Laser Shock Micro-Forming of Thin Metal Sheets: Physical Principles, Modelling and Experimental Implementation

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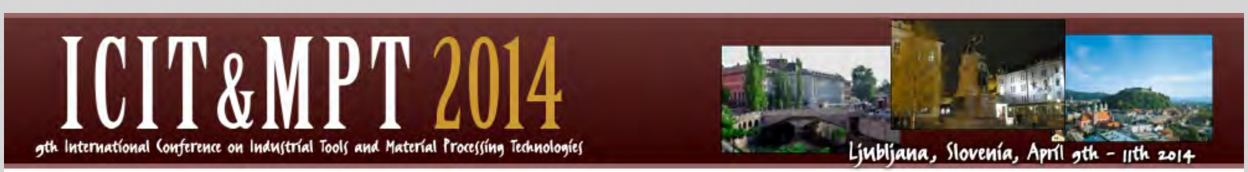

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OUTLINE:

- Introduction
- Physical Principles. Simulation Model
- Simulation Results
- Experimental Setup. Sample Preparation
- Experimental Results
- Recent Alternative Approaches
- Discussion and Outlook

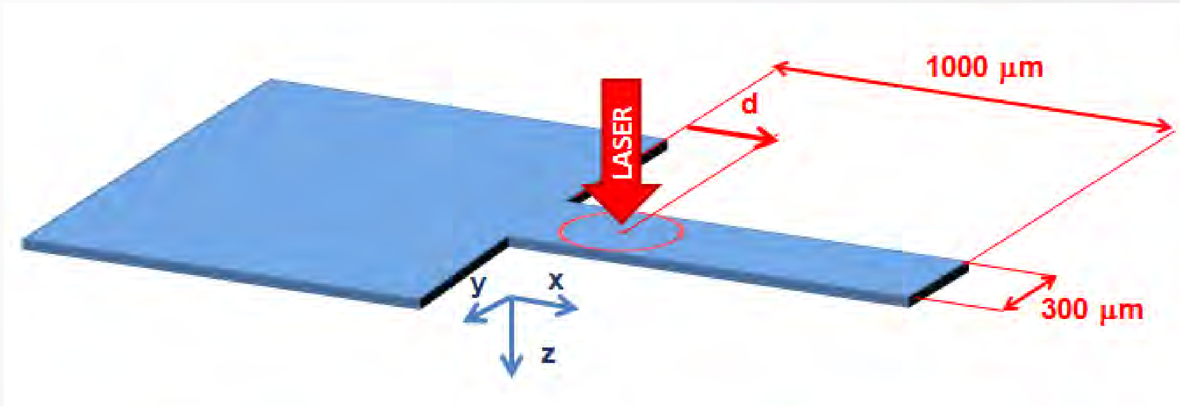
1. INTRODUCTION. MOTIVATION

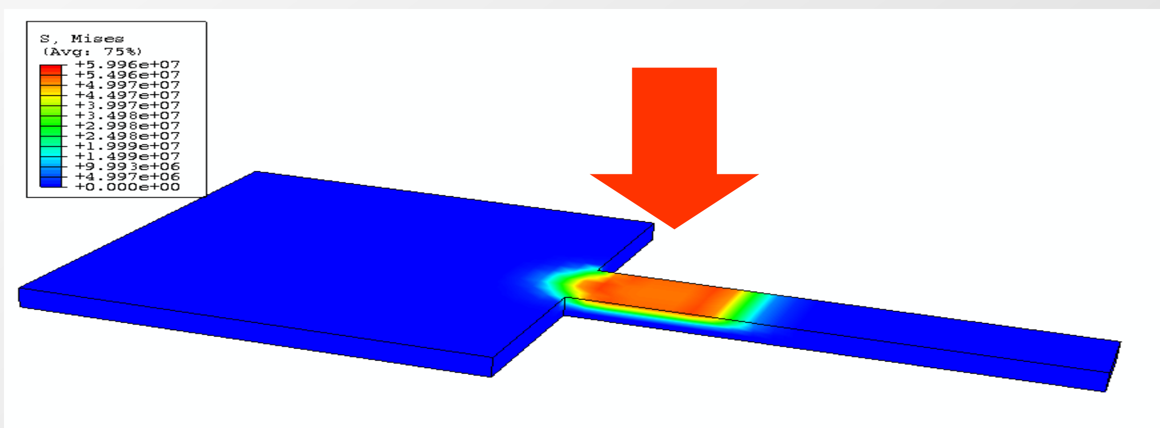
- **The increasing demands in MEMS fabrication are leading to new requirements in production technology. Especially the packaging and assembly require high accuracy in positioning and high reproducibility in combination with low production costs.**
- **Conventional assembly technology and mechanical adjustment methods are time consuming and expensive. Each component of the system has to be positioned and fixed. Also adjustment of the parts after joining requires additional mechanical devices that need to be accessible after joining.**
- **Accurate positioning of smallest components represents an up-to-date key assignment in micro-manufacturing. It has proven to be more time and cost efficient to initially assemble the components with widened tolerances before precisely micro-adjusting them in a second step.**

1. INTRODUCTION. PROPOSED APPROACH

- **Provided that mounted micro components are typically difficult to access and highly sensitive to mechanical forces and impacts, contact-free laser adjustment processes offer a great potential for accurate manipulation of micro devices.**
- **However, long relaxation-time thermal fields developed in continuous or long-pulse laser forming of metal thin sheets are responsible for the introduction of constraint residual stresses in component assembly processes.**
  - **Changes in the materials microstructure could cause changes in density and volume and create stresses**
  - **Chemical reactions of the irradiated surface, e.g. oxidation could take place and lead to stressed surface layers**
- **The use of ns laser pulses inducing predominantly mechanical deformation stresses provides the capability for a suitable parameter matching in laser bending of MEMS components.**
- **Theoretical interaction regime description, computational process simulation results and preliminary experimental results and practical issues are presented in this work.**

2. PHYSICAL PRINCIPLES





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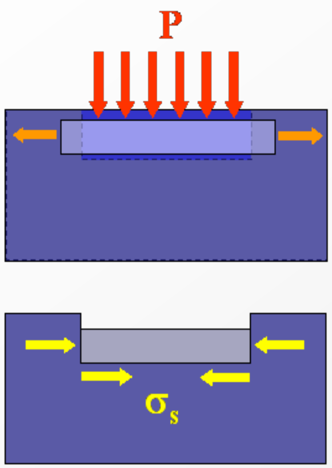

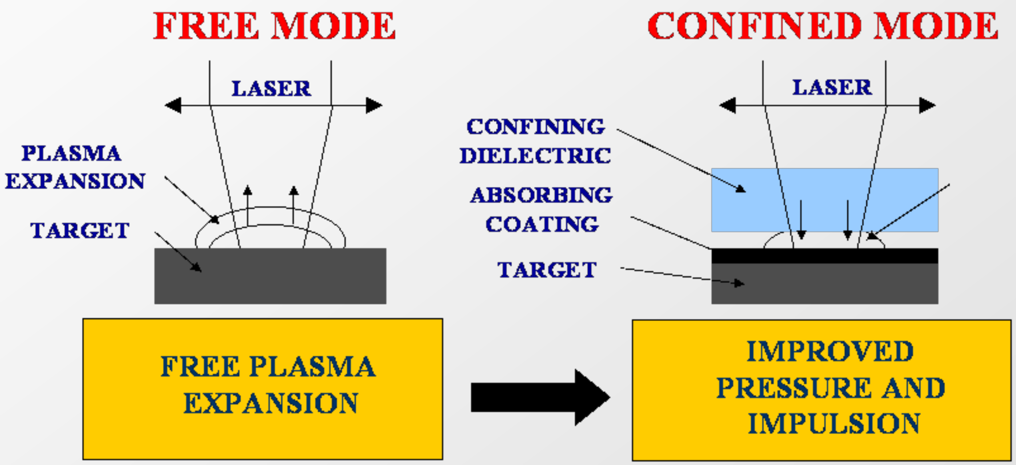

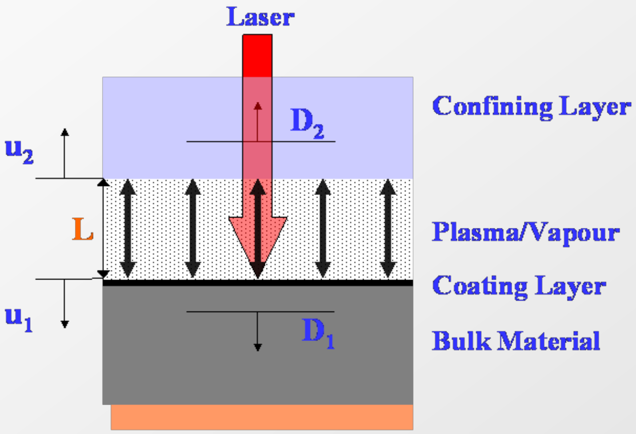

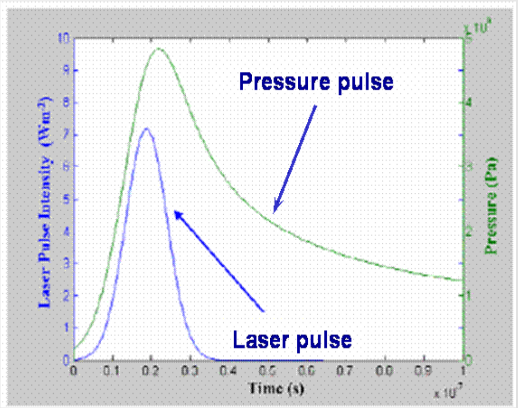

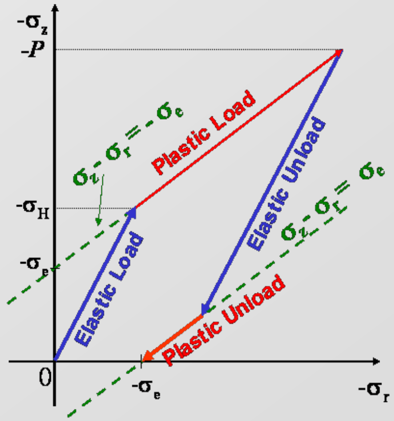

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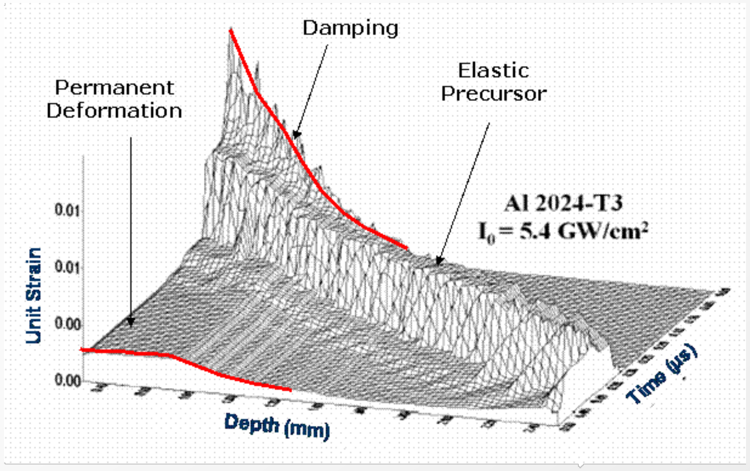
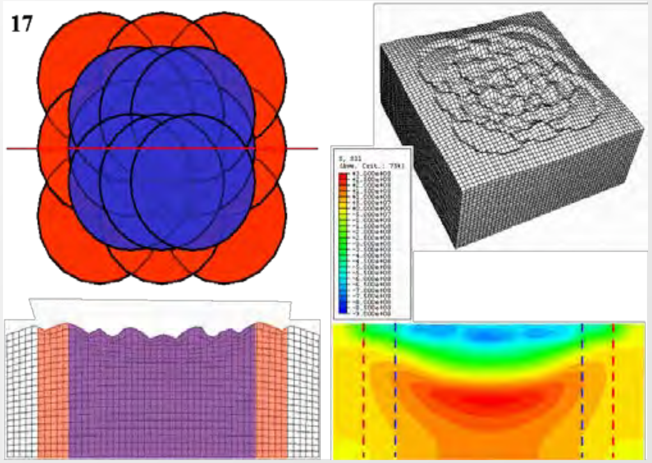
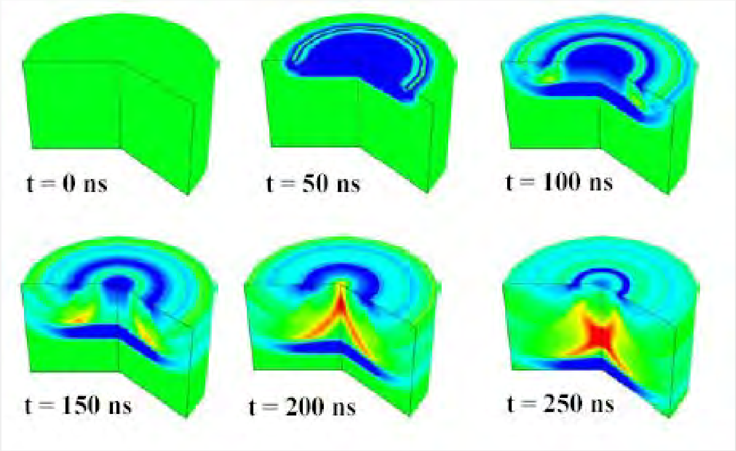
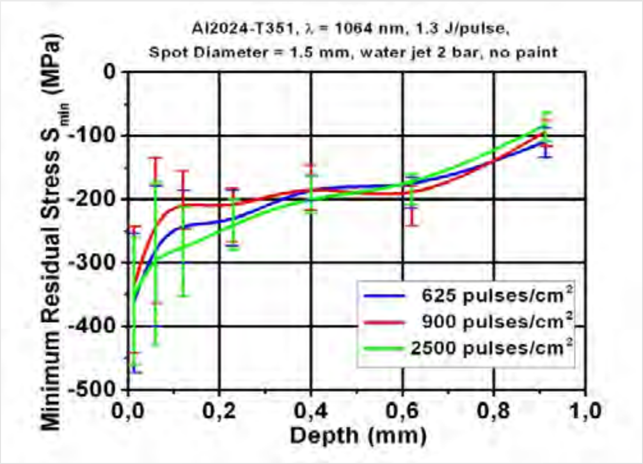
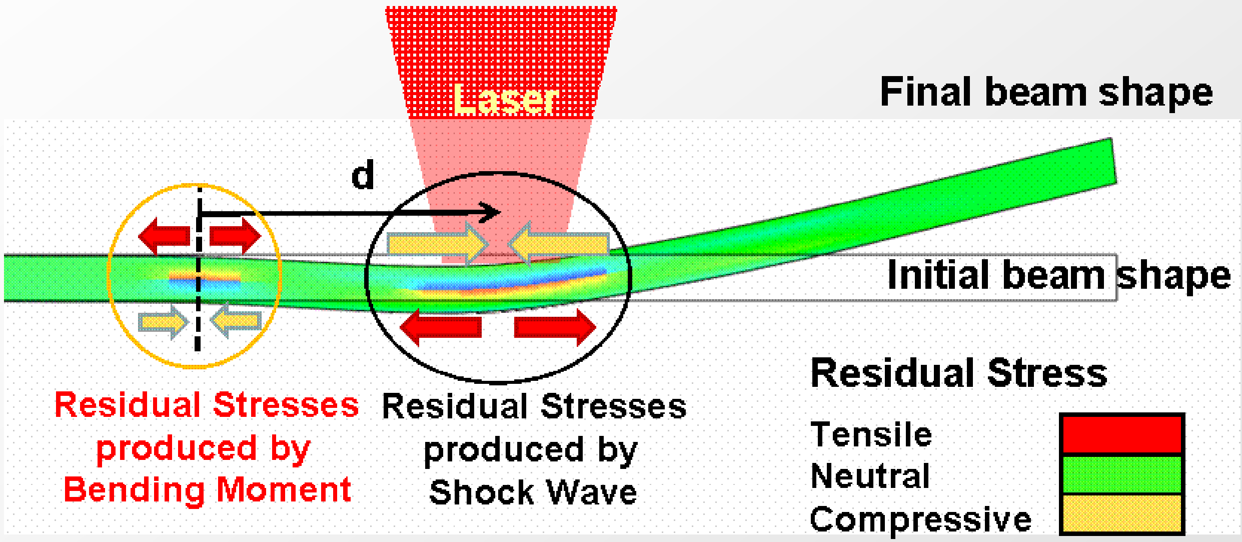


