Surface integrity optimisation in ps-laser milling of advanced engineering materials

D.M. Karnakis [1], MRH Knowles [1]
P. V.Petkov [2], T. Dobrev [2] and S. S. Dimov [2]

[1] Oxford Lasers Ltd., Unit 8, Moorbrook Park, Didcot, Oxfordshire OX11 7HP UK
[2] MEC, Cardiff University, Newport Road, Cardiff, CF24 3AA, UK
dimitris.karnakis@oxfordlasers.com

Abstract

We report on 2.5D laser micromilling of advanced engineering materials, commonly used in micro-manufacturing, utilising a high power high repetition rate fully diode-pumped picosecond laser at 355nm. Surface morphology changes induced by the 8ps (FWHM) laser pulses on stainless steel, alumina and fused silica were examined using SEM microscopy and white light interferometry. Surface topology information was correlated to incident power density in order to identify an optimum processing window for high surface integrity micromachining. It was found that surface roughness usually deteriorates with increasing power density regardless of material. However, with careful optimisation certain laser irradiation conditions can result in significant improvements of surface finish - a key factor in broadening the use of laser milling for micro structuring.

Keywords: Picosecond laser milling, stainless steel, alumina, fused silica, surface roughness

1 Introduction

Laser micromilling has become an enabling technology for device microfabrication in many industrial applications [1]. Pulsed lasers of μs- and ns-pulse width are already used satisfactorily [2] providing adequate processing speed and surface finish for mid-scale feature sizes. However, the increasing demand for component miniaturisation renders these lasers unsuitable for high quality work mainly due to the thermal nature of interaction with materials which contributes to poor feature morphology (periodic surface structures, melt, surface swelling). Ultrafast lasers (ps & fs) are of great practical importance in that sense as they minimise or eradicate completely the formation of such undesirable features. Commercial ultrafast lasers are available and although they have not been widely used in industrials applications, mainly restricted by low output power, they are starting to make a breakthrough [3].

Picosecond lasers with their short thermal penetration depths and high repetition rates provide a good compromise [4] as they can achieve high throughput and more significantly they restrict detrimental effects from high thermal load and large temperature gradients on the material. In this paper we will present an experimental investigation of ps-laser milling of commonly encountered industrial materials such as metals, ceramics and glasses with the aim to empirically determine an optimum range of ps-laser irradiation conditions that maintain high surface integrity.

2 Experimental

An Oxford Lasers 12-axis Picolase 1000 laser micromachining system was used for this work recently installed at MEC, Cardiff University. Samples of stainless steel, alumina ceramic and fused silica were cleaned in alcohol prior to laser irradiation. The 355nm harmonic output was used from a mode-locked Nd:YVO_4 amplifier (LUMERA Laser GmbH) with FWHM pulse width of the order ~8ps. The laser is described in more detail in Table 1 below. The laser exhibited a Gaussian spatial intensity profile and was focussed on the target surface via a high NA objective of focal length f=20mm or a dual head galvanometer scanner head (Nutfield XLR8, 10mm aperture) equipped with a flat-field lens (f=100mm) for each beamline. The laser was operated at fixed frequency of 10kHz with a special pulse-on-demand option and an x-y table carrying the samples was synchronised to the laser frequency to generate the desirable features. An Oxford Lasers auto trepanning head (ATH-2) was inserted prior to the objective lens to rotate the laser beam accordingly in the laser microdrilling setup. The surface morphology of the resulting features was investigated by SEM and a MicroXAM surface mapping microscope.

Table 1 Laser characteristics

Laser Model	LUMERA Super Rapid
Wavelength (nm)	355
Max.Power@250kHz (W)	2.9
Max.Pulse E @250kHz (μJ)	30
Rep.Rate Range (kHz)	0-640
Pulse Width FWHM (ps)	8
M^2	1.1

3 Results and Discussion

Figure 1 shows a typical example of laser-milled fused silica using 355nm picosecond laser pulses. The focussed incident laser power was kept low at 30 mW with a repetition frequency of 10 kHz. With a tightly focussed spot size of ~ 2 μm this resulted in an average fluence of 78 J/cm^2. The sample was translated underneath the beam at constant velocity of 1 mm/s using a rastering pattern with hatching (stepover) distance of 5μm.

