Lasers in Manufacturing Conference 2017

Advances in Spatial Beam Shaping for Ultrafast Laser Surface Functionalization

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Abstract

Ultrashort laser pulses have many advantages for surface processing at the micrometer scale. Thanks to the low onset of thermal effects related to the short pulse duration, structuring at the micro or sub micrometric scale is readily achievable with proper processing parameters. Spatial beam shaping is a well-known technique that enables to control the laser intensity distribution, usually in a processing plane to achieve an user-defined machining on the surface. The method is frequently employed with ultrashort laser pulses to generate multiple simultaneous laser spots, thus parallelizing the machining process and reducing the processing time and cost. With the growing commercial offer of high energy and repetition rate ultrashort laser sources, spatial beam shaping associated with fast surface scanning greatly help to exploit their full potential.

In this report, we present advances in spatial beam shaping in that direction. More precisely, the intensity distribution of the ultrafast laser beam is shaped in a line using a spatial light modulator. By orientating the line perpendicular to the scanning direction, high surface scanning rates (<0.1s for 1 cm²) for generating LIPSS (laser induced periodic surface structures) on metals are reported, conferring hydrophobic properties to the surface. We also present surface micro structuring results using an annular-shaped beam.

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1. Introduction

Femtosecond laser processing of surfaces is a wide spread method to achieve surface micro and nano structuring. This permits to add specific functionalities to the surface due to the change of various physical properties subsequent to the irradiation with high potential for applications (see Nolte et al. (1997), Liu and

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Mourou (1997) and Wang et al. (2010)). The specificities of the interaction of the ultrashort laser pulses with the target material renders possible to determine some irradiation conditions with a lower onset of thermal effects compared to longer irradiation pulses. Consequently, femtosecond laser processing can be used for a wide range of materials, from metallic to dielectric substrates. With a fine tuning the irradiation conditions, some post-irradiation physical properties of the laser-irradiated surfaces can be controlled. For surface functionalization, the method can been employed in various fields of applications, i.e medical (see Chung and Mazur (2009)), biology (Dumas et al. (2015)), wettability (Bizi-Bandoki 2011)), color marking (Dusser et al. (2010)), tribology (Mourier et al. (2008), or surface ablation and cutting (see Mauclair et al. (2015)).

High processing speed, with a minimum onset of side effects in the vicinity of the irradiated region, is a challenge. Current ultrafast laser source developments towards higher processing speeds are mostly conducted by increasing the laser repetition rate and energy (Mans et al. (2014)). However, the benefits of 'pure ablation' related to ultrafast pulses is reduced as the interaction is more likely to involve thermal cumulative effects. Thus, to extent the spatial energy deposition for each laser pulse is a particularly adapted solution for higher machining paces. Spatial beam shaping based on amplitude and/or phase modulation using a spatial modulator has been developed (see Sanner et al. (2005), Mauclair et al. (2009), Campbell et al. (2007) and Hayasaki et al. (2005)). For example, the technique permits to duplicate the machining laser focus into several spots enabling parallel processing. This parallelization of the process has the advantage of reducing the processing time by a factor equal or close to the number of processing foci. This is particularly adapted to the machining of a network of micro-dimples on surface at high speed (see Saint-Pierre et al. (2016)). When the surface treatment requires a 100% coverage of the surface, a close-to uniform energy deposition can be conducted by spatially overlapping the laser spots.

In this report, we present advances in spatial beam shaping to quickly achieve a 100% surface coverage to generate LIPSS (laser induced periodic surface structures). The intensity distribution of the ultrafast laser beam is shaped in a line using a spatial light modulator. The line is orientated perpendicular to the scanning direction. That way a high scanning rate is reached (<0.1s for 1 cm²) for generating LIPSS on metals, which can add hydrophobic properties to the surface. We also present surface micro structuring results using an annular-shaped beam.