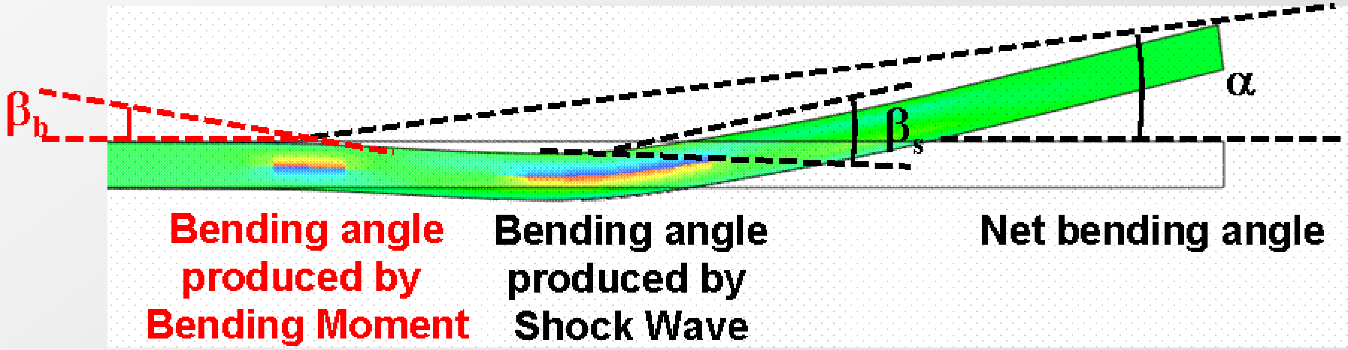






2. PHYSICAL PRINCIPLES





2. NUMERICAL SIMULATION. MODEL DESCRIPTION

PRESSURE PULSE MODEL

LSPSIM

Interface thickness

$$L(t)=\int_0^t[u_1(t)+u_2(t)]\,dt$$

Heating phase

$$I(t)=P(t)\frac{dL(t)}{dt}+\frac{d[E_i(t)L(t)]}{dt}$$

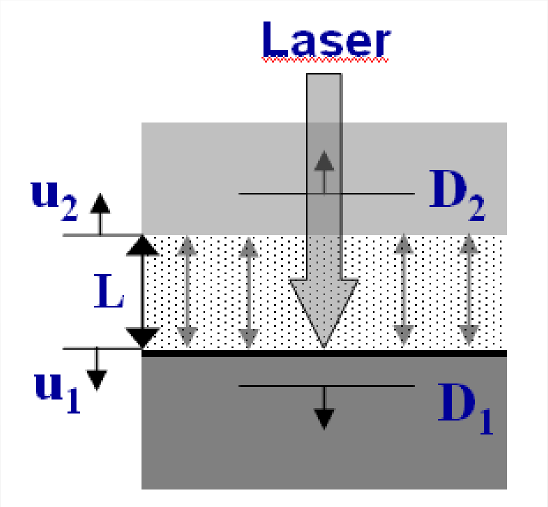
$$P(t)=\frac{2}{3}E_t(t)=\frac{2}{3}\alpha E_i(t)$$

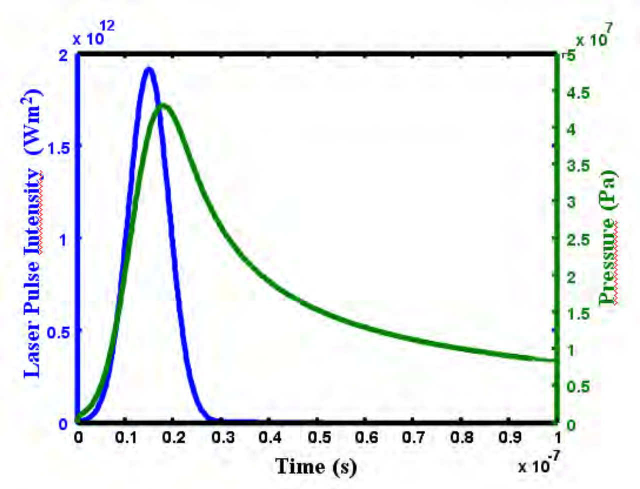
Shock wave relation

$$P=\rho_i D_i u_i$$

Solid/Liquid $D=C+S\,u$

Gas $D=u=\left(\frac{(\gamma+1)}{2}\frac{P}{\rho}\right)^{1/2}$

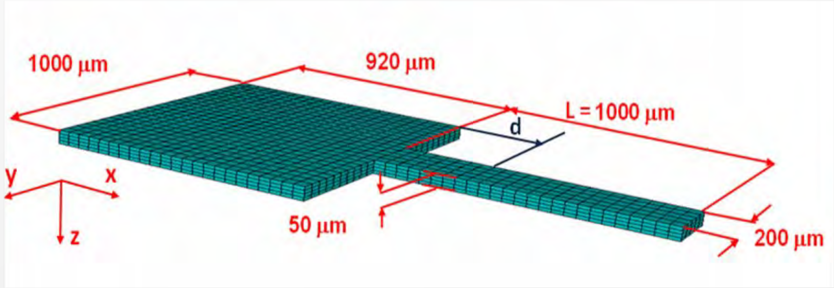




2. NUMERICAL SIMULATION. MODEL DESCRIPTION

FEM MODEL – STRESS-STRAIN ANALYSIS

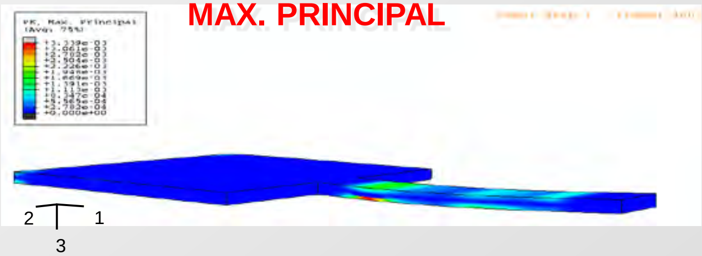
GEOMETRY AND DIMENSIONS



PLASTIC STRAIN

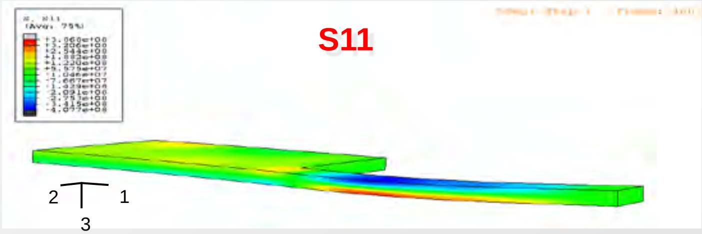
MIN. PRINCIPAL

MAX. PRINCIPAL



STRESS DISTRIBUTION

S11



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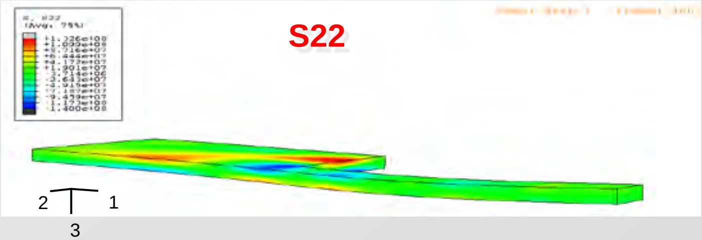


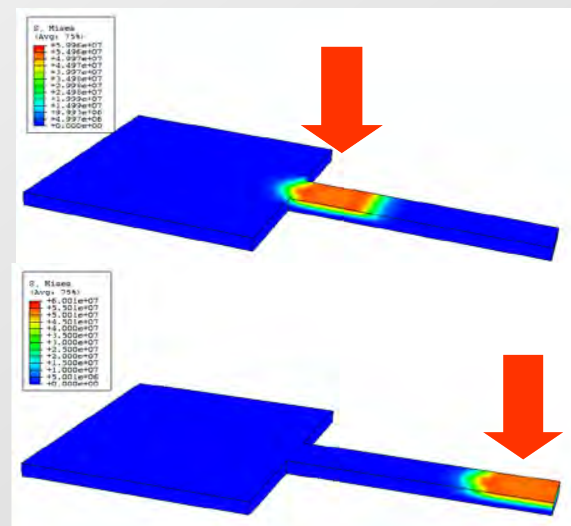
2. NUMERICAL SIMULATION. MODEL DESCRIPTION

MATERIAL PROPERTIES (AISI 304)

Target	AISI 304
Young's Modulus: E [GPa]	193
Poisson's Coeffcient: ν	0.25
Densisty: ρ [kg/m3]	7896
Melting Temperature: Tm [K]	1811
Test Temperature: T0 [K]	300
Inelastic Heat Fraction: X	0.9
Johnson-Cook parameters	
A [MPa]	350
B [MPa]	275
C	0.022
n	0.36
m	1
T_r [K]	300
$\dot{\varepsilon}_0$[s^{-1}]	1

