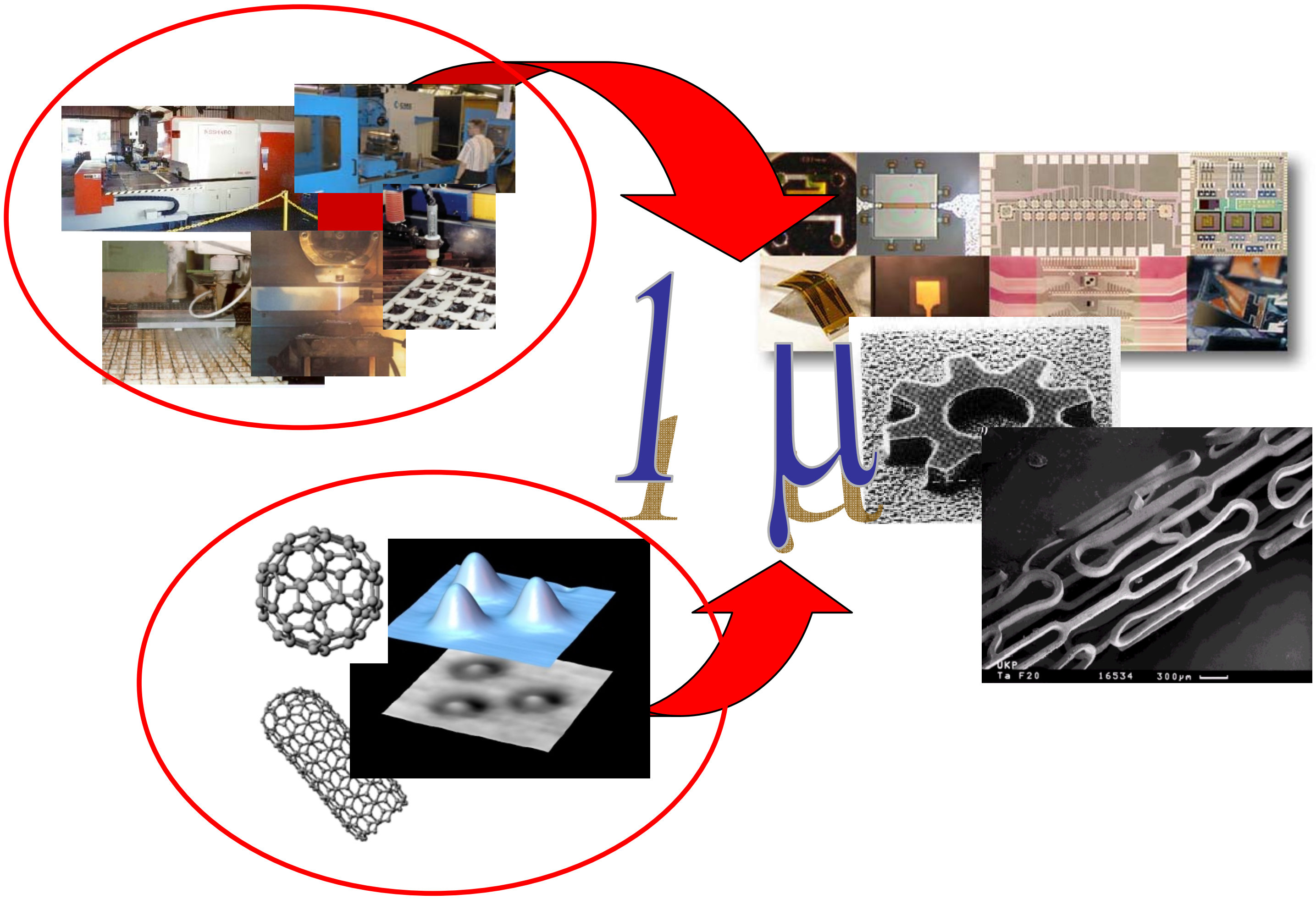
Application of high intensity short pulse lasers to precision micromanufacturing

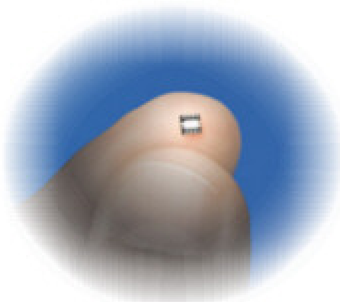
J.L. Ocaña, C. Molpeceres, M. Morales, M. Holgado, J.J. García-Ballesteros, S. Lauzurica, J.A. Porro, O. García, D. Iordachescu

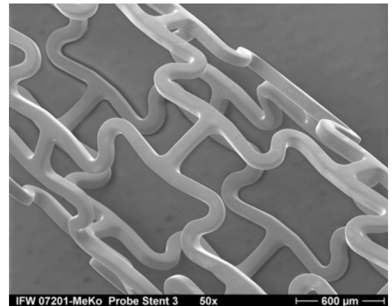
ETSII-Dept. of Applied Physics **and** *UPM Laser Centre*
Universidad Politécnica de Madrid
ETSII-UPM, C/ José Gutiérrez Abascal, 2. E-28006 Madrid. SPAIN
Tel.: (+34) 913363099. Fax: (+34) 913363000. email: jlocana@etsii.upm.es

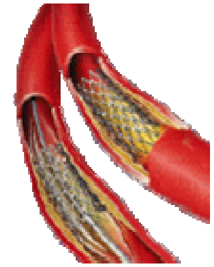
1 µm: LOOKING FOR SUITABLE FABRICATION TOOLS

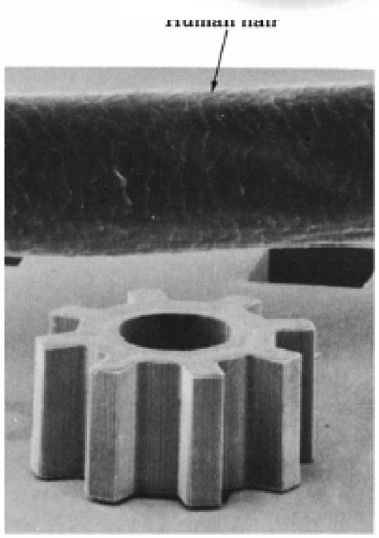


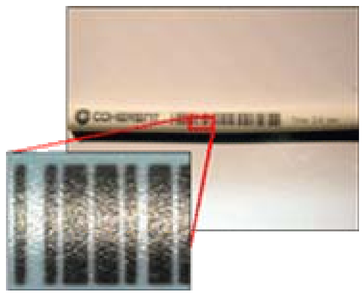
1 µm: LOOKING FOR SUITABLE FABRICATION TOOLS

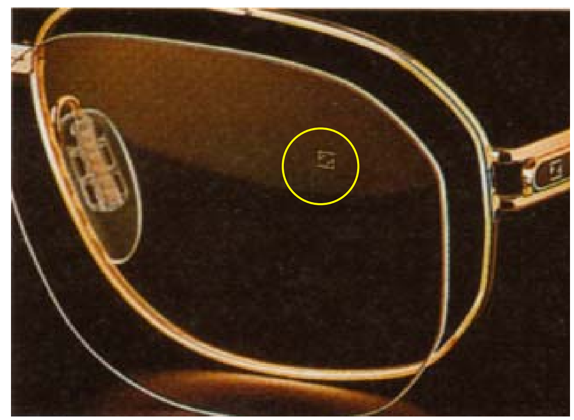












1 µm: MICRO-PROCESSING ADVANTAGES

1. High density of energy – required by very hard materials
2. Precision & repeatability
3. Enabled for high-selective ablation
4. Not intrusive – high flexibility noncontact machining
5. Very reduced HAZ

LASER MICRO vs MACROMACHINING

Are laser systems going to play the same role in micro applications that they played in macro-processing?

- **Close tolerance**
- **Excellent repeatability**
- **Unit cost reductions**
- **Material versatility**

- **Clean processing to eliminate debris**
- **Flexibility - fast setups achievement**
- **Little or no burring or affected zones**
- **Fully 3D processing**

LASER MICROMACHINING: A TECHNOLOGICAL INNOVATION?

Micromachining means cutting, welding, soldering, selective ablation, forming, patterning, etc, with dimensional details in the order of 1 μm.

- **Excimer photolitography and selective ablation ~ 20 years**
- **Semiconductor applications *dicing, drilling, engraving, cutting,* etc. in Si, TCOs, etc. ~ 20 years**
- ***ps* and *fs* lasers applications ~ 15 years**
- **DPSS Q-switch multi kHz sources ~ 10 years**

LASER MICROMACHINING FACTS

- **Laser micromachining is intended mainly for material modification near the surface or for processing with high aspect ratios.**

- Most present applications are **strictly 2D (planar or cylindrical) or are intended to process planar areas of 3D objects**. Presently **an increasing interest in fully 3D applications is developing, and in general, implying some serious mechanical problems**. These facts imply non trivial questions at the time of systems definition and design and, in particular, positioning systems characteristics and figures are of great transcendence, and not admitting simple scaled solutions from macroprocessing systems.

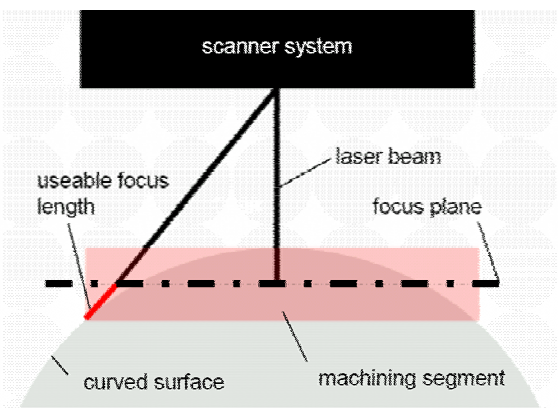
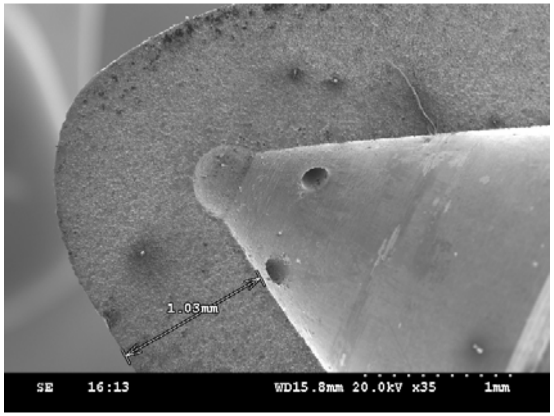


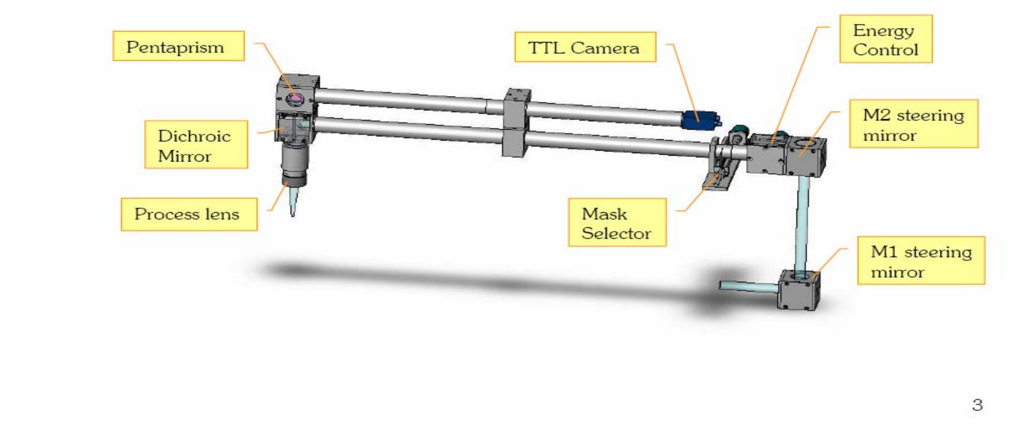
Fig. 4: Machining of a curved surface

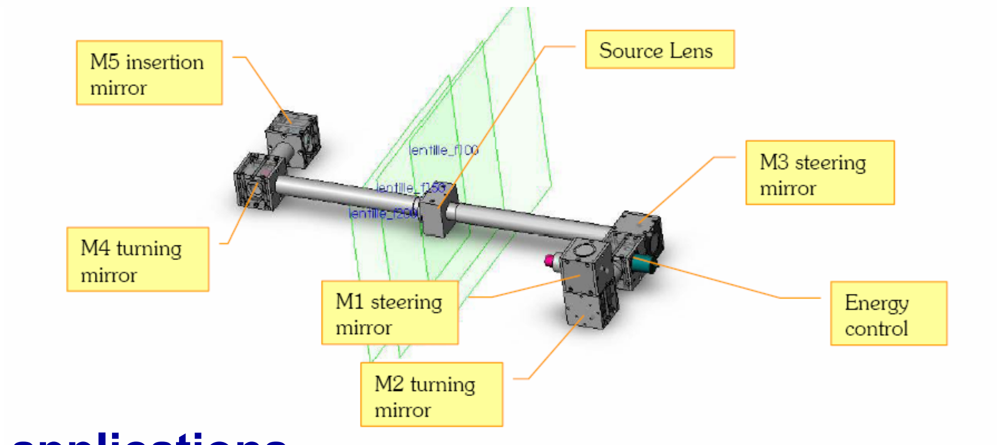
Thin Film and Surface Engineering



Fuel injector section

CML-1OO





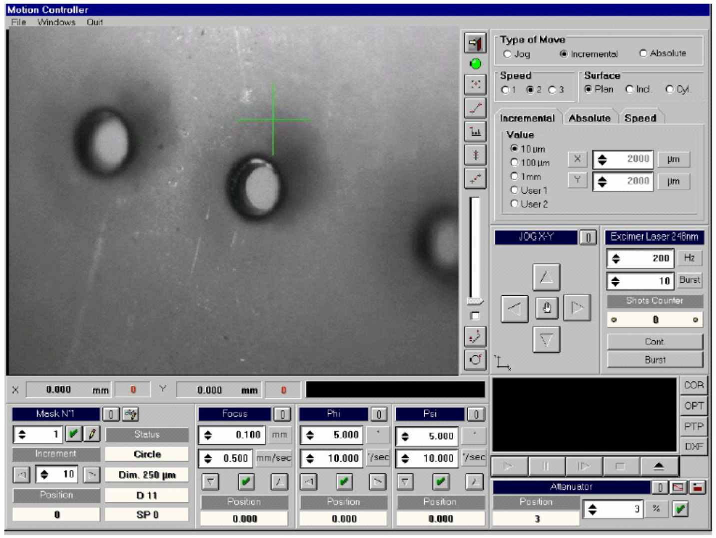
Multi-axis (6) system
with *ns* laser sources for focal point applications, mask projection and hybrid techniques.

