers, PSS have been employed for material machining processes such as patterning, engraving, structuring and texturing [25]. Nevertheless, at repetition rates ranging from few hundreds of kHz to tens of MHz, the average output power could be high enough for detrimental thermal effects to arise [26]. For instance, it has been estimated that the surface temperature in stainless steel will approach 900 °C for an average output power of about 100 W [27]. Although several laser scanning strategies have been proposed to circumvent heat accumulation and prevent undesired thermal effects [27], a sensible reduction of the energy-per-pulse J, together with the use of sub-ps laser systems, would be the leading choice for optimal USP surface texturing processes in the MHz regime.

In this context, spikes formation has been observed recently over stainless steel surface after multiple USP scanning (pulse duration 490 fs) with a fluence-per-pulse value sensibly lower (about 0.2 J/cm^2) than the ones previously reported (about 1 J/cm^2) at repetition rate up to 1 MHz and scanning speeds slightly lower than10 m/s [29]. This result opens the way to a remarkable reduc-

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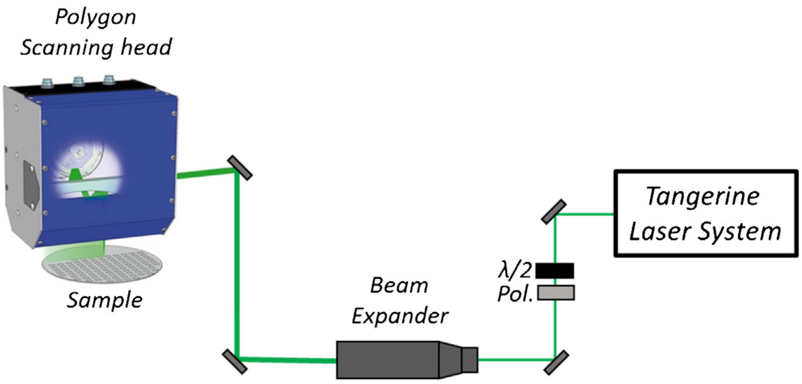

Fig. 1. Schematic view of the experimental setup. The pulse energy was controlled by the combination of half-wave plate and polarizer. The beam size was expanded of a factor 2.5 before entering the scanning head.

tion of the average power required to carry-out a large scale surface texturing with consequent benefit on the heat management.

Here for the first time, a high repetition rate (up to 2 MHz)-high average power (up to 20 W) femtoseconds laser (pulse duration < 400 fs) has been used jointly with a high speed (up to 100 m/s) polygon scanning head for texturing of stainless steel surfaces in low fluence-per-pulse regime. For a fixed value of successive over scans N, the scanning speed v has been varied over a wide range of values from $v = 90$ m/s to $v = 25$ m/s. By varying v, ripples, micro-grooves and spikes have been obtained. Furthermore, for fixed values of v and offset between scanning lines δ, we show that it is possible to control the surface blackening by varying the number N of successive scans. Our results confirm that a light trapping mechanism induced by the surface morphology is responsible for the reflectivity reduction. We believe that these results not only validate the possibility to induce surface texturing in a low fluence regime, but demonstrate that by a systematic variation of the process parameters, it is possible to obtain ripples, micro grooves and spikes with reduced average power and unprecedented scan speed values.

2. Experimental methods

Laser surface texturing tests were carried out on 316 Stainless Steel sheets (RS 559-199) with a thickness of 0.5 mm cleaned in ethanol. An IR fiber laser (emission wavelength $\lambda = 1030$ nm) delivering ultra-short pulses (pulse duration $\tau < 400$ fs) at 2 MHz repetition rate (Tangerine laser system by Amplitude Systèmes) was used for all tests. The beam was firstly magnified of a factor 2.5 and then delivered on the sample by a polygon scanning head (Next Scan Technology LSE170), which enables to scan 17 cm long lines (being 17 cm the scan field) with a scan rate varying between 100 lines/s and 400 lines/s, that is a scan speed $v = 25$ m/s and $v = 100$ m/s respectively. In our study v was varied between 25 m/s and 90 m/s. The focused laser beam spot diameter 2ω on the 316 Stainless Steel samples surface was measured to be 45 µm by means of a beam profiler (Win Cam). For every test, the energy-per-pulse J imping on the sample surface was kept constant at 1.77 µJ, corresponding to a fluence-per-pulse Φ of 0.11 J/cm^2. A schematic illustration of the experimental setup is shown in Fig. 1.

In the first set of tests, the influence of the scanning speed on the surface morphology was studied by increasing the horizontal overlapping, that is varying the spatial distance d between adjacent pulses, for a fixed value of successive scans $N = 500$. To observe the morphology evolution on a wider energy dose range, the vertical overlapping was also increased by varying the offset δ between scanning lines. This way it was possible to define the set of processing parameters, namely scanning speed and overlaps, for which defined and homogeneous spikes form on the 316 Stainless Steel sample surface. In the second set of tests, the influence of the number N of successive scans on the surface morphology and reflectivity was investigated in order to define the optimized overall process takt-time necessary to induce specific morphology changes. The process takt-time necessary to obtain homogeneous spike morphology, corresponding to complete blackening of the sample surface, was finally evaluated.

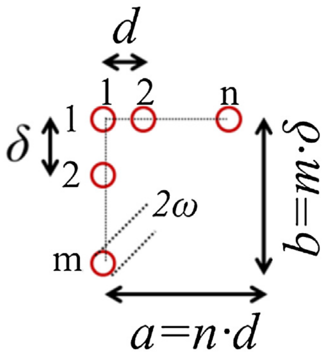

Fig. 2. Schematic illustration of the processed surface and processing parameters involved. The red circles represent the single laser spots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The textured surface was analyzed by SEM microscopy (Phantom Electronic Microscope by FEI). Finally, reflection spectra measurements in the range 350 nm–1750 nm were carried out by spectrometric analyses (Spectrophotometer Shimadzu UV 3600 plus – Reflectometer x-rite Ci6x).

3. Results and discussion

3.1. From ripples to spikes

It is well known that for a fixed fluence-per-pulse $\Phi = J/\pi\omega^2$, the cumulative laser energy dose ξ (J/cm^2) is the key physical parameter determining the surface morphology [24]. Considering for instance a rectangular surface $S = a \times b$ (Fig. 2), ξ can be expressed according to the following formula:

$$\xi = N\left(\frac{E}{S}\right) = N\left(\frac{J \times n \times m}{a \times b}\right) = N\Phi\left(\frac{\pi\omega^2}{d \times \delta}\right) \tag{1}$$

where $E = J \times n \times m$ is the total energy relative to the $(n \times m)$ pulses irradiated on S, $d = (a/n)$ the spatial distance between pulses, $\delta = (b/m)$ the offset between scanning lines and N the number of