Application of High-Intensity Short-Pulse Lasers to the Mechanical and Surface Properties Improvement of High Reliability Metallic Components by Shock Processing

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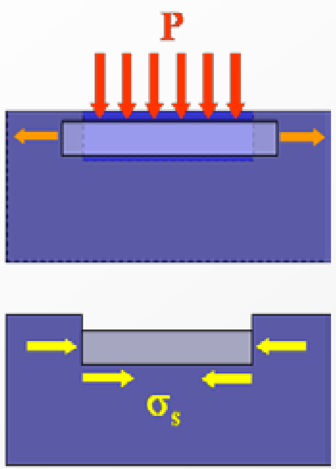
OUTLINE:

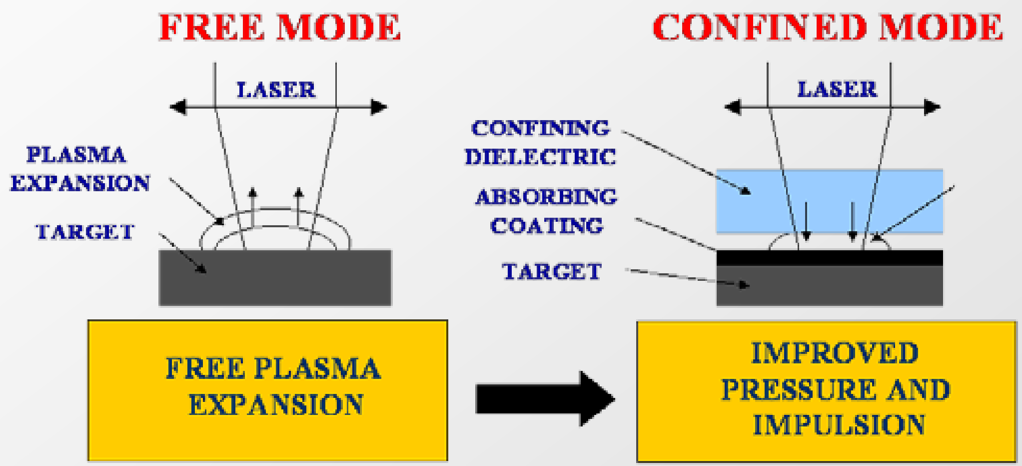
- Introduction
- Process Experimental Setup
- Experimental Procedure
- Experimental Results for Al2024-T351 and Ti6Al4V
  - Residual stresses
  - Tensile Strength
  - Fatigue Life
- Discussion and Outlook
  - Prospects for technological applications of LSP

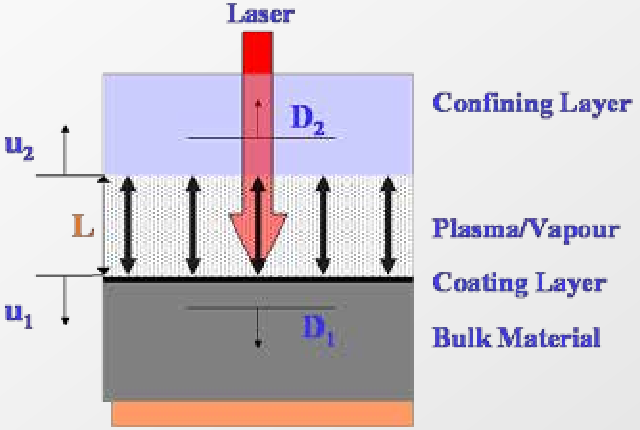
INTRODUCTION

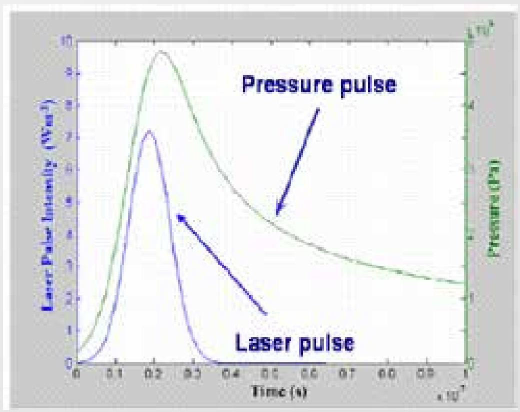
- Laser Shock Processing (LSP) is being increasingly applied as a technique allowing the effective induction of residual stresses fields in metallic materials allowing a high degree of surface material protection against fatigue crack propagation, abrasive wear, chemical corrosion and other failure conditions, what makes the technique specially suitable and competitive with presently use techniques for the treatment of heavy duty components in the aeronautical, nuclear and automotive industries.
- According to the inherent difficulty for the prediction of the shock waves generation (plasma) and evolution in treated materials, the practical implementation of LSP processes needs an effective predictive assessment capability coupled to a readily controllable experimental setup for a correct application of treatment parameters and an associate material properties characterization capability.
- In the present communication, the practical LSP treatment and associate specimens characterization capabilities developed at CLUPM (Spain) are presented along with selected results obtained in several relevant aerospace and nuclear industry alloys.

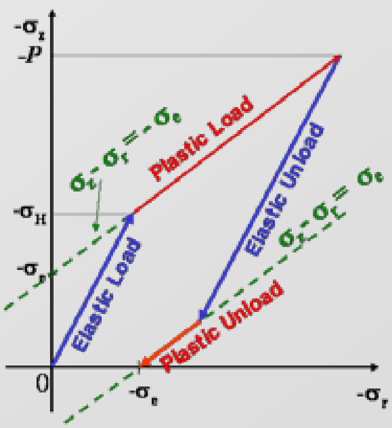
REMINDER OF LSP PHYSICAL PRINCIPLES (1/2)



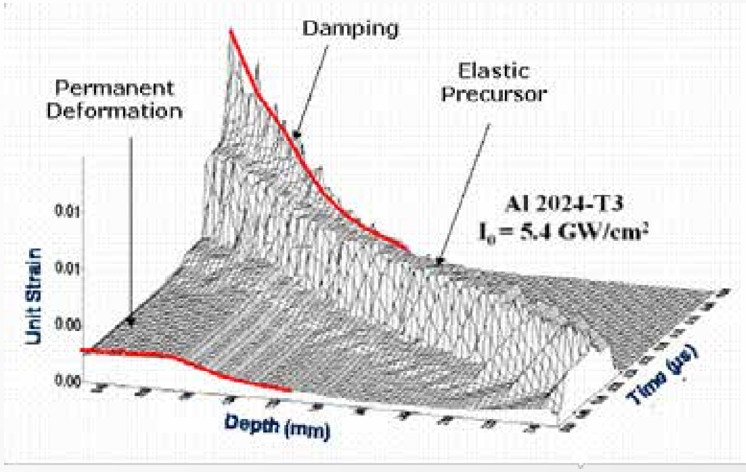


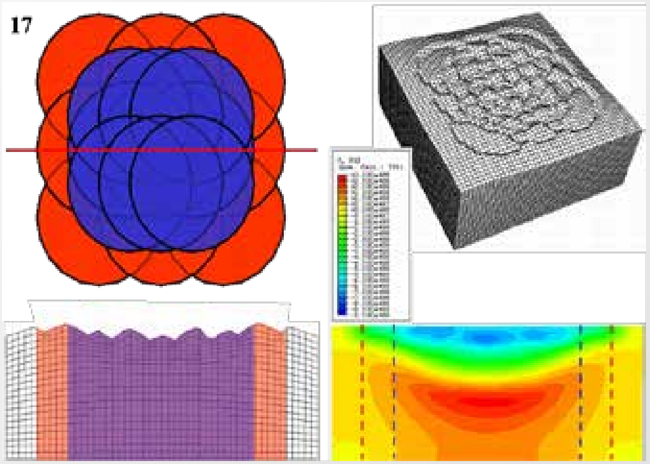


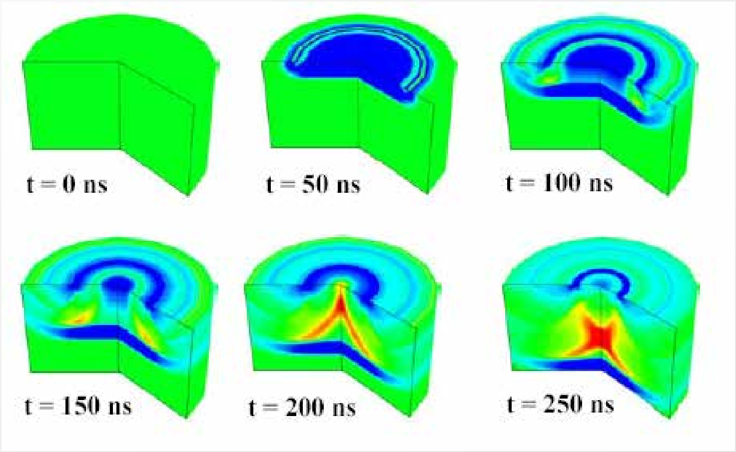


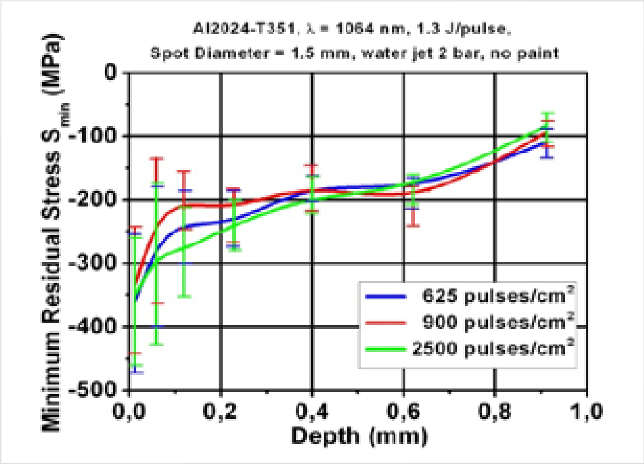


REMINDER OF LSP PHYSICAL PRINCIPLES (2/2)