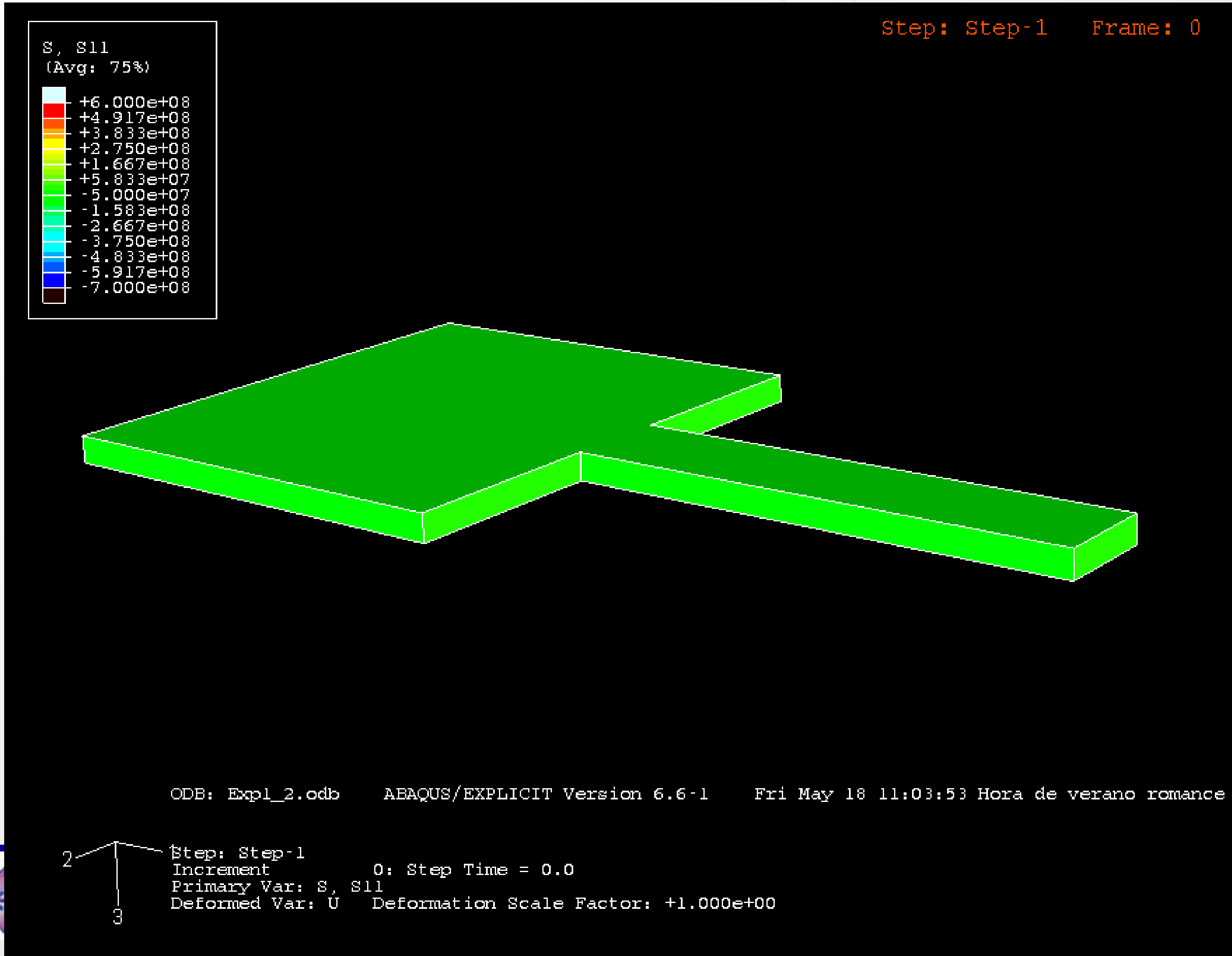
LSPSIM PARAMETERS

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



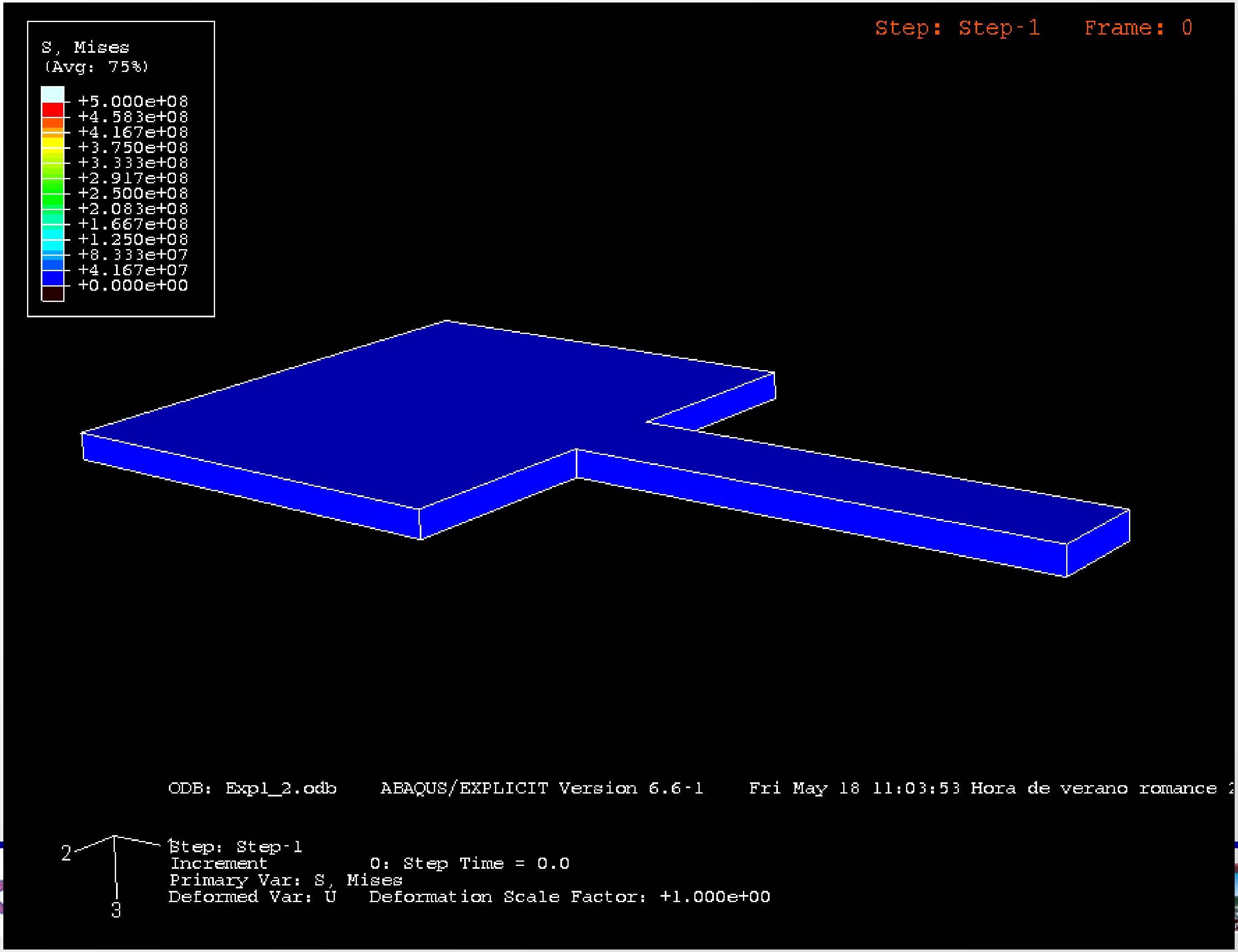
3. NUMERICAL SIMULATION RESULTS

SHOCKLAS EXPLICIT – STRESS (S11) EVOLUTION



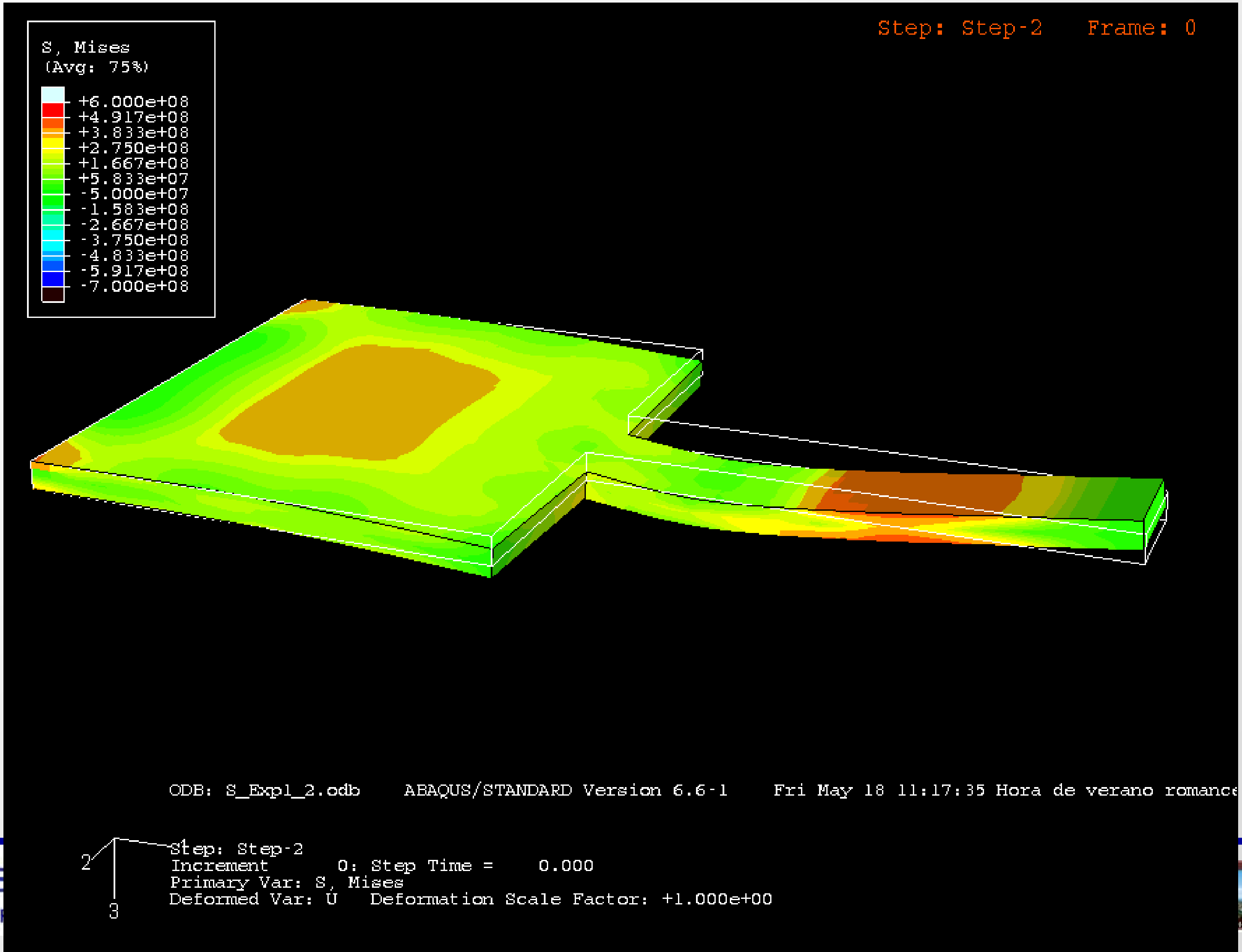
3. NUMERICAL SIMULATION RESULTS

SHOCKLAS EXPLICIT – VON MISES EVOLUTION



3. NUMERICAL SIMULATION RESULTS

SHOCKLAS STANDARD – STRESS (S11) EQUILIBRATION

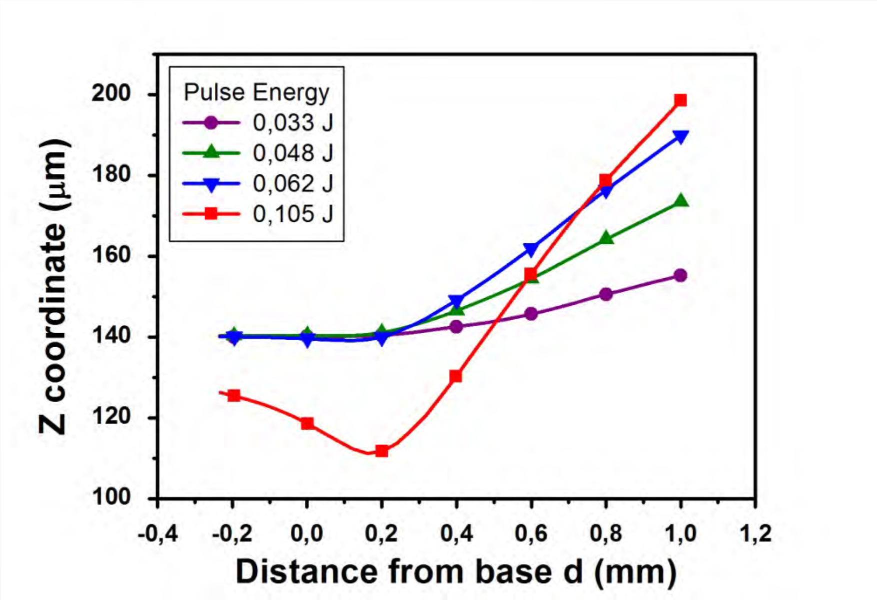


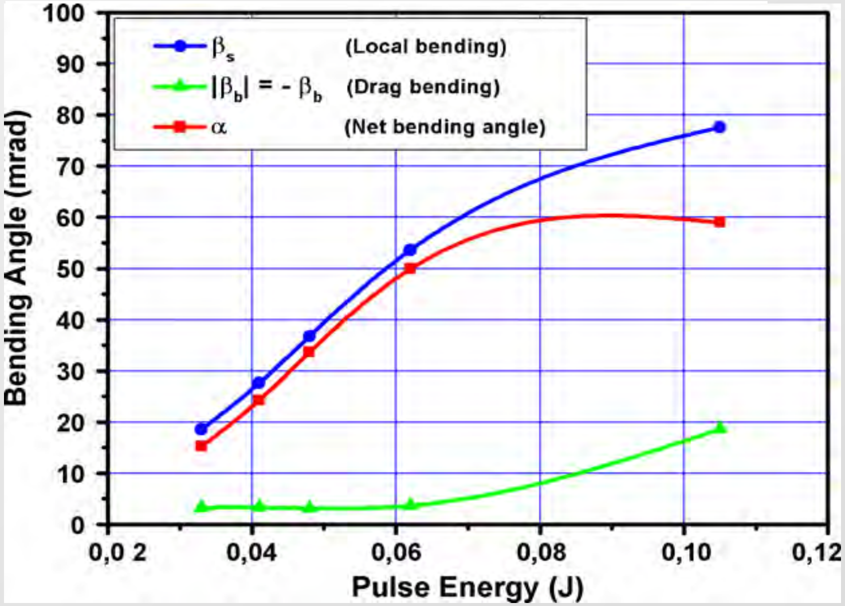
3. NUMERICAL SIMULATION RESULTS

Pulse Energy Parametrization

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

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





3. NUMERICAL SIMULATION RESULTS

Spot Center Distance Parametrization

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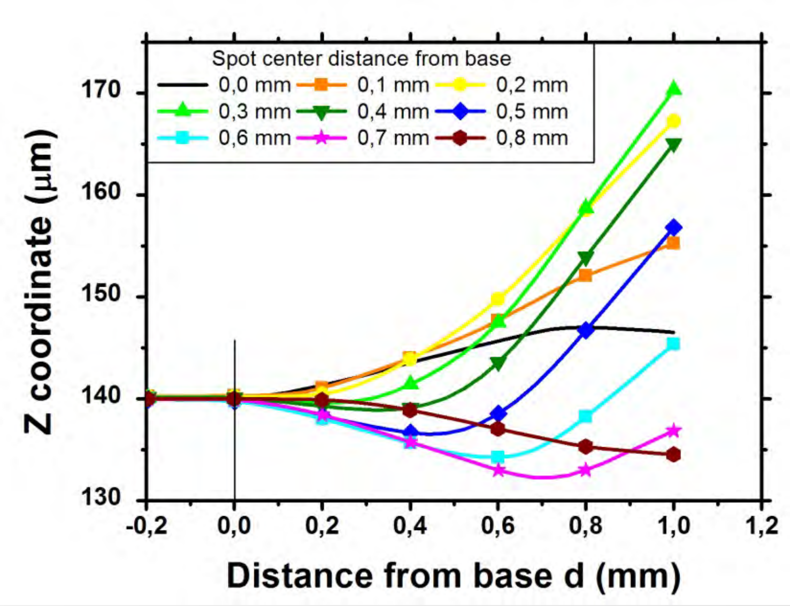
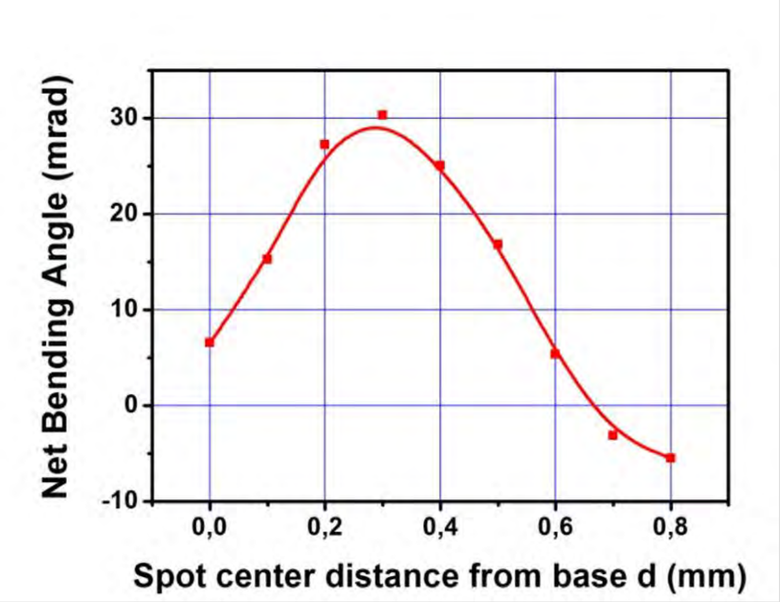
Spot Radius [μm]	175

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

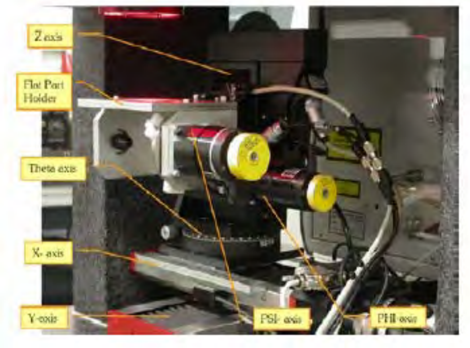




4. EXPERIMENTAL SETUP. SAMPLE PREPARATION

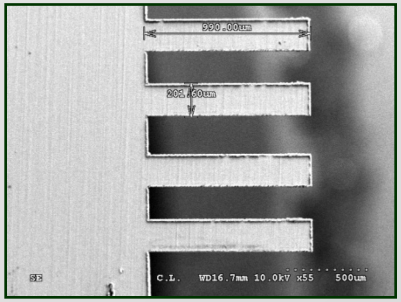
ML-100 LASER WORKSTATION

Laser media	Excimer (KrF)	DPSS 3ω
Wavelength (nm)	248	355
Pulse duration (ns)	3–7 ns	<12 ns (at 50 kHz)
Beam shape/mode	Rectangular (3.5 × 6 mm)	TEM_{00} ($M^2 < 1.3$)
Operating frequency	0–300 Hz	15–300 kHz
Average power (W)	0.3–5 (at 300 Hz)	5 W (at 50 kHz)