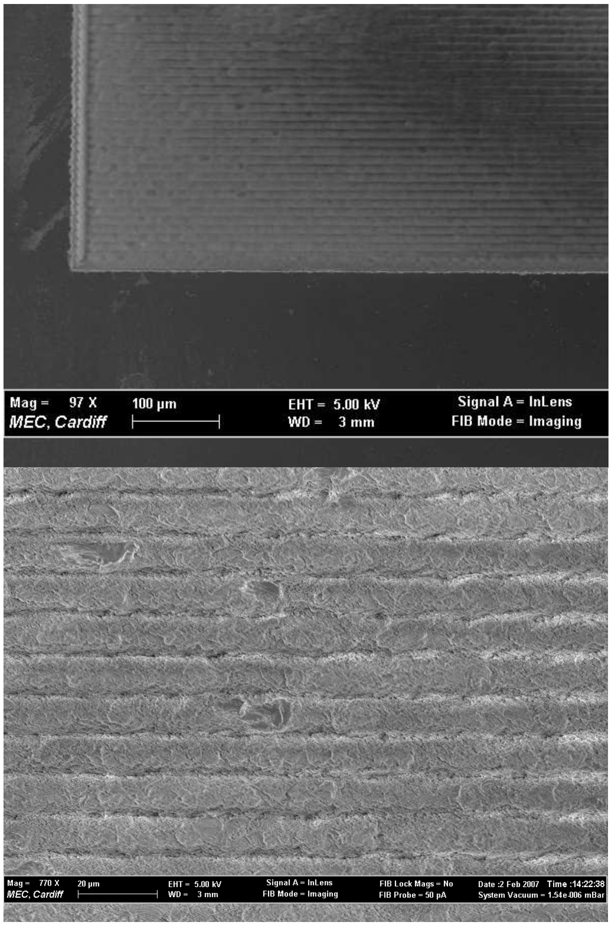
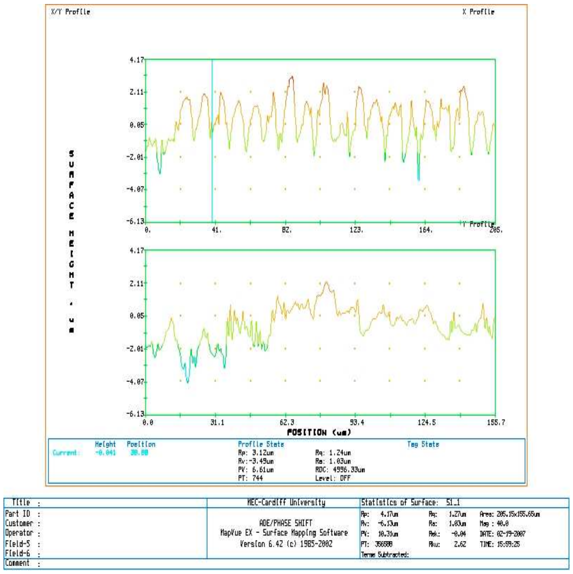


Fig.1. *SEM micrographs of ps 355nm laser milled fused silica using 30mW at 10 kHz (FWHM= 8ps). The hatching stepover distance was set to 5μm. Bottom: Detailed view of the milled floor.*



Height Position
Current: -0.041 30.00

Profile State
Rp: 3.12um
Rv: -3.49um
PV: 6.61um
PT: 744
Rq: 1.24um
Ra: 1.03um
RDC: 4996.33um
Level: OFF

Tag State

Title :
Part ID :
Customer :
Operator :
Field-5 :
Field-6 :
Comment :