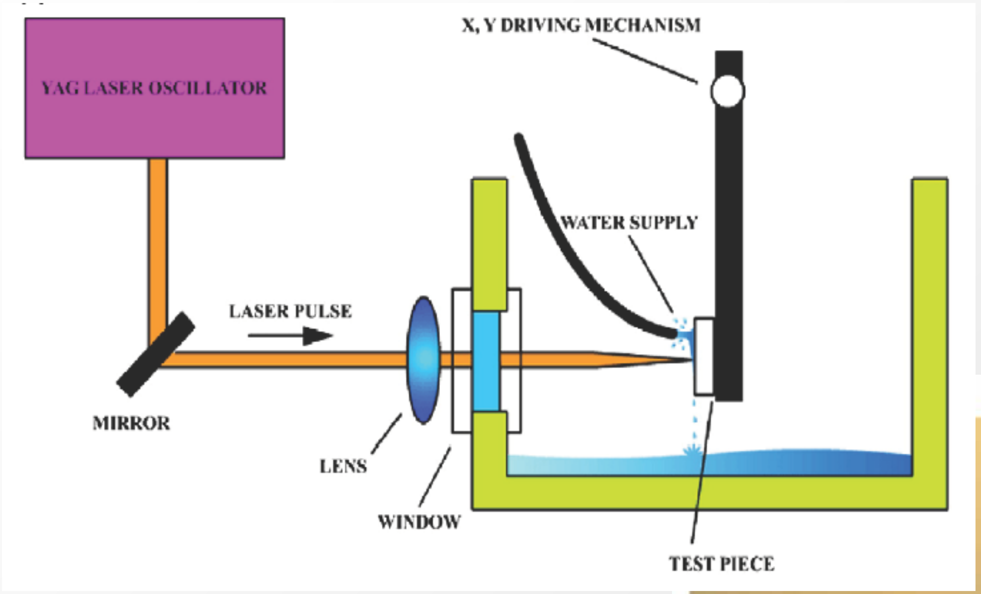


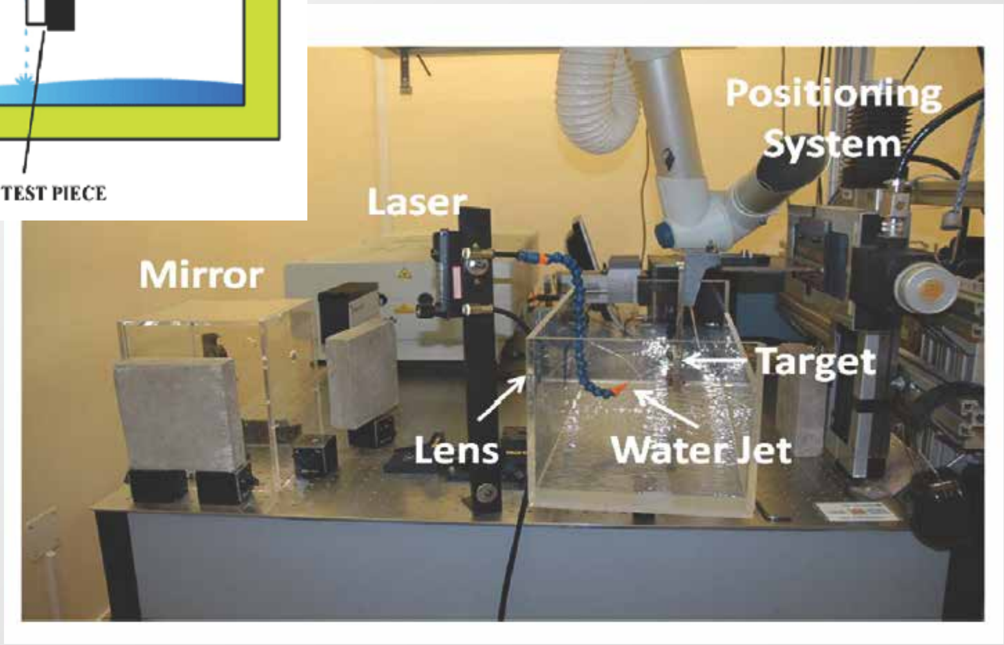






PROCESS EXPERIMENTAL SETUP





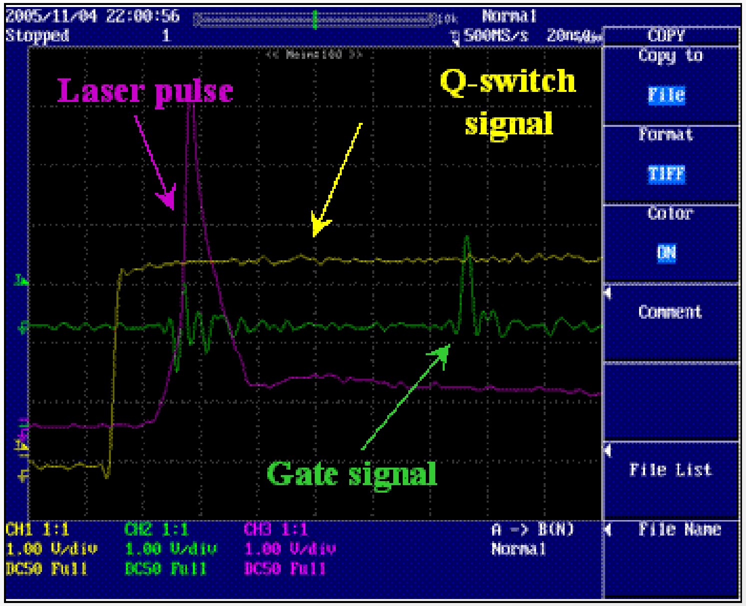
PROCESS EXPERIMENTAL SETUP

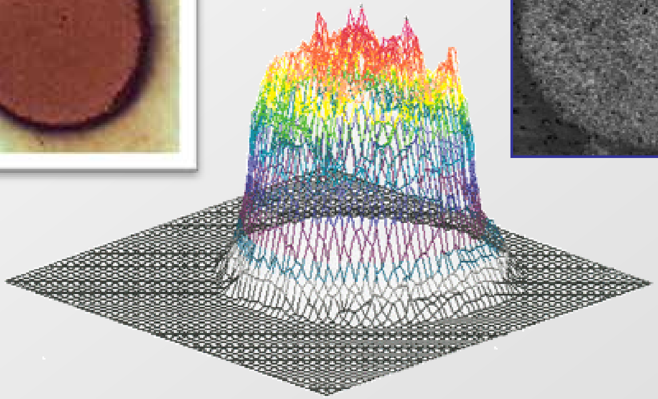
Q-SWITCHED Nd:YAG LASER

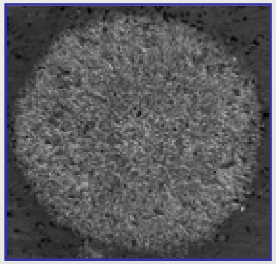
$$\begin{cases} \lambda = 1064\,\text{nm};\ E = 2{,}5\ \text{J/pulse} \\ \lambda = 532\,\text{nm};\ E = 1{,}4\ \text{J/pulse} \end{cases}$$

t = 10 ns; f = 10 Hz

PROCESS EXPERIMENTAL SETUP



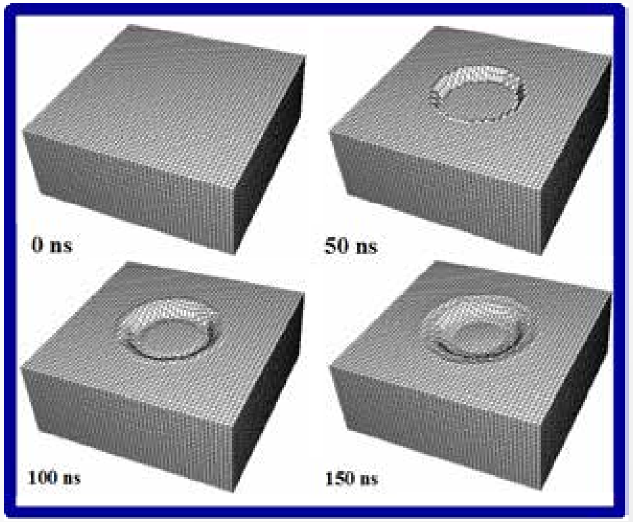


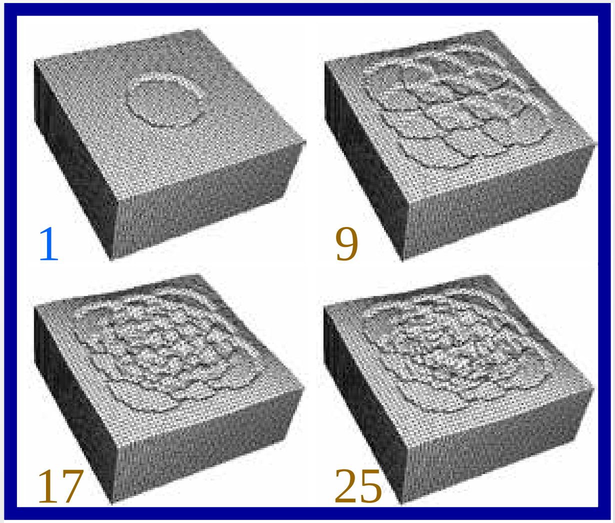


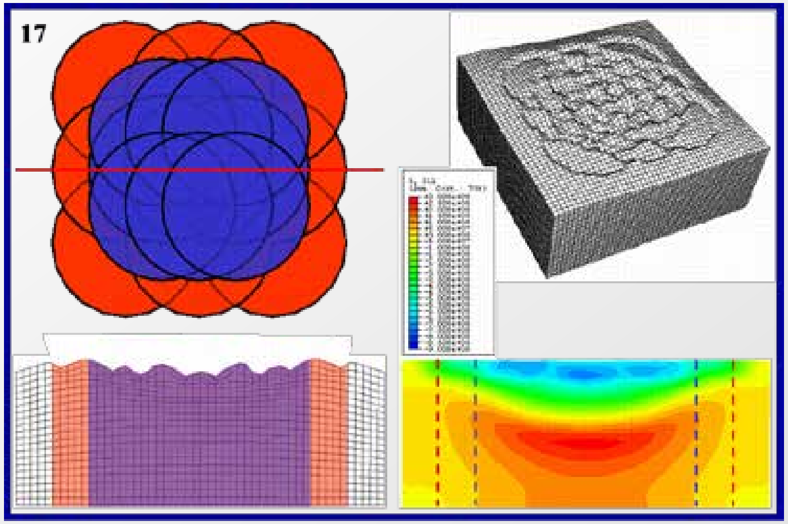
LSP TREATMENT PARAMETERS	
Laser wavelength (nm) ; Q-switched Nd:YAG	1064
Energy per pulse (J/pulse)	2,0
Pulse temporal width (ns)	≈ 9
Laser spot diameter (mm)	1.5
Ratio x-y pitch	1
Confining medium	Water jet ≈ 2 bar
Absorbing coating overlay	No

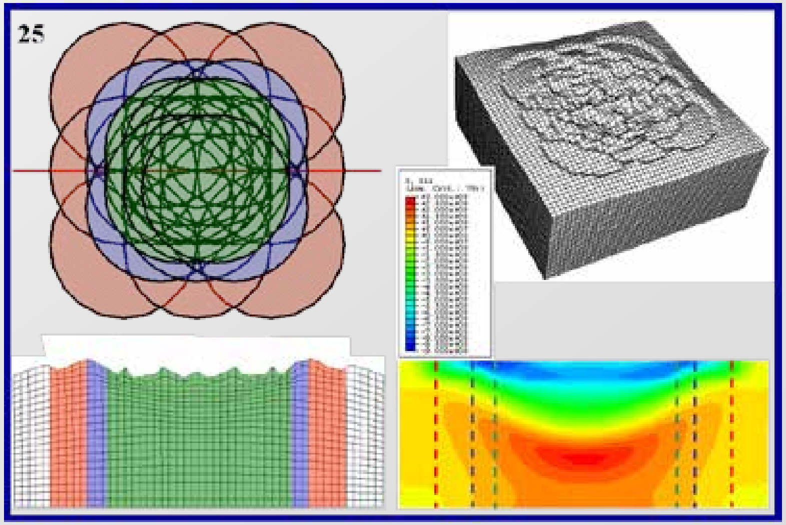
PROCESS EXPERIMENTAL SETUP

EXPERIMENTAL PROCEDURE

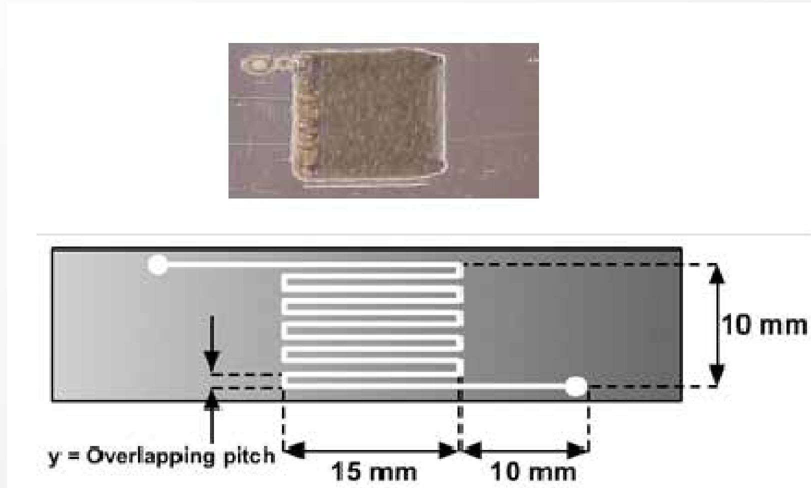








EXPERIMENTAL PROCEDURE



$$\text{Equivalent Overlapping Density} \equiv EOD = \frac{N^o \text{ of pulses}}{\text{Total treated surface}} = \frac{\frac{x}{\Delta x}\frac{y}{\Delta y}}{\Delta s} = \frac{\frac{x}{d}\frac{y}{d}}{xy} = \frac{1}{d^2}$$

$$\text{Equivalent Energy Density} \equiv EED = \frac{N^o \text{ of pulses} \times \text{Pulse Energy}}{\text{Total treated surface}} = \frac{\frac{x}{\Delta x}\frac{y}{\Delta y}E}{\Delta s} = \frac{\frac{x}{d}\frac{y}{d}E}{xy} = \frac{E}{d^2}$$

$$\text{Equivalent local overlapping factor} \equiv ELOF = \frac{N^o \text{ of pulses} \times \text{Pulse Area}}{\text{Total treated surface}} = \frac{\frac{\pi}{4}f^2}{d^2} = \frac{\pi}{4}\left(\frac{f}{d}\right)^2$$

