Fast parallel diffractive multi-beam femtosecond laser surface micro-structuring

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Abstract

Fast parallel femtosecond laser surface micro-structuring is demonstrated using a spatial light modulator (SLM). The Gratings and Lenses algorithm, which is simple and computationally fast, is used to calculate computer generated holograms (CGHs) producing diffractive multiple beams for the parallel processing. The results show that the finite laser bandwidth can significantly alter the intensity distribution of diffracted beams at higher angles resulting in elongated hole shapes. In addition, by synchronisation of applied CGHs and the scanning system, true 3D micro-structures are created on Ti6Al4V.

1. Introduction

During the last decade, femtosecond and picosecond lasers, where the pulse width \( t < 10 \text{ ps} \), have been employed to obtain high precision surface micro-structuring of materials such as metals and semi-conductors with little thermal damage due to the ultrashort timescale on which energy is coupled to the electronic system [1–5]. In metals, when the input fluence, \( F \), is kept in the low regime, a few times above the ablation threshold (\( F \sim 1 \text{ J cm}^{-2} \)), heat diffusion during the temporal ultrashort pulse width can be reduced to the nanometer scale, comparable to the optical skin depth [6–8]. Accordingly, the pulse energy used in ultrafast laser processing is often kept to the \( \mu \text{J} \) level for fine micro/nano-surface structuring due to the low and well-defined ablation thresholds. Consequently, high gain regenerative amplifier systems running at repetition rate, \( v \sim 1 \text{ kHz} \), providing mJ level output pulse energy have to be attenuated severely, thus limiting the useful throughput.

The use of multiple parallel beams is a novel method to increase throughput and efficiency of femtosecond laser processing. Periodic multiple beams patterning can be obtained by multiple-beam interference [9–12], while, by applying dynamic diffractive optical elements (e.g. spatial light modulator (SLM)), arbitrary beam patterns have been generated that are capable of flexible and variable patterning [13–16].

Following Hayasaki et al. [13,20,21], the unwanted zero order reflection from the SLM, which previously led to undesirable surface damage [16], is successfully blocked at the Fourier plane of a telescope system. In particular, an important limitation of the finite laser bandwidth leads to significant distortion of the intensity distribution of diffracted beams resulting in elongated hole shapes, in accord with simple theory. With this limitation in mind, true 3D micro-structures on Ti6Al4V fabricated by synchronisation of real time holograms with scanning have been illustrated.

2. Experimental

The experimental setup is shown in Fig. 1. The output from a femtosecond laser system (Clarke-MXR CPA2010, with 160 fs pulse width, 775 nm central wavelength, 1 mJ pulse energy and 1 kHz repetition rate) was attenuated by a half wave-plate and a Glan laser polariser. After reflection on mirrors 1 and 2, the laser illuminated a reflective SLM liquid crystal on silicon (LCOS) device with 1024 \( \times \) 768 pixels (Holoeye LC-2500), oriented at \(< 10^\circ\) angle of incidence. A beam expanding telescope, with magnification \( M \approx 2 \) was used to reduce the average intensity on the SLM, where the computer generated holograms (CGHs) were displayed. Appropriate holograms required to create arbitrary multi-beam patterns at the substrate surface were generated via an interactive
LabVIEW program using a number of algorithms to calculate the CGHs [18]. The input optical beam was represented by a complex field, \( u_0 = a \exp(i \phi_0) \), and the SLM displayed a phase hologram, \( t = \exp(i \psi_0) \). Accordingly, after reflecting on the SLM (at A in Fig. 1), the beam was modulated to be \( u_h = a \exp[i(\phi_0 + \psi_0)] \). Lens 1 and 2 were two AR coated BK7 plano-convex lenses with 50.8 mm diameter and 300 mm focal length. Referring to Fig. 1, since distance \( AB = BP = PM + MC = CN + ND = f (\sim 300 \text{ mm}) \), a 4f optical system with unity magnification was formed. Accordingly, at D, the complex field was identical with that at A. The zero order reflected beam was spatially separated and blocked at Q (Fig. 2).

Just after D, the modulated beam \( u_h \) entered the 10 mm aperture of a scanning galvo system with a flat field lens (\( f = 100 \text{ mm} \)). The proximity of the beam \( u_h \) (at D) to the input aperture of the galvo ensured that diffracted beams where transmitted cleanly to the substrate surface, while the flat field of the f-theta lens produced a near perfect focusing system. Substrates were mounted on a precision 4-axis (x, y, z, \( \theta \)) motion control system (Aerotech) allowing accurate positioning of the substrate surface at the laser focus.