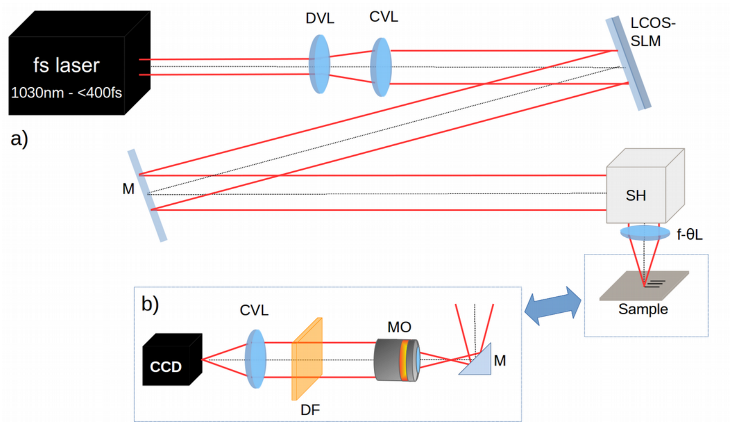

Fig. 1. Experimental set-up for (a) sample irradiation and (b) analysis of the beam shaping. DVL: Diverging Lens, CVL: Converging Lens, SLM: Spatial Light Modulator, M: Mirror, SH: Scanning Head, f θL: f-theta lens, MO: Microscope Objective, DF: Optical Density Filter.

2. Experimental set-up

The experimental set up is depicted on Fig. 1. The femtosecond laser source is a system from Amplitude (Satsuma) yielding 300 fs pulses (Full Width Half Maximum) at 1030 nm with a repetition rate up to 1 MHz. The spatial Light Modulator (SLM) is a phase-only liquid crystal component from Hamamatsu. The phase modulation mask is calculated using the well-known Iterative Fourier Transform Algorithm, except for the case of the annular beam. The total losses of whole the optical system (telescope, mirrors, SLM, scanning head, f-theta lens) from the laser output to the sample are below 30%. The f-theta lens focal length is 170 mm. It was not needed to stop the well-known zero order when performing beam shaping using electrically-addressed SLM (see Liang et al. (2012)).

The quality of spatial beam shaping is verified using a home-made beam analysis system that forms a magnified image of the beam on a CCD sensor through a microscope objective (Numerical Aperture 0.4). The output power of the laser is measured to calculate the pulse energy knowing the repetition rate. Thus, the fluence map in J/cm^2 can be easily deduced from the CCD pictures.

3. Results and discussion

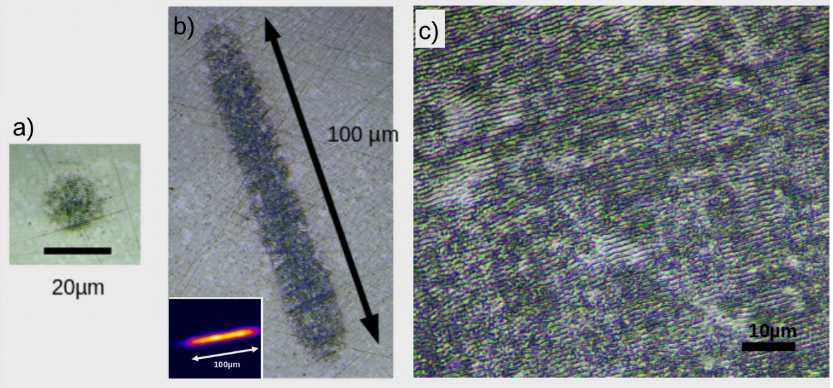

Fig. 2. Generation of LIPSS on Stainless Steel surface using ulrafast laser beam shaped in the form of a line. (a) microscopy picture of an impact on stainless steel without beam shaping showing the generation of LIPSS (Peak fluence is 0.7 J/cm^2, 5 pulses at 250 kHz). (b) Same with the line-shaped beam, same irradiation conditions, the inset shows the beam analyis. (c) Full surface treatment at 250kHz using the intensity distribution of (b) with a lateral spacing of 21 µm. The scanning is perpendicular to the line, the generation of LIPSS is observable on the microscopic picture. The method allows to use the full power of the laser source and thus to reach its maximum processing speed.

Using phase modulation, the spatial intensity distribution of the laser beam shaped in the form of a line of a length of approximately 100 µm. The phase mask (not shown) obtained from the IFTA calculation produces a similar result that can be obtained cylindrical lens. However, the possibility to dynamically change the phase mask is a strong advantage compared to the use of cylindrical lenses. Moreover, the SLM shows a high transmission and a capacity to withstand high powers (see Kaakkunen et al (2014)). The generation of LIPSS on stainless steel (316L) is shown on Fig.2 using the beam without spatial modulation (Fig.2a) and the line-shaped beam (Fig. 2b)). Both cases are obtained with the same peak fluence of 0.7 J/cm^2.

Applying the line-shaped intensity distribution, a scanning of the surface is performed perpendicularly to the line with a spacing of 21 µm at 250kHz. This corresponds to a scanning speed of 5 m/s under the 170 mm focal length lens. 5 passages are necessary to produce the regular LIPSS, yielding a treatment speed below 0.1 s for 1 cm^2.