MEC-Cardiff University
ADE/PHASE SHIFT
MapVue EX - Surface Mapping Software
Version 6.42 (c) 1985-2002

Statistics of Surface: 51_1
Rp: 4.17um
Rv: -6.13um
PV: 10.31um
PT: 356580
Rq: 1.27um
Ra: 1.03um
Rsk: -0.04
Rku: 2.62
Area: 205.15x155.65um
Mag : 40.0
DATE: 02-19-2007
TIME: 15:59:25
Terms Subtracted:

Fig.2. *MicroXAM surface roughness profile of the laser milled floor in Fig.1. The average Ra value was measured to be 1.03μm*

The laser milled floor surface was measured to have an average surface roughness of Ra 1μm following three overlapping repeat passes (Fig.2). Although this is higher than the corresponding value for unirradiated fused silica (Ra~ 20nm), as expected, it is considered fairly satisfactory compared to previous results using longer laser pulses. Preliminary measurements of the milled floor surface roughness as a function of incident laser power for 3 and 5μm raster pitch are plotted in Figure 3. It is shown that in both cases reducing laser power results in a decline of Ra reaching values as low as 0.6μm. Also the shorter raster pitch, which corresponds to a higher number of laser pulses per unit area, results by and large in lower surface roughness.

Figure 4 shows an image of laser-milled stainless steel using similar irradiation conditions to those used for fused silica in Fig.1.

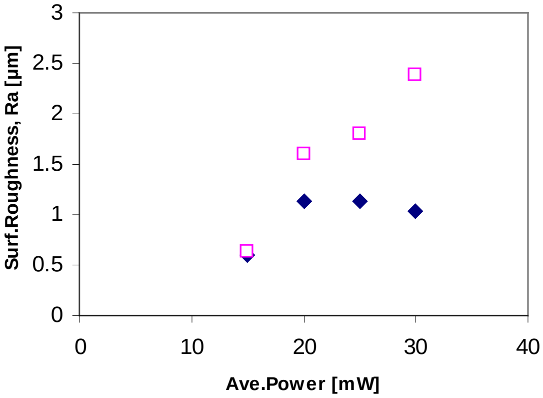


Fig.3. *Average surface roughness v incident laser power for 355nm irradiated fused silica. Rastering stepover, open sq: 3μm, solid diamond: 5μm*

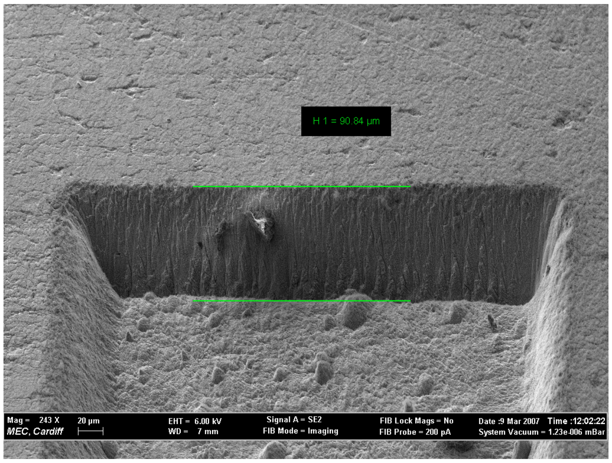


Fig.4. *SEM micrographs of ps 355nm laser milled s.steel using 35mW at 10 kHz (FWHM= 8ps). Rastering stepover distance: 5µm*

There is a marked difference between the surface morphology of the materials with the metal exhibiting stronger signs of a thermal process during laser milling. Redeposited molten material is clearly visible on the walls and floor of the cavity with edge burr also present, all of which spoil overall surface quality. This is not surprising as metals are expected to absorb strongly at this wavelength and laser ablation starts at much lower laser fluence comparing to fused silica.

