Improvement of Fatigue Life and Surface Properties of Metallic Materials of Biomedical Interest by Laser Shock Processing

J.L. Ocaña[1], J.A. Porro[1], M. Díaz[1], I. Angulo[1], F. Cordovilla[1], D. Peral[1], J.L González-Carrasco[2,3], M. Lieblich[2]

[1] UPM Laser Center. Polytechnical University of Madrid. Ctra. Valencia, km. 7.3. 28031 Madrid. Spain

[2] National Center for Metallurgical Research (CENIM-CSIC), Avda Gregorio del Amo, 8. 28040 Madrid. Spain

[3] Center for Networked Research on Bioengineering, Biomaterials and Nanomedicine (CIBER-BBN), Spain

e-mail: jlocana@etsii.upm.es

TRANSILVANIA
University of Brasov

BRAMAT 2017
10TH INTERNATIONAL CONFERENCE ON MATERIALS SCIENCE & ENGINEERING
9 - 11 MARCH 2017, BRASOV, ROMANIA

Organized by: Faculty of Materials Science and Engineering –**Transilvania** University of Brasov
Supporting Organizations: Academy of Technical Sciences of Romania – **ASTR,** Romanian Association of Heat treatment and Surface engineering – **ATTIS,** Romanian Foundry Technical Association – **ATTR,** Romanian Welding Society **– ASR**

TRANSILVANIA
University of Brasov
BRAMAT 2017
10TH INTERNATIONAL CONFERENCE ON MATERIALS SCIENCE & ENGINEERING
9 - 11 MARCH 2017, BRASOV, ROMANIA

Improvement of Fatigue Life and Surface Properties of Metallic Materials of Biomedical Interest by Laser Shock Processing

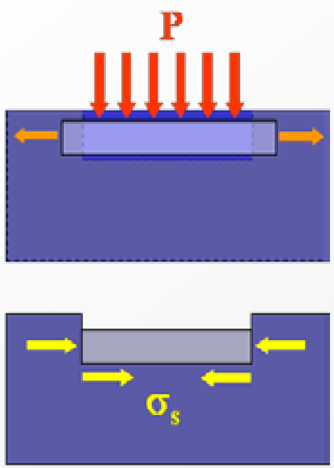
OUTLINE:

- Introduction
- Summary on the Physical Basis of LSP Treatments
- Predictive Assessment Methods developed at CLUPM
- Experimental LSP Setup at CLUPM
- Sample results on the treatment of Metallic Materials of Biomedical Interest
  - Fatigue life enhancement of AISI 316L specimens
  - Surface modification of Ti6Al4V samples
  - Compressive Residual stresses fields induced in Ti6Al4V samples
  - Computational Design of LSP Treatment for a Hip Prosthesis
- Discussion and Outlook
  - LSP treatment of new/advanced materials of biomedical interest

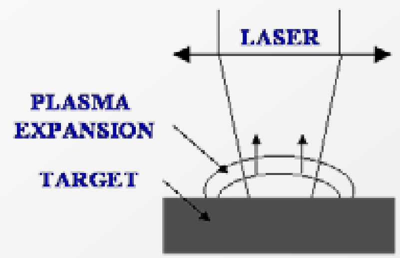
INTRODUCTION

- Laser Shock Processing (LSP) is developed 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.
- The highly beneficial effect of LSP treatments has been demonstrated in the extension of life of test specimens with induced surface notches.
- The application of the LSP treatment to concrete high reliability components, particularly in the field of metallic materials of biomedical interest is envisaged.
- In the present communication, several experimental examples of the effects introduced in this kind of materials are shown along with some computational design tools developed in relation with typical prosthetical components.
- Additionally, the prospects for the application of the LSP treatment to new/advanced materials of biomedical interest are discussed.

