Recent Advances in Ultrafast Laser Micromachining Systems for Material Micromanufacturing

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Abstract

A fully integrated 12-axis ultrafast laser micromachining system has been developed for advanced micromanufacturing. This is a highly sophisticated dual-head fully diode-pumped picosecond Nd:YVO_4 laser fabrication tool operating at 532 and 355nm, currently offering the highest output average power with output frequency ranging up to 640 kHz. It is designed to harness the benefits of ultrafast laser technology for manufacturing micro-components with emphasis on both high precision and high processing speed, achieving order of magnitude higher removal rates comparing to femtosecond laser technology. This paper describes the system concept and key features including advanced pulse output control, optical train with integrated auto trepanning head and galvanometric scanning heads, in-situ surface profiling diagnostics and also fully automated CAM software for five-axis toolpath generation. Excellent performance for micro-manufacturing is demonstrated with impressive results achieved in different industrial materials.

1 Introduction

Laser micro-machining exploits the ability of laser to direct a controlled amount of energy at a very small, well defined region of a material and in doing so “ablate” very small quantities from that region in order to drill, cut pattern, or mill out a microscopic feature. The duration of each incident laser pulse, τ is of great practical importance as it determines the penetration depth of the deposited heat on the material surface and hence largely controls the physical process of laser ablation. By and large for commonly available industrial lasers of nanosecond pulse duration and longer, this depth is proportional to the square root $\tau^{0.5}$ of the pulse duration and ranges typically between 10^{-2}–10μm depending on material. For many years this factor was presenting limitations to high quality micromachining with frequent encounters of poor feature morphology such as melt dross, surface swelling, etc. Ultrafast laser micromachining (femtosecond or picosecond) on the contrary uses a special class of short-pulsed lasers that has gradually emerged in the last decade as a robust alternative and has become an enabling technology for micromanufacturing in many industrial applications [1]. These lasers, minimise or eradicate completely the formation of such undesirable features and restrict significantly detrimental effects from high thermal load mainly due to their short optical and thermal penetration depths. They are progressively available with higher output power and high pulse repetition rate, especially in the picosecond timescale [2] and as will be discussed in this paper, that makes them an attractive laser source for high quality material micromanufacturing providing high precision as well as high throughput.

2 System Description

Oxford Lasers has recently installed the Picolase at the MEC Cardiff, a unique 12-axis ultrafast laser micromachining system which presents the state of art in this sector. It is based around a dual wavelength picosecond Nd:vanadate mode-locked fully diode-pumped solid-state laser with further stage amplification. The system is designed specifically for 2.5D laser micromachining and is virtually capable of machining any material.

Figure 1 Oxford Lasers PicoLase 1000 picosecond laser micromachining system installed at MEC, Cardiff University