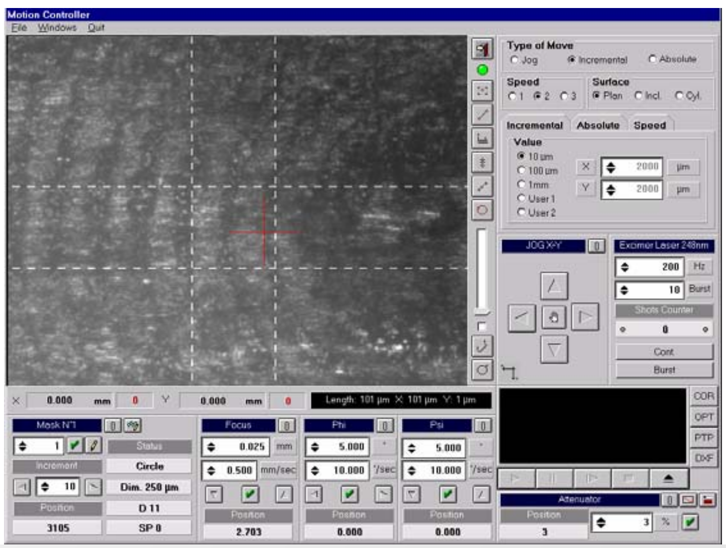
LASER PARAMETERS

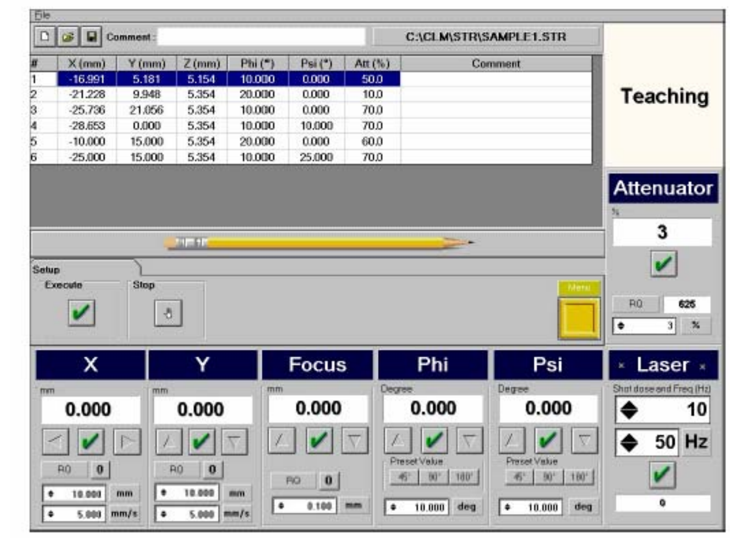
Laser Media	*Excimer (KrF)*	*DPSS 3ω (Nd: YVO_4)*	*DPSS 1 ω (Nd: YAG)*
Wavelength (nm)	**248**	**355**	**1064**
Pulse Duration (ns)	**3-7 ns**	**< 12 ns (@ 50 kHz)**	**< 70 ns (@ 7.5 kHz)**
Beam shape/mode	**Rectangular (3.5 x 6 mm)**	**TEM_{00} ($M^2 < 1.3$)**	**TEM_{00} ($M^2 < 1.15$)**
Operating frequency	**0-300 Hz**	**15 – 300 kHz**	**1-100 kHz**
Average power (W)	**0.3-5 (@ 300 Hz)**	**5 W (@ 50 kHz)**	**6.5 W (@ 50 kHz)**

- DPSS (355 & 1064 nm): Focal point processing
- EXCIMER Irradiation (248 nm): Mask projection and hybrid techniques

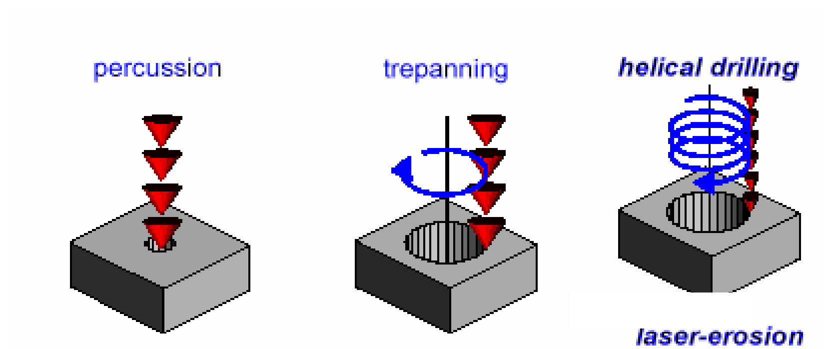
SOFTWARE FEATURES





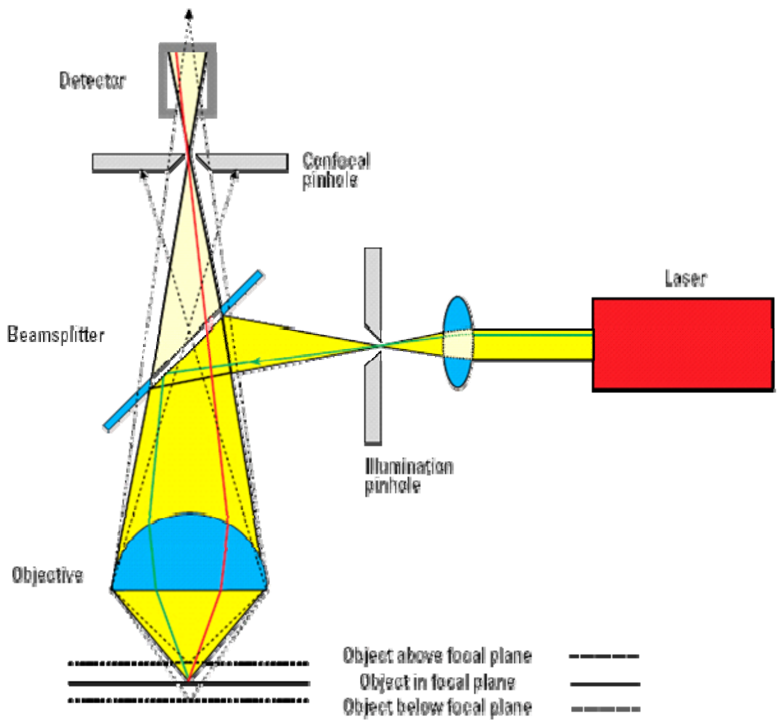


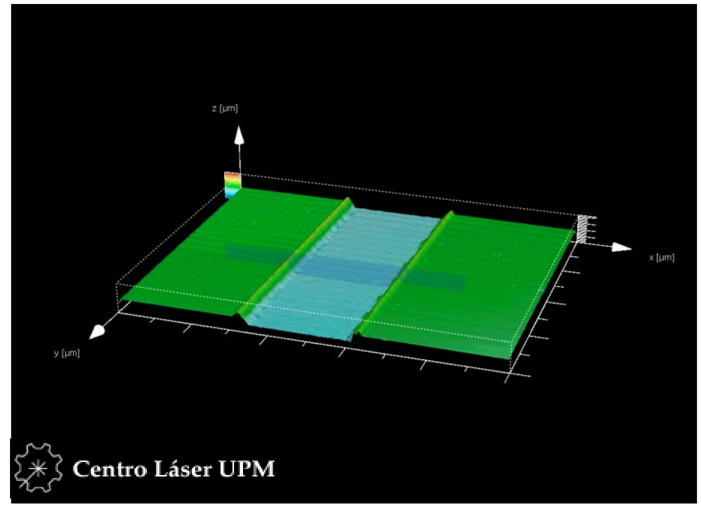
#	X (mm)	Y (mm)	Z (mm)	Phi (°)	Psi (°)	Att (%)	Comment
1	-16.991	5.181	5.154	10.000	0.000	50.0	
2	-21.228	9.948	5.354	20.000	0.000	10.0	
3	-25.736	21.056	5.354	10.000	0.000	70.0	
4	-28.653	0.000	5.354	10.000	10.000	70.0	
5	-10.000	15.000	5.354	20.000	0.000	60.0	
6	-25.000	15.000	5.354	10.000	25.000	70.0	

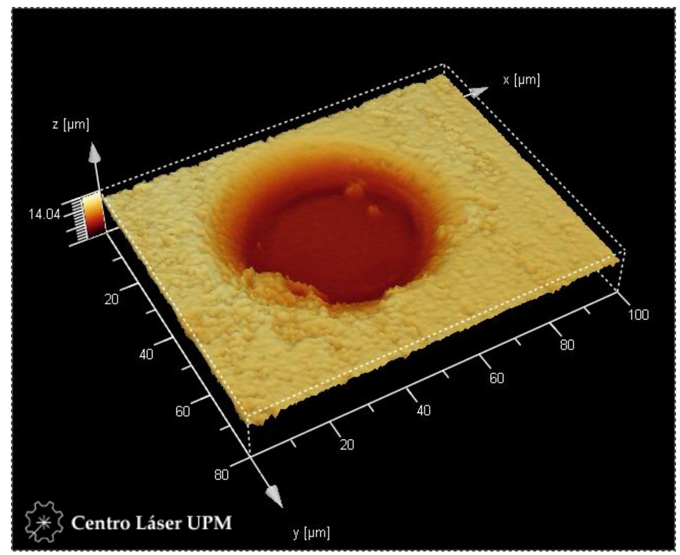


WORKPIECE ANALISYS AND MEASUREMENT

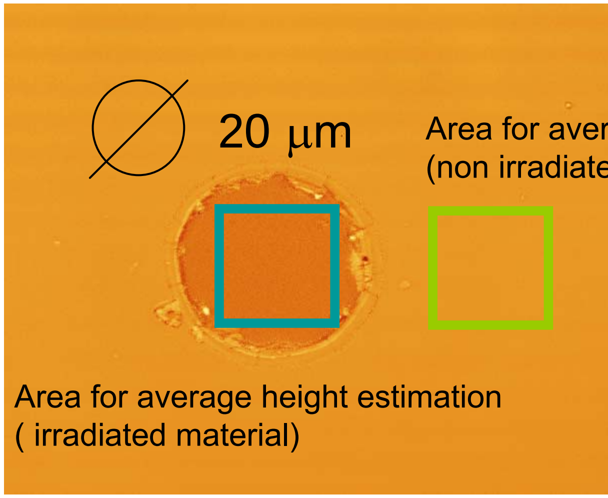
Confocal Laser Scanning Microscopy
(Leica ICM 1000, λ=635 nm)
and SEM imaging







ABLATION CURVES MEASUREMENT

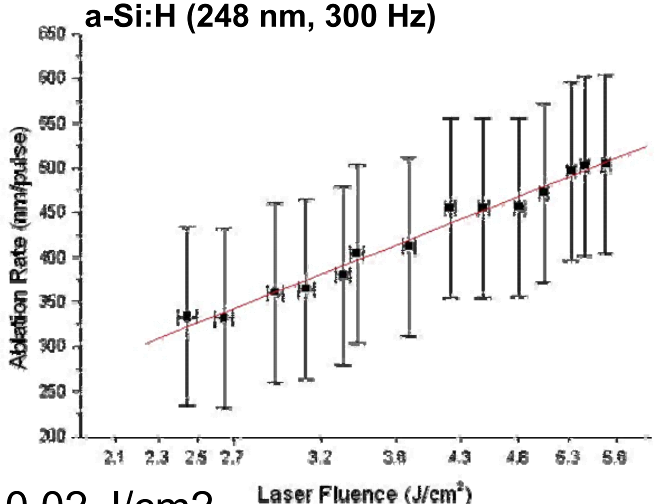


Area for average height estimation
(non irradiated material)

a.h. - a.h. = D (ABLATION DEPTH P.P.)

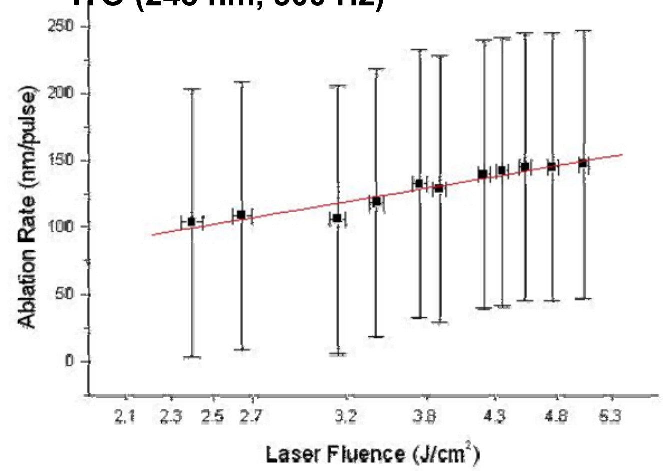
Expected accuracy:
> 20 nm in step measurements

a-Si:H (248 nm, 300 Hz)



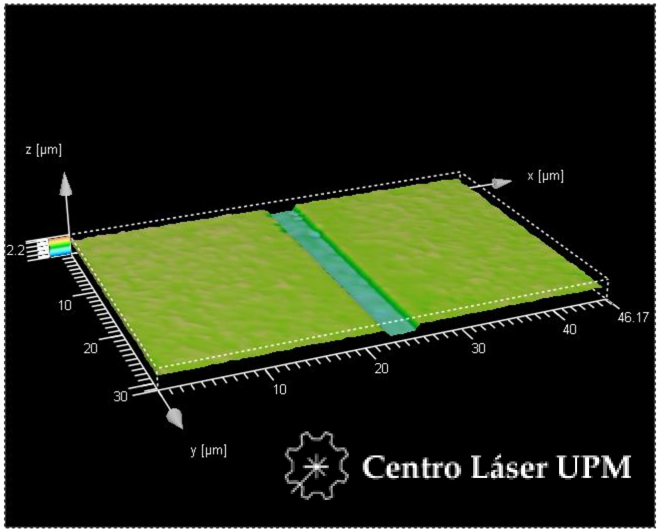
Φ_{Th} = 0.58 ± 0.02 J/cm2

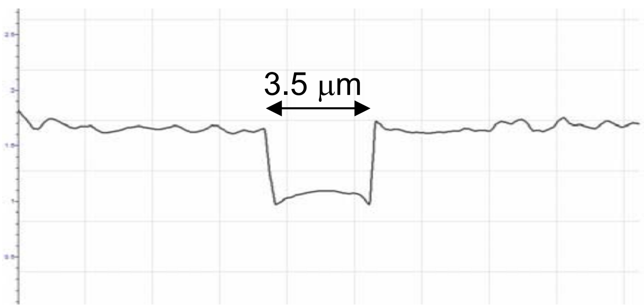
ITO (248 nm, 300 Hz)