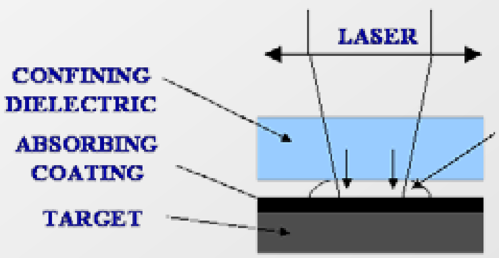
REMINDER OF LSP PHYSICAL PRINCIPLES (1/2)



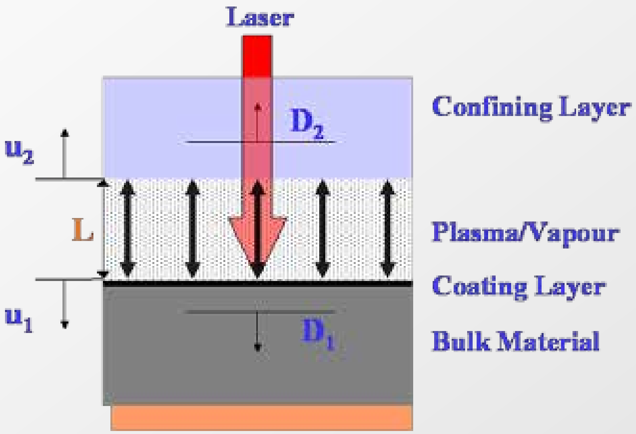
FREE MODE

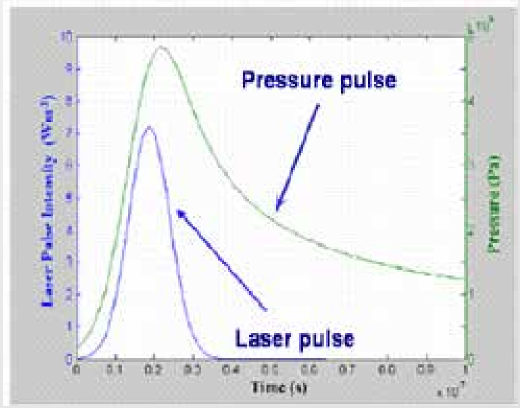


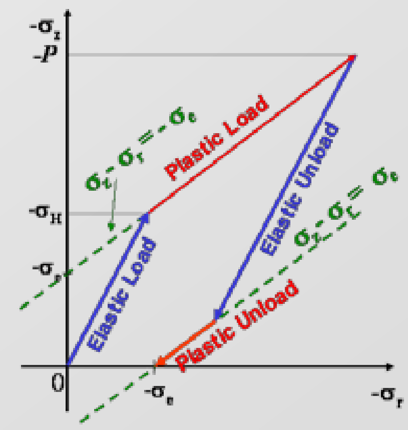
CONFINED MODE



