

Micromachining of 2D-3D structures with high intensity laser pulses

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Nowadays MEMS, fluidic devices, advanced sensors, biomedical devices and instruments etc. are important applications for strategic sectors. These are demanding suitable tools for materials processing, especially for developing tasks in different kind of materials and geometries around the micron, since this dimensional range emerged at the crossroad of nanotechnologies and conventional fabrication techniques. Specific laser based machines for each process of interest (initially working only in 2D) were rapidly developed, and an important gap has been generated, from the fabrication point of view, in targeting fully 3D applications. This paper briefly describes the design and notable applications of a multi-axis laser micromachining workstation based on the main concept of flexibility that was developed at the UPM Laser Centre of the Polytechnical University of Madrid (Universidad Politécnica de Madrid). This system integrates an advanced 6-axis positioning system and two UV laser sources, excimer and DPSS working in nanoseconds pulse regime, for precision 3D micro-machining of complex parts. A short description of the most relevant features of this micro-manufacturing cell is provided. Advanced materials (including composites) were machined at a dimensional range of microns for the processed zones. The main issues overcome by the authors in generation of 2D/3D structures by high intensity laser pulses with direct incidence are briefly described. Several examples of the applications achieved with this system, including processing of advanced sensors, organic materials for biomedical devices and metallic materials for important industrial sectors are presented.

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1. Introduction

Suitable tools for materials processing are needed, especially for developing tasks in different kind of materials and geometries around the micron, since this dimensional range emerged at the crossroad of nanotechnologies and conventional fabrication techniques. Laser systems have been widely applied in the last decades in semiconductor industry in microfabrication process development, the current availability of new excimer and diode pumped solid state lasers (DPSS) sources are broadening the applications fields of laser microprocessing, as discussed by Gower in 2000. Holmes (2002) underscores that nowadays micro-electro-mechanical systems (MEMS), fluidic devices, advanced sensors and biomedical devices and instruments are among the most promising developments of this technology.

An important issue is to define properly the concept of laser micromachining. A potential definition, with functional character not limited to applications derived directly from ablation processes could be: "Micromachining means cutting, welding, soldering, selective ablation, forming, patterning, etc., with dimensional details in the order of 1 μm ".

In this sense, and considering the previous experience in laser microprocessing and the kind of processes using lasers for precision applications in biomedicine, semiconductor industry, sensors fabrication, etc., some fundamental facts must be considered in advance. Laser

micromachining is intended mainly for material modification near the surface, or for processing with high aspect ratios (contrary to macromachining applications in which bulk processes and material removal are the main target). Additionally, and despite the fact that the majority of present applications are strictly 2D (planar or cylindrical), or are intended to process planar areas of 3D objects, an increasing interest in fully 3D applications is developing, generally generating some serious mechanical problems. These facts imply non-trivial questions at the time of systems' definition and design. In particular, the positioning systems characteristics and solutions are of great transcendence, and simple scaled solutions taken from macroprocessing systems are not allowed.

The UPM Laser Centre (CLUPM), belonging to the Polytechnical University of Madrid has designed and integrated, in cooperation with different laser systems and laser sources suppliers, the prototype of a 3D laser microprocessing cell, ML-100 (Fig. 1), presently devoted to the characterization and development of different laser micro-processes, as shown by Ocaña et al. (2008a).

Nanoseconds laser pulses represent an excellent tool for achieving the selective ablation, as presented by Molpeceres et al. (2005), and Ocaña et al. (2008b, 2009). CLUPM also offers the capacity in simulation, fabrication and characterization of materials, photonic, biophotonic and fluidic structures and devices in the framework of micro-nano technology, as presented by Aparicio et al. (2011), Holgado et al. (2009), and Casquel et al. (2010).

Ocaña et al. (2007a) described several spectacular results obtained in special applications, e.g. microstructural modifications produced by nanosecond ultraviolet ablation in neodymium doped lithium niobate crystals.

The features of the laser ablation process are mainly given by the short pulse (nanoseconds) laser regime, but the interaction with a certain material is crucial, determining also the quality of the machined parts, as presented by Ocaña et al. (2007b). Different process developments in CLUPM, ranging from pure planar applications to fully 3D parts machining are also briefly described in this paper.



Fig. 1. ML-100 UV laser micromachining workstation, at CLUPM.

The applicability of long pulse lasers in forming is limited for MEMS manufacturing due to the long-relaxation-time of the thermal fields responsible for the forming phenomena. The use of nanosecond laser pulses provides suitable parameters matching the laser non-thermal micro-forming (i.e. by laser shock processing), of an important range of sheet components used in MEMS, as shown by Ocaña et al. (2007c).