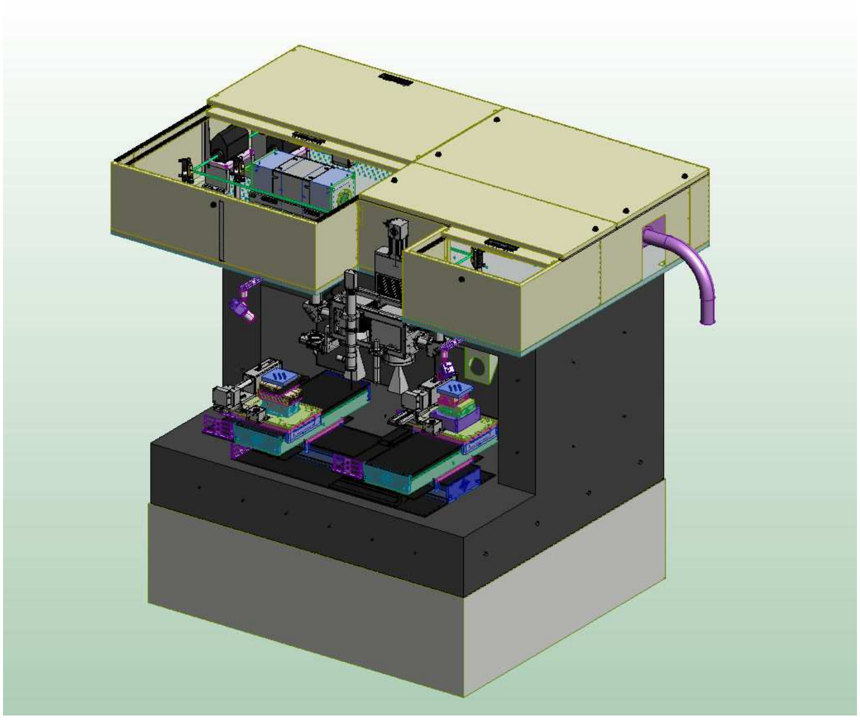


Figure 2 PicoLase 1000 system architecture. The optics box containing the ps-laser and beam delivery components is mounted on a granite based platform which also houses the 12 axis CNC assembly

The system is built on a granite gantry platform supported by special base with vibration isolation. The laser and beam delivery optics are enclosed in an optics box mounted on top of the gantry. Motion control is achieved using a 12-axis CNC assembly (8 physical & 4 optical axis) containing two dual axis galvanometer scanner heads mounted on a vertical motorised stage and controlled via a sophisticated 32 axis control interface. The system uses an Oxford Lasers auto trepanning head for hole drilling operations. There is also a suite of diagnostics with machine vision for part alignment and metrology equipment for sample feature measurements and surveillance cameras for remote monitoring of the laser machining process. The entire system including the services and controls is enclosed by a specially designed enclosure with dimensions 3500x2000x2250 mm.

1.1 Picosecond Laser

The laser source included in the Picolase is the LUMERA super RAPID. It is a state of the art industrial picosecond laser generating maximum output of 10W at 1064nm in 10ps pulses with a freely selectable pulse rate as high as 640 kHz and pulse energies up to 40 μJ. It consists of a passively mode-locked oscillator, a fast electro-optical pulse picker, laser amplifiers and a second and third harmonic generator all integrated in one box. The laser head is a rugged monolithic aluminium structure and is actively temperature controlled enhancing the laser reliability and power stability. The nominal maximum laser output at the higher harmonics is 4.5W (532nm) and 2.5W (355nm) with software controlled laser attenuation. The maximum output power for this system is plotted in Figure 3 as a function of pulse repetition frequency for all three wavelengths. An advanced fast electro-optical pulse picker provides a choice of different pulse patterns which can be externally triggered. This feature allows user selected single pulse output or groups of pulses to be repeated with variable delay thus enabling burst laser micromachining. The excellent beam quality ($M^2<1.2$) allows for tight focusing of the beam, reaching peak power densities in the TW/cm² range and so enabling micromachining of virtually any material.

Table 1: Super RAPID laser characteristics

LASER PROPERTIES	SHG	THG
Wavelength (nm)	532	355
Repetition Rate (kHz)	0-640	0-640
Average Power@250kHz (W)	4.8	2.9
Max.Pulse E @250kHz (μJ)	19.3	11.6
Pulse Width FWHM (ps)	9	8.5
Pulse energy stability	<1% RMS	<1% RMS
M^2	<1.2	<1.2

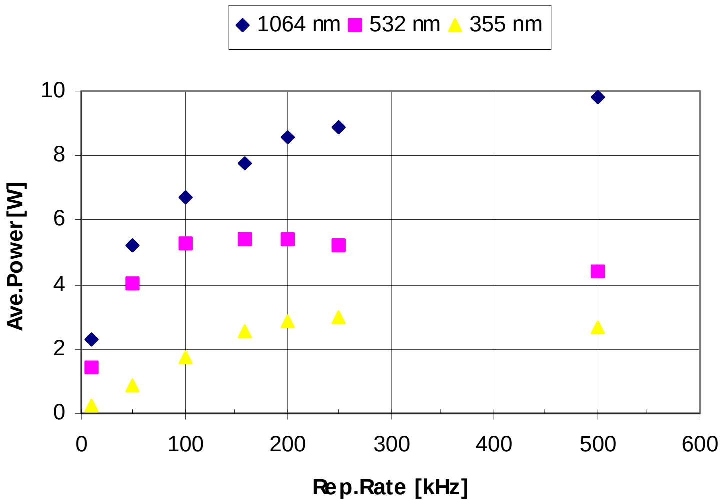


Figure 3 Maximum output power v pulse repetition frequency from the super RAPID picosecond laser