Φ_{Th} = 0.47 ± 0.02 J/cm2

THIN FILM SELECTIVE ABLATION

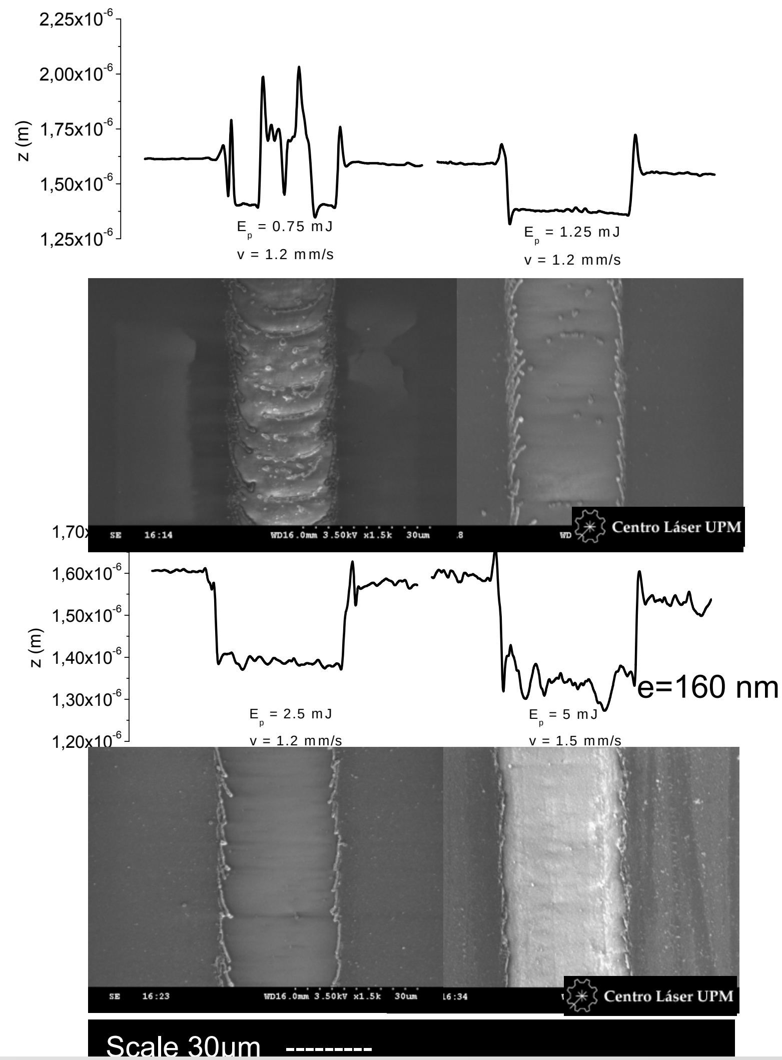




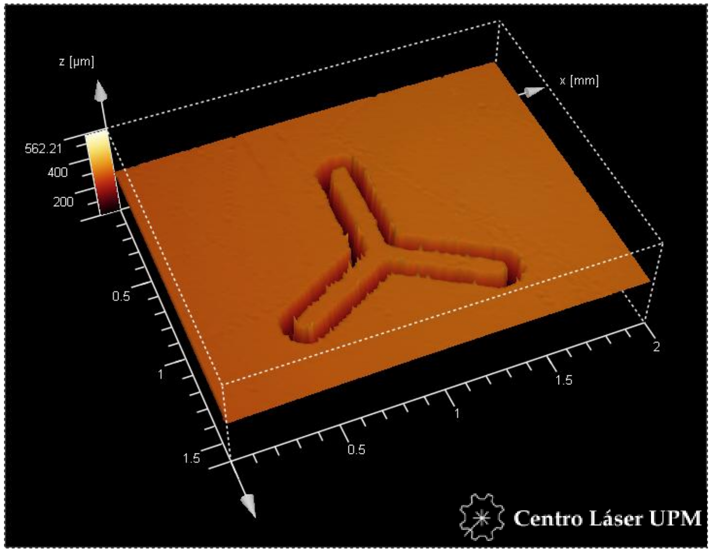
TCO SELECTIVE ABLATION

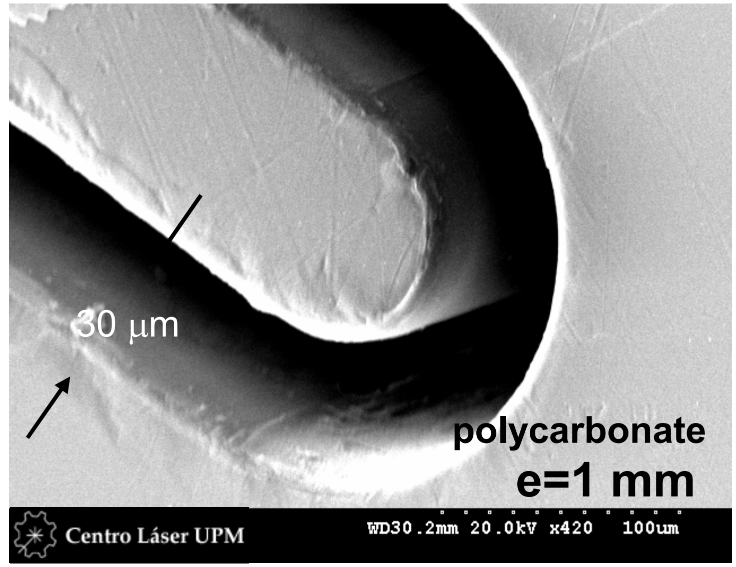
e=500 nm

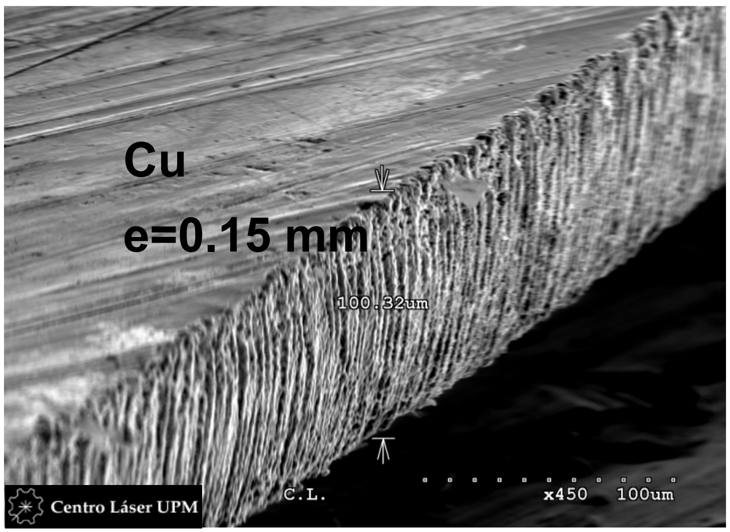
a-Si SELECTIVE ABLATION

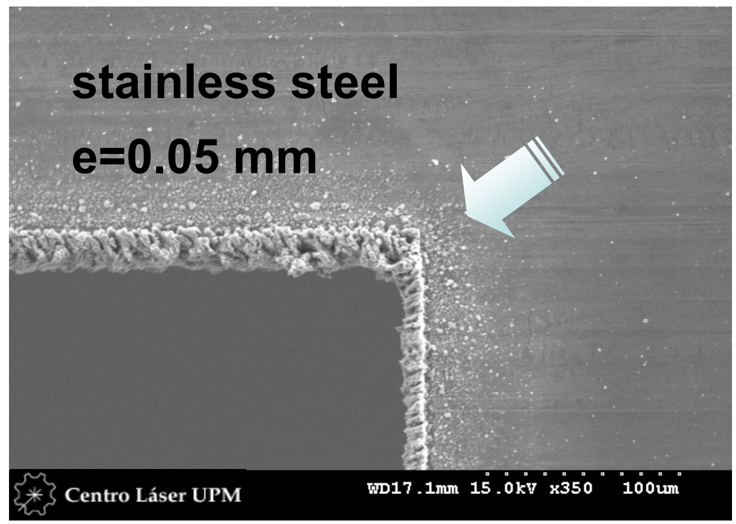


PLANAR CUTTING APPLICATIONS

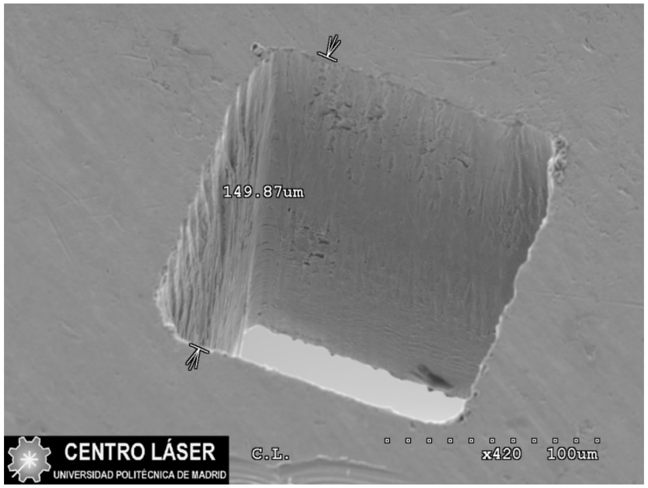






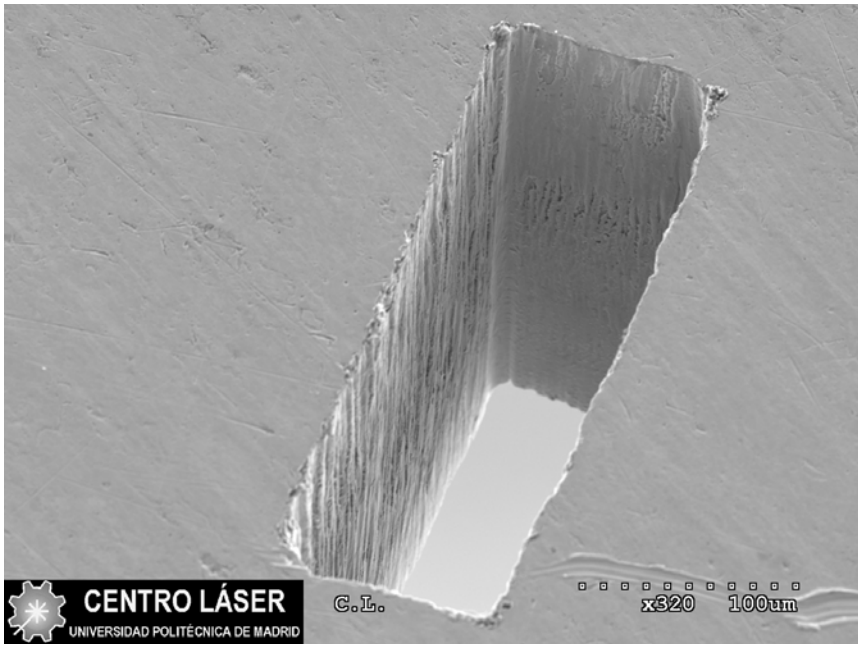


PLANAR CUTTING APPLICATIONS

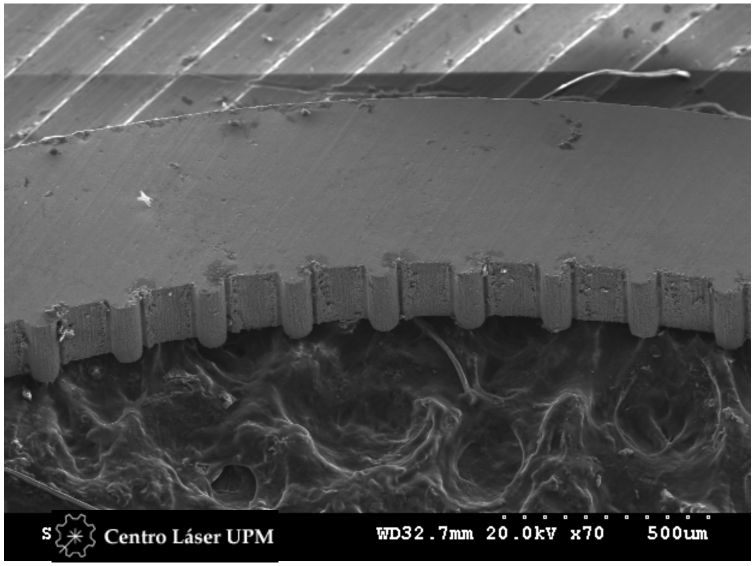


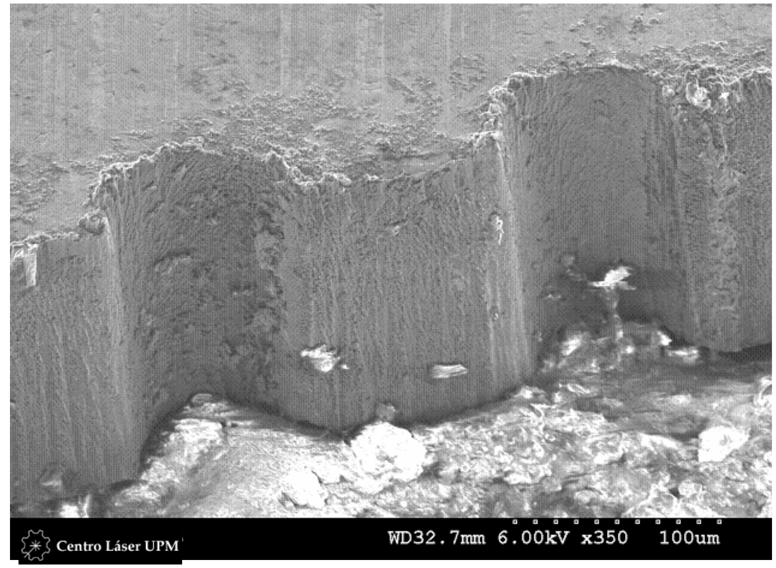
Mo

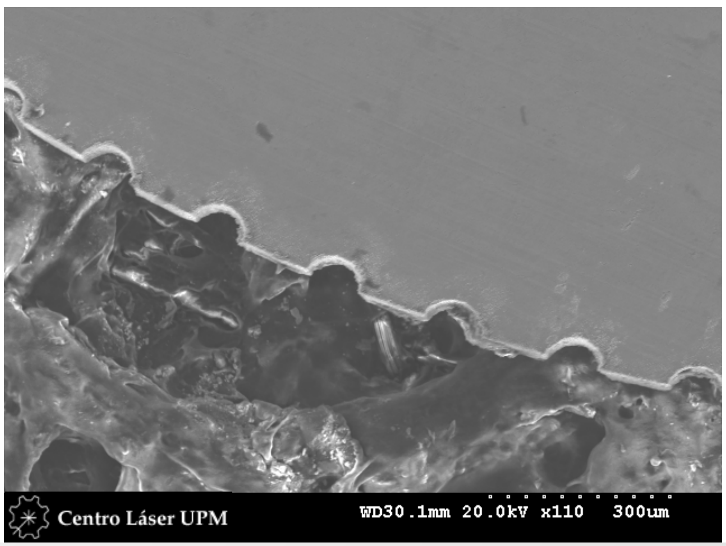
e=0.2 mm

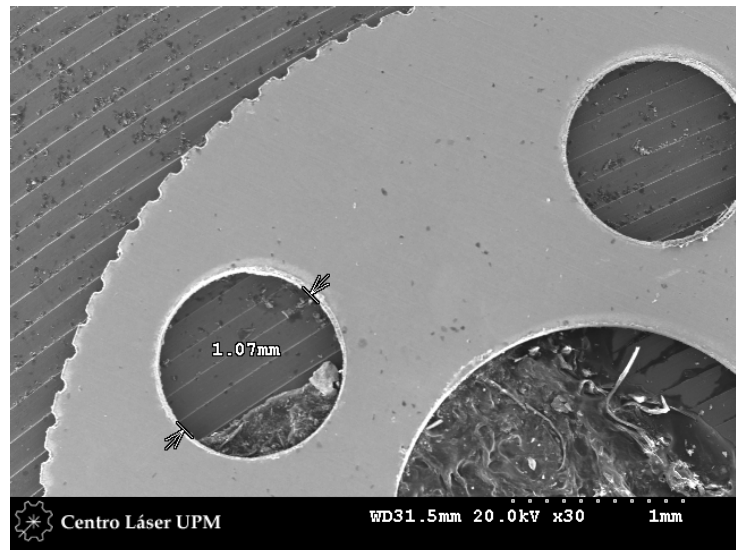


MICROGEARS CUTTING

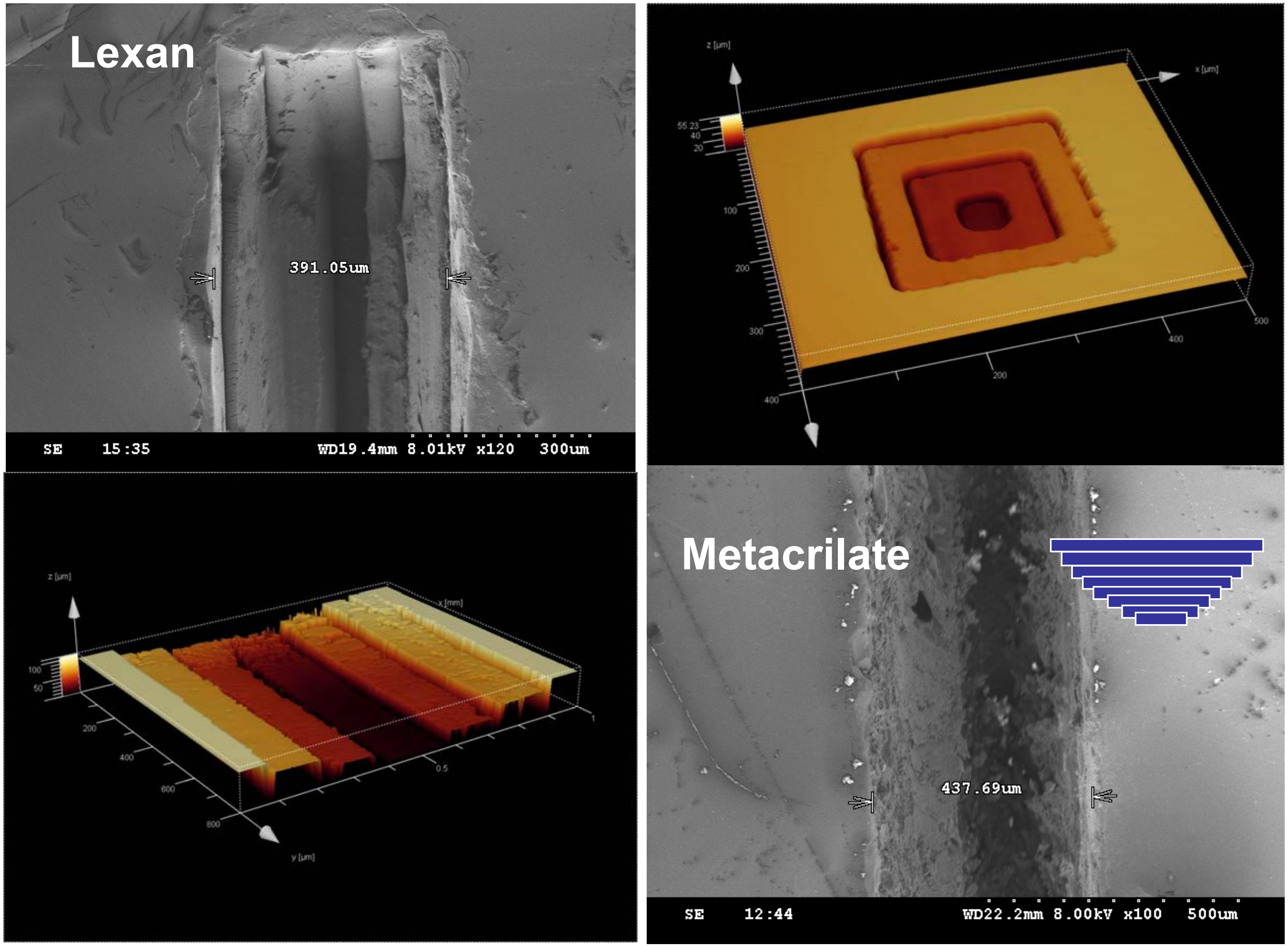




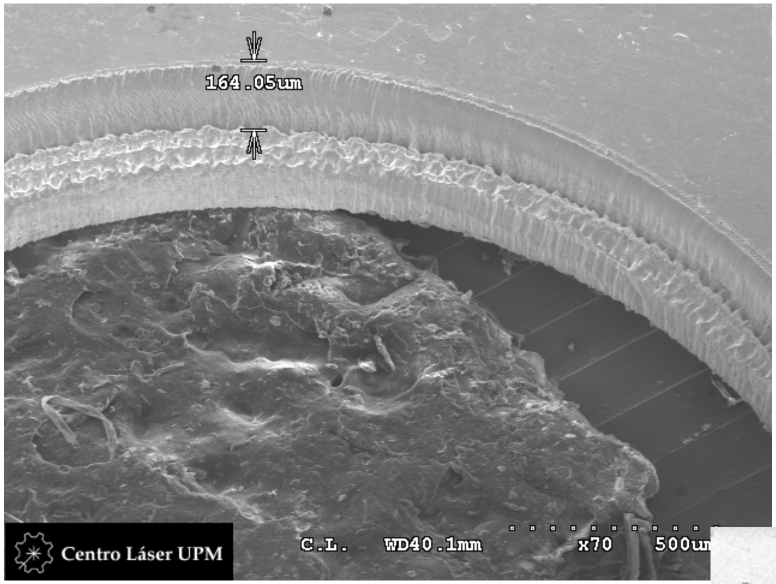