2. Laser micro-machining workstation

The main features and potential applications of ML 100 3D laser micromachining 6-axis workstation is based on the main concept of geometrical flexibility (Fig. 1). This system integrates two UV laser sources, excimer and DPSS working in ns-pulse regime (Table 1), and an advanced 6-axis positioning system for complex parts machining (Fig. 2).

The system also integrates other important features, such as a nozzle for extracting process fumes, a vacuum chuck for planar parts holding, a clamping system for axis-symmetrical work pieces, and a TTL system (x500 magnification) for process viewing and in situ measurements, if properly calibrated. The software includes teaching options, reticle projection for in situ

spatial calibration, special trepanning options, and other personalized features in order to improve, via software, the mechanical yield of the system.

Table 1. Characteristics of the UV laser sources integrated in ML-100 system.

Laser Media	Excimer (KrF)	DPSS 3 ω
Wavelength (nm)	248	355
Pulse Duration (ns)	3-7 ns	< 12 ns (@ 50 kHz)
Beam shape/mode	Rectangular (3.5 x 6 mm)	TEM ₀₀ ($M^2 < 1.3$)
Operating frequency	0-300 Hz	15 – 300 kHz
Average power (W)	0.3-5 (@ 300 Hz)	5 (@ 50 kHz)

2.1 The positioning system

The 6-axis part positioning system mounted on ML-100 specially designed for 3D processing is presented in Fig. 2. Main part motion is assured by the X,Y stages, which are servomotor driven stages with linear position encoder (resolution of 0.1 μ m in each axis). Overall precision in the XY working area (100 x 100 mm) is about 1 μ m. The Z-axis is used to bring the part to the laser focus.

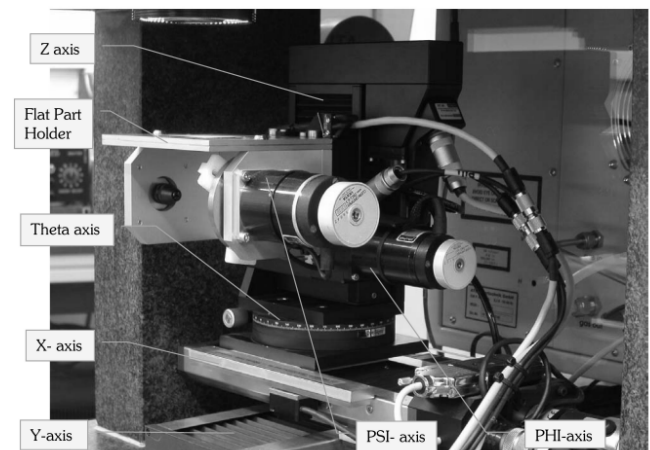


Fig. 2. ML-100 UV laser micromachining workstation: multiaxis positioning system, at CLUPM.

Rotary axes are included for full 3D spatial control. A low profile Theta trim allows squaring of parts relative to X, Y stages. Phi axis allows parts to be tilted (max. 90°) and Psi axis, in fact a part lathe, is used to mount objects with rotational symmetry. The Sphere of Confusion for the whole system is 50 μ m.

2.2 Laser systems and optical paths

The ML-100 laser workstation designed by CLUPM combines two different UV laser sources: a Nd:YVO4 (Spectra Physics HIPPO) emitting pulsed UV radiation at 355 nm for focal point processing, and a KrF excimer laser (ATL Laser Technik SP300i) emitting pulsed UV

radiation at 248 nm for mask projection processing (Table 1).

For only IR irradiation, a simplified set up with a Nd:YAG laser source (Spectra Physics NAVIGATOR) emitting pulsed IR radiation at 1064 nm for focal point processing mounted over an XY positioning system is used.

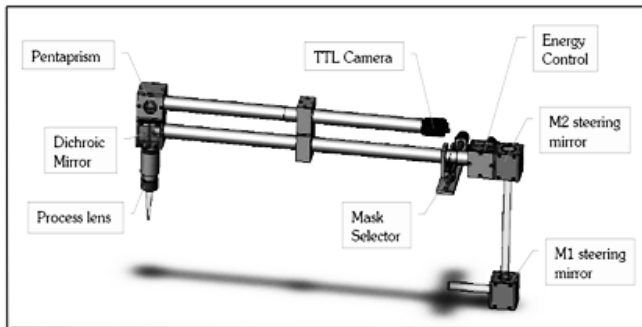


Fig. 3. ML-100 micromachining station: excimer laser path.

The excimer laser emits a beam of approximately 4x6 mm that is directed to the mask and lens, via the energy controller, through two steering mirrors (Fig. 3). A 3-element process lens images the mask onto the part, via a dichroic mirror, at nominal 10:1 demagnification.

The DPSS 355 nm laser source is steered in the insertion mirror (Fig. 4), which is placed in the excimer beam path whenever Nd:YVO₄ processing is required. The process lens gives a 10x demagnified image of the virtual point source formed by a lens in the middle of the beam path.