1.2 Beam Delivery

Two completely separate beamlines are used, each dedicated to a laser wavelength of either 532 nm (visible) or 355nm (ultraviolet). The laser harmonic module bolted at the front of the oscillator is manually interchangeable and is used to switch between laser wavelengths. The beam is steered with special dielectric mirrors and circularly polarised with quarter waveplates prior to entering the focussing lenses. Beam focussing is either via galvanometer scanner telecentric lenses of focal length f=100mm capable of covering a maximum field of 60x60mm or a high numerical aperture UV objective of f=20mm in the case of 355nm for high definition work. Beam expanders (2x-8x) are used to control the final beam spot. A fully automated trepanning head is used for high speed rotational beam steering, particularly useful in microhole drilling that is described in more detail below. Finally a fail-safe laser safety shutter interlocked to the enclosure guarantees safe use of the system.

1.3 12-Axis CNC Motion

An advanced automated 12 axis motion control system is used consisting of CNC stages (physical axes) and galvanometer scanners (optical axes). This allows the laser beam and/or stages to move with respect to each other. The CNC motion system is comprising of high accuracy (±1µm) direct drive linear axes together with either a goniometer pair or XYZ nanopositioning stages all

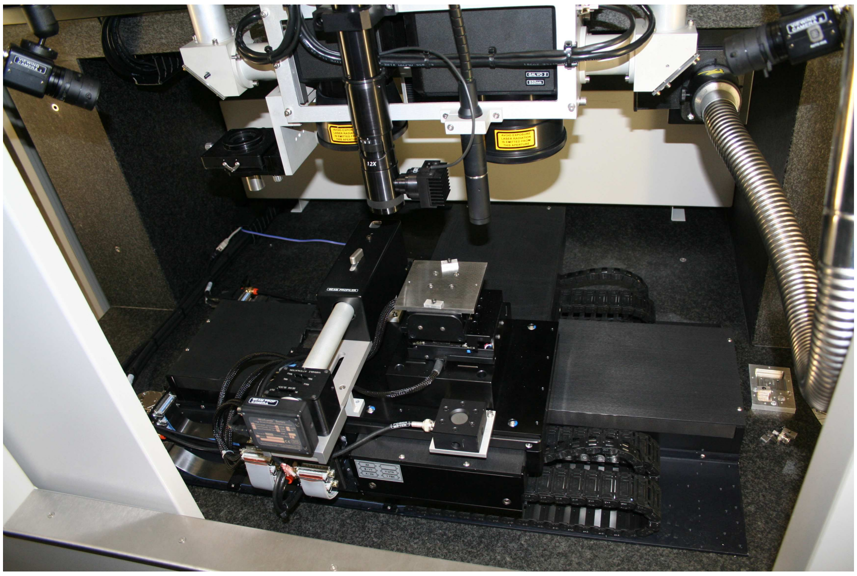


Figure 4 Photo showing the 12-axis CNC configuration. The X,Y,A,B axis goniometer assembly shown (bottom) is mounted on granite base and carries the sample jig. The vertical Z-axis carries the two dual head optical GX,GY galvanometer mirror axes.(top)

Table 2: CNC goniometer setup performance characteristics

AXIS	X	Y	Z	A	B
Travel (mm)	600	300	100	±10deg	±10deg
Resolution (µm)	0.05	0.05	0.1	0.05 arcsec	0.05 arcsec
Accuracy per axis (µm)	±1	±1	±5	+/-0.5 arcsec	+/-0.5 arcsec
Repeatability (µm)	±1	±1	±1	±10 arcsec	±10 arcsec

Table 3: CNC nanopositioning setup performance characteristics

AXIS	X	Y	Z	XX	YY	ZZ
Travel (mm)	600	300	100	50	50	4
Resolution (µm)	0.05	0.05	0.1	0.01	0.01	0.01
Accuracy per axis (µm)	±1	±1	±5	0.05	0.05	0.05
Repeatability (µm)	±1	±1	±1	0.3	0.3	0.2