EXPERIMENTAL PROCEDURE

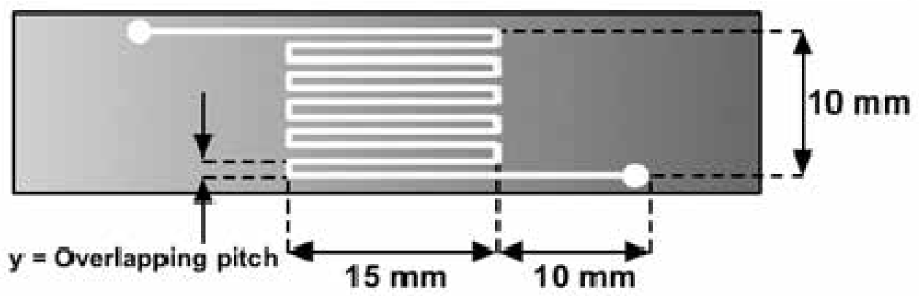
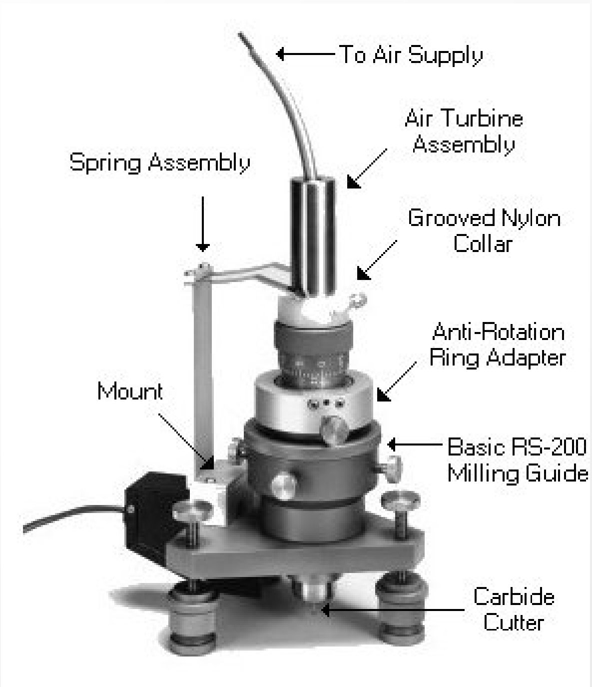


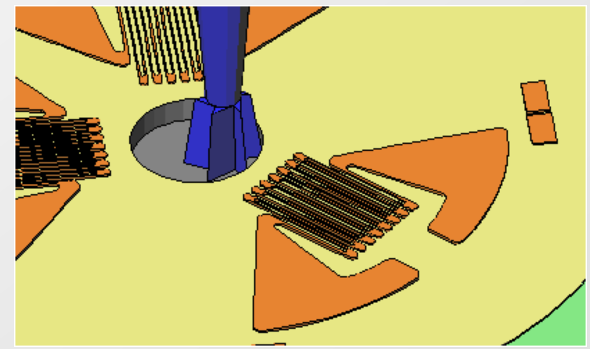
Table I: Relation between overlapping pitch and equivalent number of pulses per unit surface corresponding to the defined sweeping procedure.

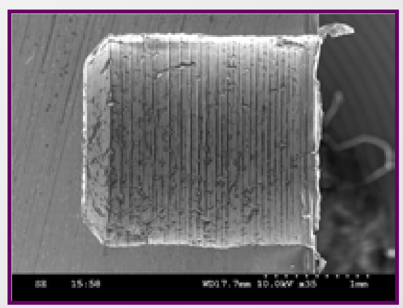
Overlapping pitch Y (mm)	Equivalent overlapping density (pulses/cm^2)
0.588	289
0,33	900
0.285	1225
0.2	2500
0,141	5000

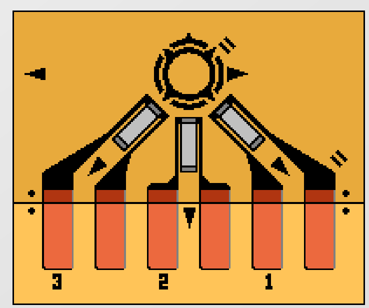
EXPERIMENTAL RESULTS

Residual Stresses (According to ASTM E837-08)









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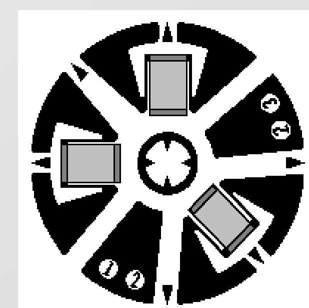
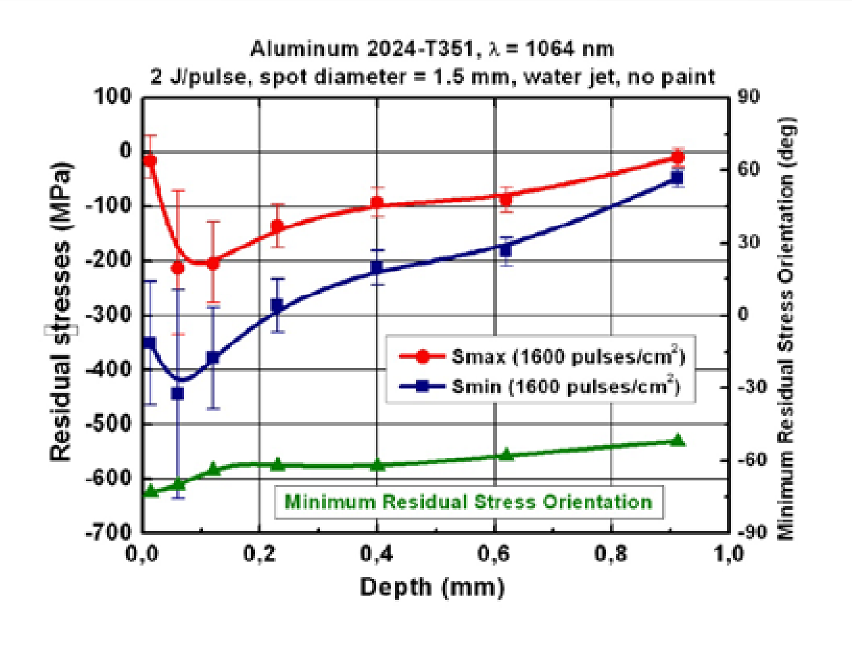


EA-XX-062RE-120

EXPERIMENTAL RESULTS

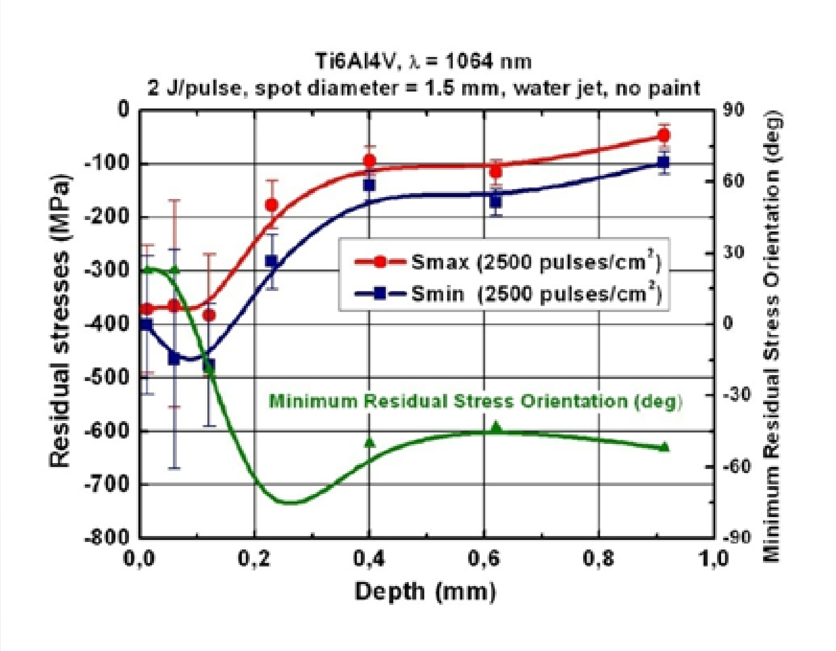
Residual Stresses (According to ASTM E837-08)

Al2024-T351



Relatively broad difference between S_{max} and S_{min} in Al2024-T351

Ti6Al4V

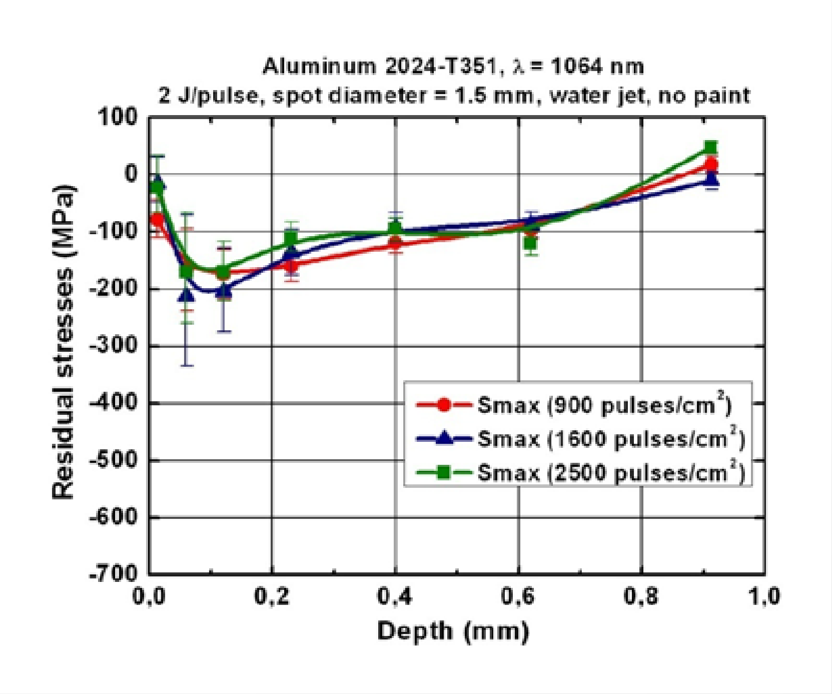


Relatively small difference between S_{max} and S_{min} in Ti6Al4V

EXPERIMENTAL RESULTS

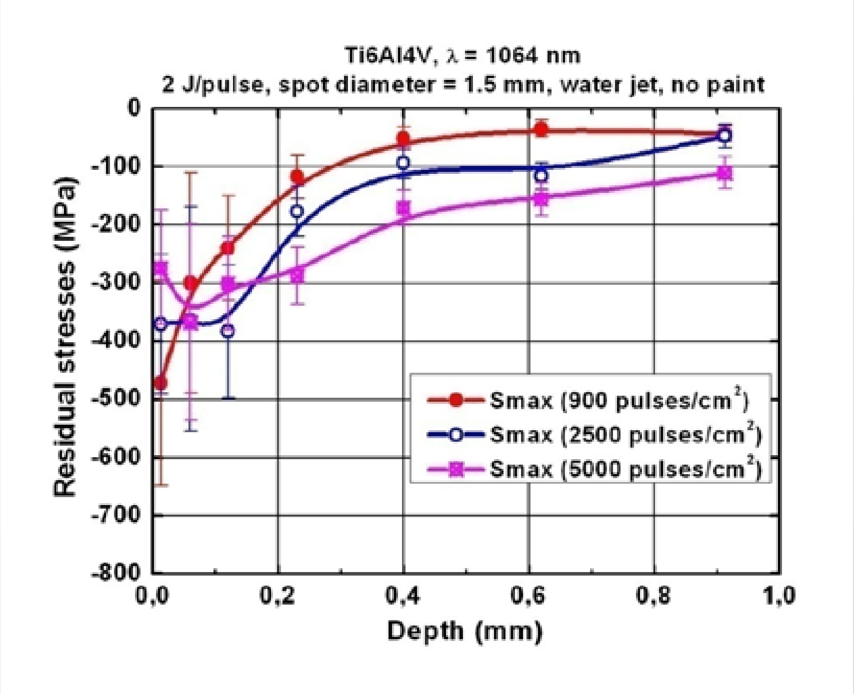
Residual Stresses (According to ASTM E837-08)