An important feature is the possibility of external energy control using an attenuator in the beam path (Fig. 4).

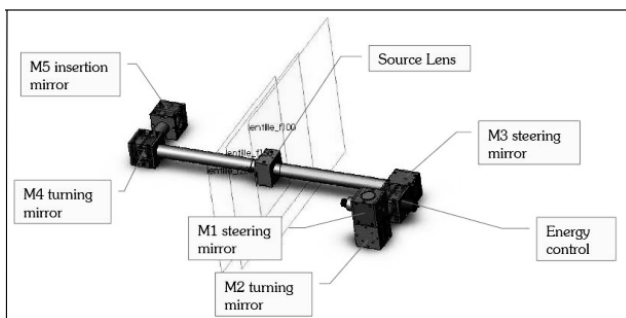


Fig. 4. ML-100 micromachining station: DPSS laser path.

In most laser microprocessing applications, very low power densities are required in order to avoid material or substrate damage, and usually the energy control integrated in the commercial laser sources does not give good result for laser energy fine tuning.

2.3 Measurement and imaging

Confocal Laser Scanning Microscopy (CLSM) has been used for ablation curves characterization, ablation profile measurements and morphological characterization. In this work measurements have been made using a Confocal Laser Scanning Microscope (Leica ICM 1000).

The equipment operational wavelength, together with the objective numerical aperture and pinhole diameter gives the final resolution in axial direction.

3. Laser based optics, micro-nano photonics and fluidics applications

This field of investigation mainly includes design and simulation of photonic structures, micro-fabrication of photonic and biophotonic devices, and optical characterization of photonic and biophotonic devices.

The fabrication of photonic structures by means of laser micro-fabrication based techniques offers advantages such as cost reduction, capability of processing a great diversity of materials, and complex geometries.

Among the variety of materials, polymeric materials are remarkable when are processed by UV lasers in the ns, ps or fs regime for direct scribing ablation processes. Particularly in the micro-nano fabrication field, CLUMP has developed optical lithography deep UV (DUV) by means of mask projection and excimer laser.

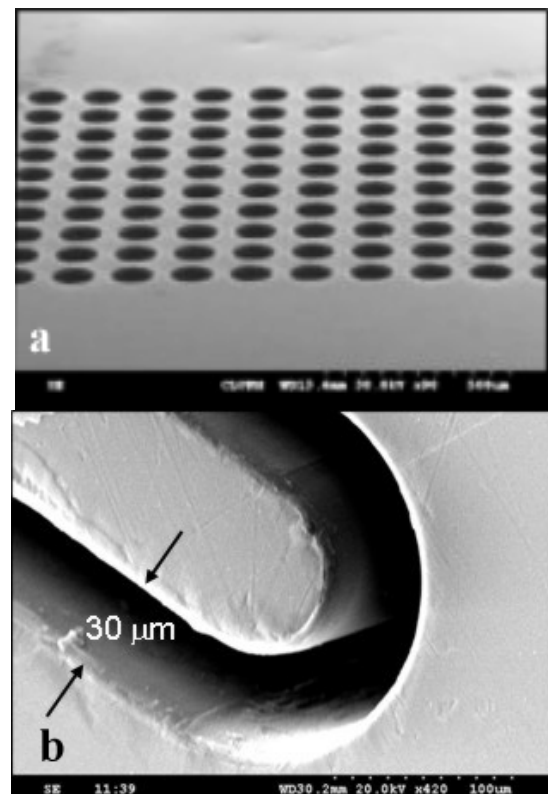


Fig. 5. Precision microfabrication: a. lattice of micro-holes made in polymeric material b. polycarbonate cutting, 1 mm thickness.

CLUPM has a broad experience in developing preparation of thin layers of polymeric materials for use in fluidic, photonic and biophotonic devices, such as PDMS Sylgard (Dow Corning) and a photoresist SU8 (Microchem).

Laser assisted cleaving of photonic devices is of particular interest to avoid the polishing process of photonic chips, which is normally costly and time consuming.

4. 2D, 2D+1/2 and 3D micro-machining

Although laser micromachining processes in planar geometry have a long tradition, several notable results showing the potential of ML 100 system integrating both excimer and DPSS laser sources are presented in this paper. With the same machine it is possible to process polymers (Fig. 5) with the high quality characteristics of excimer irradiation of 248 nm, and metallic materials with DPSS of 355 nm (Fig. 6).

It is a common task to process pieces (both planar and axi-symmetric) in 2D+1/2 geometry in case of macro-machining systems. The factor 1/2 makes reference to a possible reorientation of the tool (using a rotary axis for colatitude control), with respect to a characteristic plane (Fig. 7).