Table 4: CNC galvanometer scanner and trepanning head characteristics

AXIS	GX	GY	TR	TRR
Travel (mm)	60	60	360deg	360deg
Resolution (µm)	1	1	0.1	0.1
Accuracy per axis (µm)	±5	±5		
Max.Speed (m/s)	>5	>5	100Hz	100Hz

controlled by an intelligent multi-axis motion controller (Aerotech A3200). Their performance characteristics are described in more detail in Tables 2 and 3. The control system uses a high speed firewire communication system with digital drives and advanced servo algorithms which enables rapid update of all motion parameters. This gives the system the advantage of being capable of high speed with high accuracy motion simultaneously for all 12 axes. An integrated 10/100 Base T Ethernet interface is included which permits local and remote processing and communication with other devices such as PLCs and a multi I/O facility for interfacing with other devices. A special feature of this controller is that the CNC contains onboard encoder tracking and synchronised pulse generation hardware, referred to as the PSO (Position Synchronised Output) option. The PSO option is very conveniently used for syncronised laser firing especially for blind feature machining. This feature guarantees overall uniformity of the machined part avoiding the frequently encountered overburning dips or ramps at the beginning and end of a laser run and operates with a 50 nm resolution in this case.

Two dual head telecentric galvanometer scanner heads optimised for each wavelength provide the two optical axes at any one time offering the advantage of very high speed laser machining. This is particularly attractive when coupled with a high repetition rate laser as it maximises process speed. The scanners can be operated independently or via a specially designed interface which islinked to the A3200 controller, effectively operating the scanners as CNC axes. This is a unique way of operating up to 9 axes simultaneously and is particularly useful in 2.5D laser micrmilling. Special independent software is also supplied to operate the optical scanners in combination with the vertical z-axis as part of a 3D rapid prototyping scheme for material deposition rather than ablation.

A direct-drive laser optical trepanning head for micro-hole drilling is also provided operating at both wavelengths. This is fully integrated with the A3200 controller and is used for many drilling strategies including simple trepanning, helical drilling, spiral helical drilling and cylindrical milling operations when resolution is of paramount importance. The revolution speed is 100 revs/sec.

1.4 Diagnostics

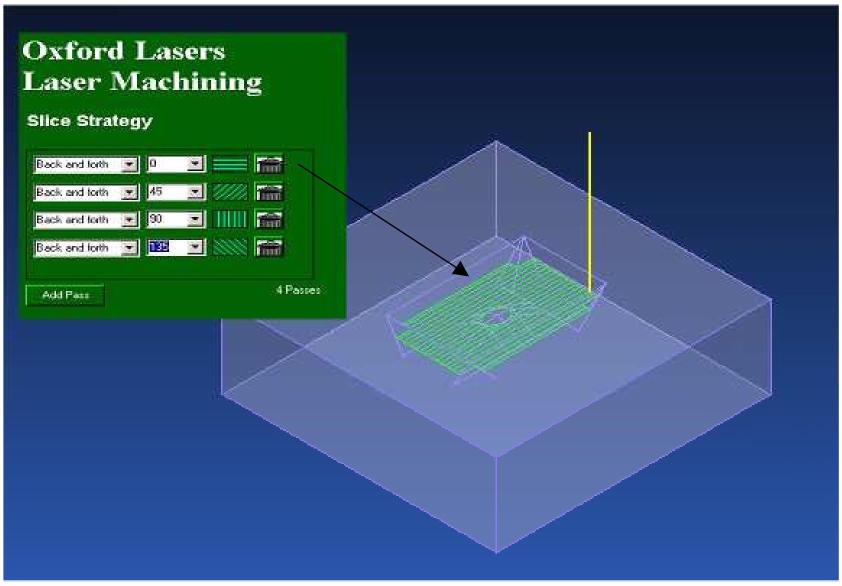
The system includes a suite of diagnostics which aid the user in ensuring that it is operating under optimum conditions. These include a confocal depth sensor, in chuck beam profiler, laser powermeter, temperature sensors, machine vision with alignment and surveillance CCD cameras and datalogging with software interface.

The non-contact depth sensor is used to check the depth of milled areas. It has a spot diameter of 10µm and operates within a 1mm measuring range with resolution of 40nm, accuracy of better than 0.5µm and full scale output repeatability of 0.01%. The beam profiler is integrated into the XY linear axes and is used to check the intensity profile of the focussed beam at the workpiece as well as beam position fluctuations. The laser powermeter is used to adjust incident laser power on the workpiece.