Al2024-T351



S_{max} in Al2024-T351 for different irradiation intensities

Ti6Al4V

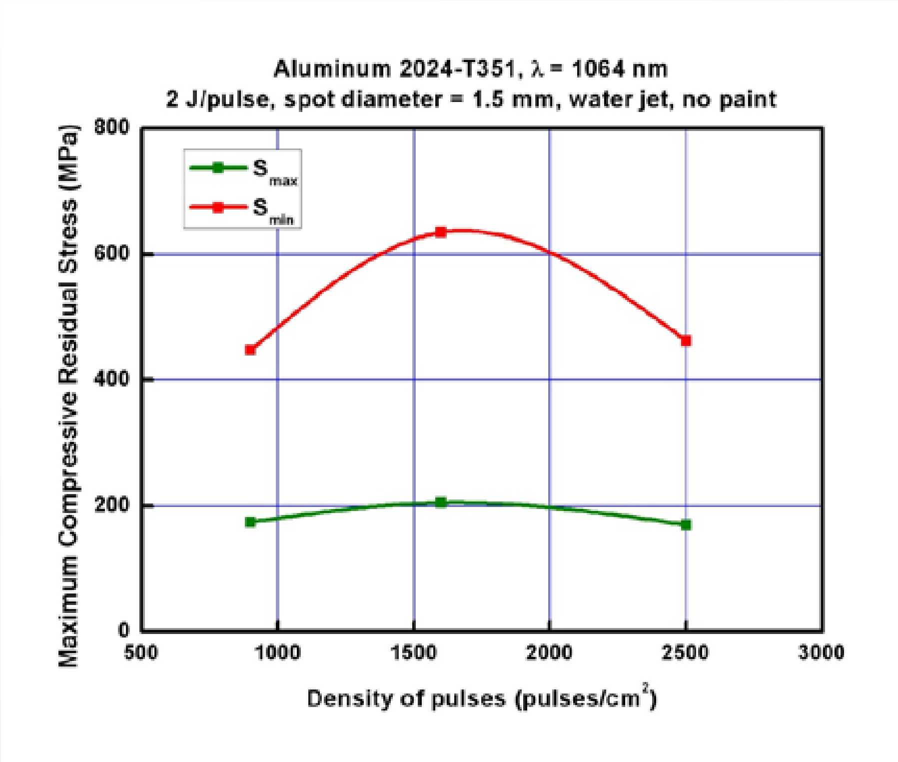


S_{max} in Ti6Al4V for different irradiation intensities

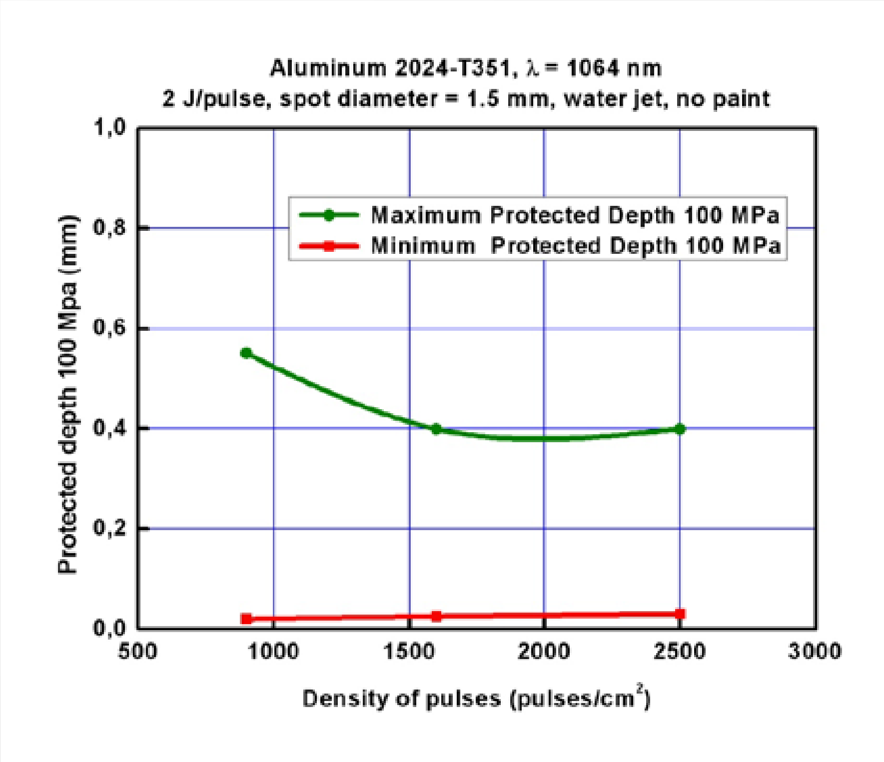
EXPERIMENTAL RESULTS

Residual Stresses (According to ASTM E837-08)

Al2024-T351



S_{max} and S_{mio} extremes reached in Al2024-T351 for different irradiation intensities

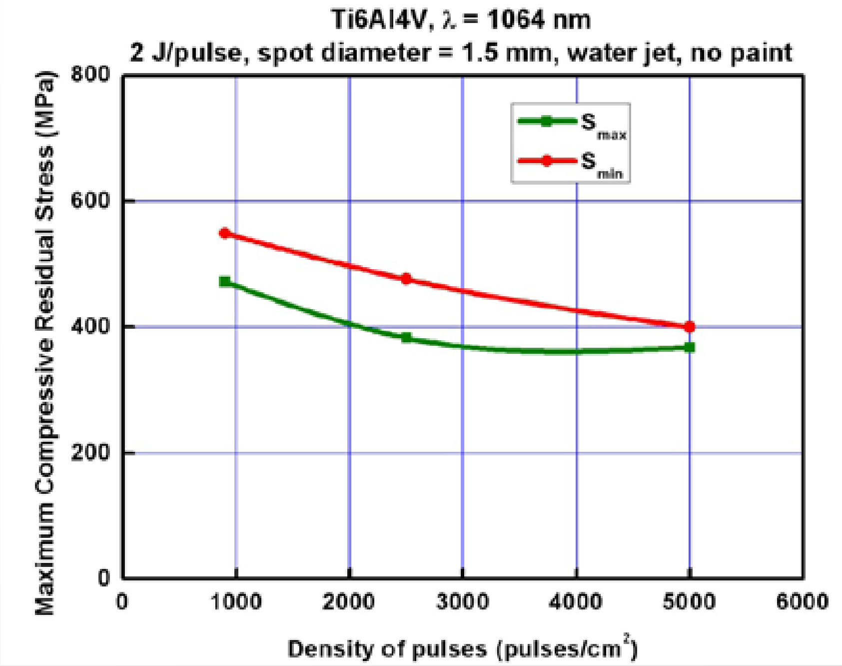


Compressively protected depth (100 MPa) reached in Al2024-T351 for different irradiation intensities

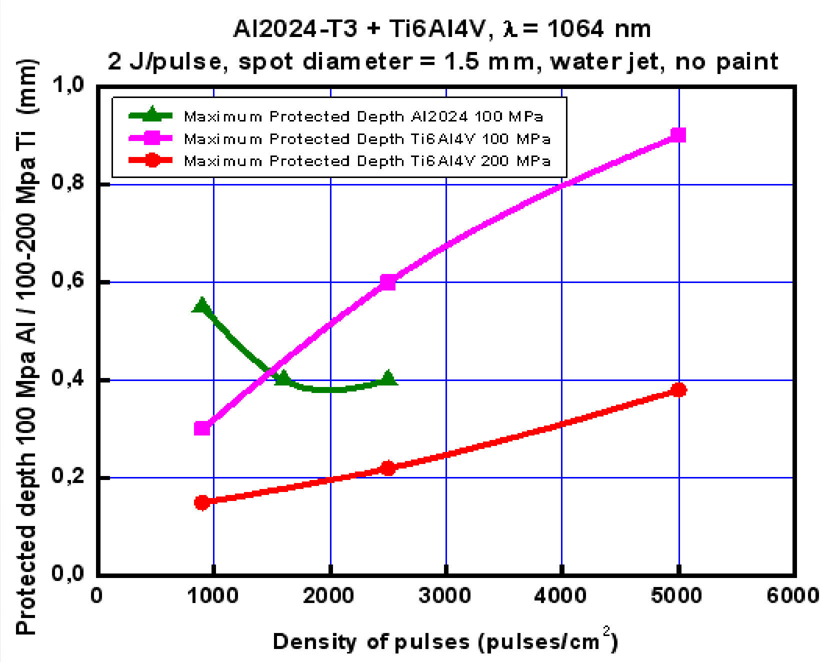
EXPERIMENTAL RESULTS

Residual Stresses (According to ASTM E837-08)

Ti6Al4V



S_{max} and S_{mio} extremes reached in Ti6Al4V for different irradiation intensities

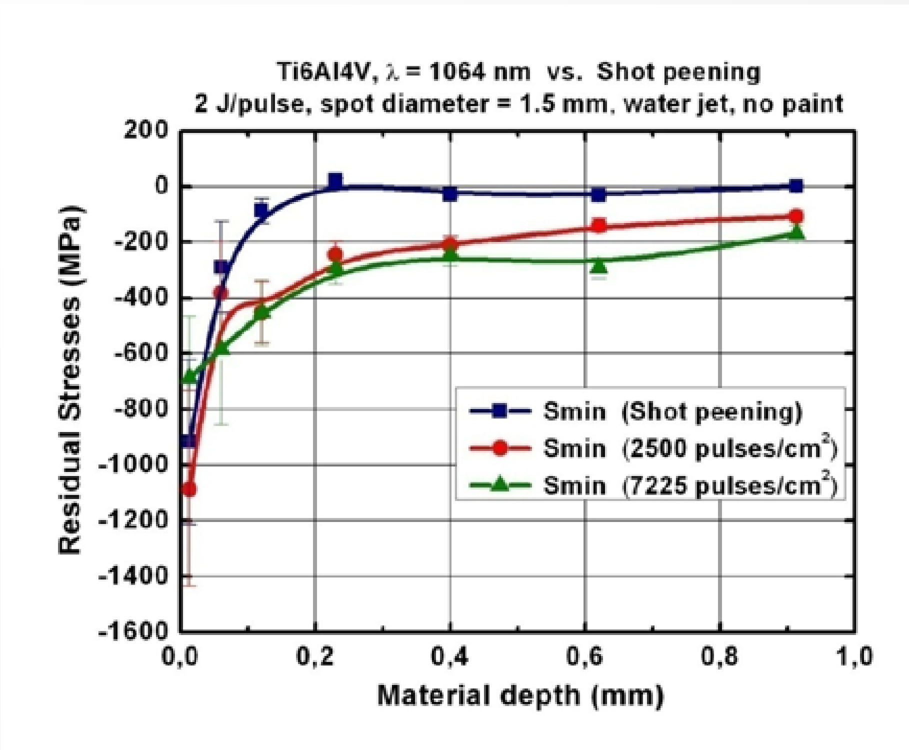


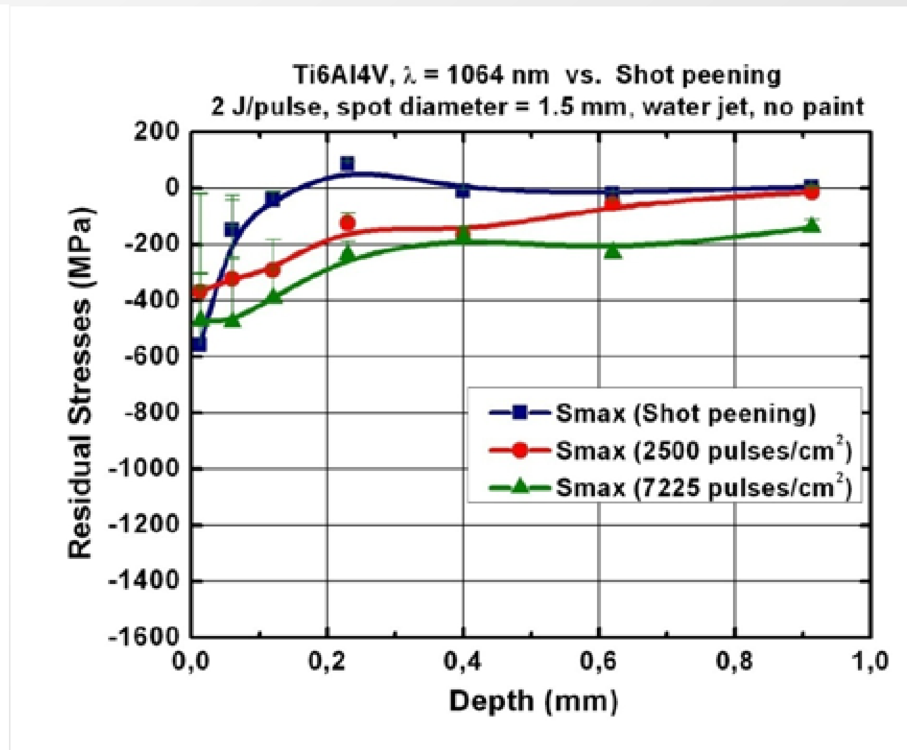
Compressively protected depth (100-200 MPa) reached in Ti6Al4V for different irradiation intensities

EXPERIMENTAL RESULTS

Residual Stresses (According to ASTM E837-08)