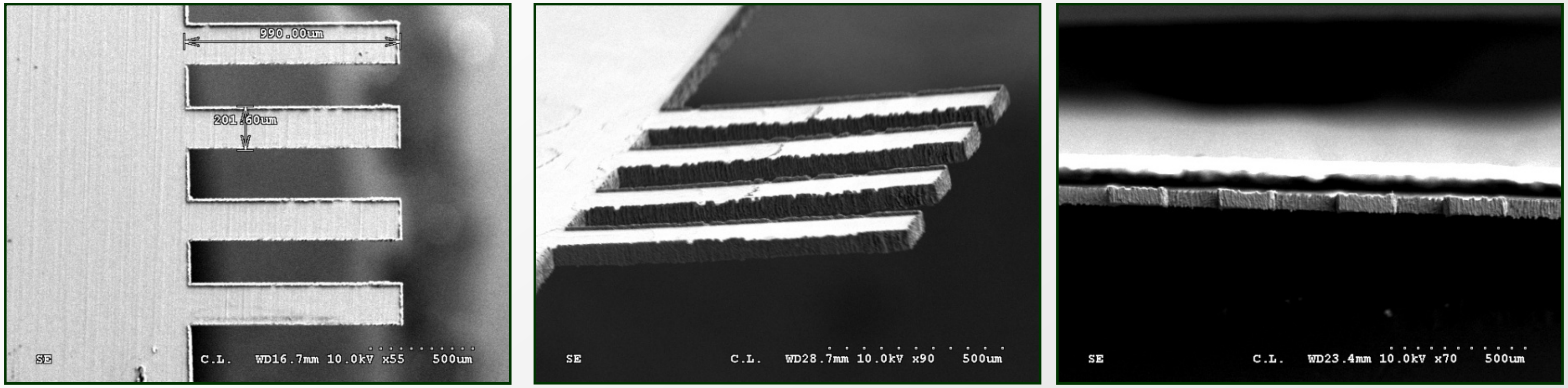
- Dual Excimer/DPSS Laser processing
- Multiaxis (6) System
- Work volume: 120*100*50 mm
- XY accuracy: 1 μm
- Global positioning accuracy: 40 μm
- CCD direct vision (x 500)

AISI 304
1000 x 200 x 50 μm

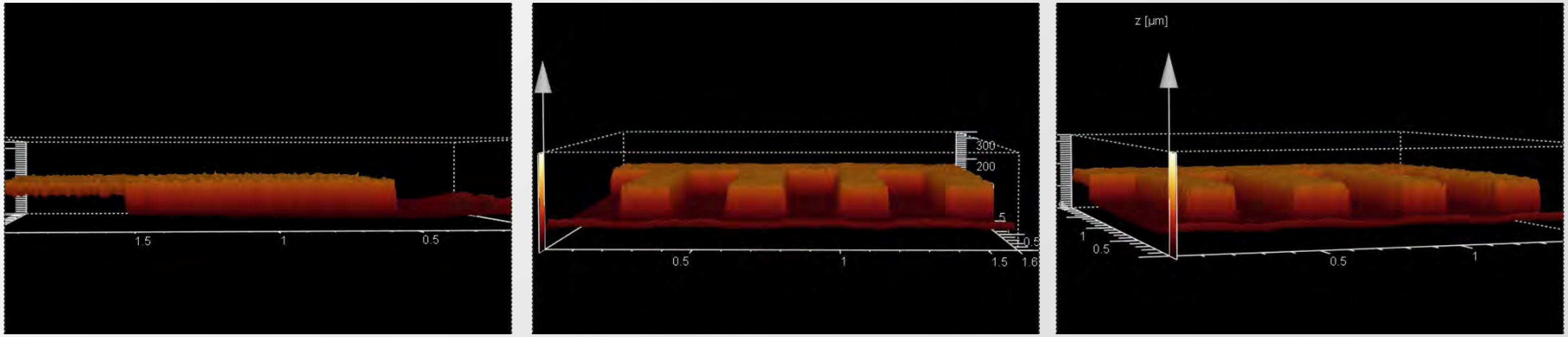


4. EXPERIMENTAL SETUP. SAMPLE PREPARATION

SEM IMAGES OF LASER CUT SHEET



CONFOCAL IMAGES OF LASER CUT SHEET



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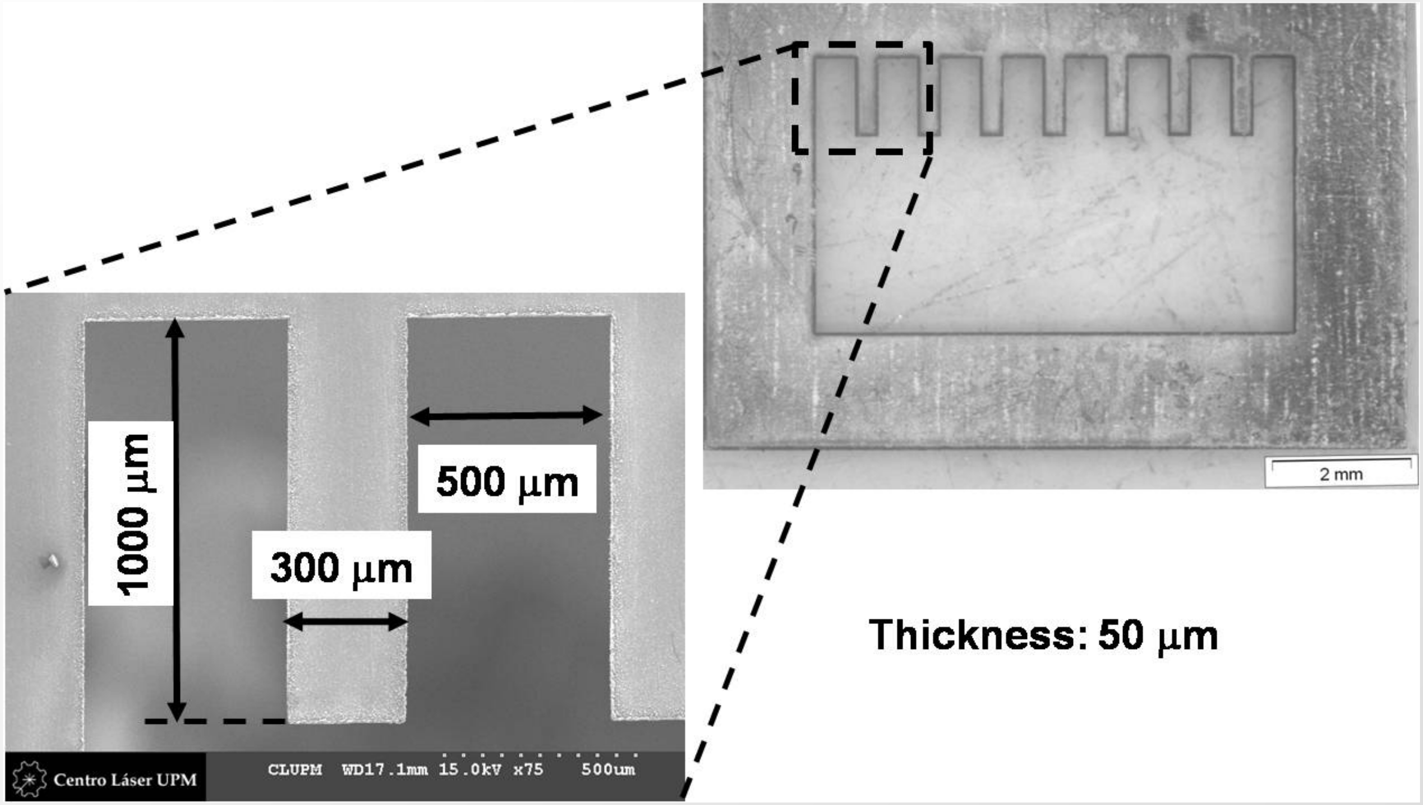
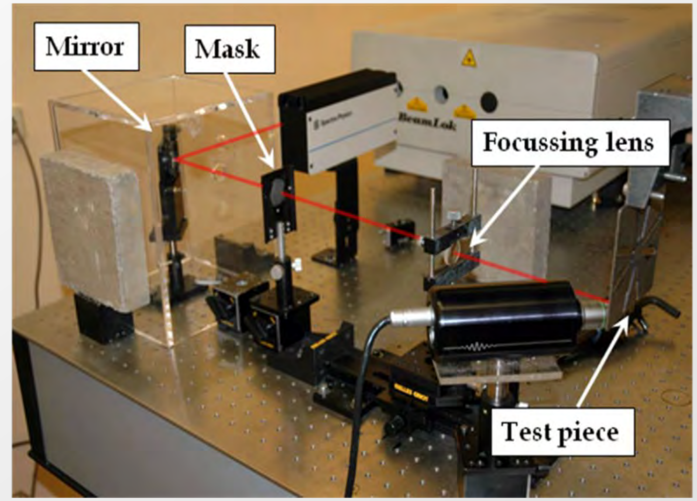
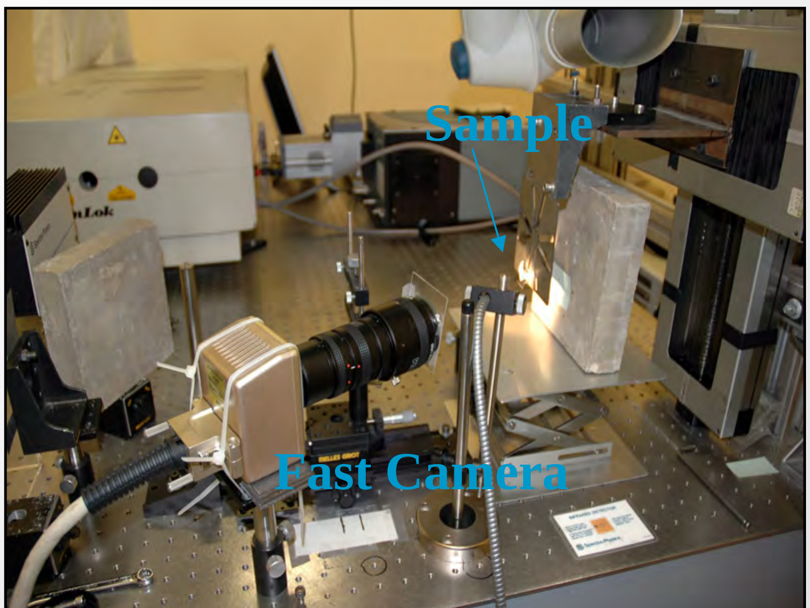
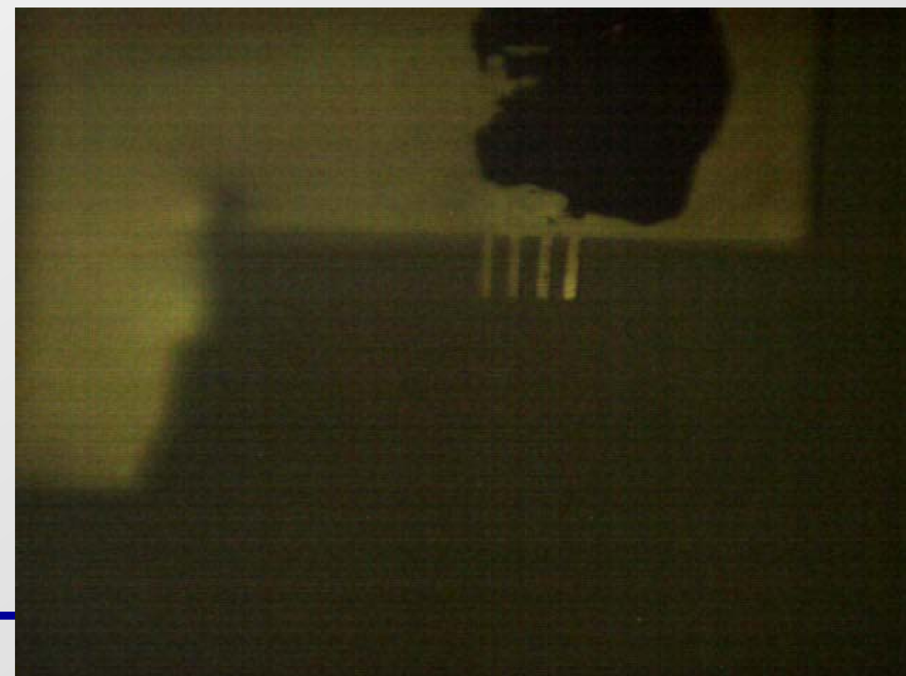


4. EXPERIMENTAL SETUP. SAMPLE IRRADIATION

Nd:YAG Laser Wavelength [nm]	1064
Energy per pulse [J]	1.651
Laser Pulse length FWHM [ns]	9
Laser Beam radius [mm]	14
Confining layer	Air
Thin sheet material	AISI 304
Thin sheet thickness [μm]	50