1.5 5-axis CAD/CAM for Laser Micromilling

The main application for Picolase at MEC is 2.5D micro-milling to produce micromoulds. It uses Oxford Lasers proprietary software to provide a unique laser micromachining solution. The software utilises the scanners or CNC stages and allows for special stiching when features larger than the scanner filed are to be machined. Rotation of the part is fully synchronised to provide full 5-axis motion.

The creation of 2.5D features with lasers is a complex process. A 3D CAD model must be sliced into a series of layers with compatible characteristics to the system accuracy and resolution and then analysed. Each layer is now a 2D drawing for which the CADCAM software generates an appropriate toolpath. With conventional milling, the depth of material removed can be simply controlled by the position of the tool and hence the model layer thickness can be easily determined. But with laser milling, certain ablation characteristics such as beam spot size, laser pulse energy, depth removed per single pulse and pulse overlap, affect the removal rate and need to be considered. These are extra user-defined parameters that have to be analysed by the software before a toolpath is created. Subsequently different hatching and profiling strategies can be applied on each slice as seen in figure 5. In addition, laser cleaning passes can be performed with lower incident energy density by defocusing the laser beam on the surface. The generated toolpaths are then loaded to the controller



Back and forth 0
Back and forth 45
Back and forth 90
Back and forth 135

Figure 5 5-axis CADCAM interface for 2.5D laser machining.

and processed layer by layer thereby creating a 2.5D feature. One critical feature of the software is the ability to take account of the natural wall taper associated with high aspect ratio laser processing, automatically tilt the part and machine again at an angle to control the taper (figure 6). The angle of tilt may be preconfigured with the part then automatically tilted when the laser encounters any such wall in its path during processing. Alternatively it can be measured using the confocal depth sensor at predefined intervals. To maintain a constant removal rate, the laser pulse overlap must be fixed. The system synchronises the laser firing rate with the CNC motion using the PSO function

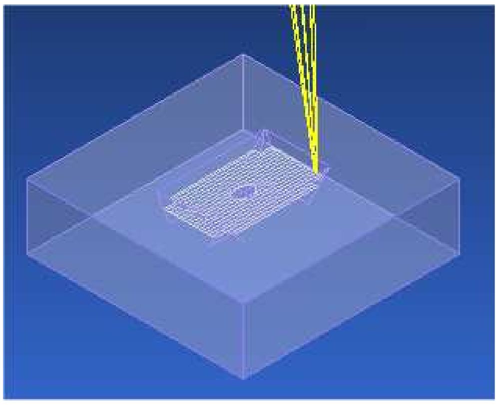


Figure 6 Laser machining at an angle to correct wall taper angle

described earlier. In order to improve the depth accuracy and ensure that the laser remains well focussed on the material surface, the depth sensor with its nm-resolution is interfaced with the software and can be used to monitor the amount of material that has been removed and adaptively adjust the laser etch depth.

3 Results

Preliminary results from the Picolase are shown below to demonstrate the systems's laser drilling and micromilling capabilities. In figure 7 images of ps-laser drilled holes in stainless steel are shown from the laser entrance and exit sides. The edge definition and overall quality of the surface finish is excellent given the samples have not been cleaned following machining. There is total absence of any redeposited debris or evidence of other damage. By contrast the ns-laser drilled hole shown in figure 8 shows signs of a laser-induced thermal process involving heating and solidification of material as evidenced by the ripple effects inside the hole walls.