Ti6Al4V: Comparison LSP-Shot Peening





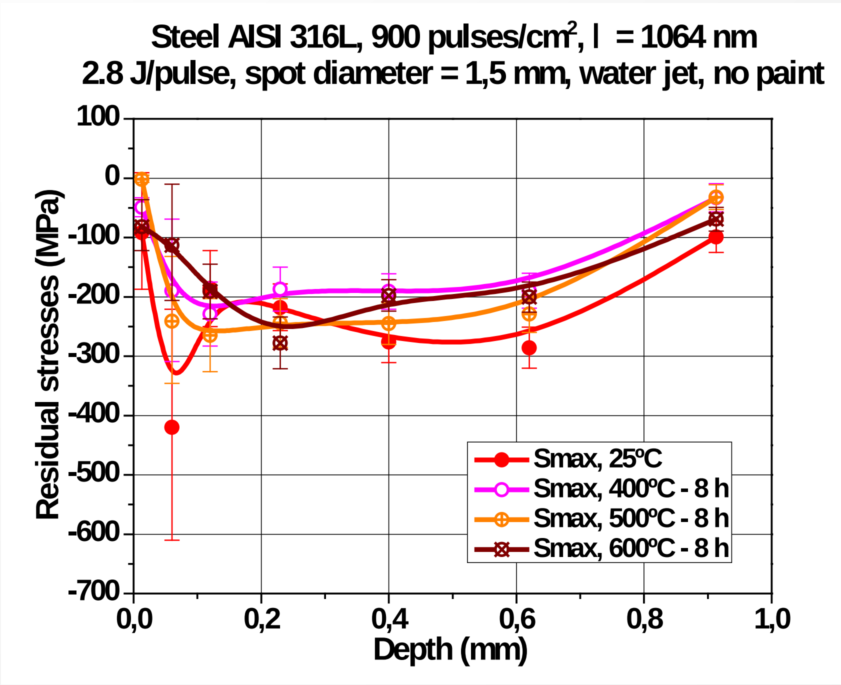
Substantial improvement in Residual Stresses Field in Ti6Al4V vs. to Shot Peening

Decisive improvement in protected depth reached in Ti6Al4V for different irradiation intensities

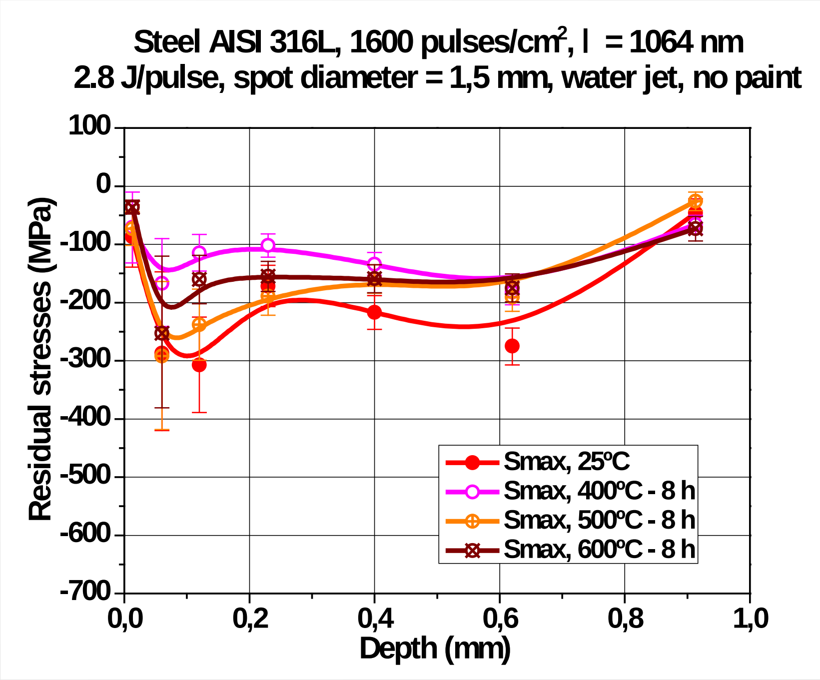
EXPERIMENTAL RESULTS

Residual Stresses Permanence upon Thermal Treatment

AISI 316L Steel

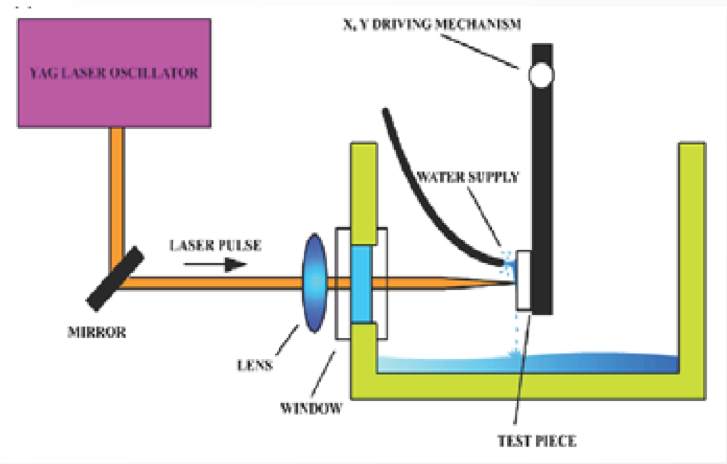


S_{max} permanence in AISI 316L Steel after different Thermal Treatment Temperatures for a 900 pulses/cm² LSP Treatment Intensity



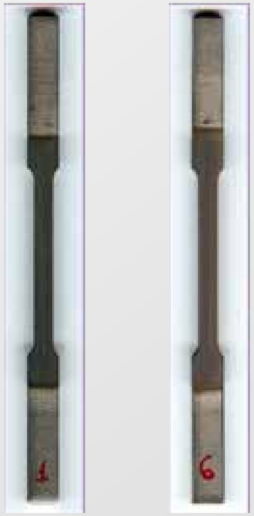
S_{max} permanence in AISI 316L Steel after different Thermal Treatment Temperatures for a 1600 pulses/cm² LSP Treatment Intensity

EXPERIMENTAL RESULTS

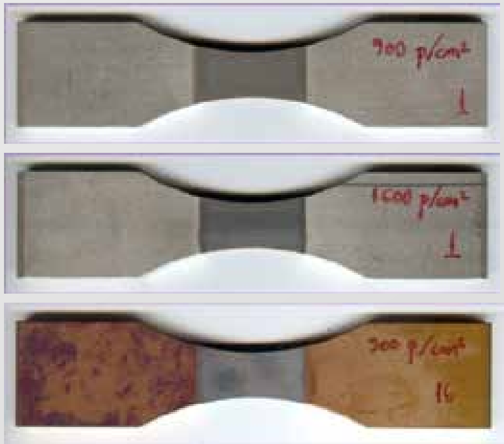


Process parameters	
Wavelength (nm)	1064
Frecuency (Hz)	10
Energy (J/pulse)	2.8
Pulse width (ns)	~ 9
Spot diameter (mm)	~ 1.5
Overlapping (pulses/cm^2)	900
	1600
Confining medium	Water jet
Absorbent coating	No

Experimental setup LSP CLUPM



900 pul/cm^2 1600 pul/cm^2



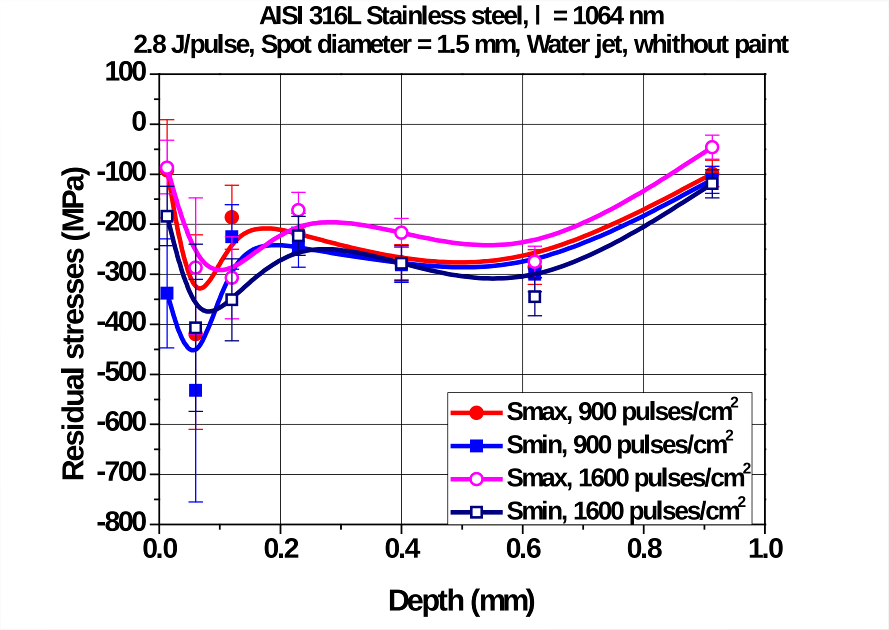
900 pulses/cm^2

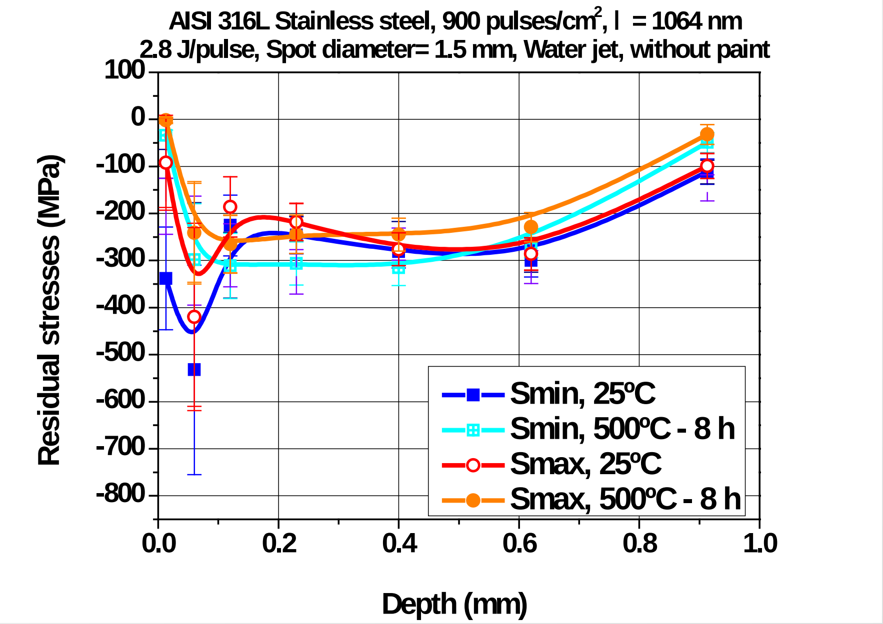
1600 pulses/cm^2

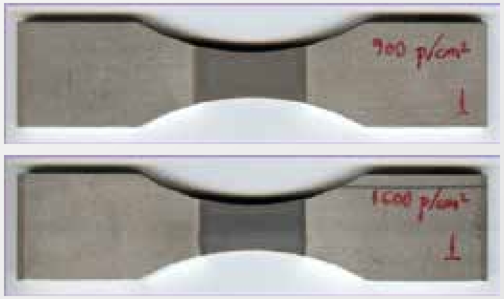
900 pulses/cm^2 + Heat treat.: 500 ˚C, 8h

EXPERIMENTAL RESULTS

Residual Stresses:







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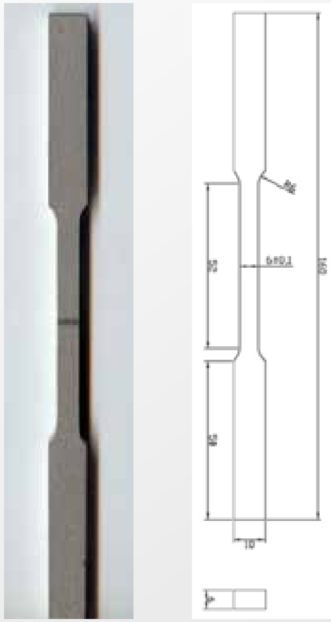
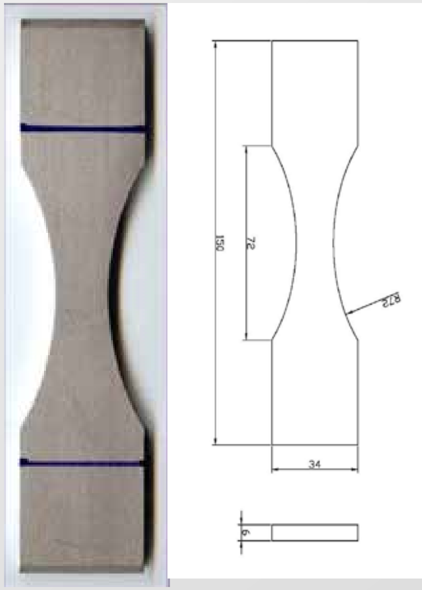
EXPERIMENTAL RESULTS