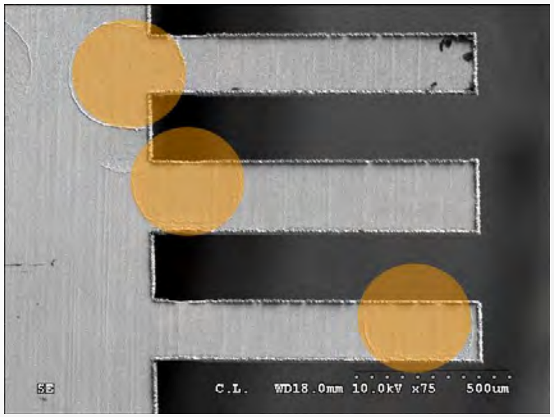


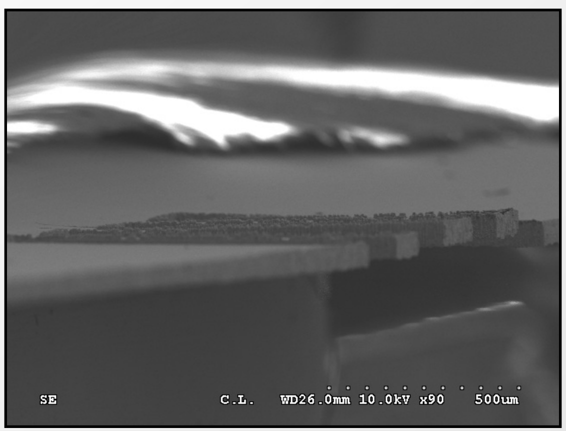




5. EXPERIMENTAL RESULTS. INFLUENCE OF SPOT CENTER DISTANCE

SEM IMAGES





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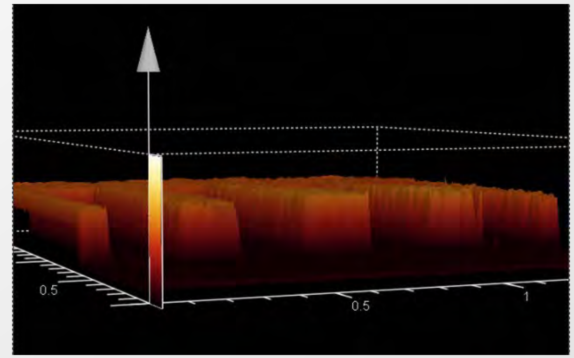
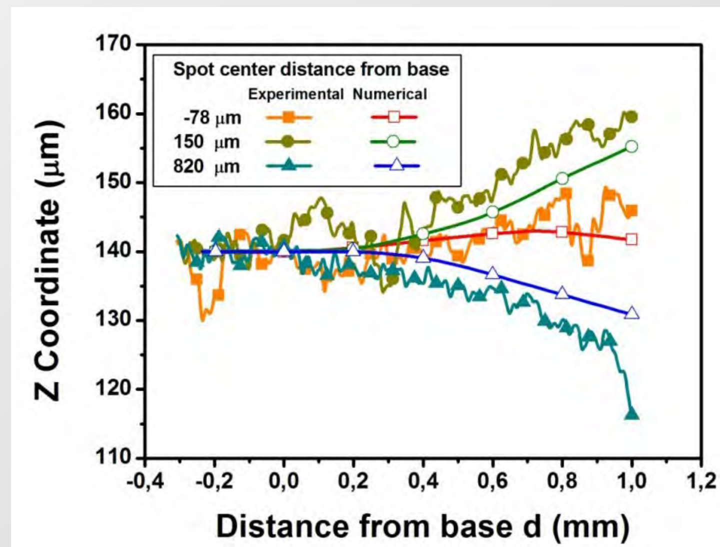
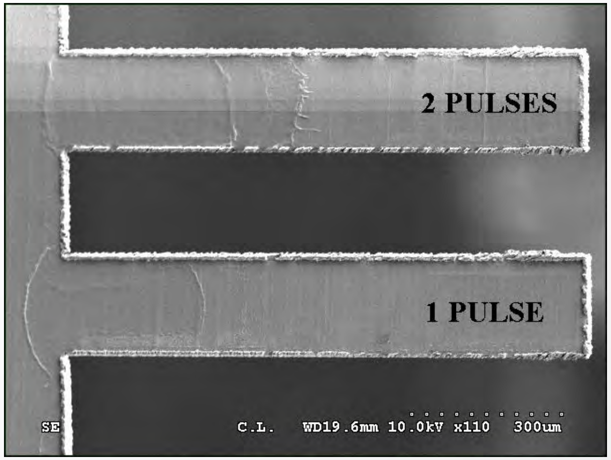
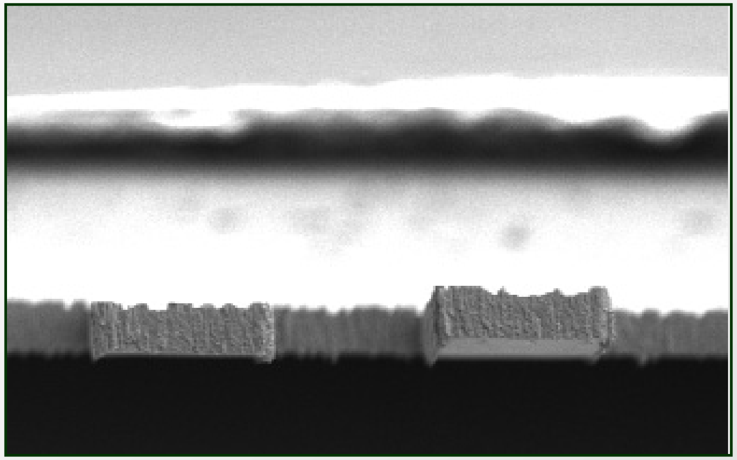




5. EXPERIMENTAL RESULTS. INFLUENCE OF NUMBER OF PULSES

SEM IMAGES





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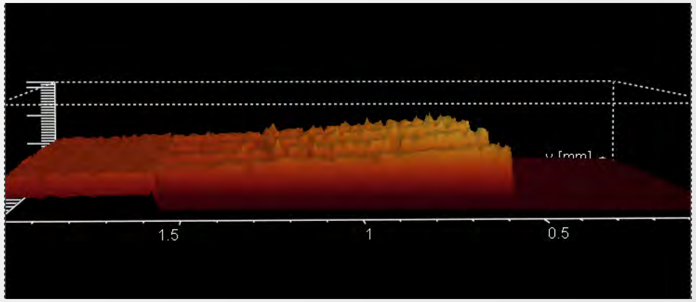
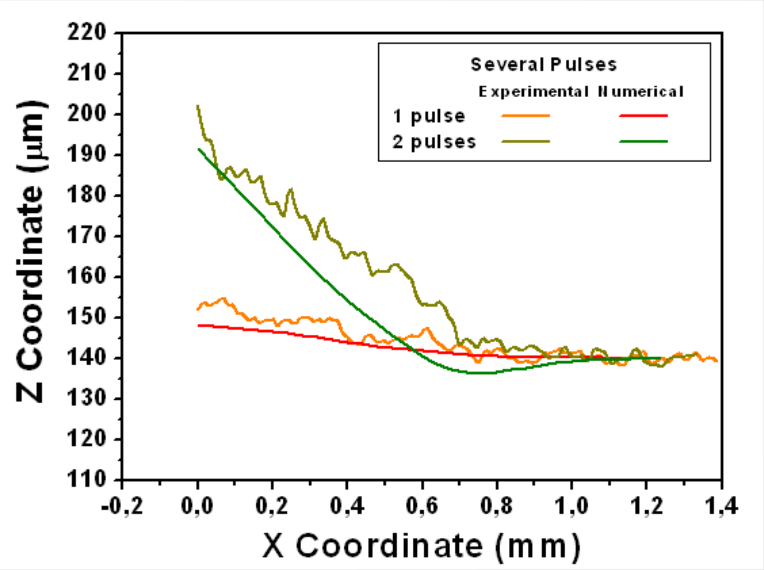
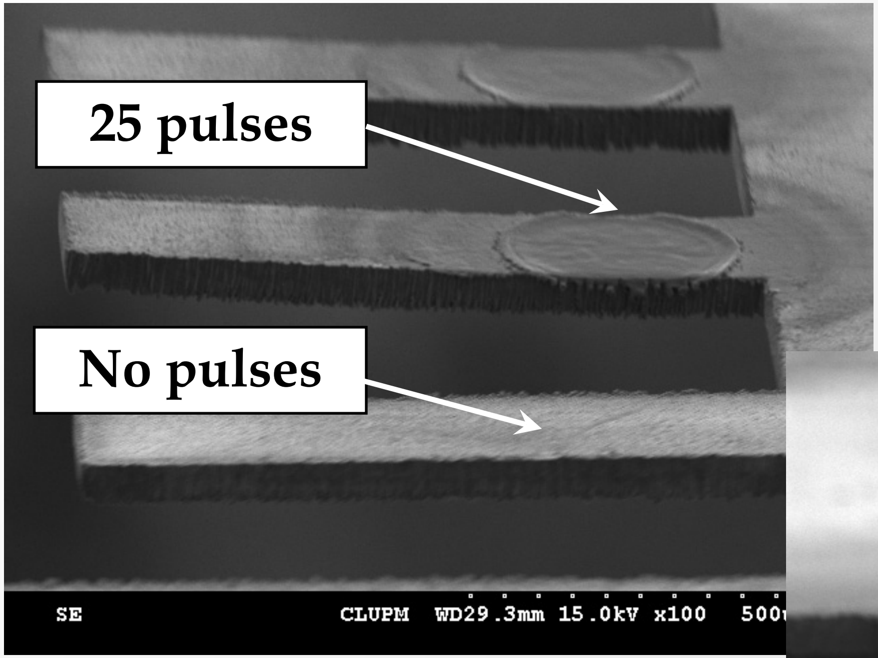
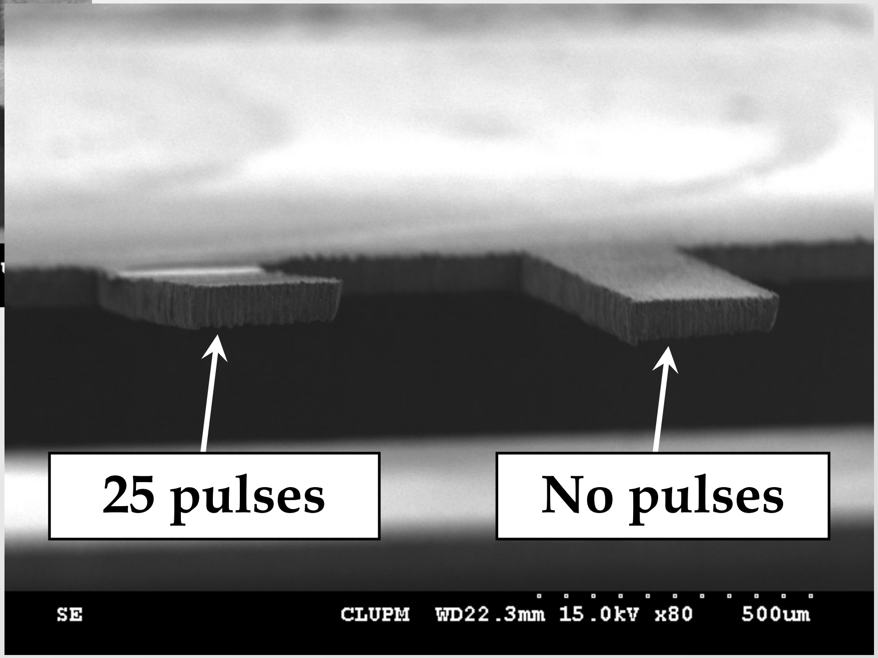




5. EXPERIMENTAL RESULTS. INFLUENCE OF NUMBER OF PULSES





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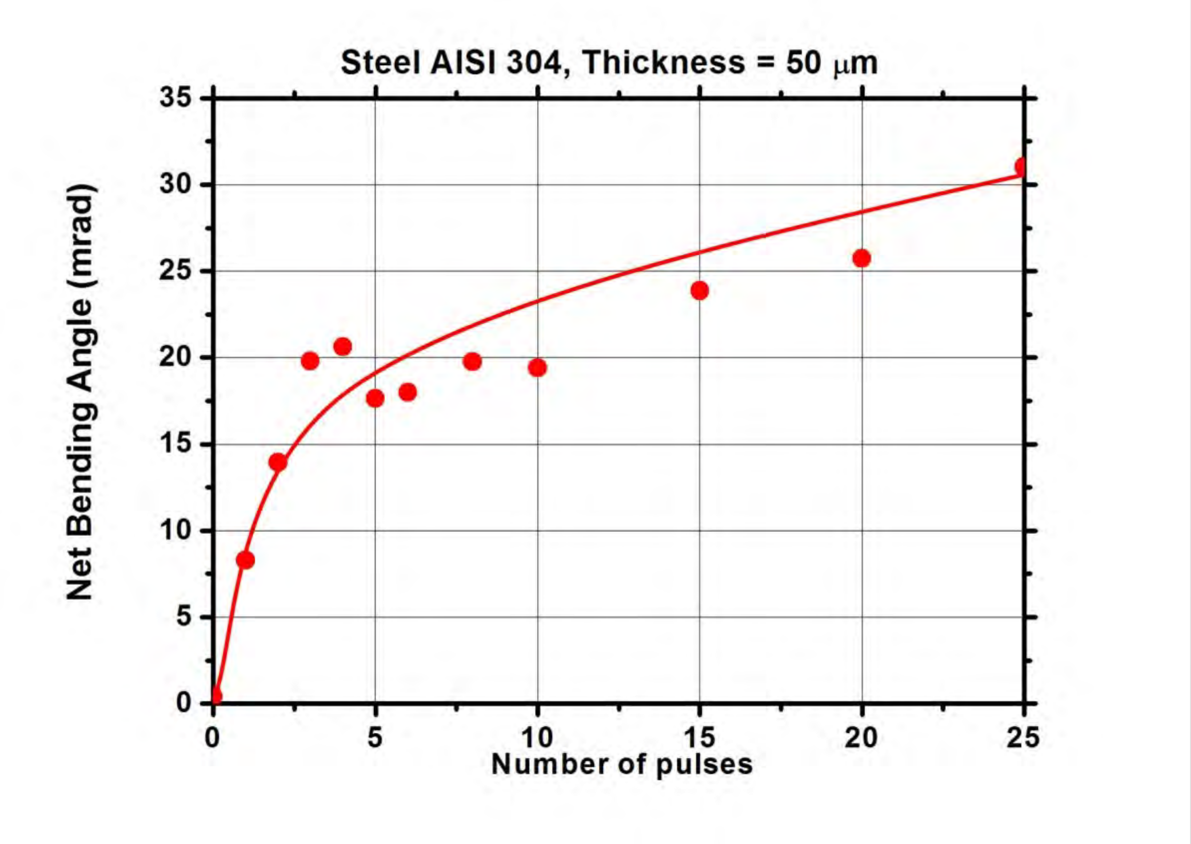
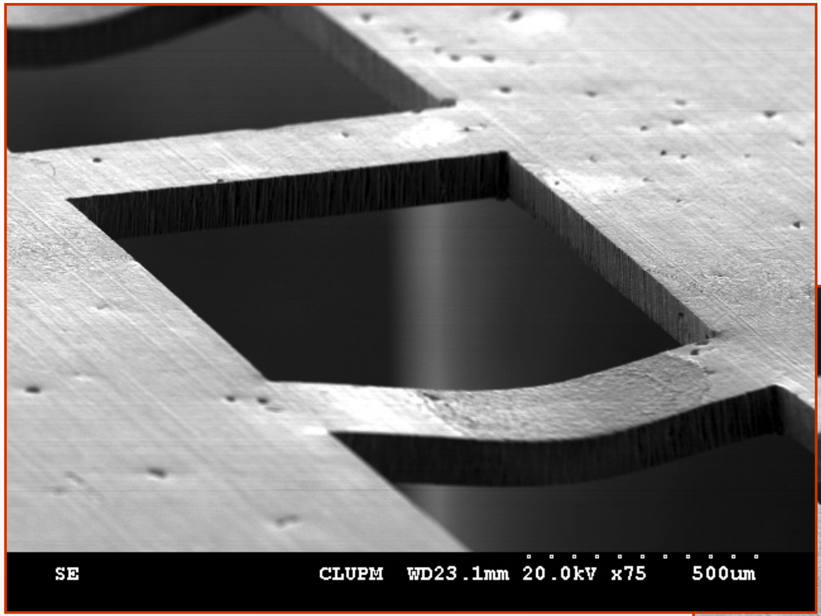
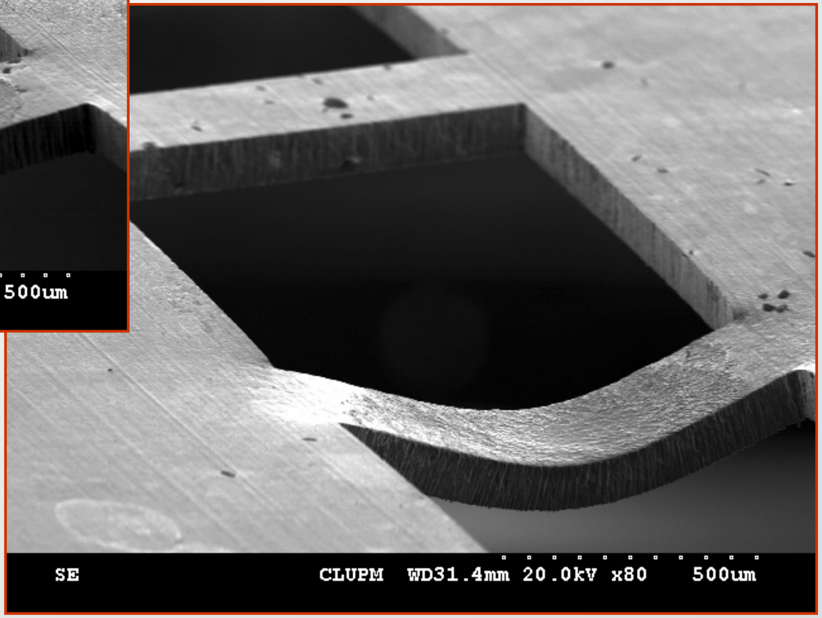