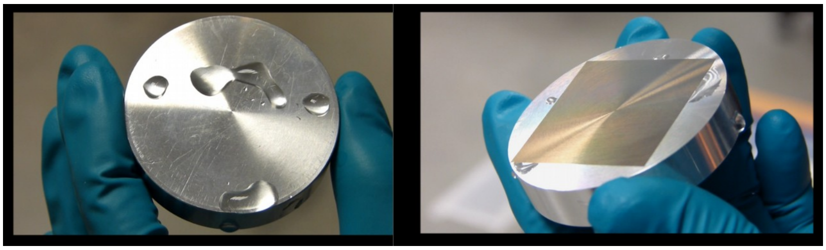

Fig. 3. Illustration of wettability behavior on Aluminium. (left) Sample without laser treatment showing a mostly hydrophylic behavior with distilled water drops. (right) Sample with a squared surface having LIPSS where no water drops can be deposited and thus illustrating a strong hydrophobicity.

As an illustration, distilled water drops were deposited on an Aluminum sample with and without laser structuring as depicted on Fig. 3. The LIPSS turn the surface from hydrophilic to hydrophobic. A detailed wettability study depending on the surface topology, chemistry, liquid and so on is outside the scope of this paper, but can be found in our previous work (Bizi-Bandoki et al, 2014) and the work of several research teams.

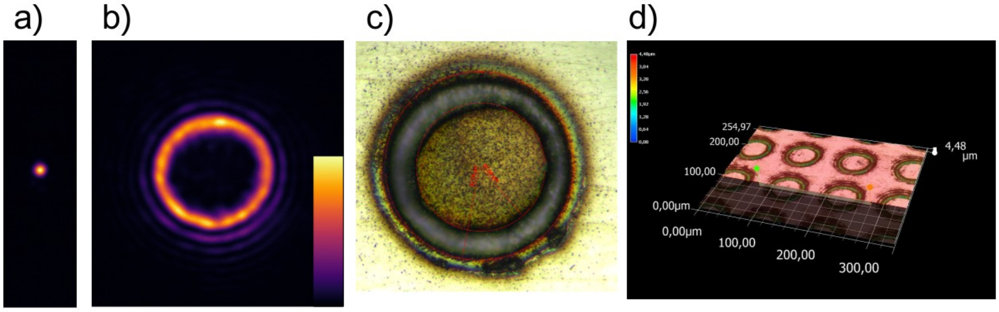

Fig. 4. Annular beam shaping for surface machining of stainless steel. (a) Original Gaussian intensity distribution. (b) Annular-shaped intensity distribution with a radius of 27 µm. (c) and (d) Optical microscopy picture and profilometry showing an annular machining of 1 µm depth and 27 µm radius with 30 pulses with a peak fluence of 1 J/cm^2.

Another type of spatial beam shaping is shown in Fig.4. There, a phase modulation following a vortex (not shown) is employed. The phase incongruity that is position in the center of the beam generates an annular beam distribution all along the beam propagation, also in the focal plane (see Heckenberg et al, 1992). Fig. 4 shows the original Gaussian beam distribution (Fig. 4a)) and the annular beam beam distribution (Fig. 4b)). Surface processing with such a beam can have many advantages to produce annular shapes, and also for drilling larger holes without beam displacement, thus reducing the processing time and complexity. Also, annular shapes can be employed to fabricate hierarchical surfaces, for example with an additional machining to generate LIPSS. Fig 4 c) and d) shows optical microscopy pictures and topology measurement of machined stainless steel surface, respectively. These structures were obtained with 30 pulses having a peak fluence of 1 J/cm^2. The annular-shaped micro dimples have a uniform depth of 1 µm and the same radius of the beam.

4. Conclusion

We have presented advances in spatial beam shaping to accelerate surface processing with ultrashort laser pulses. Using a spatial light modulator, the spatial distribution of the ultrafast laser beam can be shaped in the form of a line. Using a high speed scanning mirror, high surface laser treatment rates (<0.1s for 1 cm^2) for generating LIPSS can be achieved, by scanning in a direction perpendicular to the line. As an illustration, LIPSS were produced to add hydrophobic properties on an Aluminum surface. Surface micro structuring results on stainless steel using an annular-shaped beam are also reported.

Acknowledgements

The financial support of ANR Equipex Manutech-USD (ANR-10-EQPX-36-01) and ANR (ANR-13-RMNP-0010) Topoinjection are gratefully acknowledged. We thank Alina Hamri for the illustration of hydrophobicity.

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