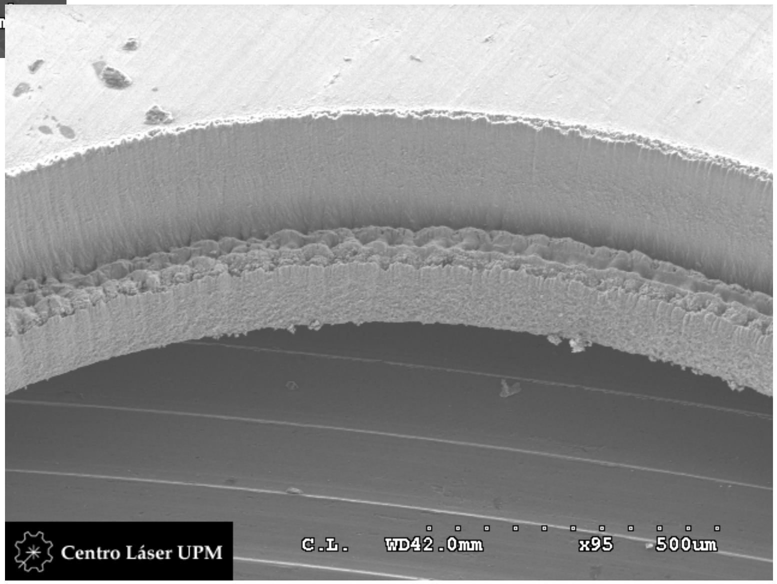


MICROMILLING USING HYBRID TECHNIQUES



MICROMILLING: STEP GENERATION FOR ASSEMBLING



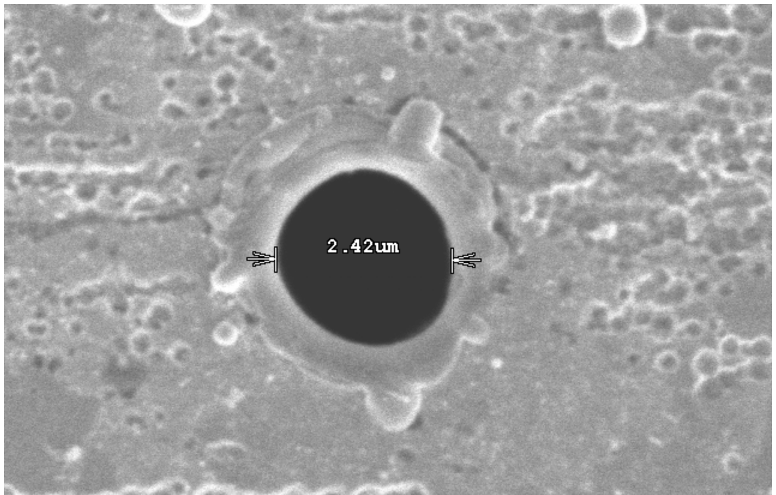


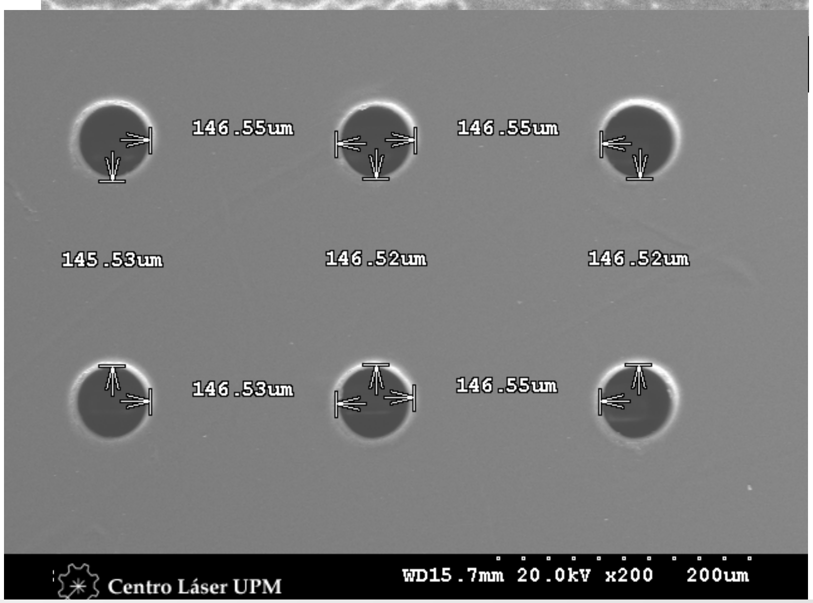
Material: Ta
e= 0.3 mm

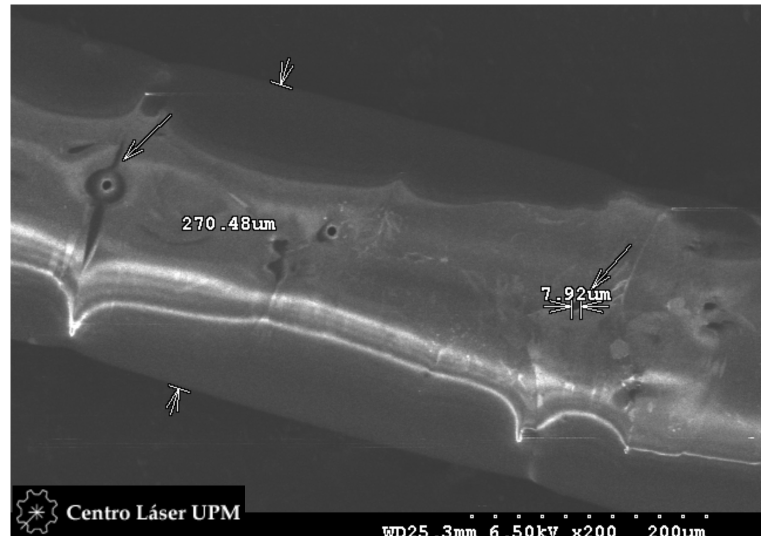
Step Dimensions:
H:0.1 mm - W:0.05 mm

2D HOLE DRILLING

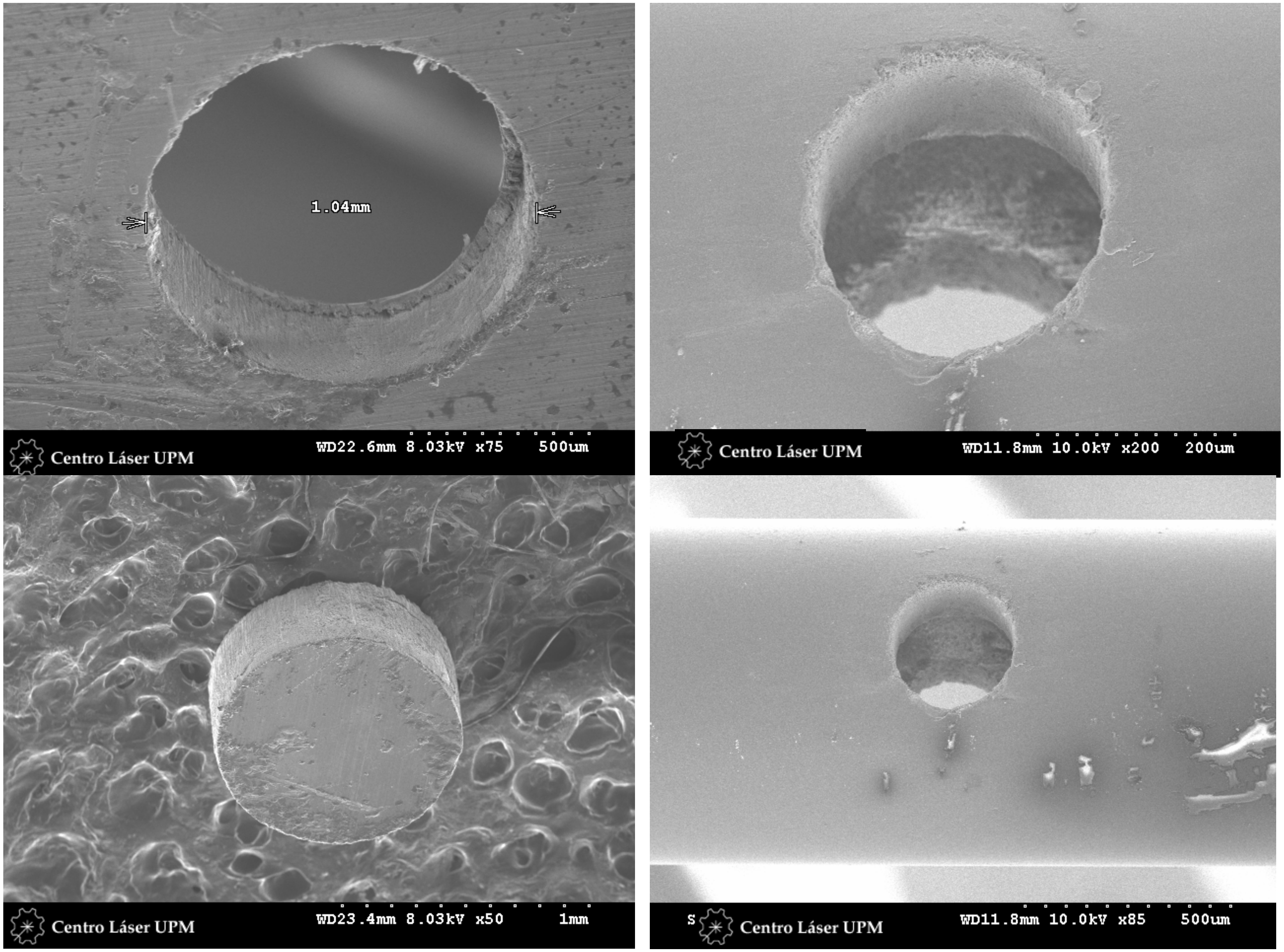
Planar **Fused Silica** **Cylindrical**



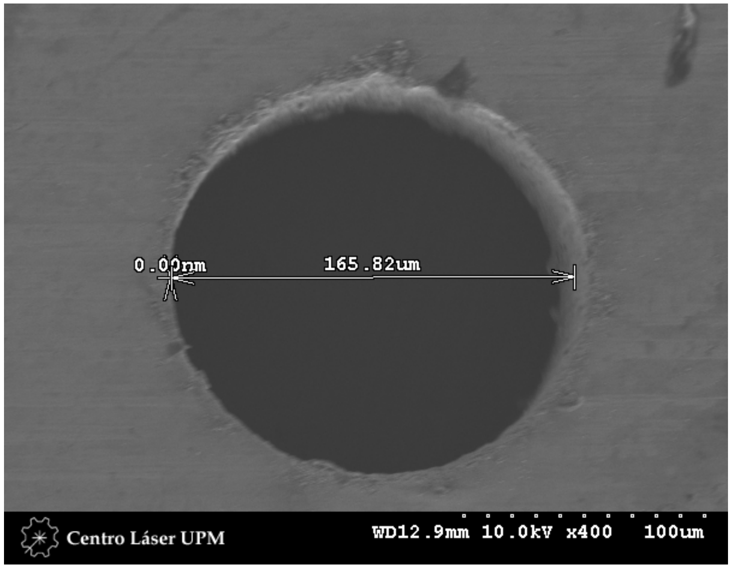


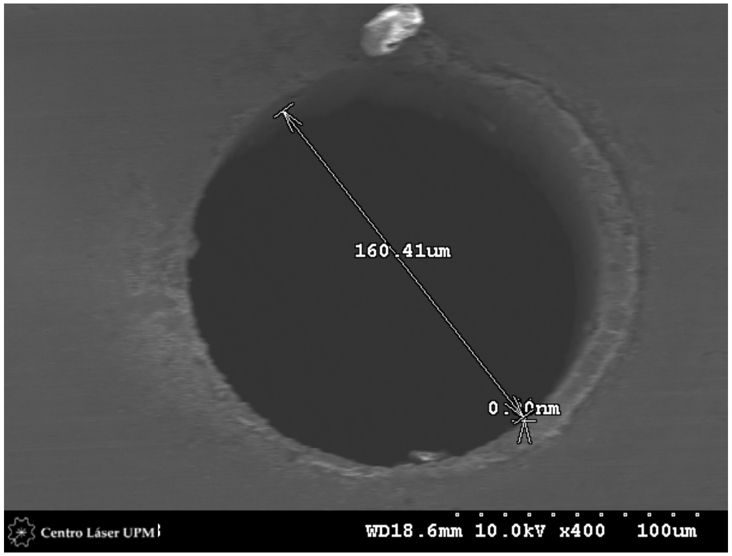


2D TREPANNING



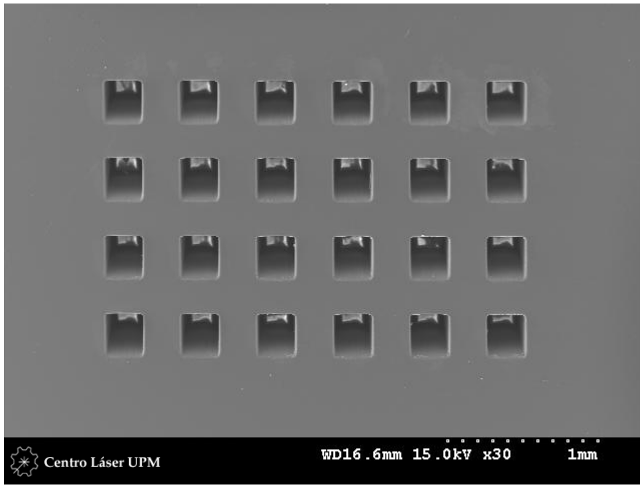
2D TREPANNING



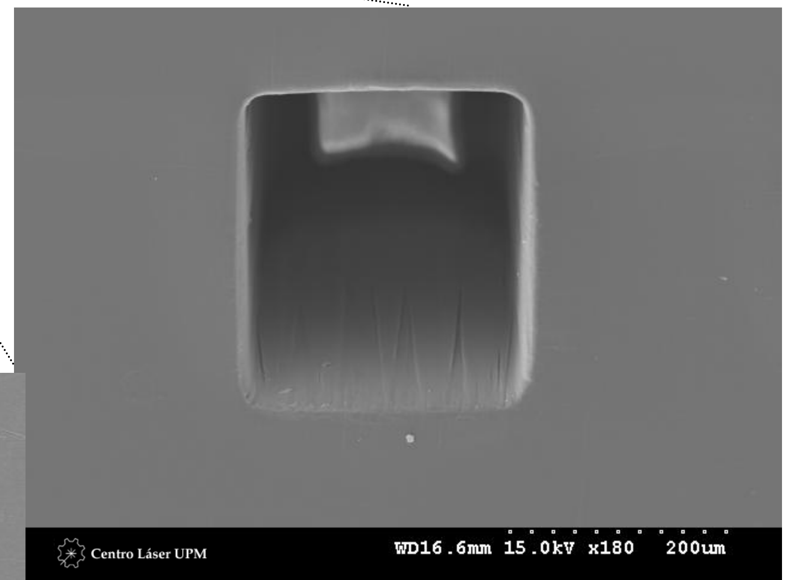


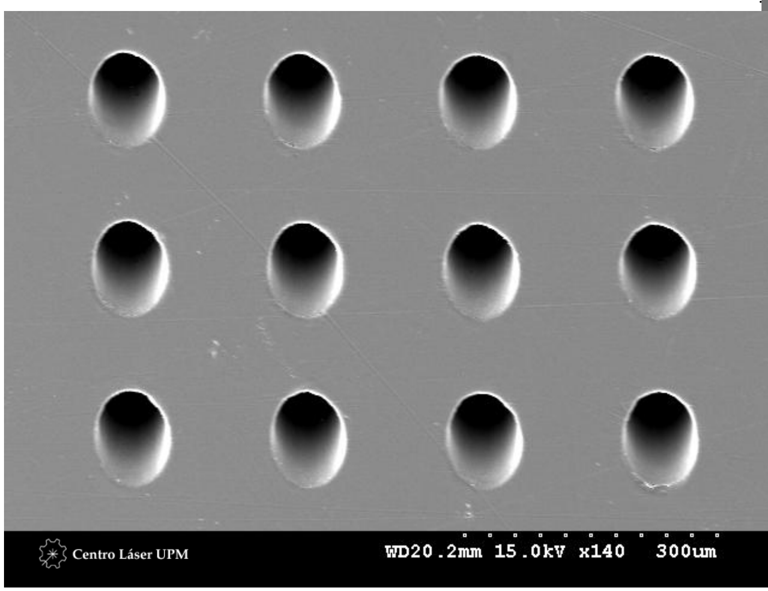
Steel: 1mm

CHANNELS FABRICATION WITH COLATITUDE CONTROL (2 + ½ D)