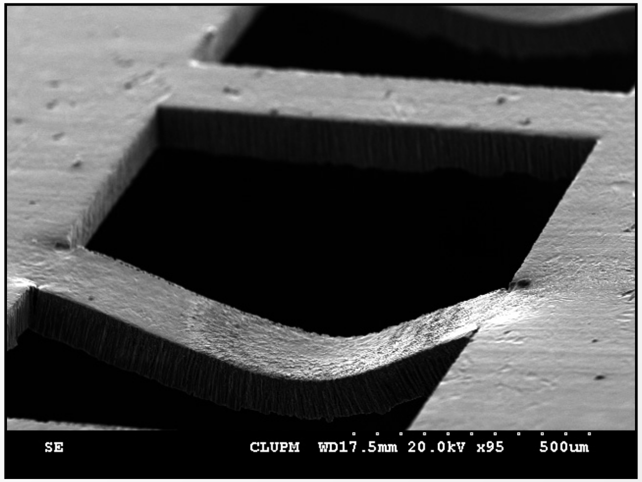


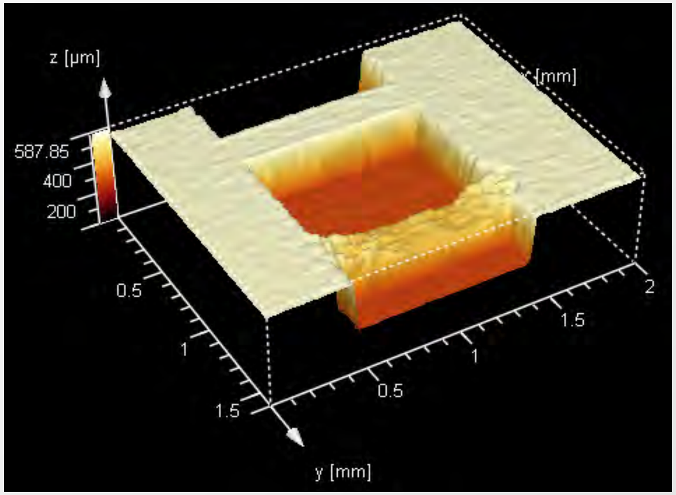
1 pulse

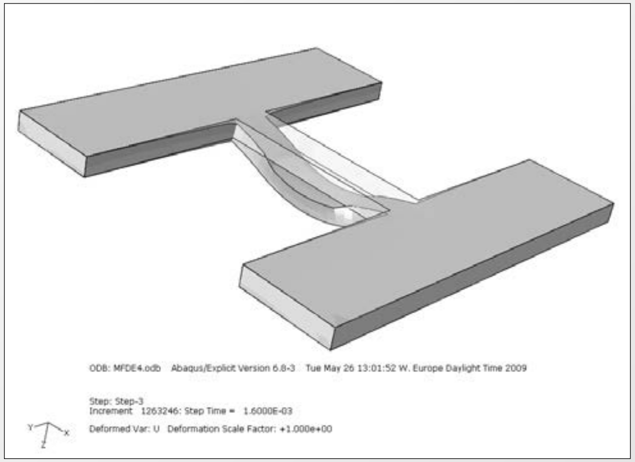


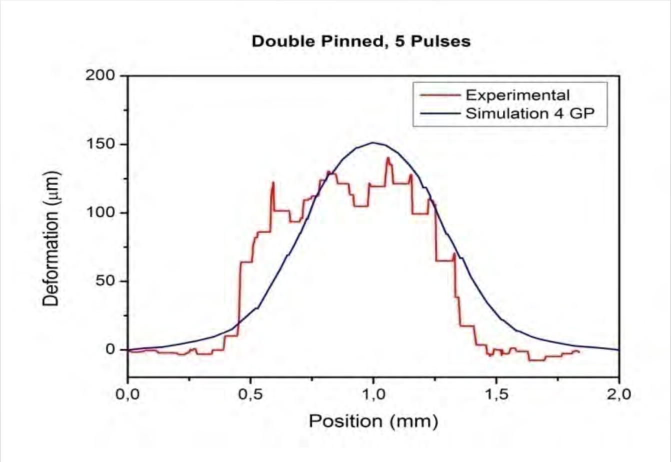
4 pulses

5. EXPERIMENTAL RESULTS. LAST RESULTS. CONFINED REGIME









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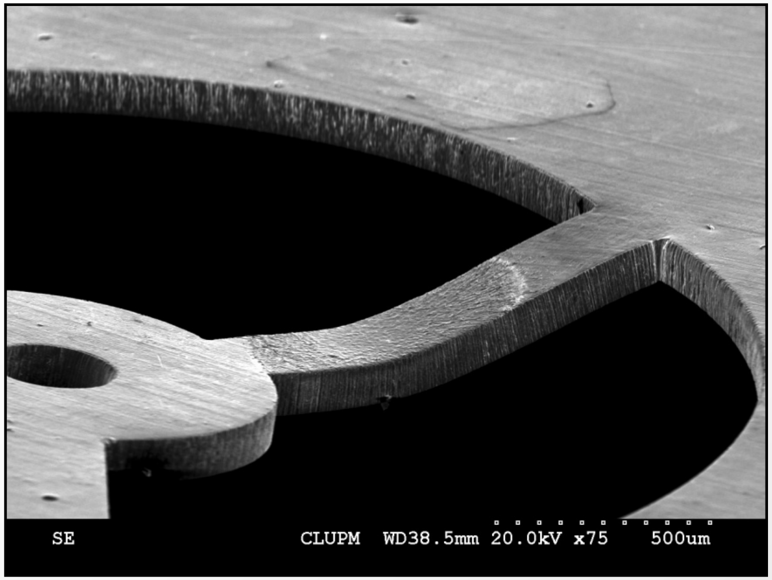
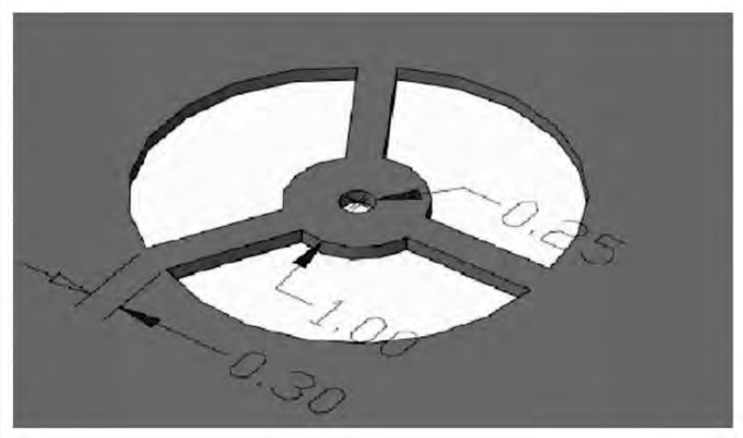
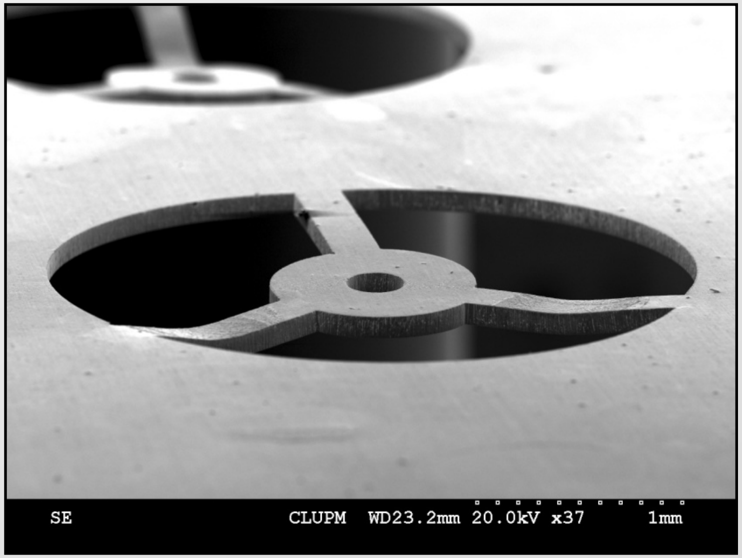


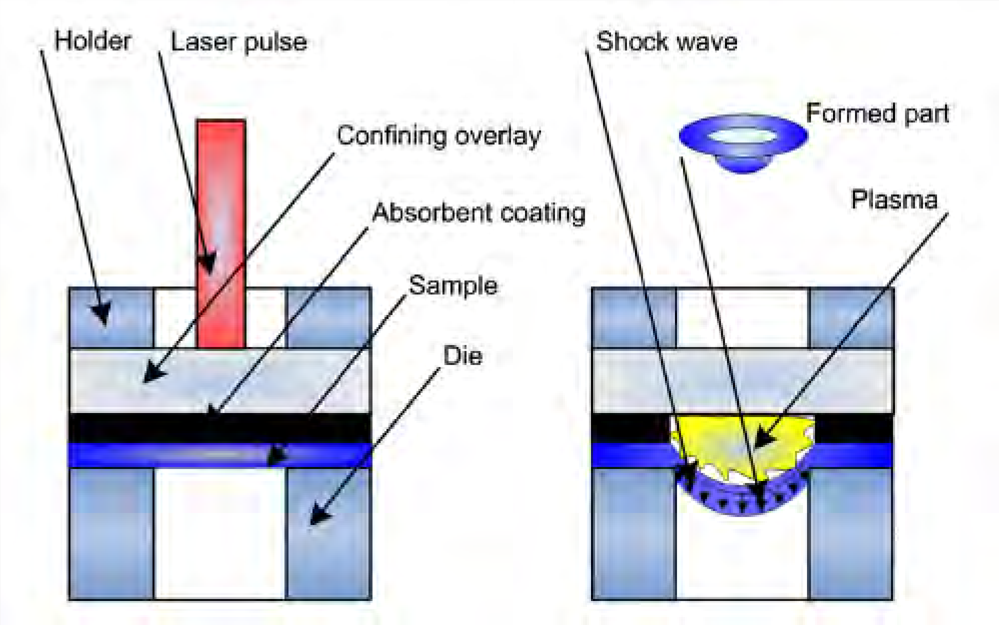


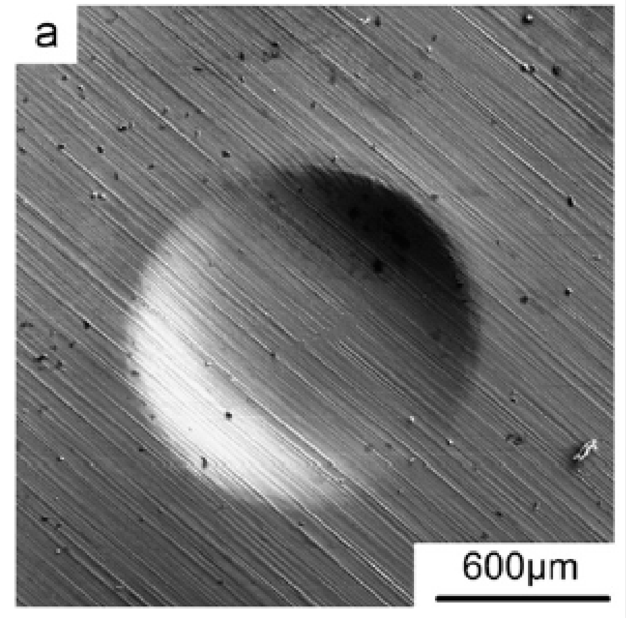
5 pulses

5 pulses in two arms



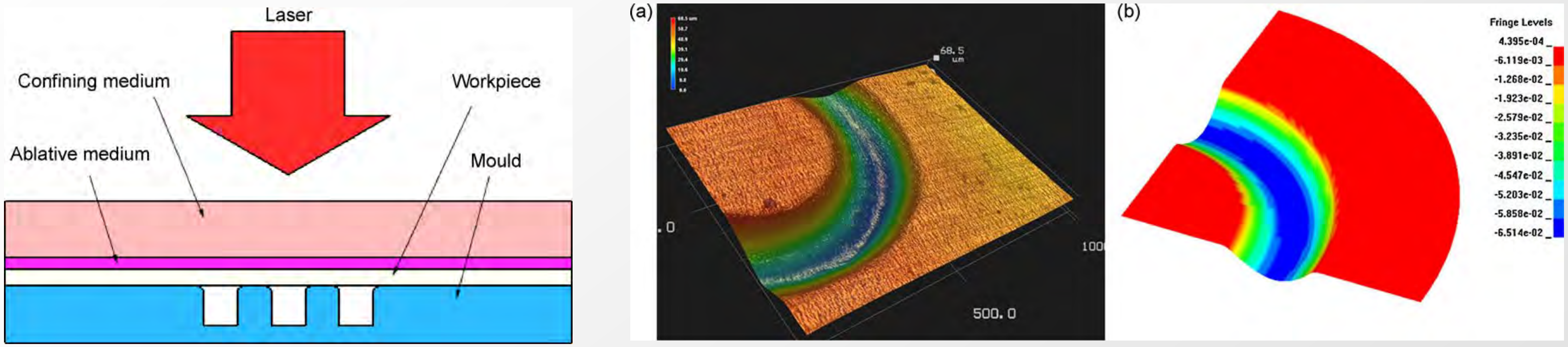
Microscale laser bulge forming:

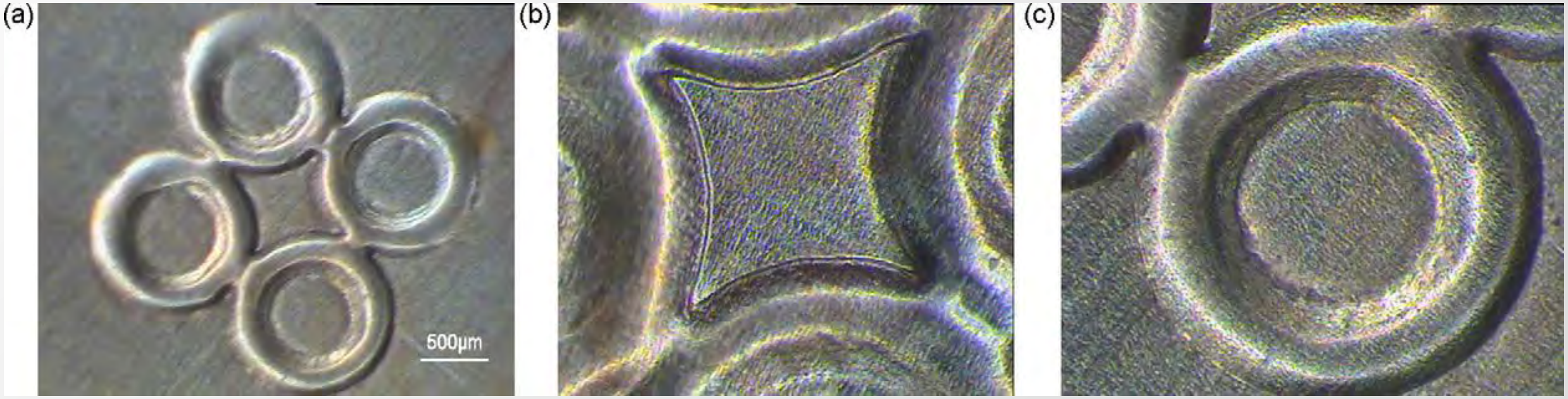




C. ZHENG et al.: Int. J. Machine Tools & Manufacture, 50 (2010), 1048–1056

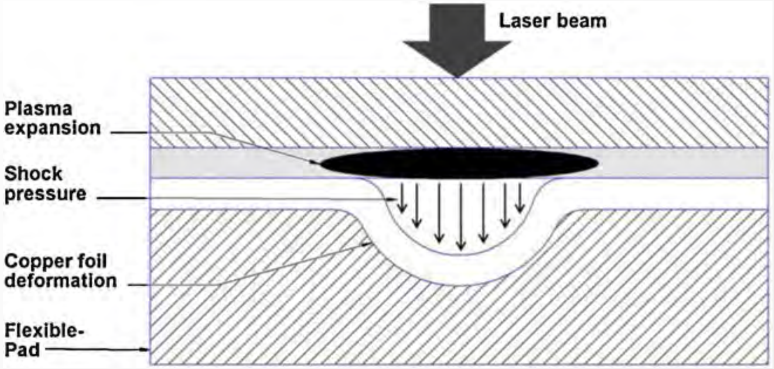
Micromould based laser shock embossing:

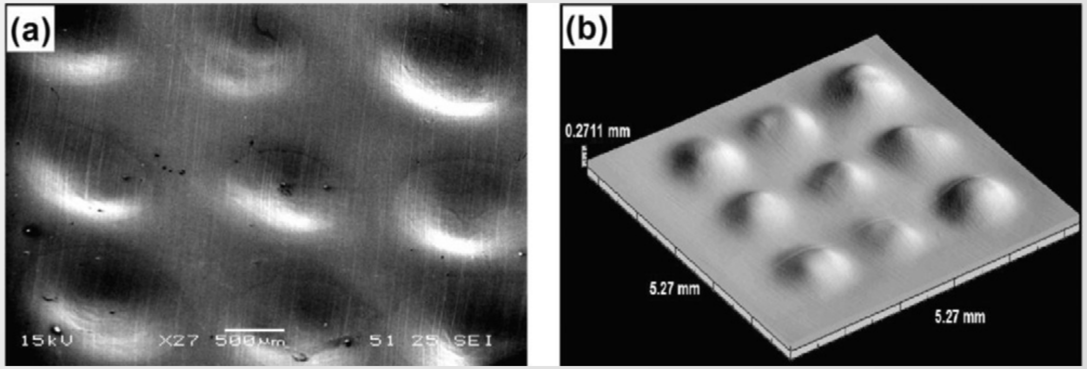




H. LIU et al.: Applied Surface Science, 256 (2010), 4687–4691

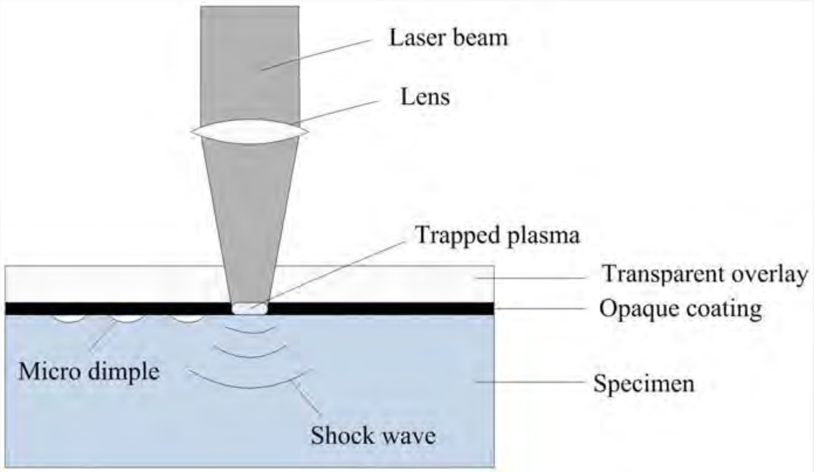
Mold-free fabrication of 3D microfeatures with laser shock:

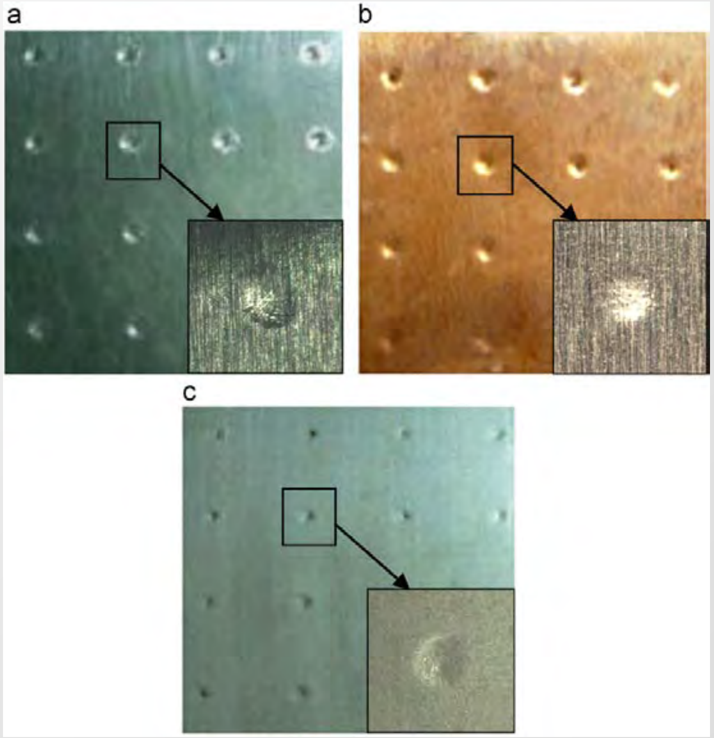




B. NAGARAJAN et al.: Applied Surface Science, 268 (2013), 529– 534

Micro dimple fabrication based on laser shock processing:



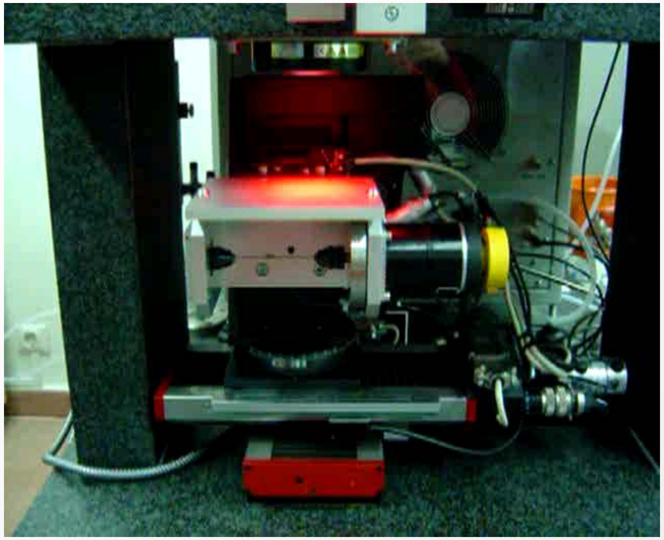


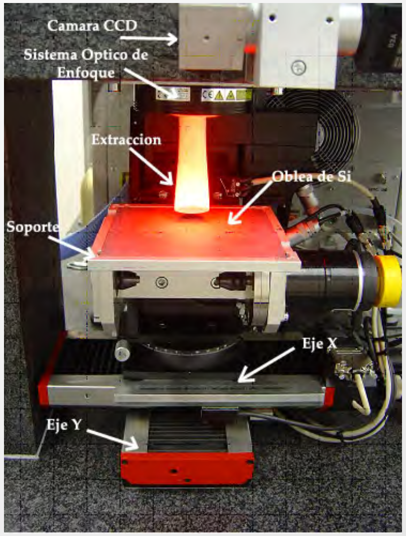
K. LI et al.: Optics & Laser Technology, 48 (2013), 216–225

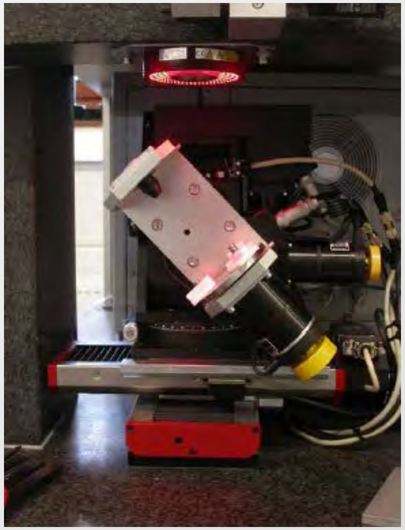
6. DISCUSSION AND OUTLOOK

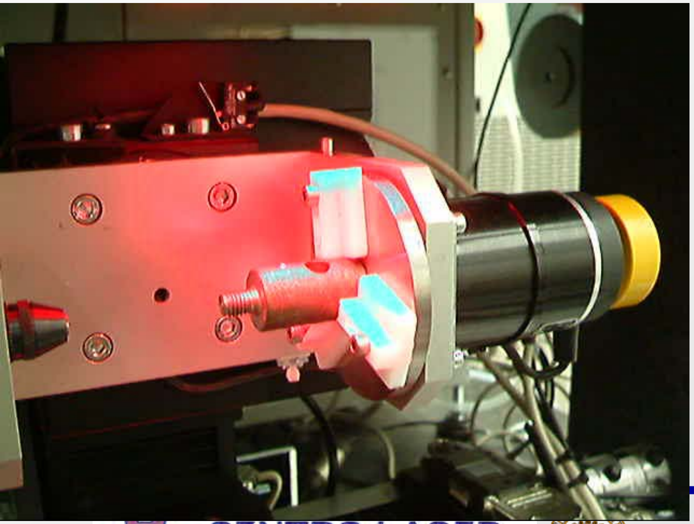
- **The suitability laser micro-bending of thin metal parts by means of ns pulsed lasers with average power in the range of several Watt has been experimentally demonstrated.**
- **The micro-bending process can be developed both in free and confined environment with good tuning capability in both cases but with much more efficient results in the latter case. The numerical simulation capabilities developed by the authors allow a full predictive assessment of the bending process and final result.**
- **Based on the same predictive assessment capabilities the release of residual stresses in MEMS components can be properly handled.**
- **According to the authors' experience, the use of ns laser pulses in laser shock regime provides a really suitable parameter matching for the laser forming of an important range of MEMS sheet or stripe components. New alternative forming and embossing approaches based on the same principle reinforce this vision.**
- **Laser shock microforming and adjustment stresses release of arbitrary geometry components is envisaged as a promising technology for MEMS development.**