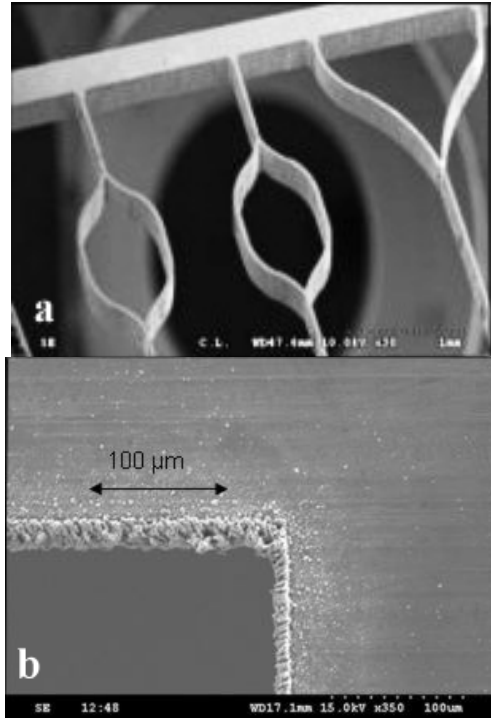


Fig. 6. Precision microfabrication: a. metal mask for projection photolithography b. Stainless Steel using DPSS at 355 nm (50 μm thickness).

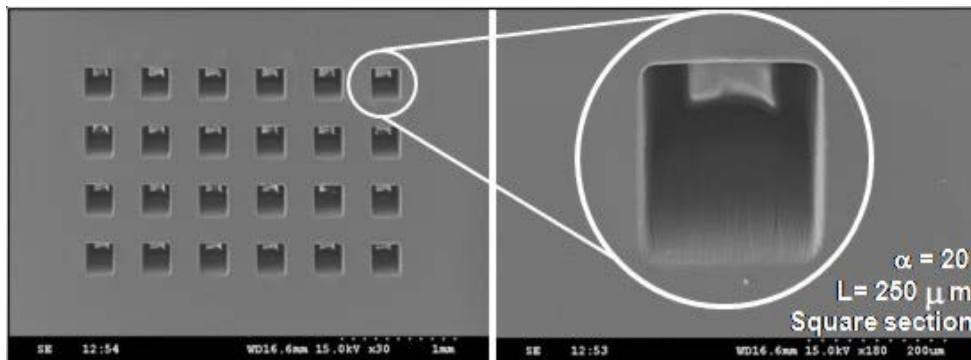


Fig. 7. 2D+1/2 application: square section channel fabrication with colatitude control in polycarbonate (1 mm thickness).

In Fig. 8, the excimer laser with hybrid mask projection technique was used for machining and surface texturing of a glass sphere, namely drilling 75 μm blind

holes on the sphere surface - a good example of the fully 3D micro-machining capability.

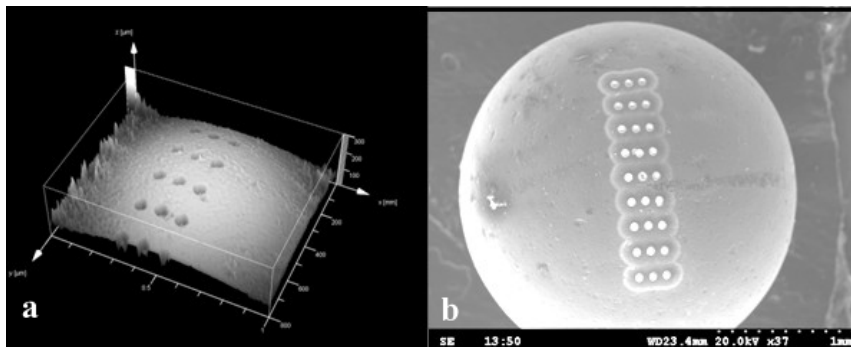


Fig. 8. Surface texturing: small blind holes (75 μm in diameter generated at 248 nm onto a spherical surface of 2.5 mm in diameter): a. confocal microscopy 3D reconstruction; b. SEM image.

5. Conclusions

A prototype of a fully 3D flexible laser micromachining system has been designed and presently is completely operative in order to give a potential answer to the increasingly demand in different strategic sectors of 2D, 2D + $\frac{1}{2}$ and 3D processes development in the micron range.

As has been shown in this work, integration of excimer and DPSS UV laser in the same system has demonstrated to be an added value for this kind of equipment. Complex geometries (concerning the workpiece and the pattern to be processed) have been obtained in different materials with appropriate quality for the related applications.

Additionally, the integration of standard robotics control functions such as teaching for spatial repositioning or TTL view for process control appears as valuable tools for complex tasks development from the point of view of in situ control and analysis.

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