Polycarbonate

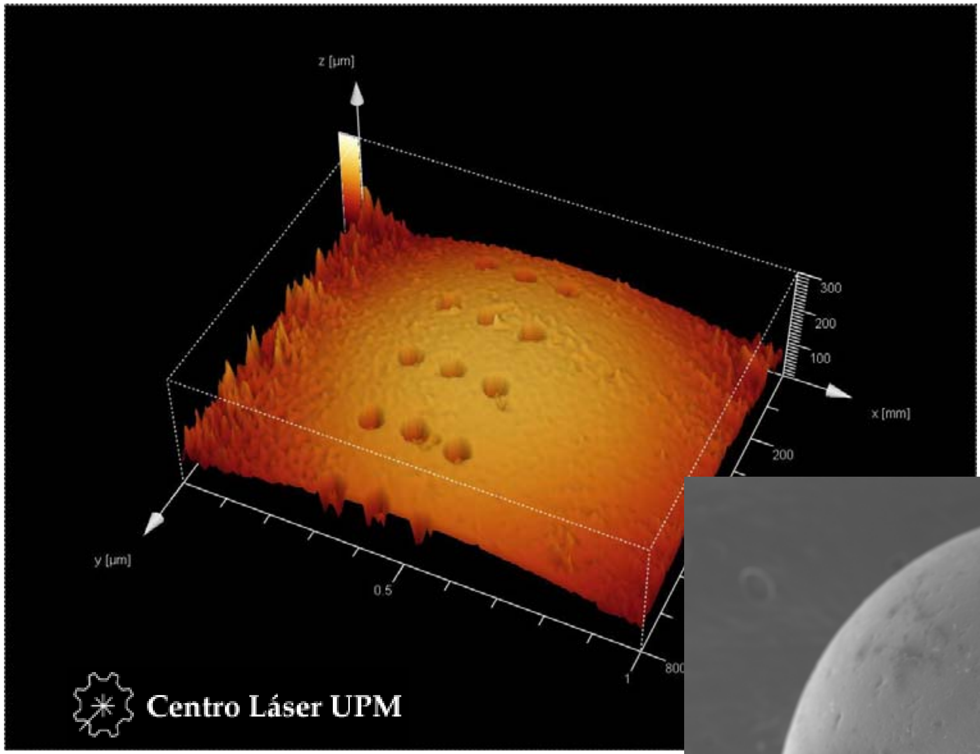




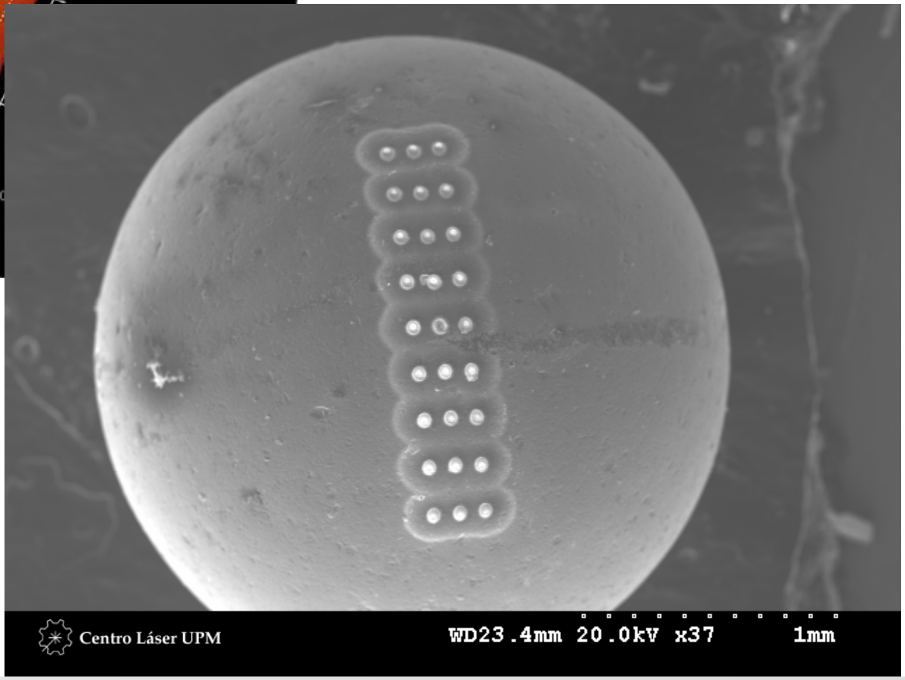
e=1 mm

L= 250 μm
α= 30º
Circular section

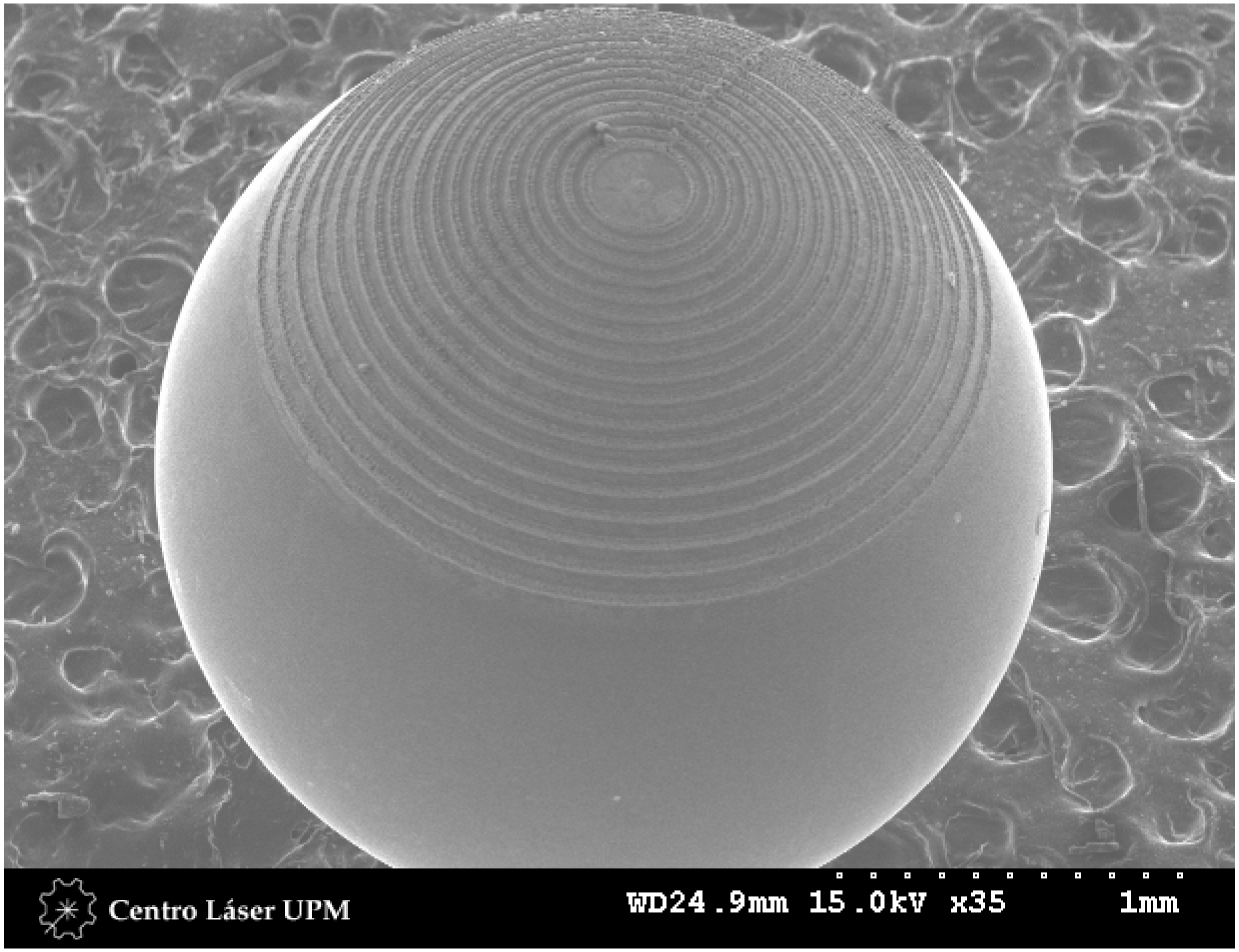
3D SURFACE TEXTURING



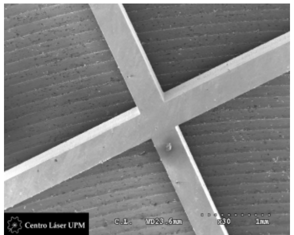
Sphere diameter = 2.5 mm
Φ = 75 µm

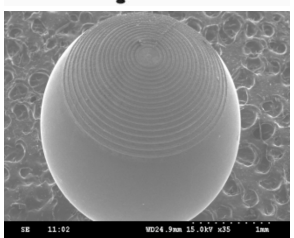


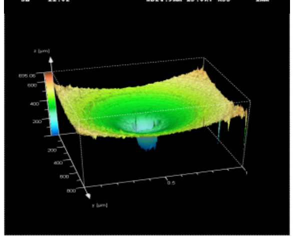
3D SURFACE TEXTURING

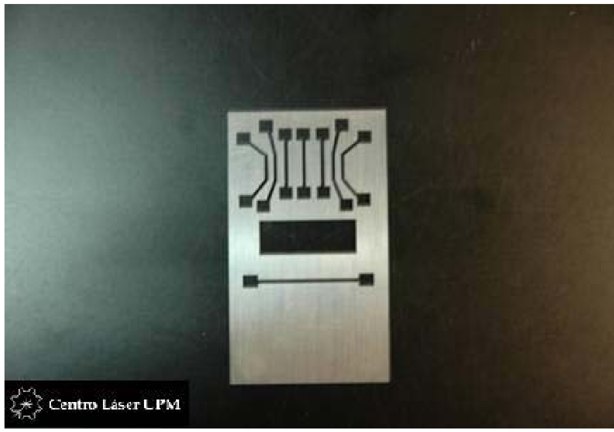


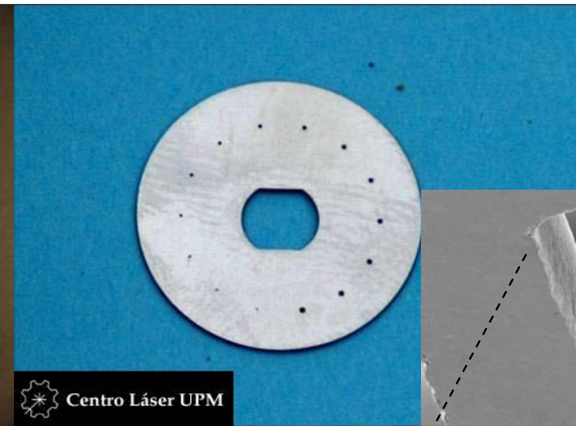
MICROMACHINING EXAMPLES

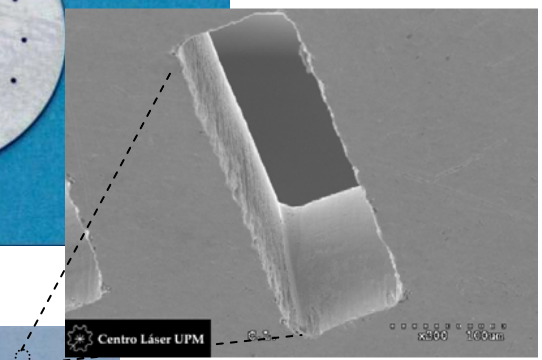


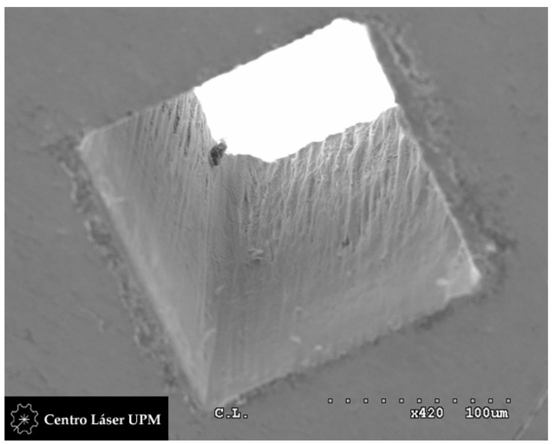


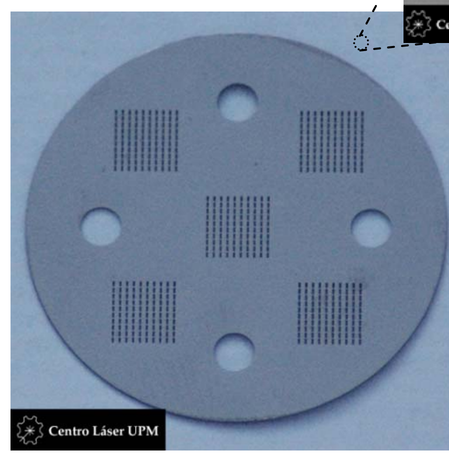




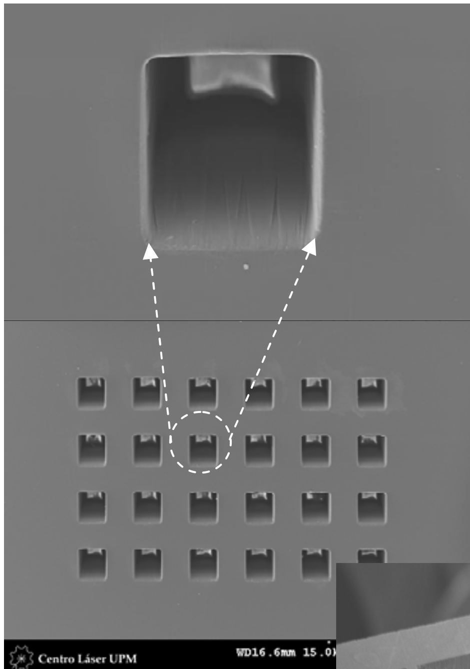


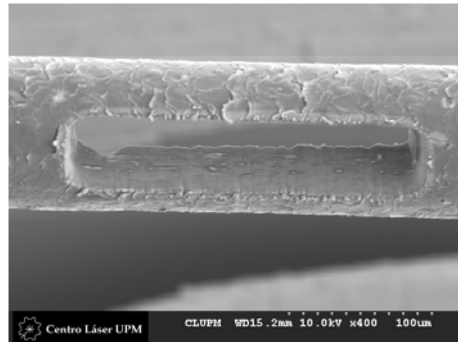


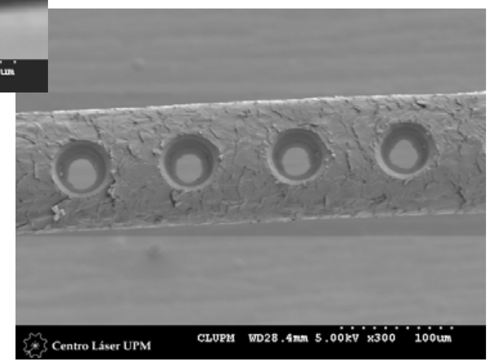


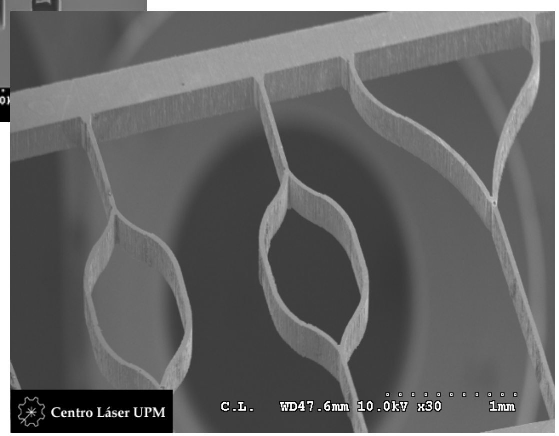


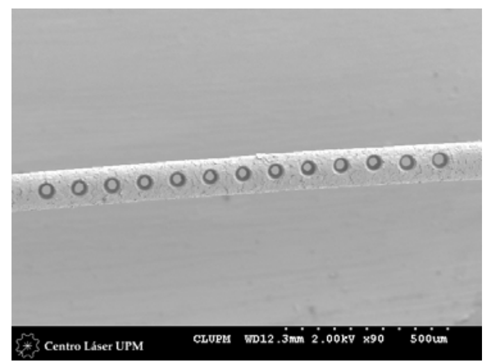
MICROMACHINING EXAMPLES











MICROPROCESSING: CML-1OO

CONCLUSIONS

- A prototype of a fully 3D flexible laser micromachining system has been designed and presently is completely operative