### 3. Results and discussion

The Gratings and Lenses algorithm [17,18,22], which is simple and computationally fast, was used to calculate computer generated holograms producing multiple independent diffractive +1 order beams for processing.

The undiffracted zero order beam containing approximately 50% of the input pulse energy was blocked by a metallic target at position Q (Fig. 3). This method used to block zero order in femtosecond laser processing was first adopted by Hayasaki et al. [13,20,21]. Referring to Fig. 3, the digital camera images show the holographically produced energy distribution of ‘LLEC’ pattern on a paper screen near the Fourier plane. The +1 order beams contain the majority of the diffractive energy because the CGH was designed to enhance them, while –1 order beams with much lower energy (\( \lesssim \) material’s ablation threshold) leave the substrate unaffected.

Fig. 4 shows optical micrographs of surface structuring on silicon with an ‘LLEC’ pattern comprising 32 blind holes and a random spot pattern comprising 30 holes. The incident pulse energy on the SLM was \( E_p = \sim 300 \mu \text{j} \). The lower two pictures of
Fig. 4 demonstrate the absence of large holes showing that the zero order beams have been successfully removed. Excellent uniformity of the diffractive spots ('LLEC' pattern: \( \Phi_1 = 20.3 \pm 1.2 \mu m \), random spots pattern: \( \Phi_2 = 21.7 \pm 1.1 \mu m \)) indicates the accurate calculation of the CGHs using the Grating and Lenses algorithm.

A significant increase in eccentricity when applying a larger diffractive angle, probably due to the lateral chromatic aberration caused by the finite bandwidth (\( \Delta \lambda \)) of the laser source [15,19], was found previously [16]. To further investigate this phenomenon, holes were fabricated on silicon by the +1 order beams with varying angle of diffraction (Fig. 5). Referring to Fig. 5(a), the results show that the long axis of the elliptically fabricated structure was slightly tilted away from the direction towards the zero order beam instead of aligning with the axis. This may be explained by
micro-machining, in this case, at a significant distance from the centre of the flat field of the f-theta lens, where the slight astigmatism of the femtosecond beam becomes apparent if the focus wanders away from the true f-theta plane. The combination of this minor effect and the primary effect of chromatic dispersion has probably led to a rotation of the long axis. Secondly, the ablation debris on the surface is deposited non-uniformly, aligning along the short axis of the ellipse, which is due to an asymmetric expansion of the plasma following ablation, driven by the much higher intensity gradient along the short axis.

By taking greater care with regard to the SLM alignment in the optical line and positioning the zero order close to the centre of the f-theta lens field, improved results demonstrate that the long axis of the elliptically fabricated structure is indeed aligned to the direction toward the zero order beam (Fig. 5(b)). In this case, the debris was easily removed with methanol and a lens tissue.

The bandwidth limitation, mentioned above, is a characteristic of all diffractive optics when used with a broadband source (in this case, \( \Delta \lambda \sim 5 \text{ nm} \)). Based on the grating equation, \( \Lambda (\sin \theta_i + \sin \theta_i') = m \lambda_i \), where \( \Lambda \) is the grating period and \( m \) is order of diffraction, the expected graph of eccentricity \( e \) versus diffractive angle can be used to predict the drilled hole shape. Here, the incident angle \( \theta_i \) on the SLM is \(<10^\circ\), and +1 order \((m = 1)\) diffractive angle \( \theta_1 \) is \(<2^\circ\), hence \( \sin \theta_1 \sim \theta_1 \). The grating equation can be simplified to: \( \theta_1 \sim \sin \theta_1 = \lambda_i / \Lambda \) (where \( \Lambda \) is the grating period), hence by differentiating, the following is obtained:

\[
\frac{\Delta \theta_1}{\Delta \lambda} = \frac{1}{\Lambda} \quad \text{or} \quad \Delta \theta_1 = \frac{\Delta \lambda}{\Lambda}
\]  

The graph of experimental and calculated eccentricity \( a/b \) of machined holes versus angle of diffraction showing excellent agreement. Eccentricity grows linearly with angle of the diffraction.

Fig. 6. Graph of experimental and calculated eccentricity \( a/b \) of machined holes versus angle of diffraction showing excellent agreement. Eccentricity grows linearly with angle of the diffraction.