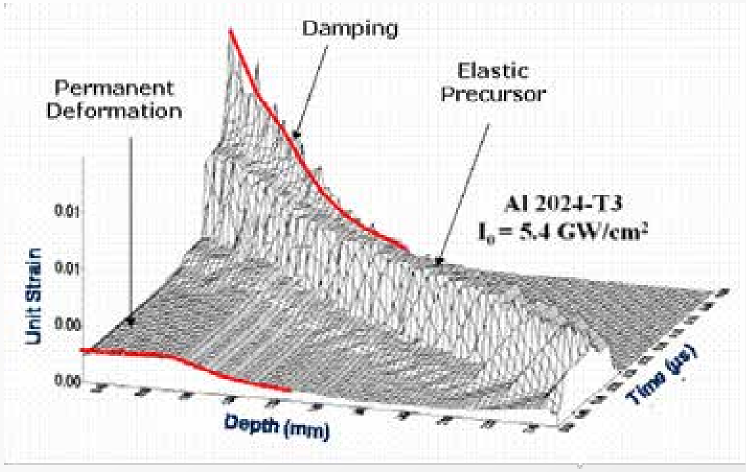
FREE PLASMA EXPANSION → **IMPROVED PRESSURE AND IMPULSION**

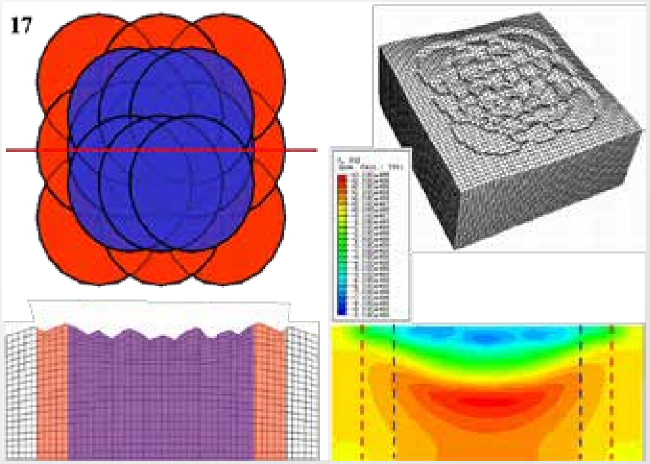


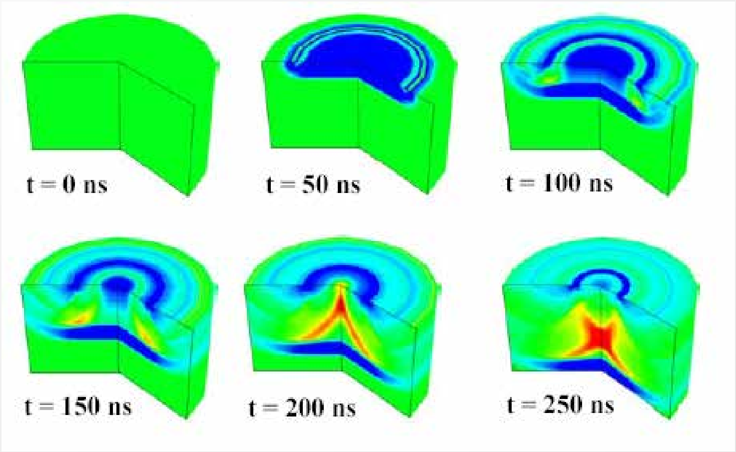


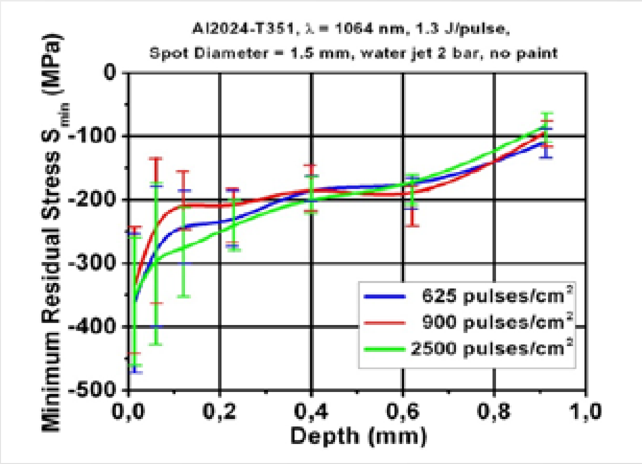


REMINDER OF LSP PHYSICAL PRINCIPLES (2/2)