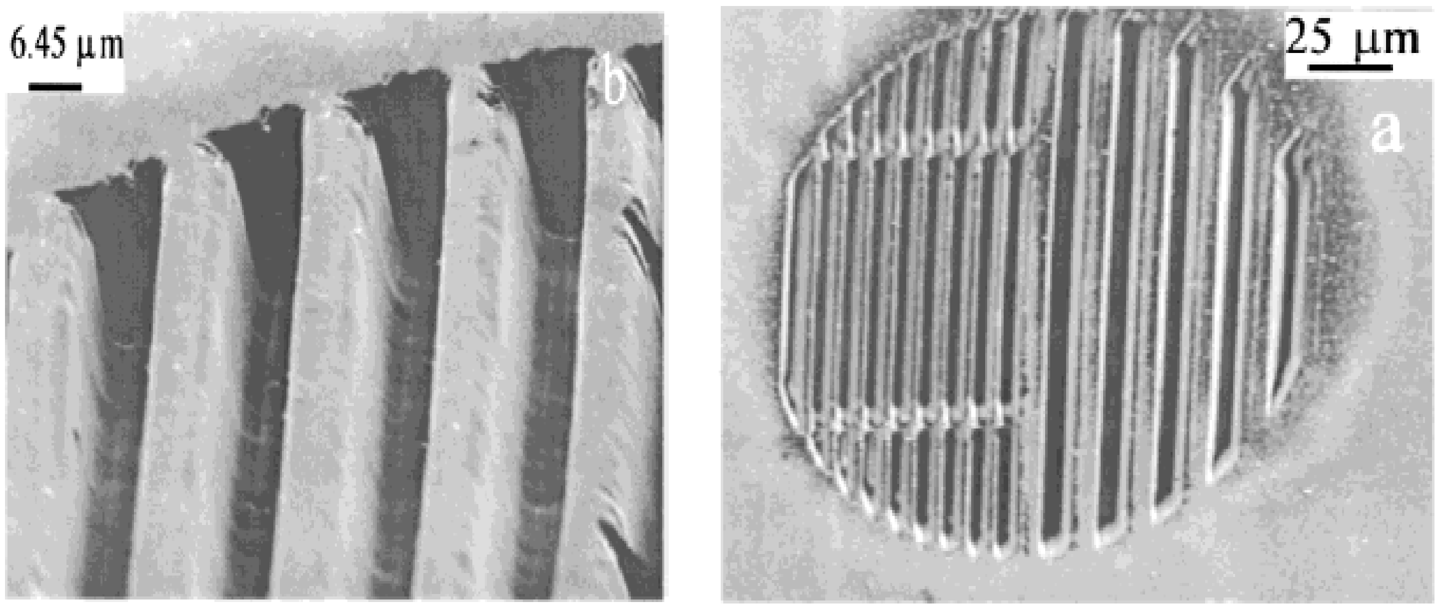
- Integration of excimer and DPSS UV laser in the same system has demonstrated to be an added value for this kind of equipment

- Complex geometries (concerning the workpiece and the pattern to be processed) have been obtained in different materials

- Nowadays there is an important demand for 2D and 2D + ½ applications and the appearance of fully 3D applications is expected for the next years

Morphological Surface Microstructuring by High Intensity Short Pulse Laser Interaction

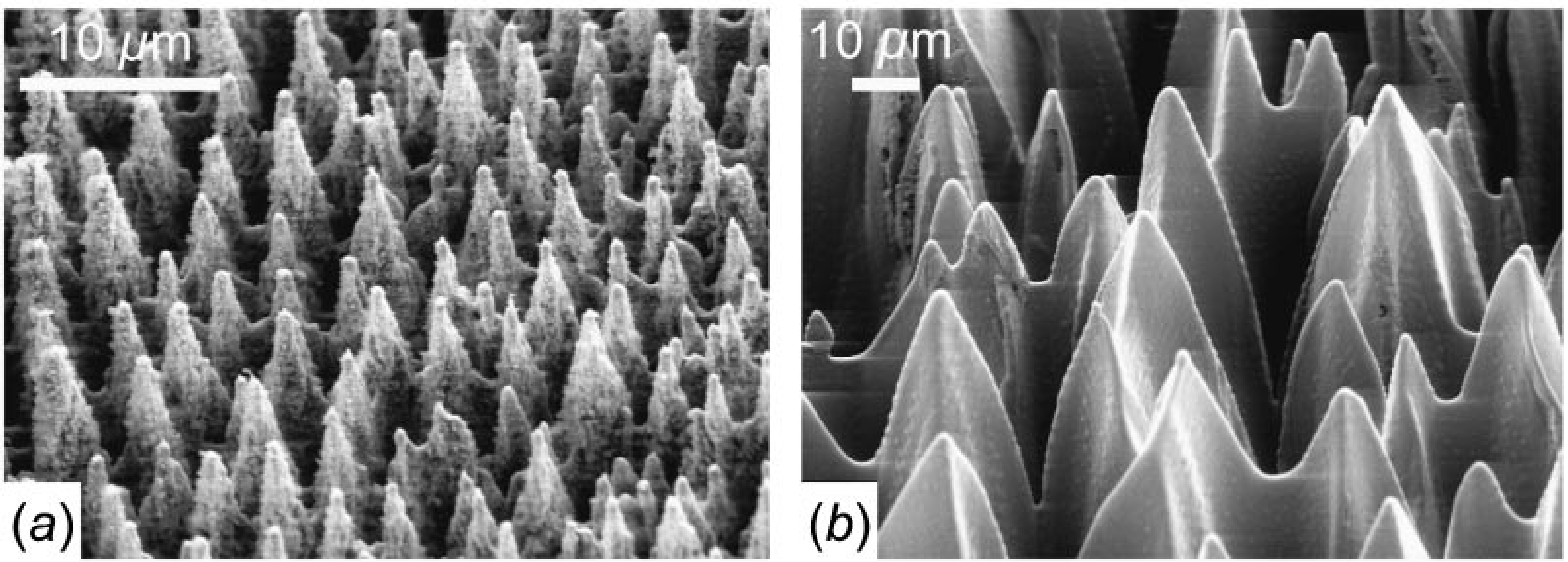
a. Laser surface microstructuring of polymeric surfaces



SEM micrographs of microstructures produced by a 20 ns pulse XeCl laser in different polymers : (a) structure in MP2C irradiated at 4.6 J cm-2 with 9 pulses; (b) structure in TM2C irradiated at 4.6 J cm-2 with 11 pulses.

Morphological Surface Microstructuring by High Intensity Short Pulse Laser Interaction

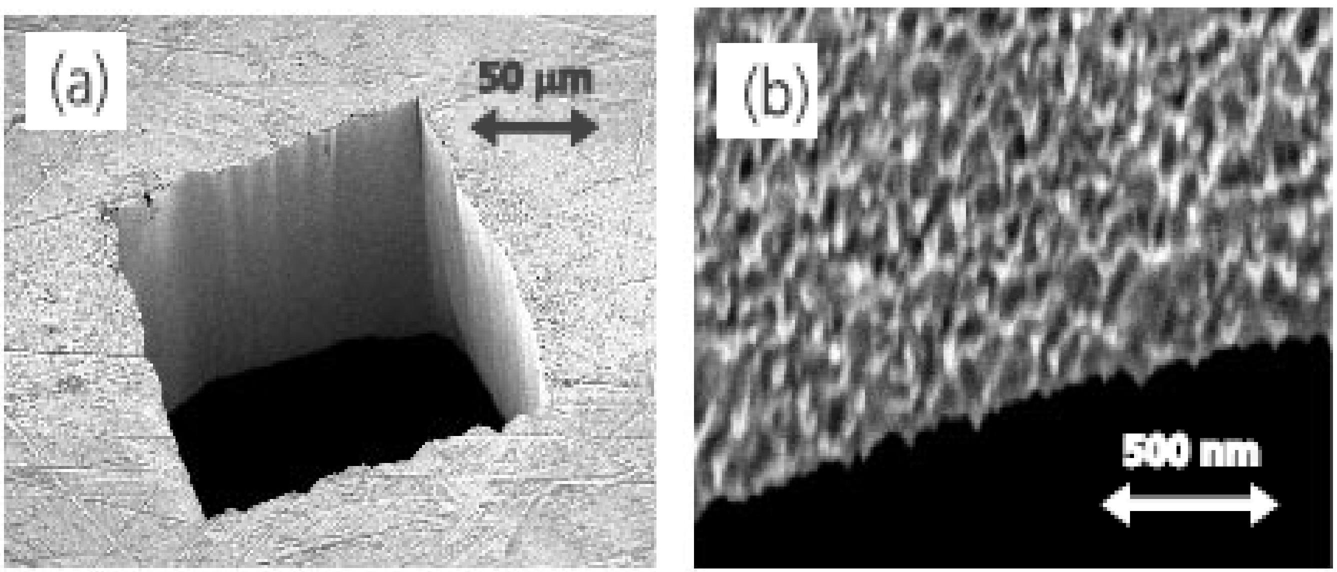
b) Laser surface microstructuring of semiconductors



Microstuctures formed in crystalline Si by laser pulses: a) Ti:Saphire laser of 100 fs pulse length up to 10 kJ/m2 fluence; b) KrF laser of 30 ns pulse length up to 30 kJ/m^2 fluence.

Morphological Surface Microstructuring by High Intensity Short Pulse Laser Interaction

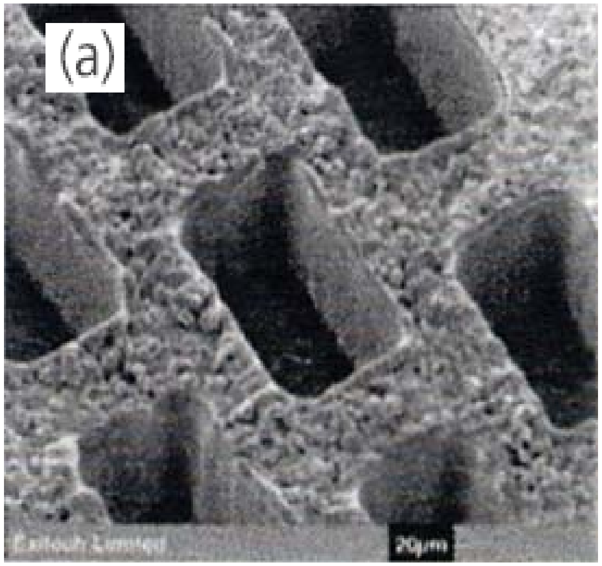
c) Laser surface microstructuring of metals and metallic alloys

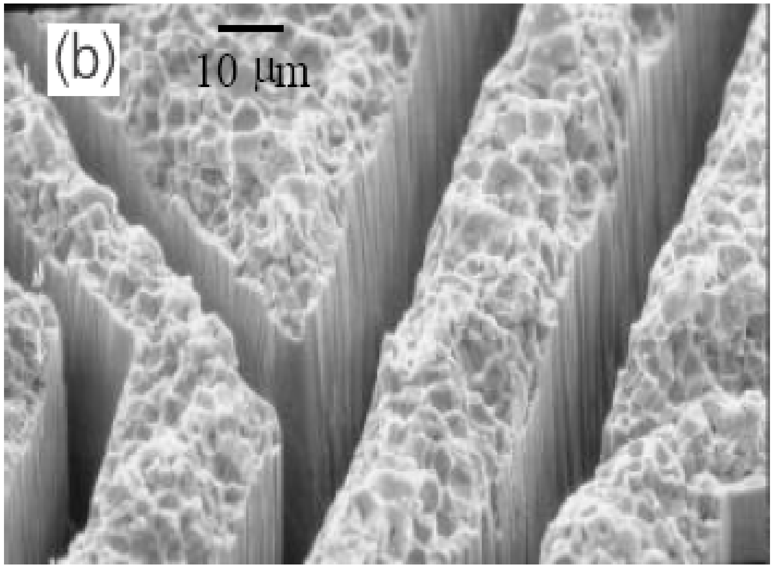


Microstructure generated in a stainless steel sheet with KrF laser radiation.
a) Rectangular hole machined with 120-fs pulses at 1013 W/cm2.; b) Magnified view of the microstructure of the exit edge of the exit edge of the same.