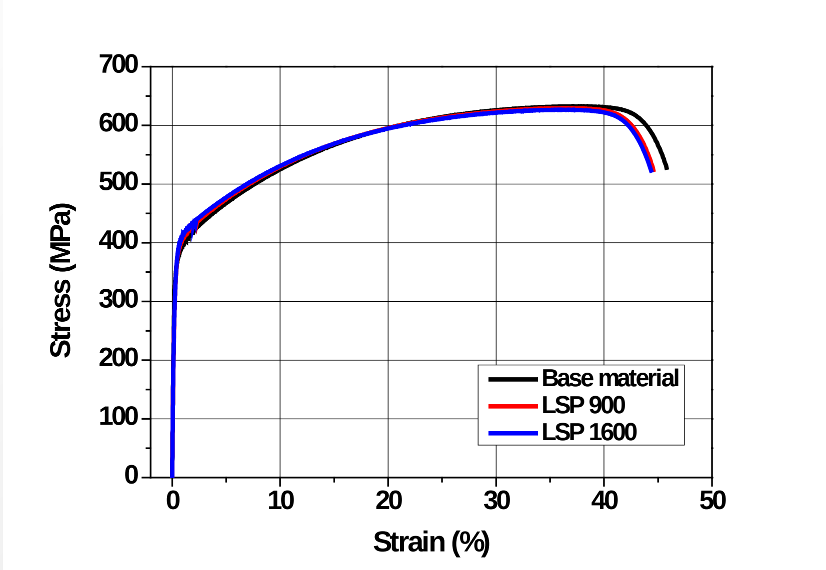
"Sub-size" Tensile Specimen
ASTM E 8M



"Bone" Fatigue Specimen
ASTM E 466

EXPERIMENTAL RESULTS

Tensile Tests:

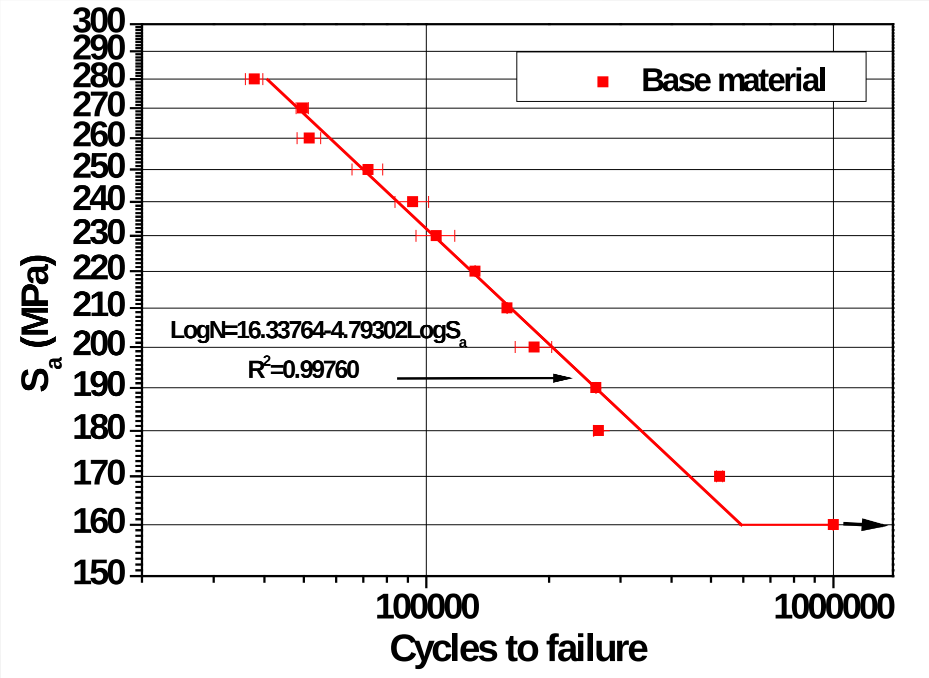


Property	Base material	LSP 900	LSP 1600
Young Modulus (GPa)	177.205	182.099	185.446
Engineering elastic limit (MPa)	355.410	356.390	359.930
Maximun tensile stress (MPa)	633.608	629.700	626.870

EXPERIMENTAL RESULTS

Fatigue Tests:

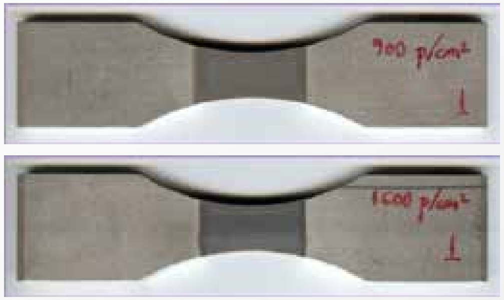
Base Material: AISI 316L Stainless Steel				
S_a (Mpa)	S_{Max} (Mpa)	F_{max} (kN)	F_{mean} (kN)	Cycles
280	622	54.507	29.979	**37752**
270	600	52.560	28.908	**49580**
260	578	50.613	27.837	**51513**
250	556	48.667	26.767	**71850**
240	533	46.720	25.696	**92466**
230	511	44.773	24.625	**105771**
220	489	42.827	23.555	**131677**
210	467	40.880	22.484	**157696**
200	444	38.933	21.413	**184158**
190	422	36.987	20.343	**260974**
180	400	35.040	19.272	**264889**
170	378	33.093	18.201	**661126**
160	356	31.147	17.131	**1000000**

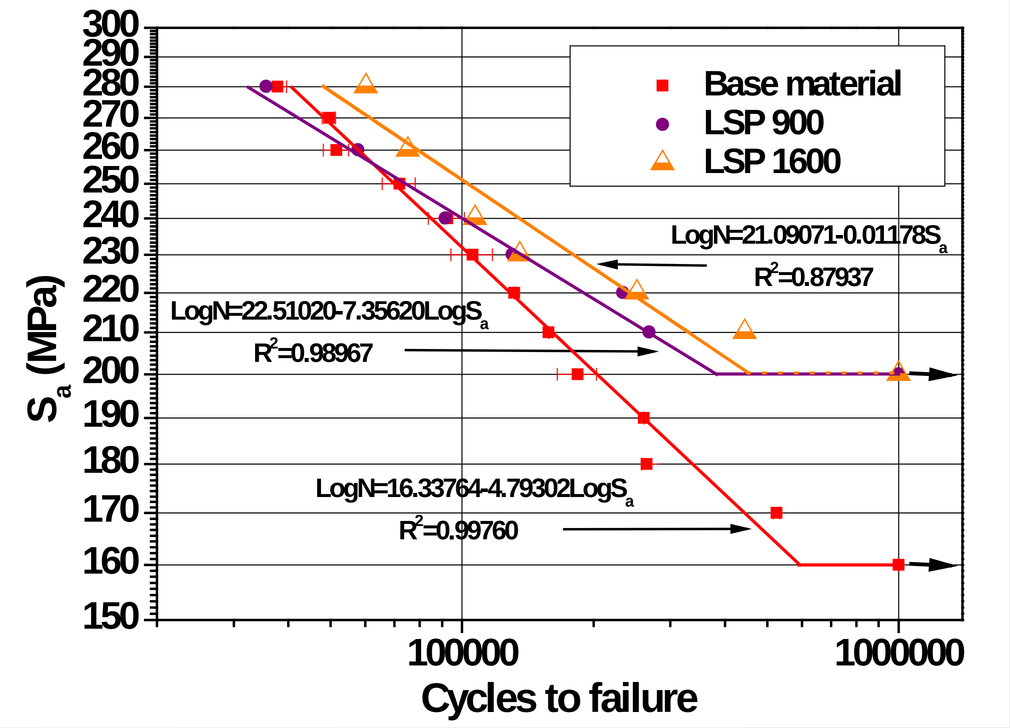


EXPERIMENTAL RESULTS

Fatigue Tests:

AISI 316L Stainless Steel + LSP 900 + LSP 1600 pulses/cm²					
S_a (Mpa)	S_{max} (Mpa)	F_{max} (kN)	F_{mean} (kN)	Cycles 900	Cycles 1600
280	622	54.507	29.979	**35574**	60199
260	578	50.613	27.837	**57777**	75105
240	533	46.720	25.696	**91471**	107098
230	511	44.773	24.625	**130302**	165560
220	489	42.827	23.555	**233301**	185802
210	467	40.880	22.484	**268180**	444006
200	444	38.933	21.413	**1000000**	1000000





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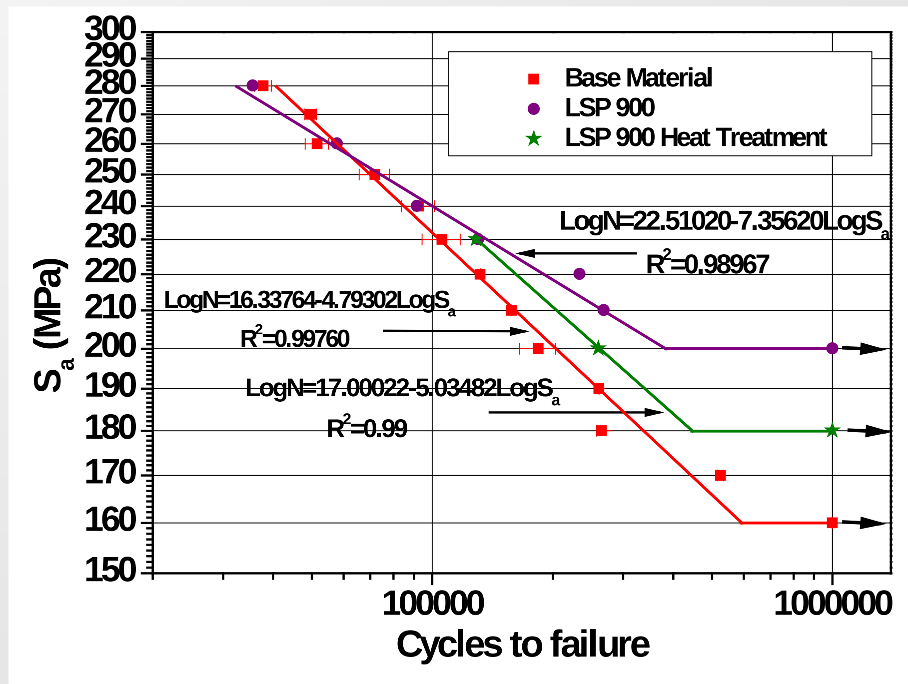
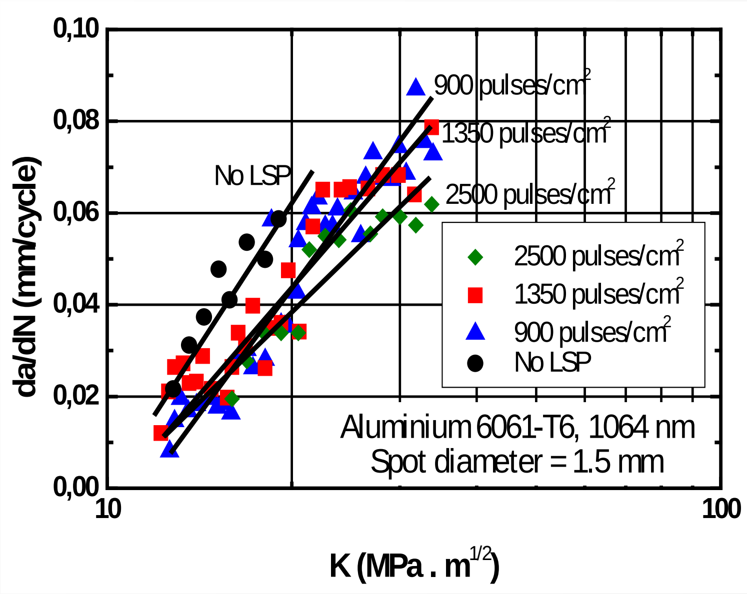
EXPERIMENTAL RESULTS