The average surface roughness measured as a function of the incident laser power is plotted in Figure 5. The etched depth of the milled cavity is also plotted on the same graph. It is noted that the surface roughness initially decreases with increasing laser power reaching a minimum value of ~0.8µm around 35mW but then sharply increases again. It is not yet clear why this happens but similar observations have been made before in laser milling of metals with other lasers. This result clearly demonstrates that for a given raster pitch an optimum laser power exists where minimum surface roughness can be obtained.

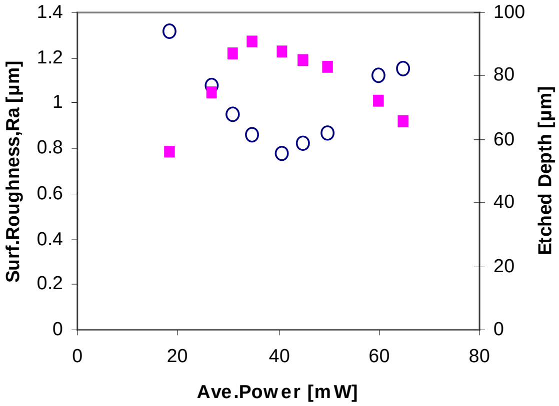


Fig.5. *355nm ps laser milled stainless steel. Average surface roughness (open circles) and milled depth (solid sq.) v incident laser power. Laser rep.rate: 10 kHz. Rastering stepover distance: 5µm*

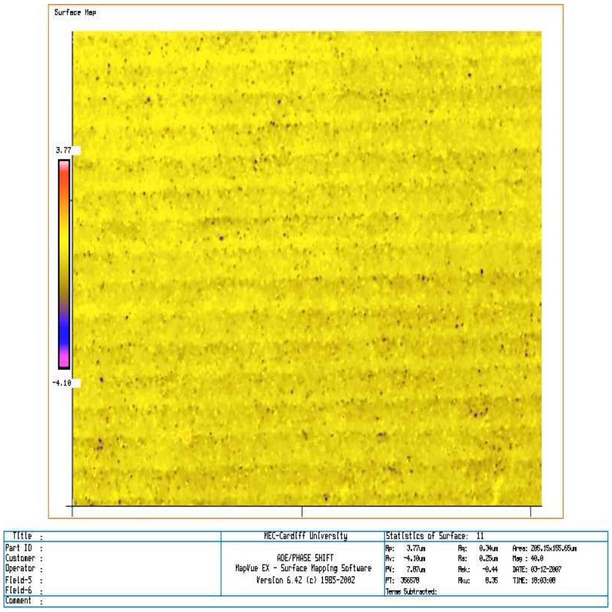


Fig.6. *Surface map of the ps-laser milled floor in alumina. The surface roughness Ra was only 0.25µm*

Figure 6 shows a surface mapping image of a ps-laser milled cavity floor in alumina ceramic. The incident laser power was only 7.5 mW at 10 kHz resulting in average laser fluence of ~20 J/cm^2. The sample was milled using velocity of 1 mm/s and a raster pattern with stepover distance of 5µm. The resulting floor smoothness is remarkably low at Ra of only 0.25 µm.

The average floor surface roughness is plotted as a function of incident average power in Figure 7. The cavity etched depth is also shown in the same graph. The laser repetition rate was kept at 10 kHz and the samples were cleaned prior to measuring. The average surface roughness Ra starts from a low value of 0.25µm and increases rapidly to 1.2 µm. It then shows a steady decline with power until about 35 mW and

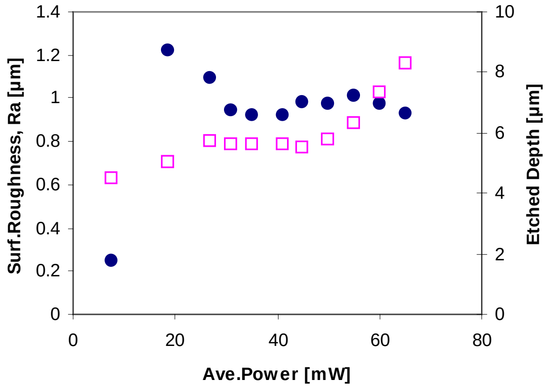


Fig.7. *355nm ps laser-milled alumina. Average surface roughness (solid circles) and milled depth (open sq.) v incident laser power. Laser rep.rate: 10 kHz. Rastering stepover distance: 5µm*

thereafter it remains almost steady at about 1 μm within the measured power range of 10-65 mW. The associated etched depth of the milled cavity was ranging between 4-8.5 μm following five repeat passes.