Morphological Surface Microstructuring by High Intensity Short Pulse Laser Interaction

d) Laser surface microstructuring of glass and ceramics (1/2)

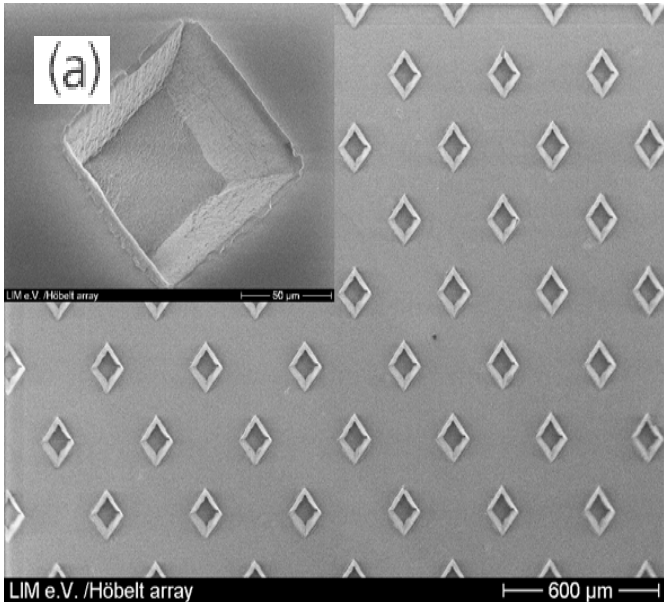


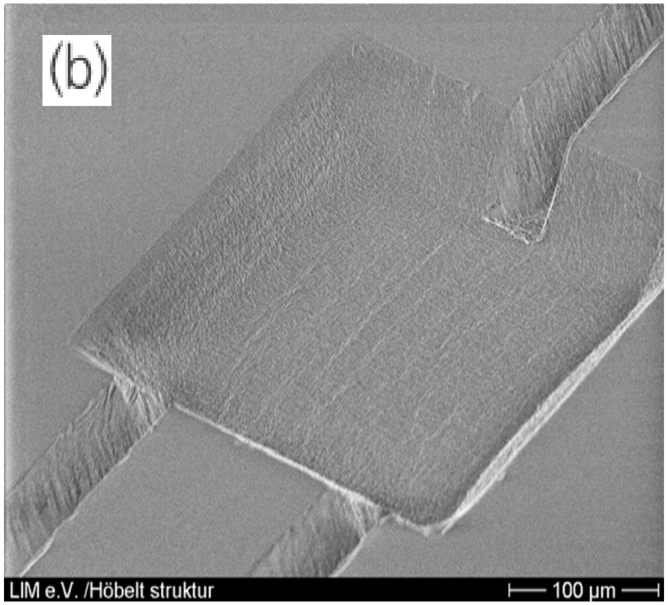


Samples of laser microstructuring of ceramic materials with high aspect ratio using a mask projection technique with UV lasers: a) alumina b) PZT

Morphological Surface Microstructuring by High Intensity Short Pulse Laser Interaction

d) Laser surface microstructuring of glass and ceramics (2/2)

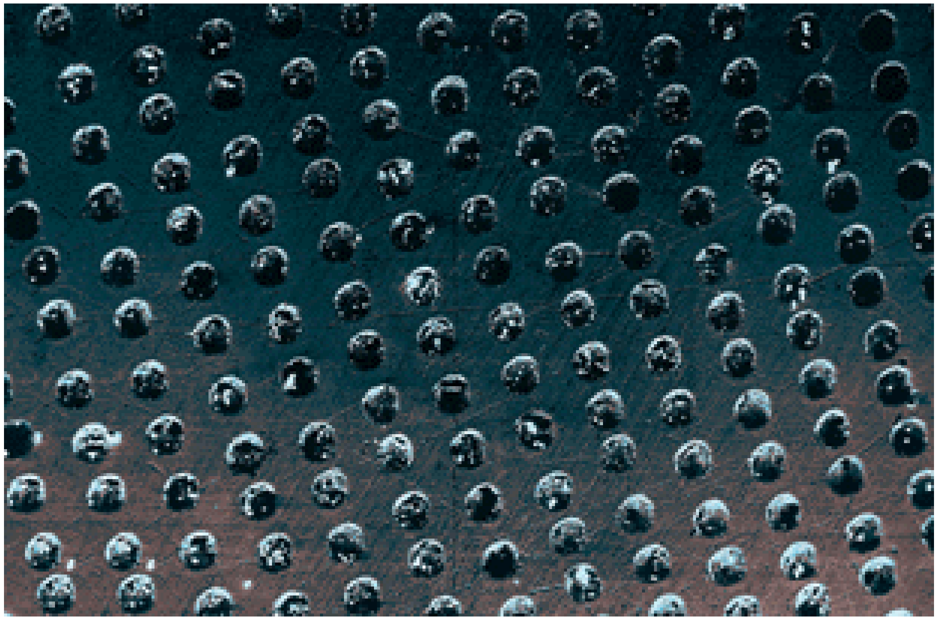




Laser generated structures in Pyrex® glass: a) Array of micro wells with 50 µm edge length and depth; b) cavity 350 x 350 x 55 µm3 with channels: 50 µm width, 55 µm depth.

Morphological Surface Microstructuring by High Intensity Short Pulse Laser Interaction

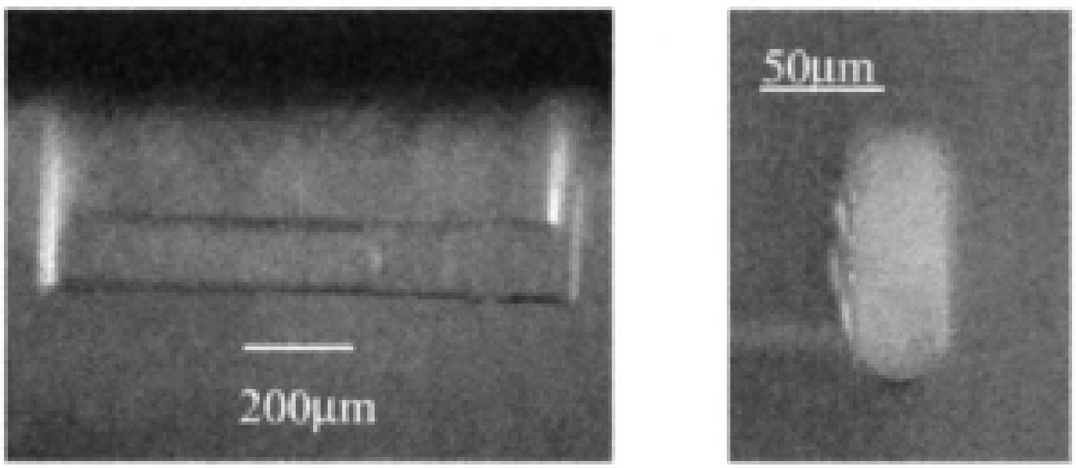
e) Laser Surface Texturing



Regular micro-surface in the form of micro-dimples structured by ns laser.

Morphological Surface Microstructuring by High Intensity Short Pulse Laser Interaction

f) 3D Laser glass microstructuring

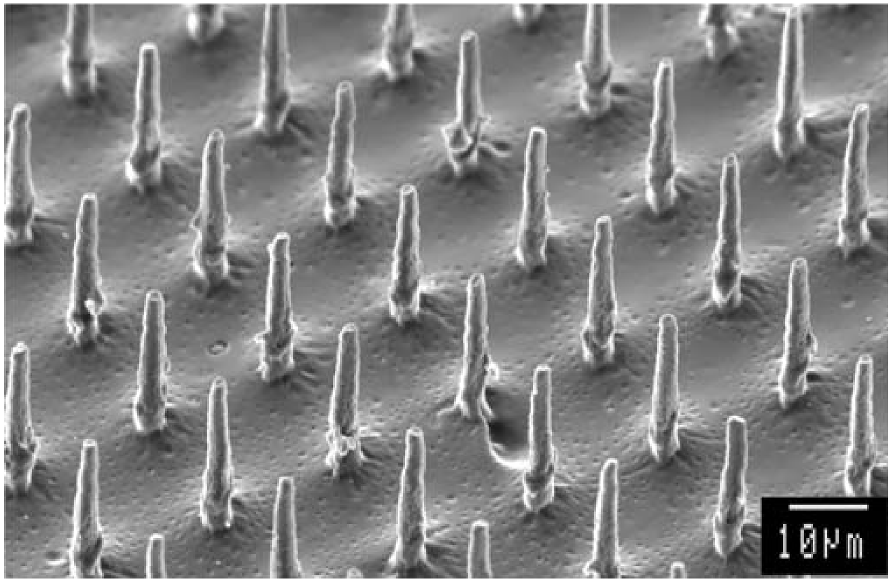


(a) (b)

3D Bridge-like microstructure generated by a 140 fs, 775 nm laser in Foturan®.

Morphological Surface Microstructuring by High Intensity Short Pulse Laser Interaction

g) Microstructuring by laser sintering and other techniques



Scanning electron micrograph showing a microscopic pillar array fabricated by casting a heat shrunk polymer template. (Courtesy of A.J. Lee et al.: Appl. Phys. A 80, 1447–1449, 2005)

MICRO-FORMING

LSPSIM PARAMETERS

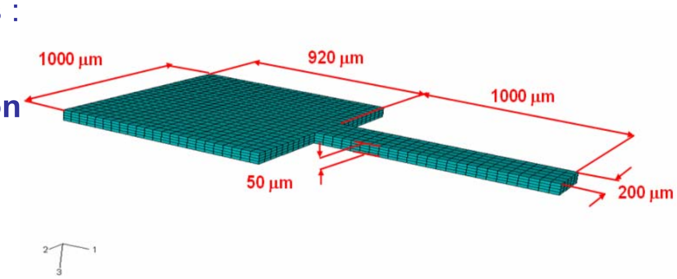
Nd:YAG Laser [nm]	1064
Energy per pulse [mJ]	33 - 150
Pulse length [ns]	9.4
Spot Radius [μm]	175
Target	SS304
Confining medium	Air
Interaction parameter α	0.2

ABAQUS PARAMETERS

Pressure Pulse Temporal Evolution	LSPSIM
Pressure Pulse Spatial Distribution	Top Hat
Spot Center Position	variable

GEOMETRY AND DIMENSIONS

- **Boundary Conditions** : pinned end.
- **Mechanical Simulation Elements:** C3D8R, 8-node brick reduced integration with hourglass control

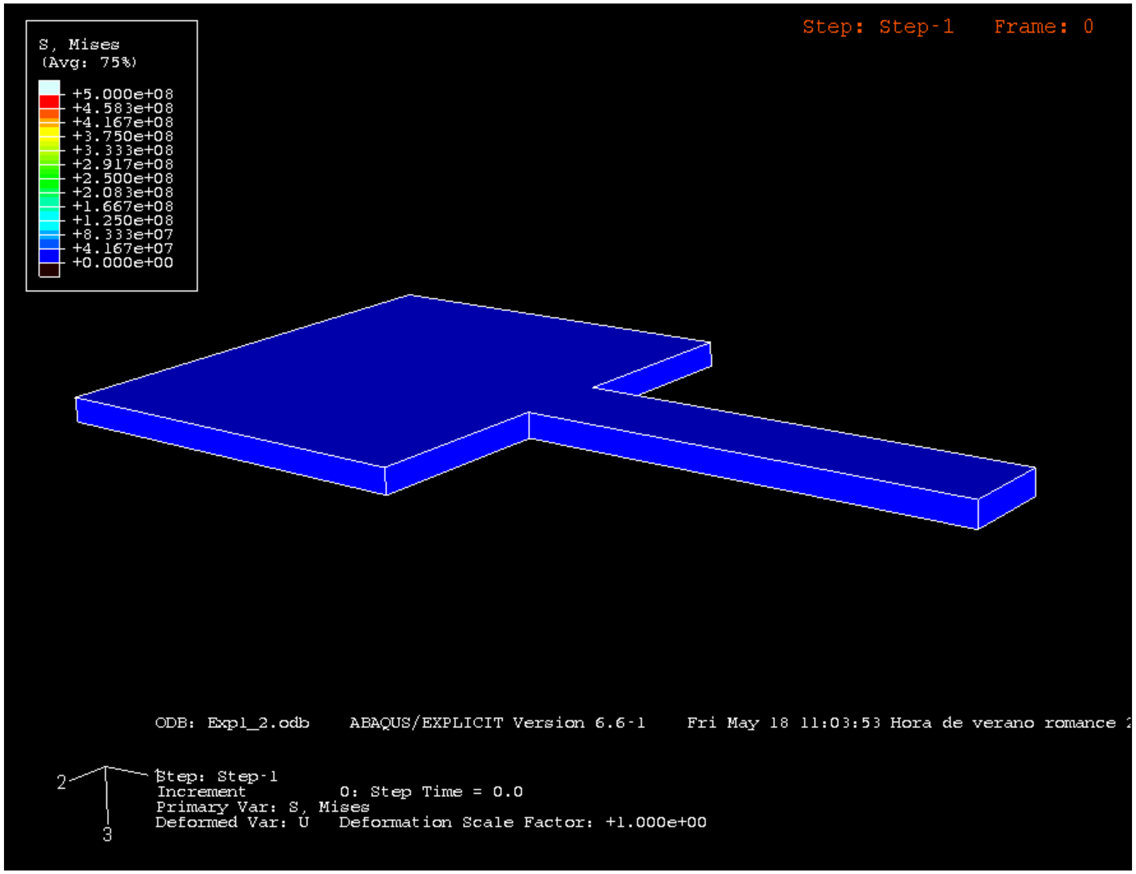


MATERIAL PROPERTIES (SS304)

Young's Modulus: E [GPa]	193
Poisson's Coeffcient: ν	0.25
Denssity: ρ [kg/m^3]	7896
Melting Temperature: T_m [K]	1811
Test Temperature: T_0 [K]	300
Inelastic Heat Fraction: X	0.9
Johnson-Cook	
A [MPa]	350
B [MPa]	275
C	0.022
n	0.36
m	1
T_r [K]	300
$\dot{\varepsilon}_0$ [s^{-1}]	1