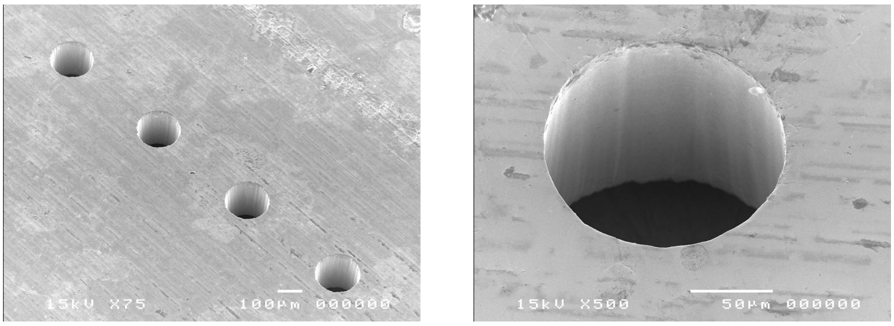


Figure 7 Picosecond 532nm laser drilling of 0.2mm thick stainless steel. The lack of thermal damage is remarkable in both entrance (left) and exit (right) sides

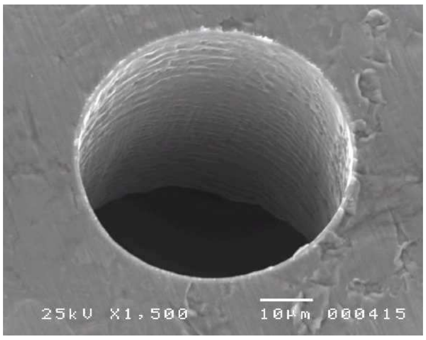


Figure 8 Nanosecond 511nm laser drilling of stainless steel. Evidence of thermal effects is present on the inner walls.

Additionally the laser can be used for high quality laser milling of blind features such as the pocket shown in figure 9 machined in fused silica with 355nm. Fused silica is trasparent to most laser wavelengths but using the ultra high peak power density from a tightly focussed beam, succesful machining can be achieved with no signs of microcracking or other colateral damage. By varying the incident laser power the floor surface roughness can be optimised to values as low as Ra~0.3µm [3]. Some recent results on laser milling of glassy carbon have even showed lower floor surface roughness of Ra~0.1µm [4] which highlights the ability of the system for surface integrity optimisation.

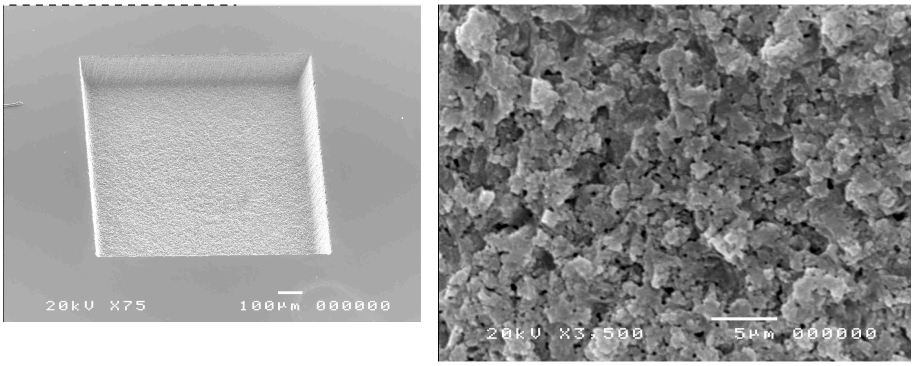


Figure 9 Picosecond laser micromilling of fused silica at 355nm. (Inset) Closeup of the laser milled floor. The floor surface roughness could be adjusted in some cases to values as low at Ra~0.3µm

4 Conclusions

A fully integrated 12-axis ultrafast laser micromachining system has been developed for advanced micromanufacturing. Excellent performance for micro-manufacturing is demonstrated with impressive results achieved in different industrial materials and emphasis on precision and processing speed.

References

[1] Knowles MRH.; Rutterford G.; Karnakis DM.; Dobrev T.; Petkov P.; Dimov S.: Laser micromilling of Ceramics, Dielectrics and Metals using nanosecond and picosecond lasers. In Proc.4M 2006, 2nd Int. Conf. on Multi Material MicroManufacture, 2006, 131-134

[2] Klimt, B: New tool for the toolbox, Industrial Laser Solutions, December 2006, 9-11

[3] Karnakis, DM Knowles MRH, Petkov PV, Dobrev T,Dimov SS, Surface integrity optimisation in ps-laser milling of advanced engineering materials, Proc.Fourth Int WLT-Conference on Lasers in Manufacturing 007,Munich, June 2007 (accepted)

[4] T.Dobrev, MEC, Cardiff University (private communication)