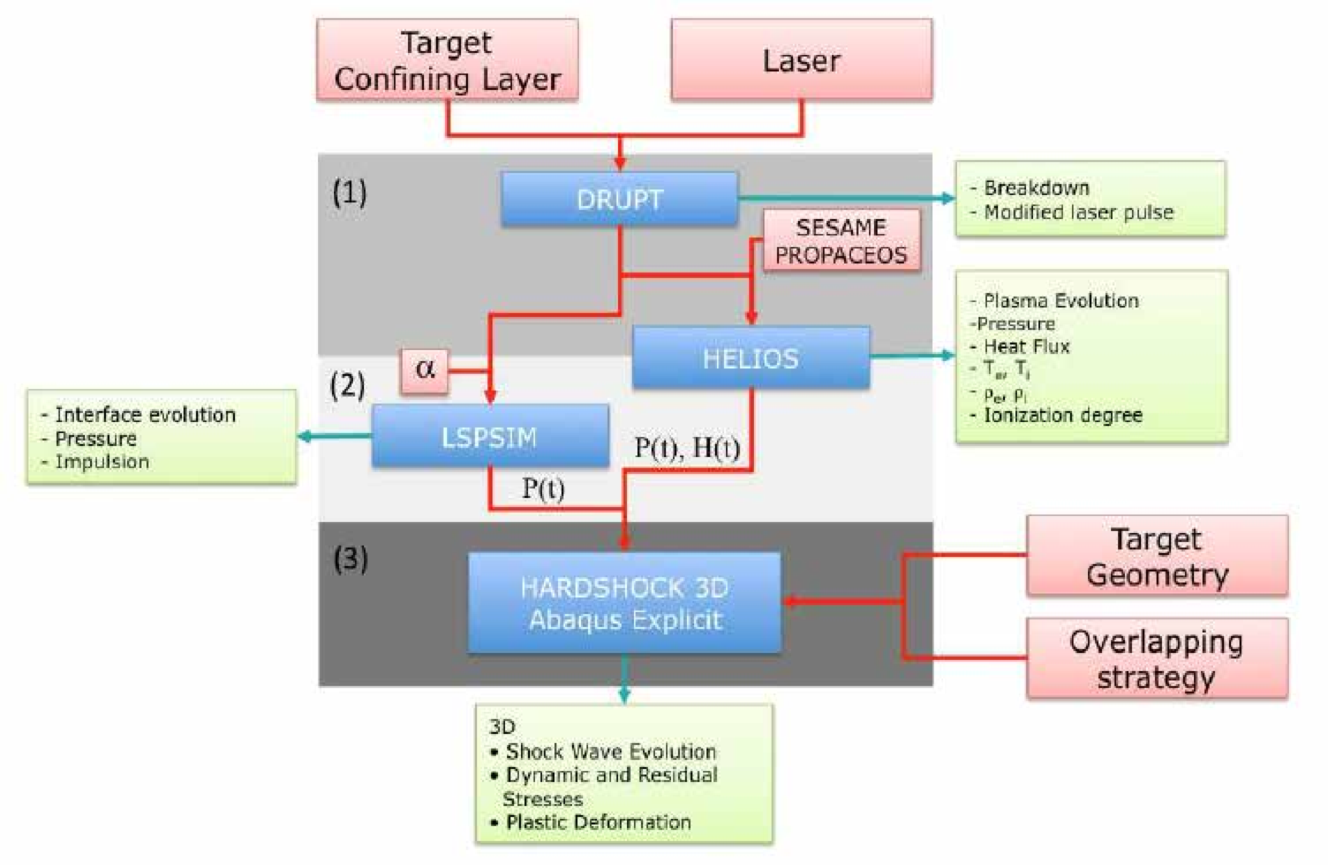






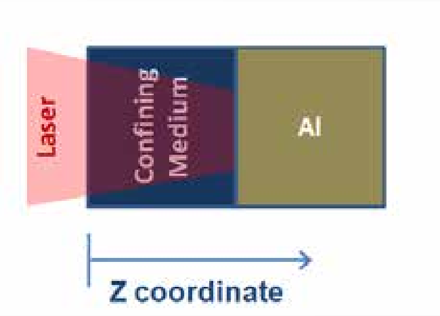


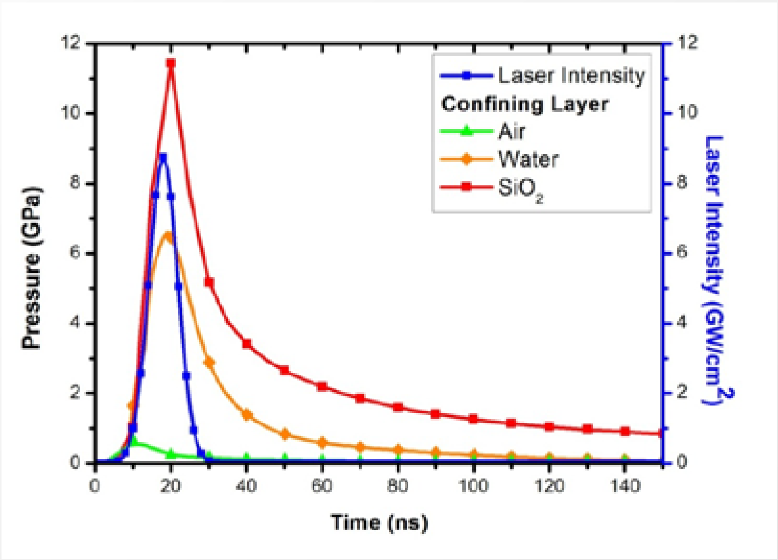
The SHOCKLAS Calculational System