MICRO-FORMING

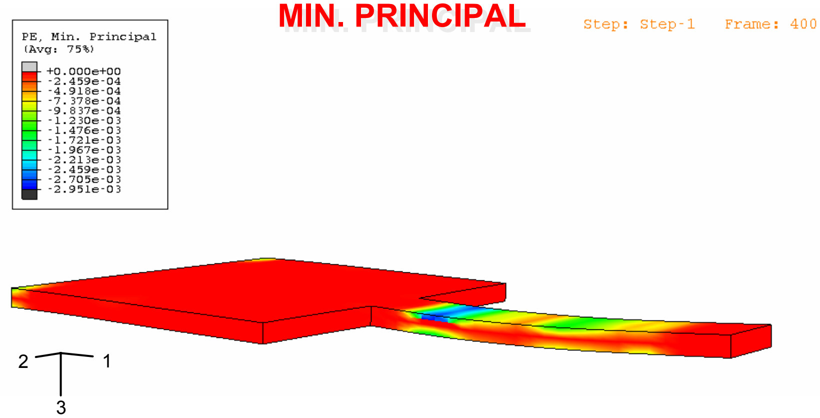
ABAQUS EXPLICIT – VON MISES EVOLUTION



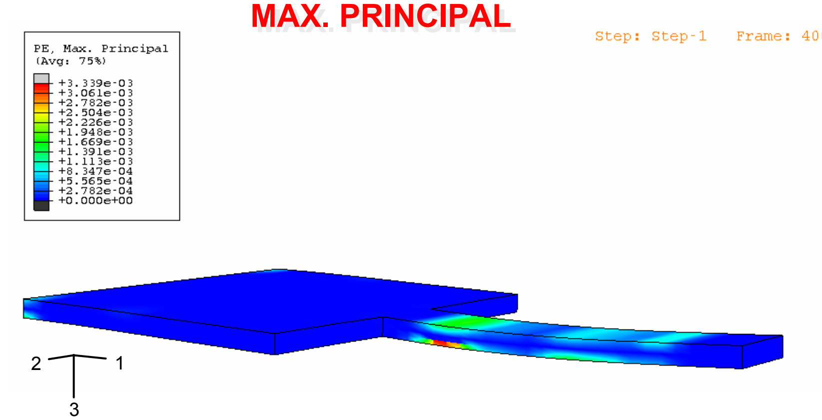
MICRO-FORMING

PLASTIC STRAIN

MIN. PRINCIPAL

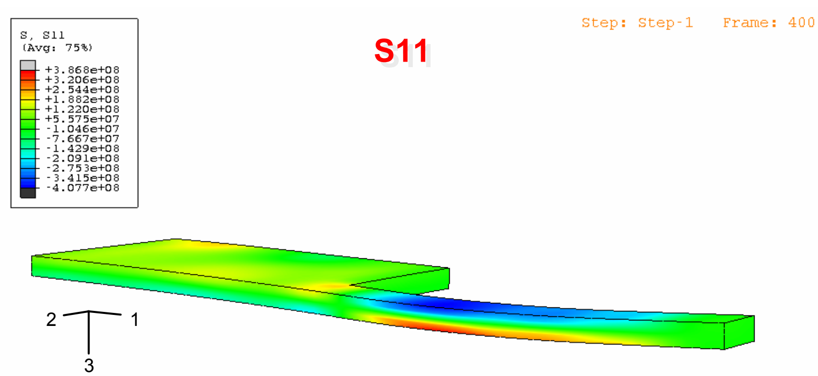


MAX. PRINCIPAL

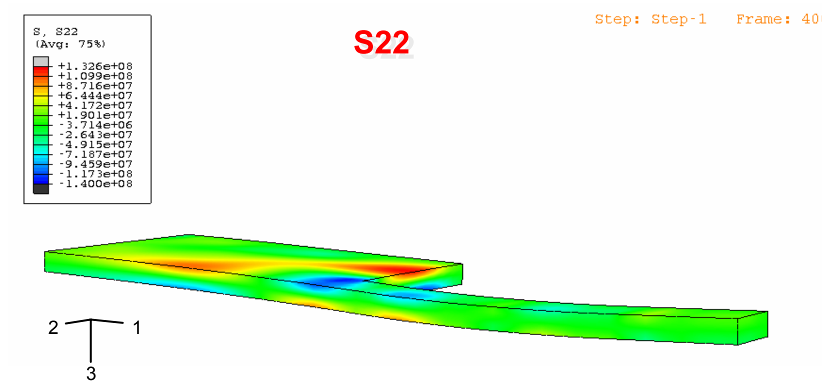


STRESS DISTRIBUTION

S11



S22

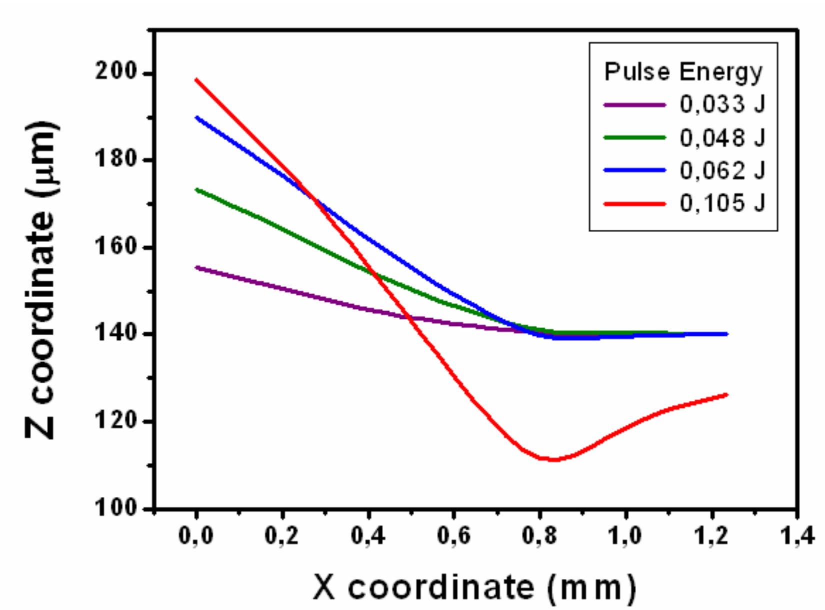


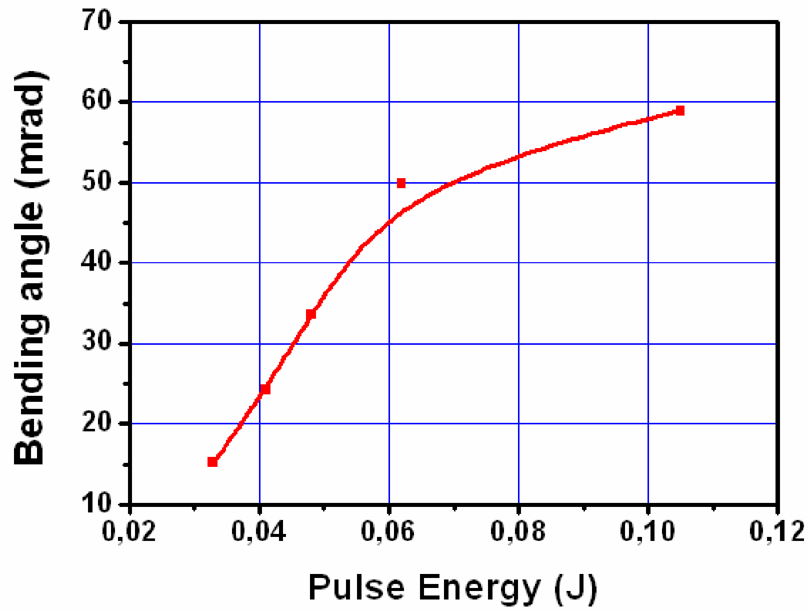
MICRO-FORMING

Pulse Energy Parametric Depency

Nd:YAG Laser [nm]	1064
Energy per pulse [mJ]	variable
Pulse length [ns]	9.4
Spot Radius [μm]	175

Material Model	SS304 = JC
Confining medium	Air
Interaction parameter α	0.2
Spot center distance [μm]	150



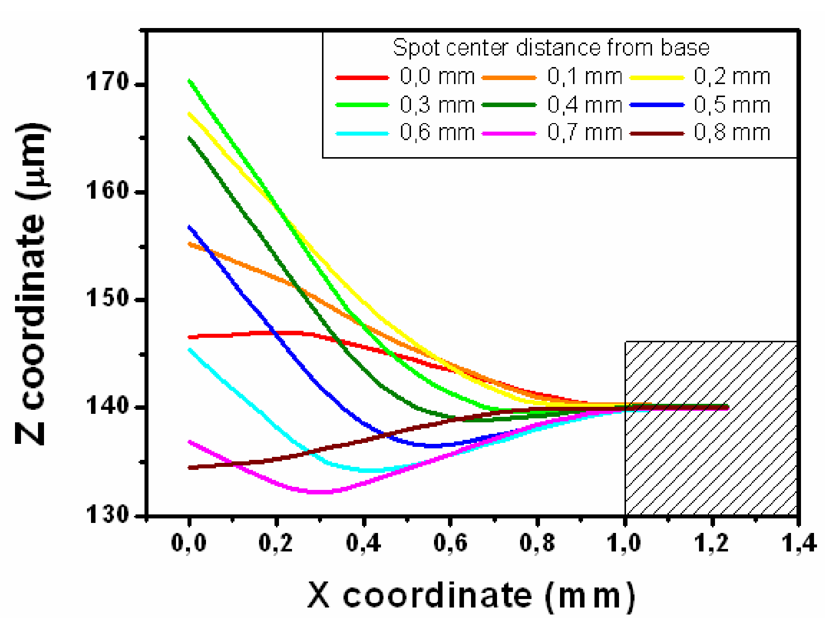


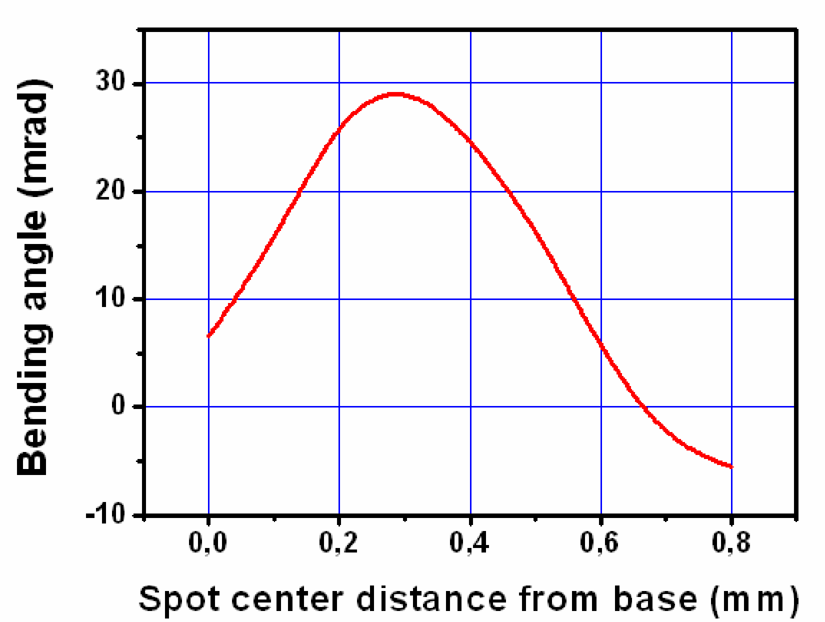
MICRO-FORMING

Spot Center Distance Parametric Dependency

Nd:YAG Laser [nm]	1064
Energy per pulse [mJ]	33
Pulse length [ns]	9.4
Spot Radius [μm]	175

Material Model	SS304 = JC
Confining medium	Air
Interaction parameter α	0.2
Spot center distance [μm]	variable



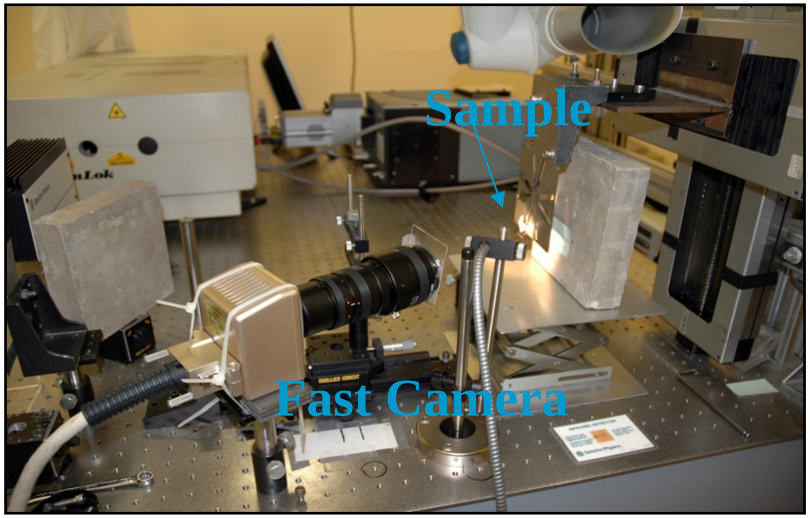


MICRO-FORMING

EXPERIMENTAL SETUP

MicroForming Parameters

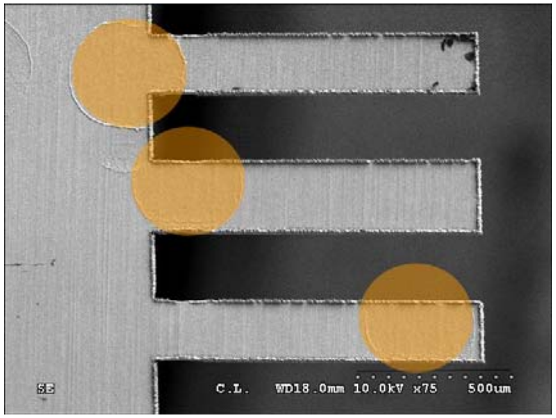
Nd:YAG Laser Wavelength [nm]	1064
Energy per pulse [J]	1.05
Pulse length FWHM [ns]	9.4
Beam radius (mm)	15
Mask radius [μm]	750
Energy per pulse (after mask) [J]	0.033
Spot radius [μm]	175
Confining layer	air

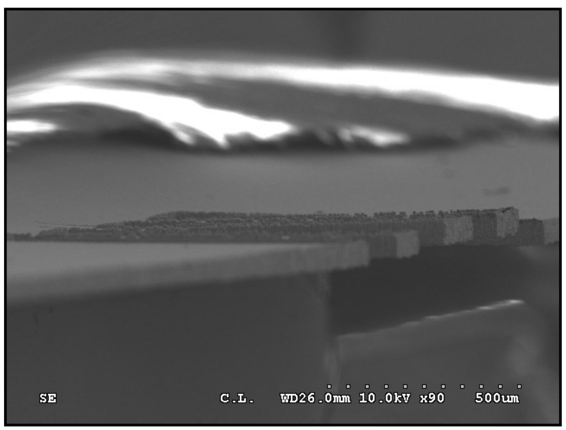


MICRO-FORMING

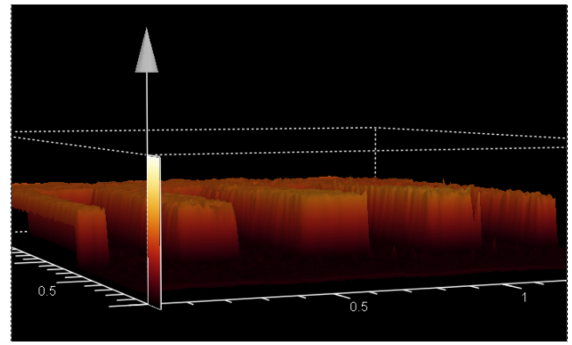
SPOT CENTER DISTANCE INFLUENCE

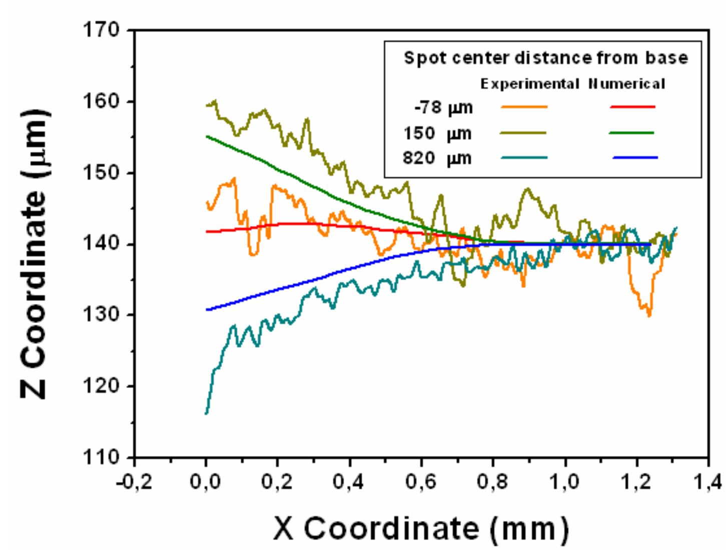
SEM IMAGES





CONFOCAL MICROSCOPY





MICRO-FORMING

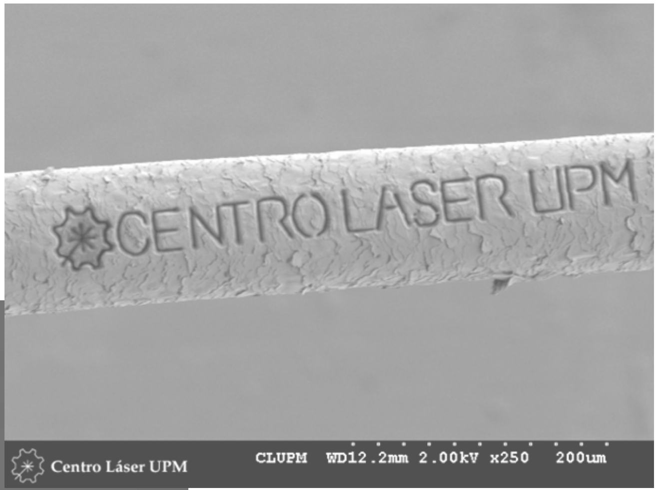
REFERENCES

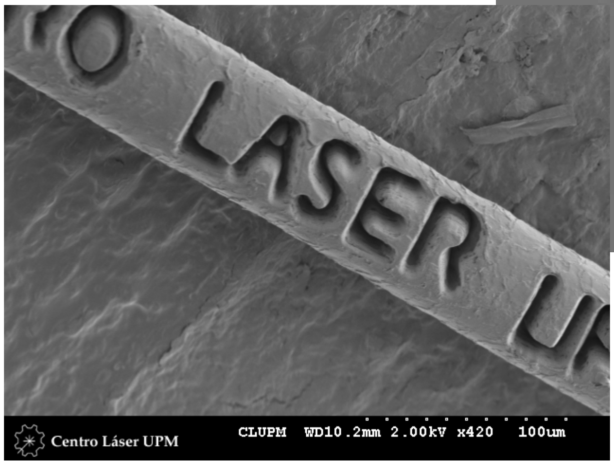
1. Ocaña, J.L. et al.: "A Model for the Coupled Predictive Assessment of Plasma Expansion and Material Compression in Laser Shock Processing Applications". In: High-Power Laser Ablation II, Claude R. Phipps, Masayuki Niino, Eds., SPIE Proceedings , Vol. 3885, 252–263 (2000)
2. Ocaña, J.L. et al.: "Predictive assessment and experimental characterization of the influence of irradiation parameters on surface deformation and residual stresses in laser shock processed metallic alloys". In: High-Power Laser Ablation V, Phipps C.R., Ed.. SPIE Vol. 5548, 642-653 (2004)
3. Ocaña, J.L. et al.: High Power Laser Ablation V. SPIE Proc. 5548 (2004) 642-653
4. Ocaña, J.L. et al.: Appl. Surf. Sci., 238 (2004) 242-248
5. Rubio-González, C. et al.: Mat. Sci. Eng. A., 386 (2004) 291-295
6. Ocaña, J.L. et al.: "Laser Shock Processing as a Method for Surface Properties Modification of Metallic Materials". In: Shot Peening and other Mechanical Surface Treatments, V. Shulze, A. Niku-Lari, Eds. I.I.T.T. Paris (2005), 466-471.
7. Sanchez-Santana, U., et al.: Wear, 260 (2006) 847-854
8. Rubio-González, C. et al.: Appl. Surf. Sci., 252 (2006) 6201-6205

ACKNOWLEDGEMENTS

Work partly supported by MEC (Spain; DPI2005-09152) and EADS-MTD-Spain

ABLATION





Inscription on human hair

Thank you !