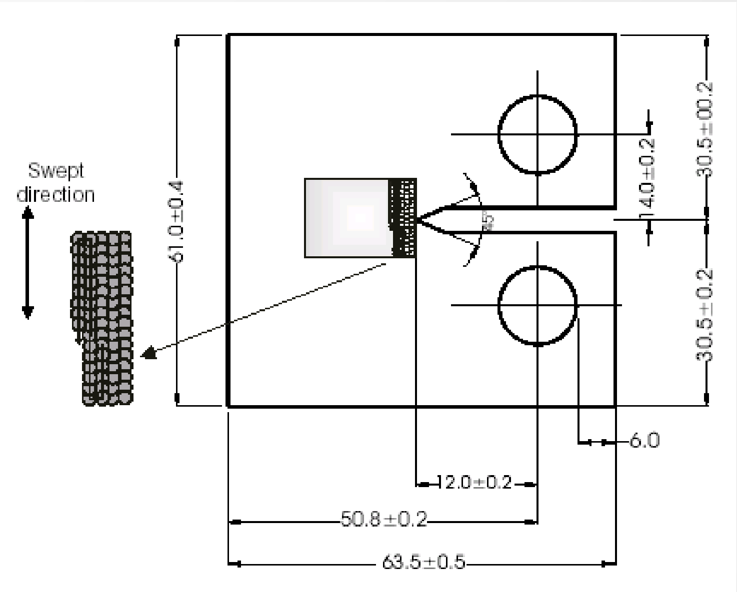
Fatigue Tests:

LSP 900 + Heat treatment (500ºC; 8h)				
S_a (Mpa)	S_{Max} (Mpa)	F_{max} (kN)	F_{mean} (kN)	Cycles
280	622	54.507	29.979	**6000**
230	511	44.773	24.625	**128632**
200	444	38.933	21.413	**259987**
180	400	35.040	19.272	**1000000**



EXPERIMENTAL RESULTS



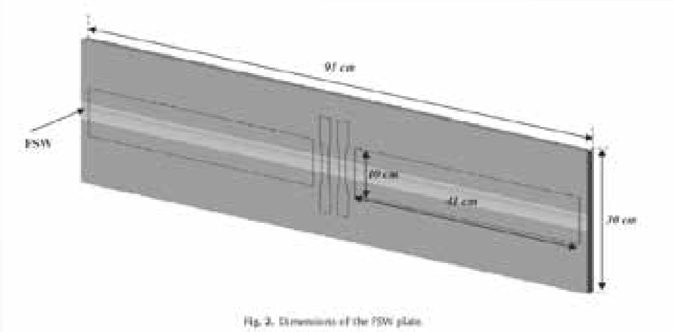


$$\frac{da}{dN} = C.K^{m}$$

Pulse density (cm^{-2})	C (mm/cycle)	M (dimensionless)
0 (No LSP treatment)	4×10^{-13}	7.664
900	8×10^{-13}	6.818
1350	2×10^{-11}	5.733
2500	3×10^{-10}	4.723

Rubio-González, C. et al.: Mat. Sci. Eng. A., 386 (2004) 291-295

A typical prospective LSP application to welding technology



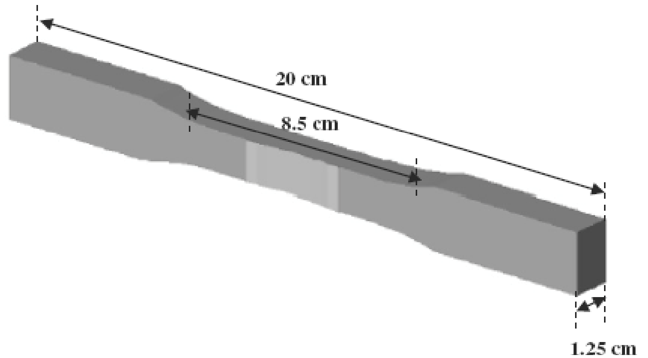
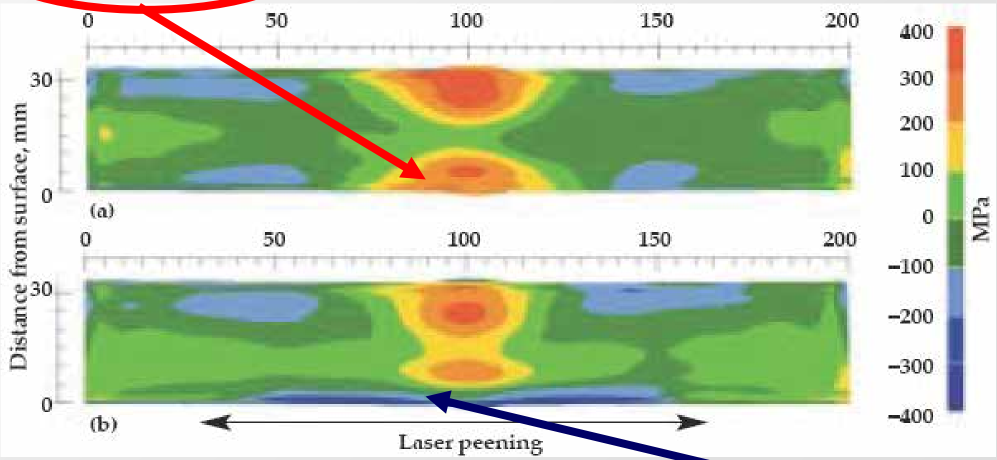


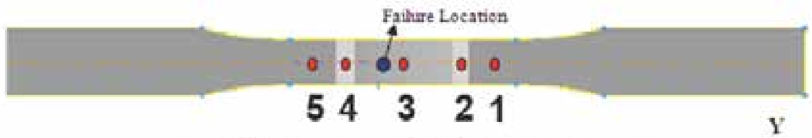
Fig. 4. Dimensions of the tensile specimen.

Problem

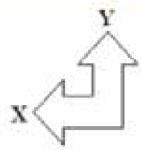


Solution

DISCUSSION AND OUTLOOK



Location 1	HAZ *(Advancing Side)*
Location 2	TMAZ *(Advancing Side)*
Location 3	Weld Nugget
Location 4	TMAZ *(Retreating Side)*
Location 5	HAZ *(Retreating Side)*



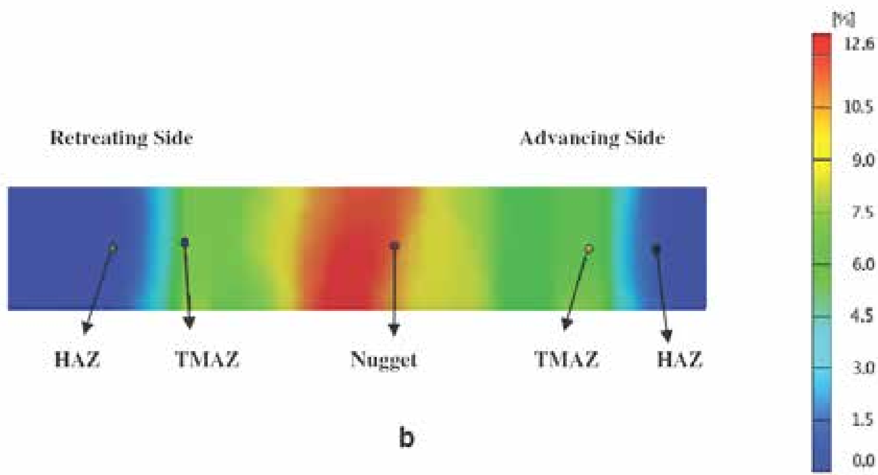


Fig. 10. (a) Tensile properties at different regions of the weld (b) Strain fields in the x-direction for the specimen before failure.

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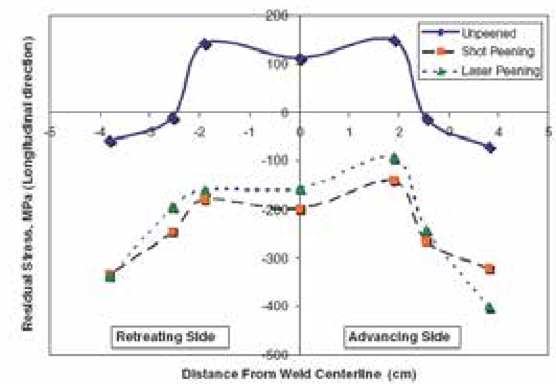


Fig. 11. Residual stresses for the various peened FSW specimens.

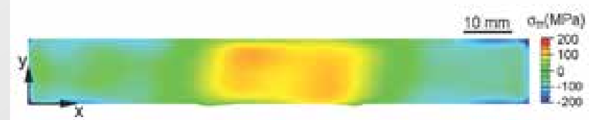


Fig. 12. Two-dimensional map of the measured residual stress for the unpeened FSW specimen.

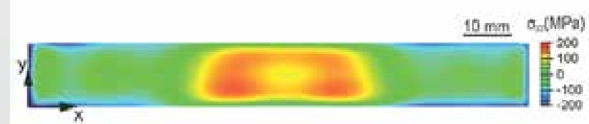


Fig. 13. Two-dimensional map of the measured residual stress for the shot peened FSW specimen.

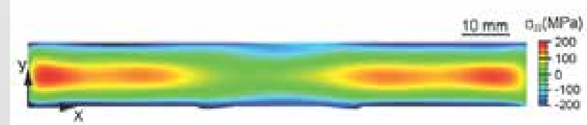
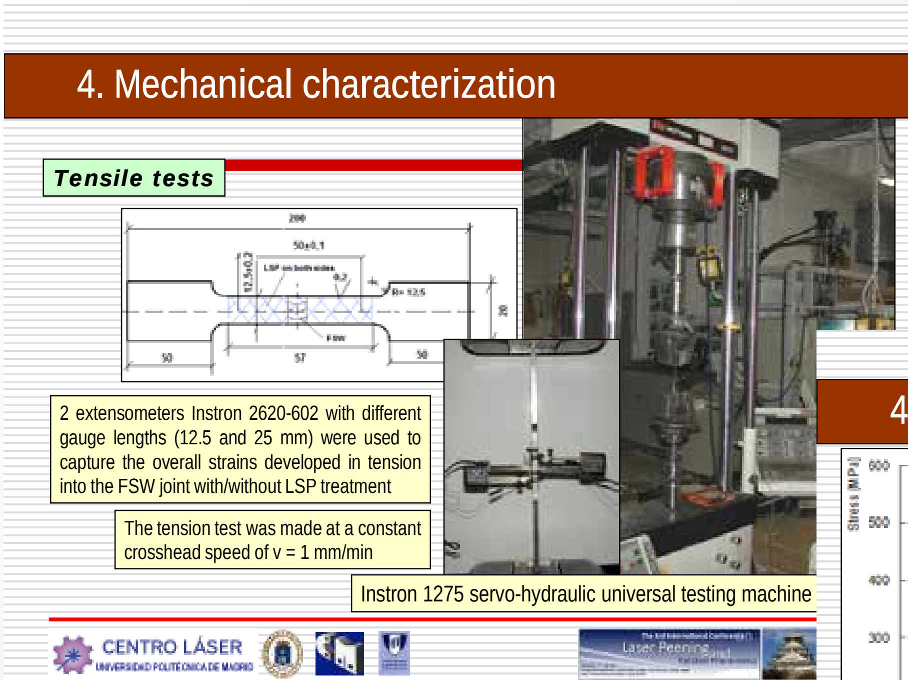
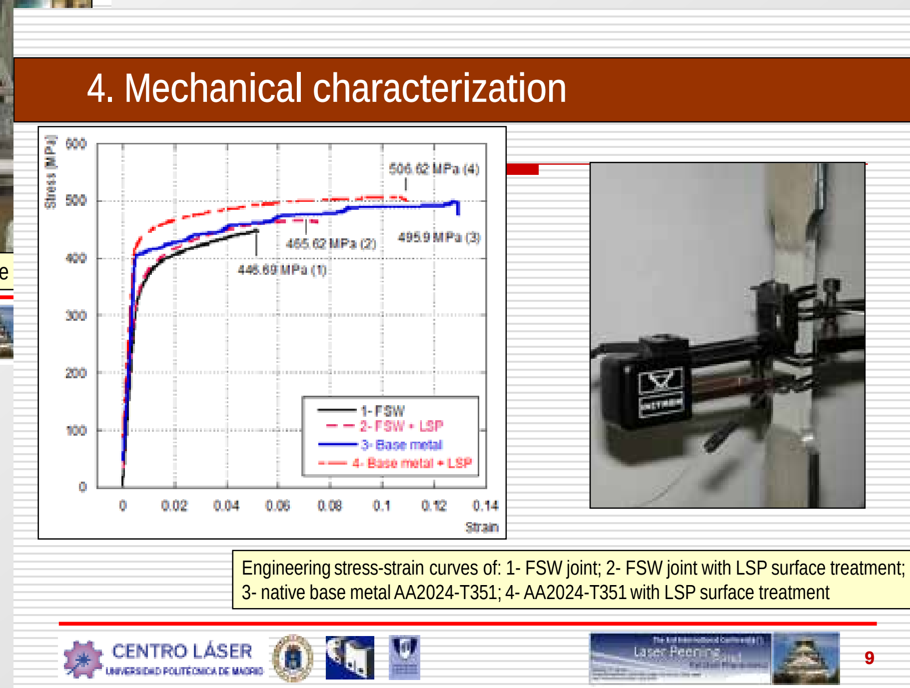