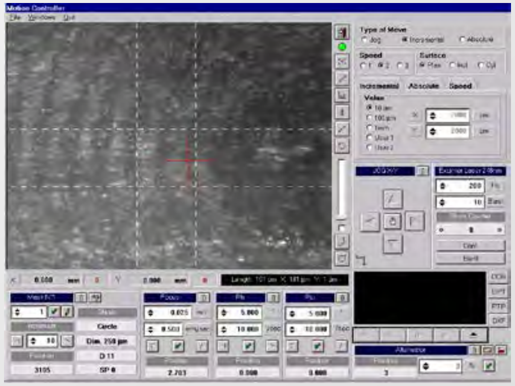
MICROMANUFACTURING EXPERIMENTAL SETUP AT CLUPM

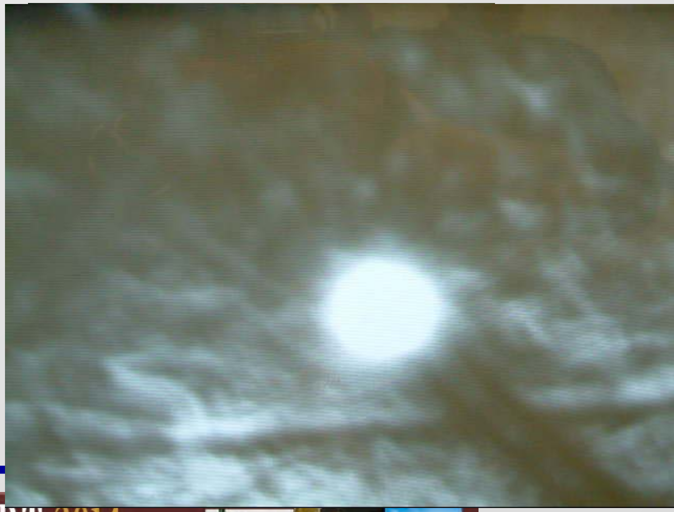


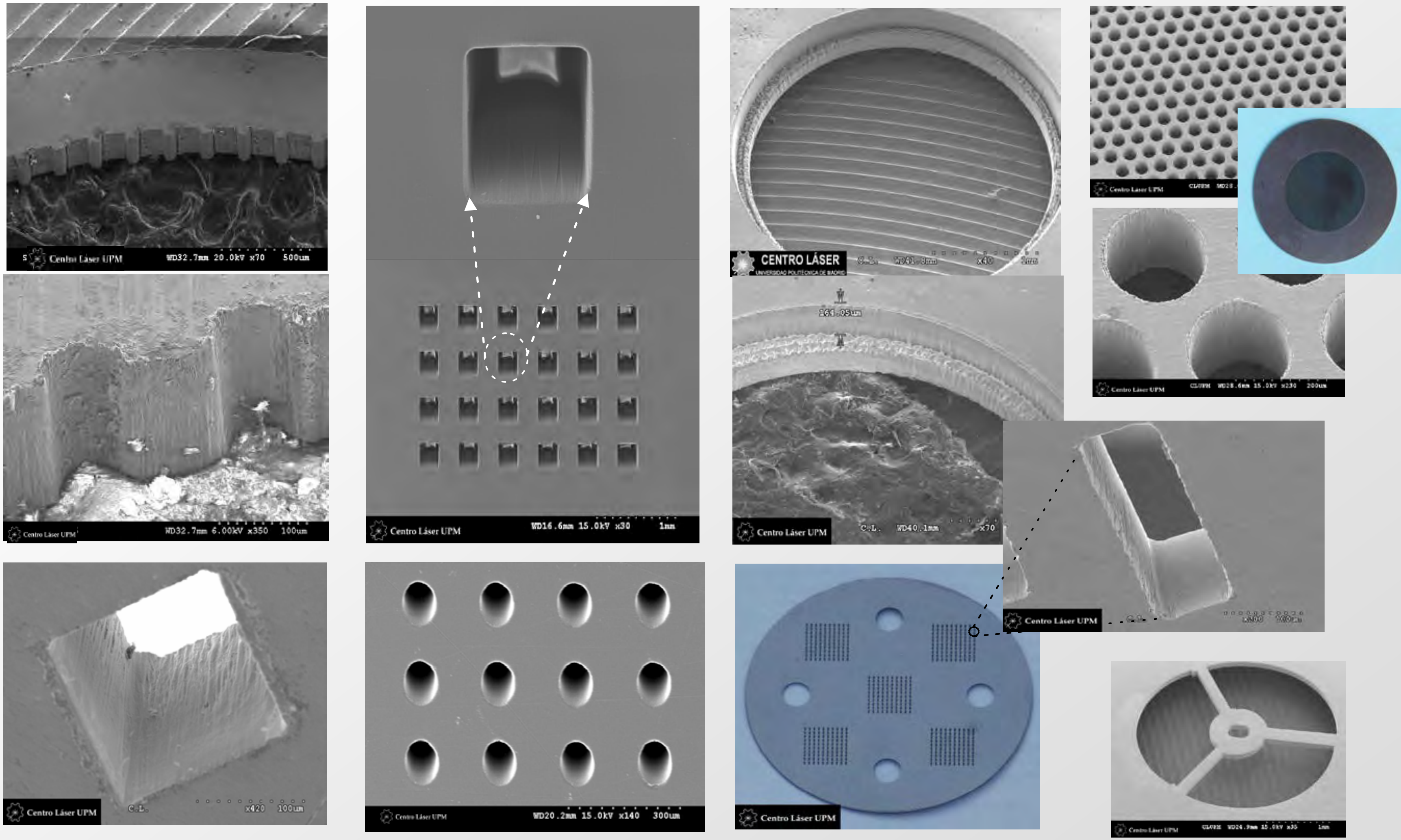


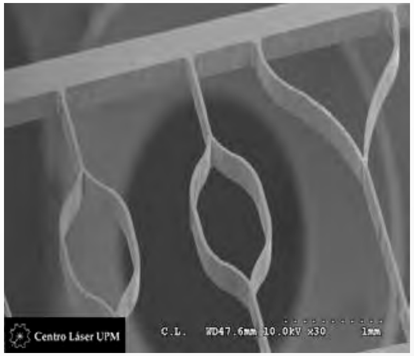


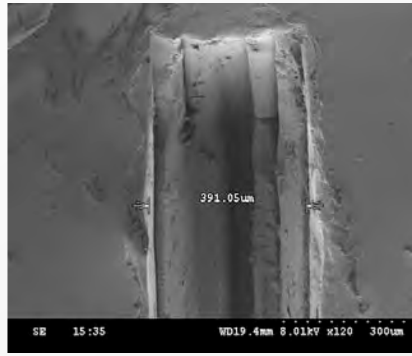


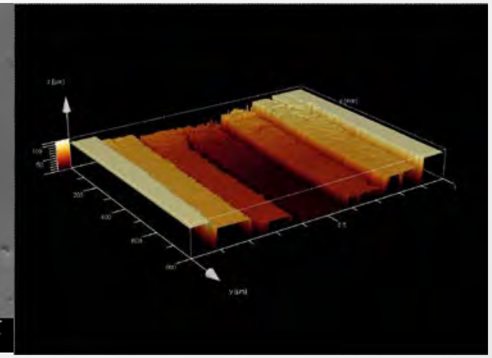


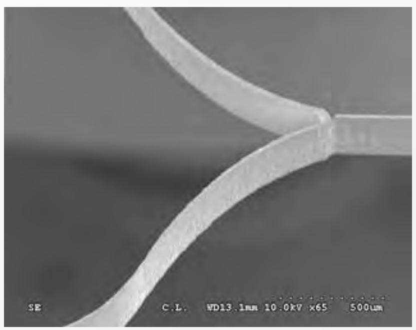


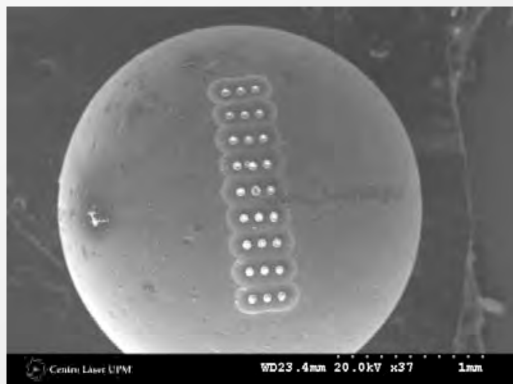

Centro Láser UPM
WD32.7mm 20.0kV x70 500um
WD32.7mm 6.00kV x350 100um
WD16.6mm 15.0kV x30 1mm
CENTRO LÁSER
UNIVERSIDAD POLITÉCNICA DE MADRID
261.05um
x420 100um
WD20.2mm 15.0kV x140 300um

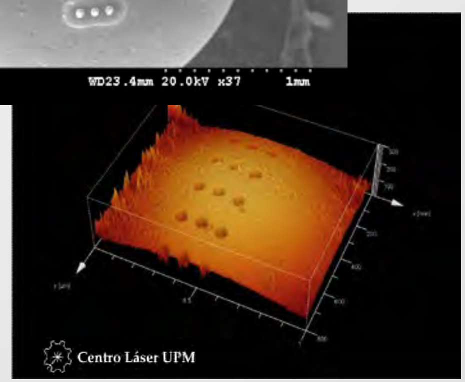

Centro Láser UPM
C.L. WD47.6mm 10.0kV x30 1mm

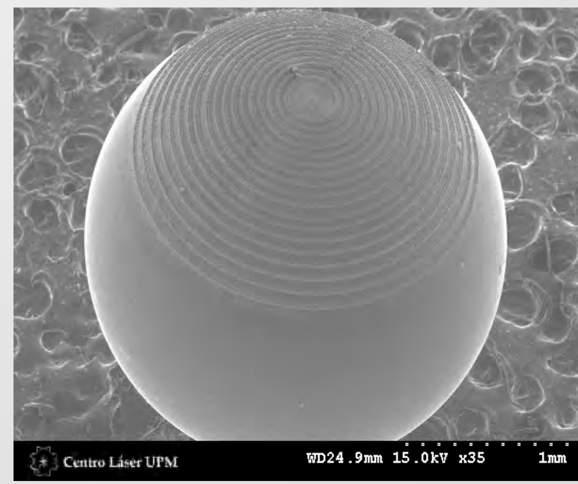

391.05um
SE 15:35 WD19.4mm 8.01kV x120 300um

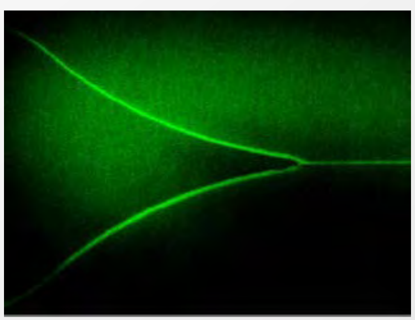


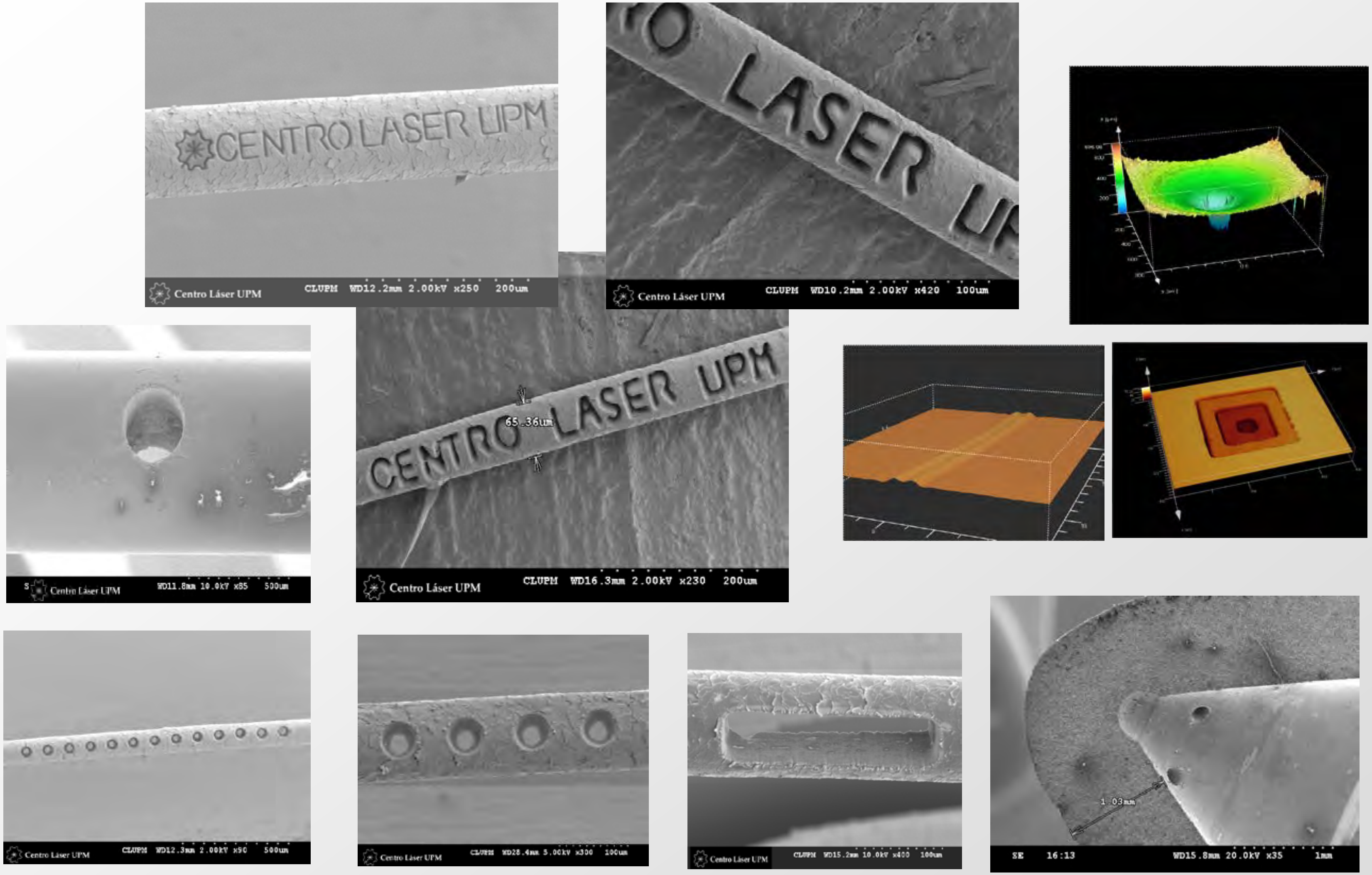

SE C.L. WD13.1mm 10.0kV x65 500um

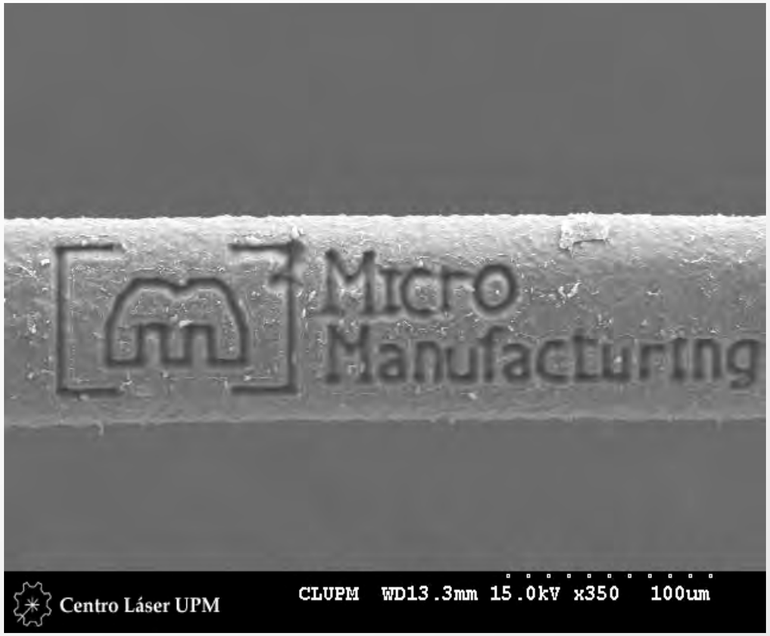

Centro Láser UPM
WD23.4mm 20.0kV x37 1mm

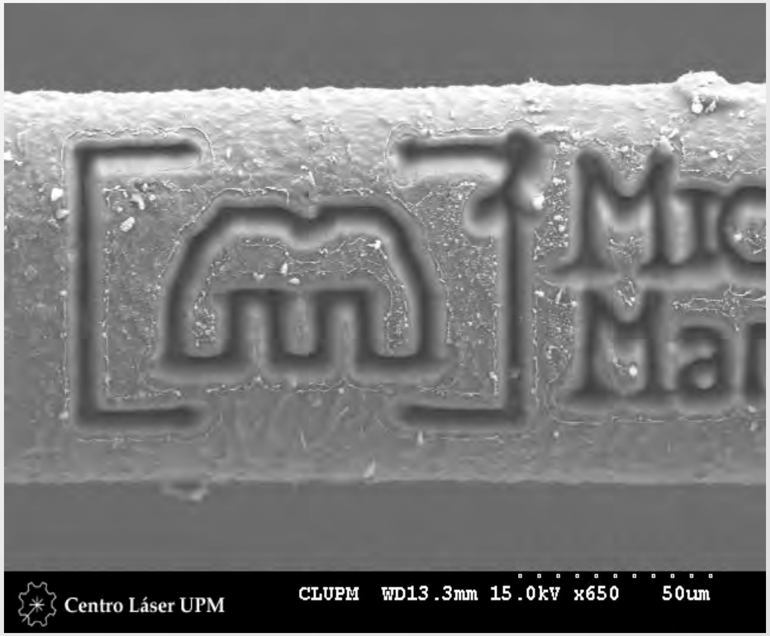

Centro Láser UPM


Centro Láser UPM
WD24.9mm 15.0kV x35 1mm




CENTRO LASER UPM
Centro Láser UPM CLUPM WD12.2mm 2.00kV x250 200um
LASER
Centro Láser UPM CLUPM WD10.2mm 2.00kV x420 100um
CENTRO LASER UPM
65.36um
Centro Láser UPM CLUPM WD16.3mm 2.00kV x230 200um
1.03mm
SE 16:13 WD15.8mm 20.0kV x35 1mm


Micro
Manufacturing
Centro Láser UPM
CLUPM WD13.3mm 15.0kV x350 100um


Centro Láser UPM
CLUPM WD13.3mm 15.0kV x650 50um

ACKNOWLEDGEMENTS

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Thank you very much for your attention !

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