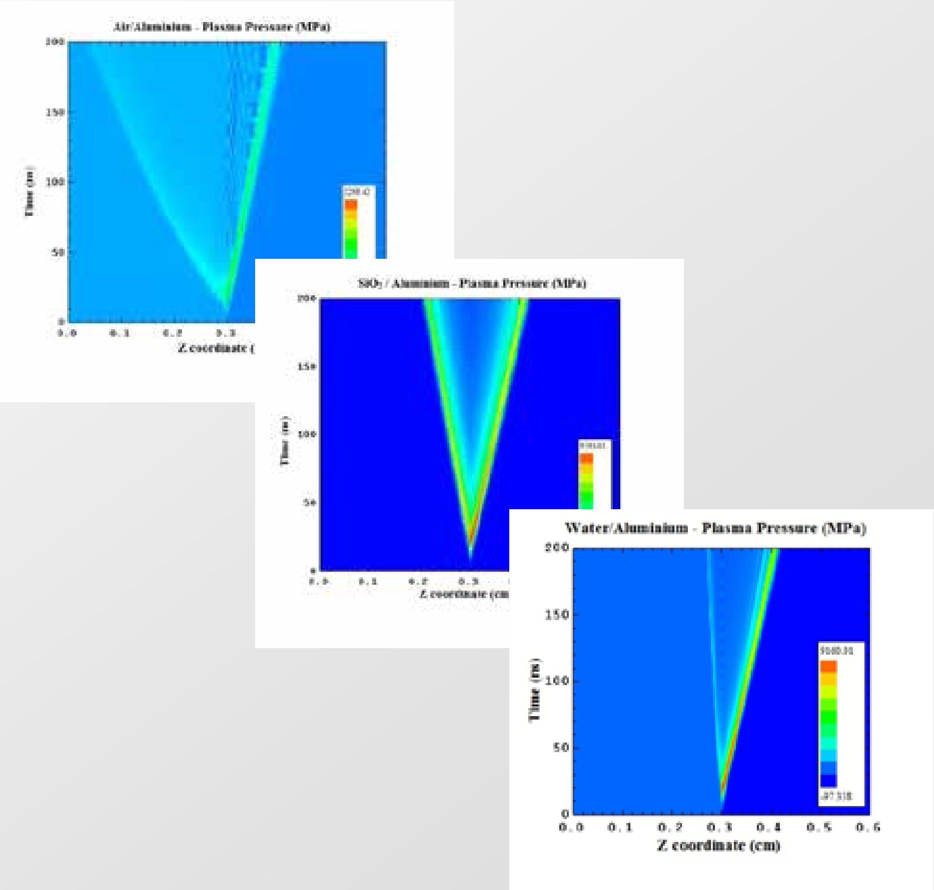


CONSISTENT MODEL FOR CONFINED PLASMA EXPANSION IN LSP

HELIOS Analysis of relative influence of confining material