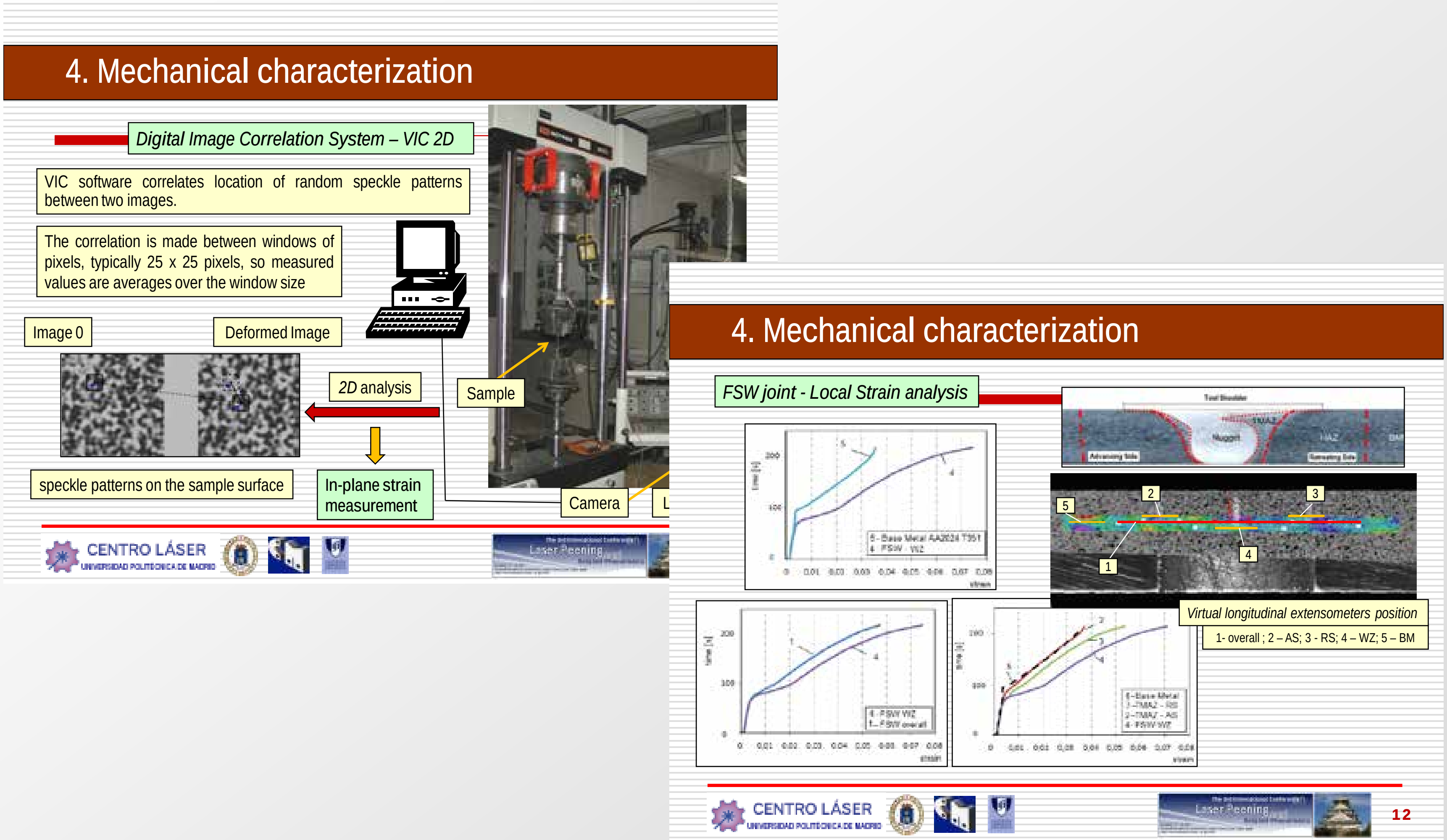
Fig. 14. Two-dimensional map of the measured residual stress for the laser peened FSW specimen.

DISCUSSION AND OUTLOOK

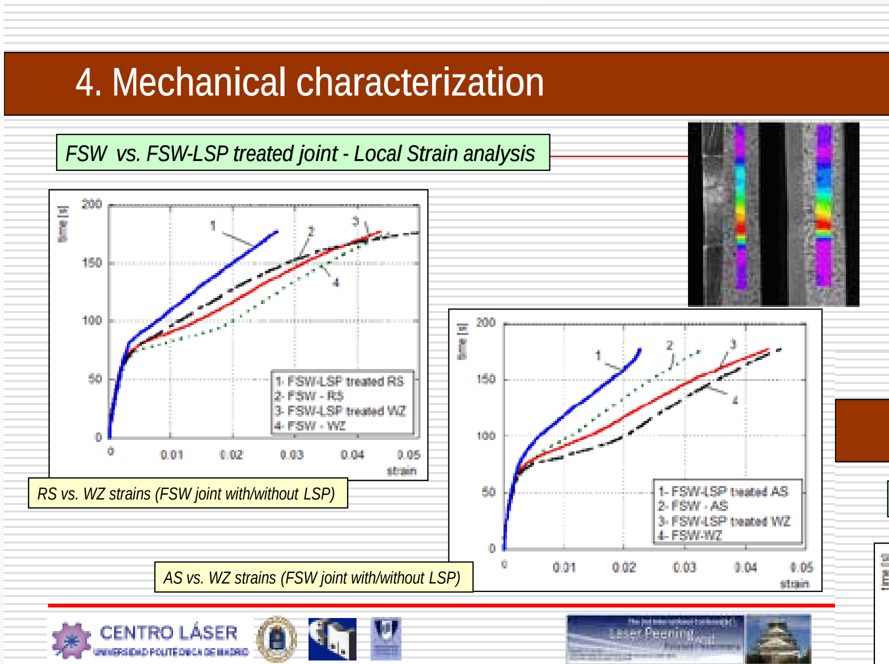


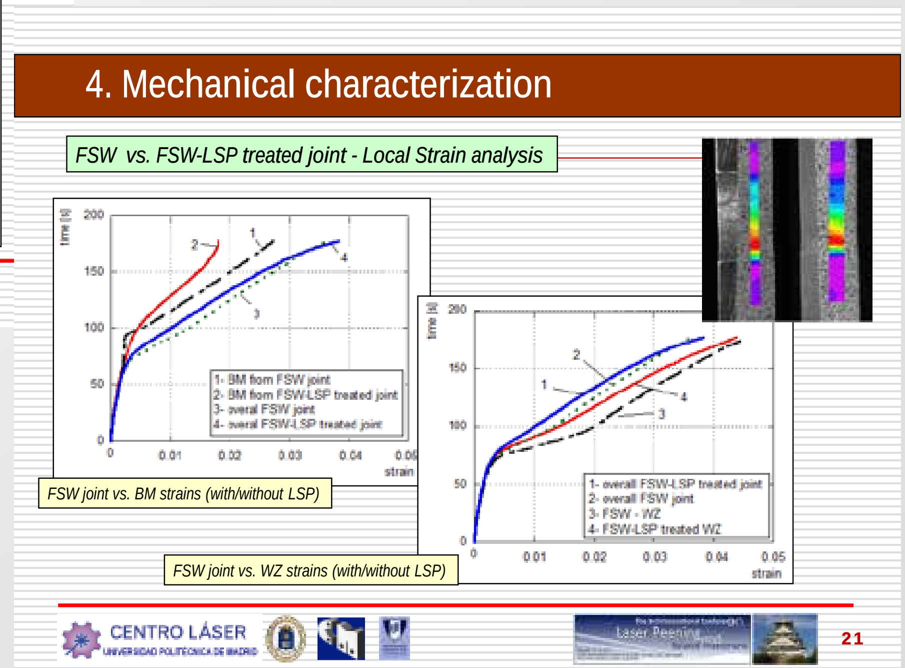


DISCUSSION AND OUTLOOK



DISCUSSION AND OUTLOOK





DISCUSSION AND OUTLOOK

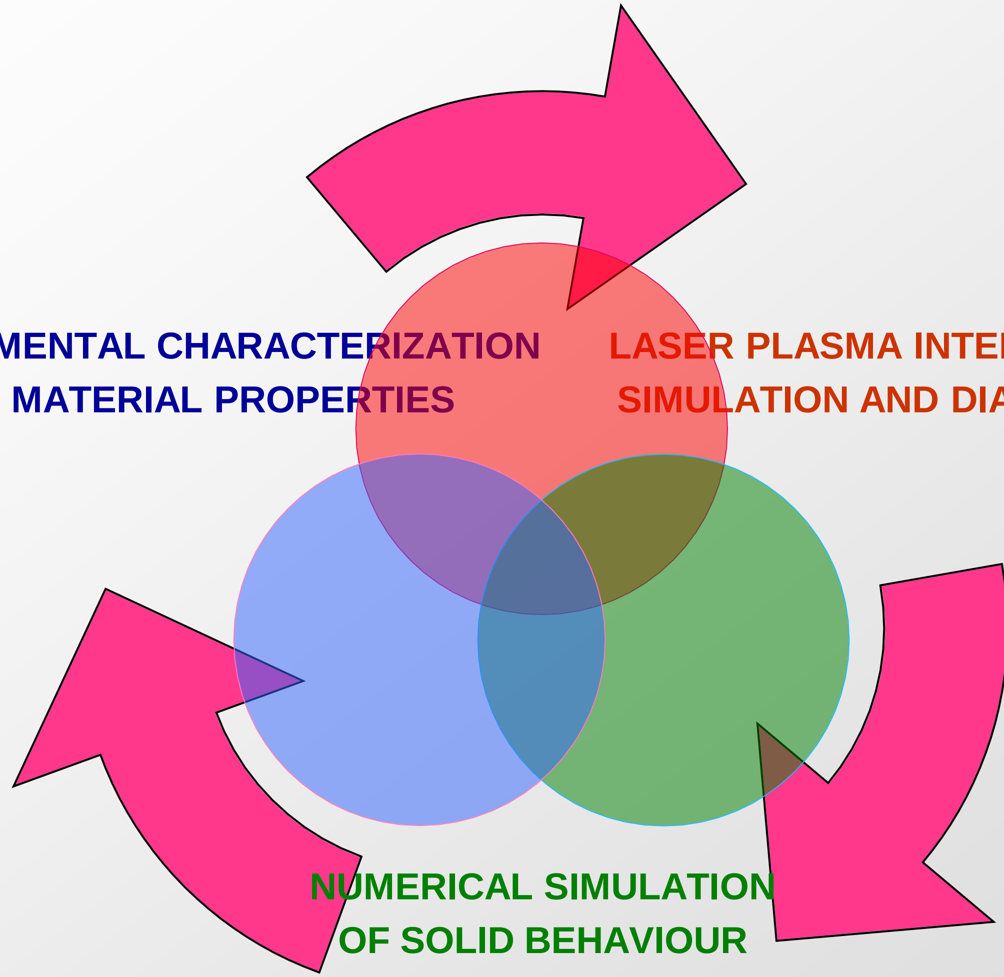
§ With the aid of the experimental irradiation and process diagnosis system implemented at CLUPM (Spain), a complete feasibility of the LSP technique at laboratory scale for the induction of improved material surface properties has been accomplished. The implementation of the appropriate experimental diagnosis methods enables a reliable process predictive assessment capability in view of process industrial implementation.

§ On the other side, the need for a practical capability of LSP process control in practical applications has led to the joint development of comprehensive theoretical/computational models and related material properties characterization capabilities able to properly assess the complex material issues arising in the process.

§ With the aid of the developed experimental testing capability, a specifically targeted analysis of LSP induced effects (such as surface morphology, surface composition transformations, surface mechanical behaviour, deep residual stress fields and others) is made possible, thus allowing a practical development of the technique from an industrial point of view.

§ Representative applications of the LSP technique to the treatment of typical aeronautic grade alloys (typically Al and Ti) and stainless steels characteristic of the aerospace, nuclear, biomedical and equipment industries, as well as to the post-treatment of welded metallic joints have been successfully conducted to the induction of compressive residual stresses fields decisively improving their fatigue life.

DISCUSSION AND OUTLOOK



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LSP: An emerging industrial technology

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NUMERICAL SIMULATION. MODEL DESCRIPTION

The SHOCKLAS Calculational System