Fig. 7. A comparison of ablation depth on Ti6Al4V with angle of diffraction and pulse number, showing that the ablation depth drops at higher angles due to increasing distortion of the intensity profile.

Fig. 5. (a) Observed growing eccentricity of micro-machined holes on silicon substrate with increasing diffractive angle of +1 orders, showing a slight tilt of the major axis. The ablation debris is deposited non-uniformly due to the asymmetric expansion of the plasma. The zero order is marked. (b) Improved result over (a) in which the major axis of the elliptical structures aligns to the zero order. The debris has been simply removed using methanol.
If \( f \) is the focal length of the f-theta lens, the elongation \( \Delta l \) caused by \( \Delta \lambda \) at the focal plane is then

\[
\Delta l = f \Delta \theta_1 = \frac{f}{2} \Delta \lambda
\]

while the diameter of the focused spot can be calculated by

\[
2\alpha_0 = \frac{4M^2 f \lambda}{\pi D}
\]

where \( D \) is the raw beam (spot) diameter and \( M^2 \sim 1 \) is the beam quality factor. Thus, the eccentricity, \( e \) at a given diffractive angle can be calculated by \( e = a/b = (\Delta l + 2\alpha_0)/2\alpha_0 \). The graph shown in Fig. 6 indicates excellent agreement between the experimental and calculated eccentricity \( e \) which increases linearly when varying the angle of diffraction.

The distorted intensity profile at higher angles of diffraction also affects ablation (Fig. 7) which shows a comparison of measured ablation depth on Ti6Al4V with angle of diffraction and pulse number. In each case, pulse energy was \( E_p \sim 5 \mu J \) and ablation depth decreased with increasing angle of diffraction due to the growing ellipticity of beam shape. Accordingly, to ensure precision femtosecond processing with a 5 nm bandwidth (at \( \lambda = 775 \text{ nm} \)), the diffractive angle should be limited to \( \theta_1 < 0.5^\circ \).

A pattern 'OPTICS' (in Chinese and English) comprising 129 holes processed on a Ti6Al4V substrate using 7 CGHs combined with the galvo scanner is shown in Fig. 8(a), while Fig. 8(b) shows the pattern with zero order removed. Incident pulse energy on the SLM was \( E_p \sim 150 \mu J \), and the measured hole diameter (\( \Phi \sim 25 \mu m \)) and depth (\( \sim 2.3 \mu m \)) corresponds to an exposure time of 200 ms (i.e. 200 pulses), with pulse energy \( E_p \sim 5 \mu J \) in each +1 diffracted order beam. Each CGH generated more than 15 higher order holes simultaneously, a throughput gain of factor >15 was demonstrated compared to single beam processing in this case.

Fig. 9(a) illustrates the design of a \( 10 \times 4 \) hole array pattern formed by four asymmetric patterns to keep the uniformity of the +1 order beams [22], and Fig. 9(b) shows its processing results on Ti6Al4V with incident pulse energy, \( E_p \sim 100 \mu J \) on the SLM. The holes were reasonably uniform (\( \Phi = 25.3 \pm 1.6 \mu m \)) and round (maximum eccentricity \( a/b < 1.5 \)). Fig. 9(c) shows this pattern repeated using the scanning galvo hence increasing the processing area. By using the patterns created by the offset holograms of Fig. 9(a), while scanning with the galvo, a 3D chessboard type structure was

![Fig. 8.](image-url)
created in real time by scanning 200 μm × 200 μm squares (10 μm offsets, 10 mm/s) and varying numbers of overscans (n). Here, CGH1 and 2 were applied with n₁ = 50, generating a 5 μm deep structure (d₁); while, CGH3 and 5 were applied with n₂ = 10, creating shallower structures with d₂ ~ 1 μm (Fig. 9(d) and (e)).

4. Conclusions

Highly parallel femtosecond laser surface micro-structuring is demonstrated with the aid of a SLM using the “Gratings and Lenses” algorithm to create computationally fast and accurate...
CGHs. The undiffracted zero order beam is eliminated at the Fourier plane of a 4f optical system. The finite laser bandwidth is shown to significantly alter the intensity distribution of diffracted beams at higher angles resulting in elongated hole shapes and confirmed by a simple calculation using the grating equation. By applying CGHs in real time while synchronising the scanning galvo movement, true 3D precision surface micro-structuring is demonstrated, with potential industrial applications.

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References