In the absence of a detailed study, a full explanation of the observed effects cannot be considered. We are looking for optimum irradiation conditions that will minimise or suppress the melt flow and result in high surface integrity. Because the ablation mechanism varies from material to material affecting the melt thickness and lifetime we should expect significant variations in surface morphology between metals, ceramics and glasses when using similar irradiation conditions. Some theoretical efforts have focused in the past in thermocapillary mechanisms to describe laser induced surface roughness [6]. These developed certain criteria for clean processing that associate surface roughness to the temperature dependent viscosity of the melt within the framework of surface or volume heating mechanisms.

Ultrashort-pulsed laser ablation is mostly driven by explosive mechanisms and hydrodynamic effects usually responsible for lateral melt expulsion around the irradiated spot are probably playing less of a role. The explosive character of ablation must be the main reason why although very high intensities are used, with presumably very high associated transient temperatures, there is still very little evidence of melt debris. Large associated stresses expel violently most of the hot energetic ablation products with little accompanying lateral heat flow. The high laser fluences used here as well as laser-induced plasma heating could contribute to surface melting as evidenced mostly in the milled metal case. At 8ps completely melt free processing of metals should be impossible [7] as shown in Fig.4. Lowering the laser fluence can minimise the melt layer thickness and also reduce the vapour pressure to low enough levels insufficient to induce melt expulsion. Additionally the rapid relaxation of the low viscosity melt might contribute to surface smoothing. Even lower values of surface roughness to those reported here should not be surprising if laser fluences closer to the ablation threshold were used. This trend is seen in the alumina case where for a lower fluence of 20 J/cm^2 the surface roughness is very low.

Given fused silica is totally transparent at 355nm, laser milling must proceed via a defect related or non-linear absorption mechanism. After the initiation of laser ablation strong absorption ensures controlled laser milling with remarkably good edge definition, lack of burr and seemingly complete lack of cracking despite the intense thermal cycling experienced in the material. Crack growth is possibly inhibited by strain frozen in a swallow surface layer due to short optical and thermal penetration depths, quite plausible given the non-linear interaction of the ps-laser with fused silica.

Fig.8. *Oxford Lasers PicoLase 1000 picosecond laser micromachining system installed at MEC, Cardiff University*

Future experiments will investigate surface roughness in more detail at much lower fluence levels for all above examined materials aiming to optimise further surface finish quality in ps-laser milling.

4 Picolase 1000- New machine tool for high-speed laser micromilling

Oxford Lasers has specifically developed the PicoLase 1000 (Fig.8), a dedicated 12-axis station for ps-laser micromilling. The tool utilises the advantages of the latest DPSS ps-laser technology and incorporates advanced optical techniques to deliver the laser beam on target via a dual beamline (532 and 355nm).

It consists of a stable base with granite supported x-y-rho-theta table to position the substrate and uses an overhead gantry housing the laser, beam delivery optics and moving optical assembly. 2.5D laser milling is possible via specialist 3D CAM software that allows vertical wall machining in blind features. The tool is also capable of producing sub- μm features in thick substrates (up to 2mm thickness) with true accuracy of better than 2μm. A range of processing strategies can be employed resulting in high quality micromachining of metals, ceramics, semiconductors, polymers and glass at high processing speeds.

5 Conclusions

We have demonstrated that high quality laser milling can be achieved in metals, ceramics and fused silica using high repetition picosecond lasers. Careful optimisation allows for sub-μm surface roughness distinctly advantageous comparing to ns- or longer pulsed lasers.

Acknowledgement

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