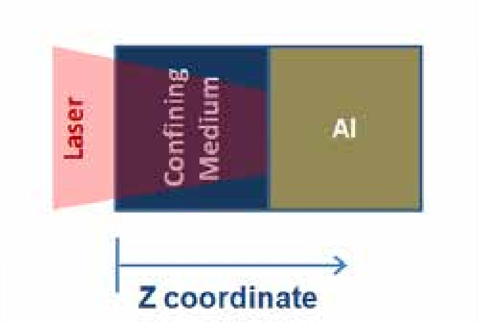


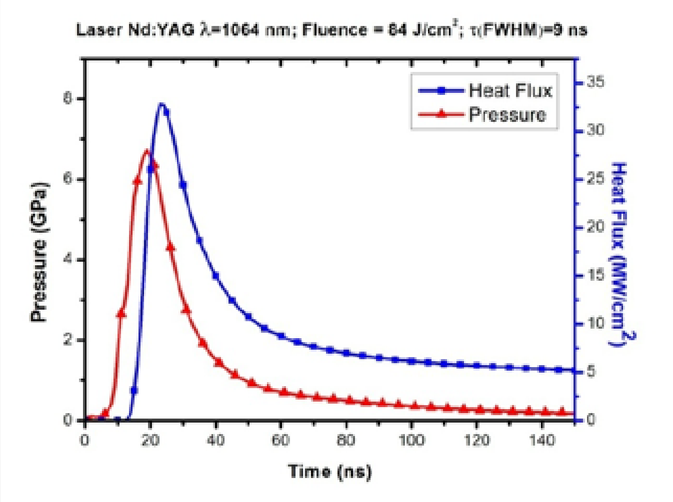


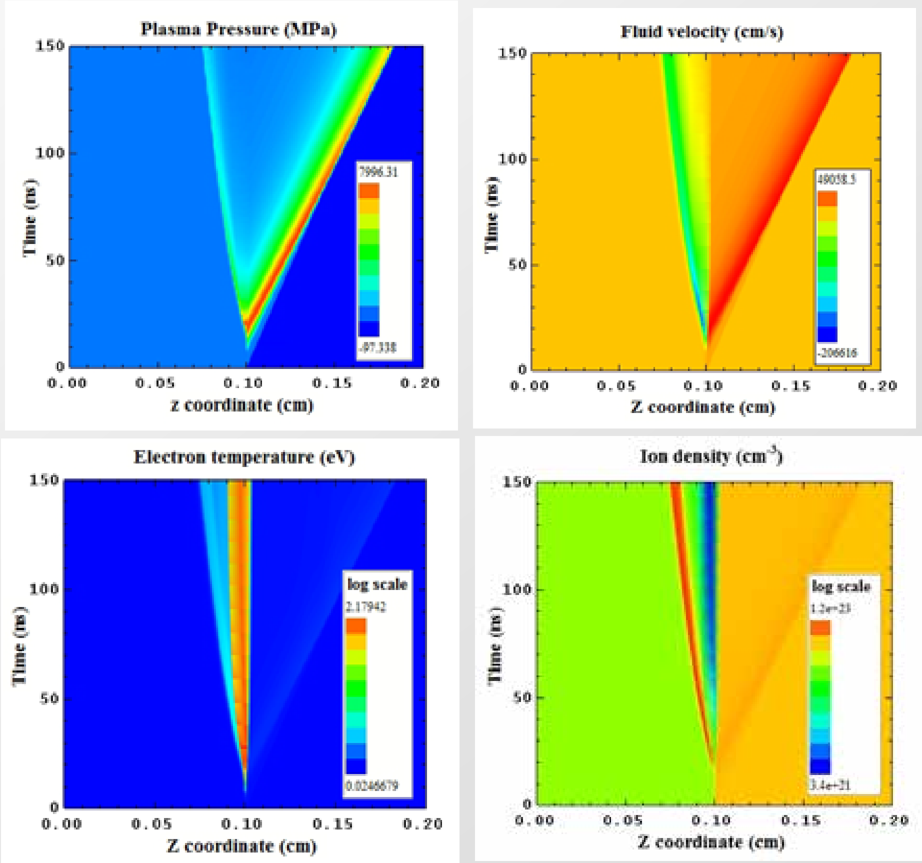
CONSISTENT MODEL FOR CONFINED PLASMA EXPANSION IN LSP

HELIOS

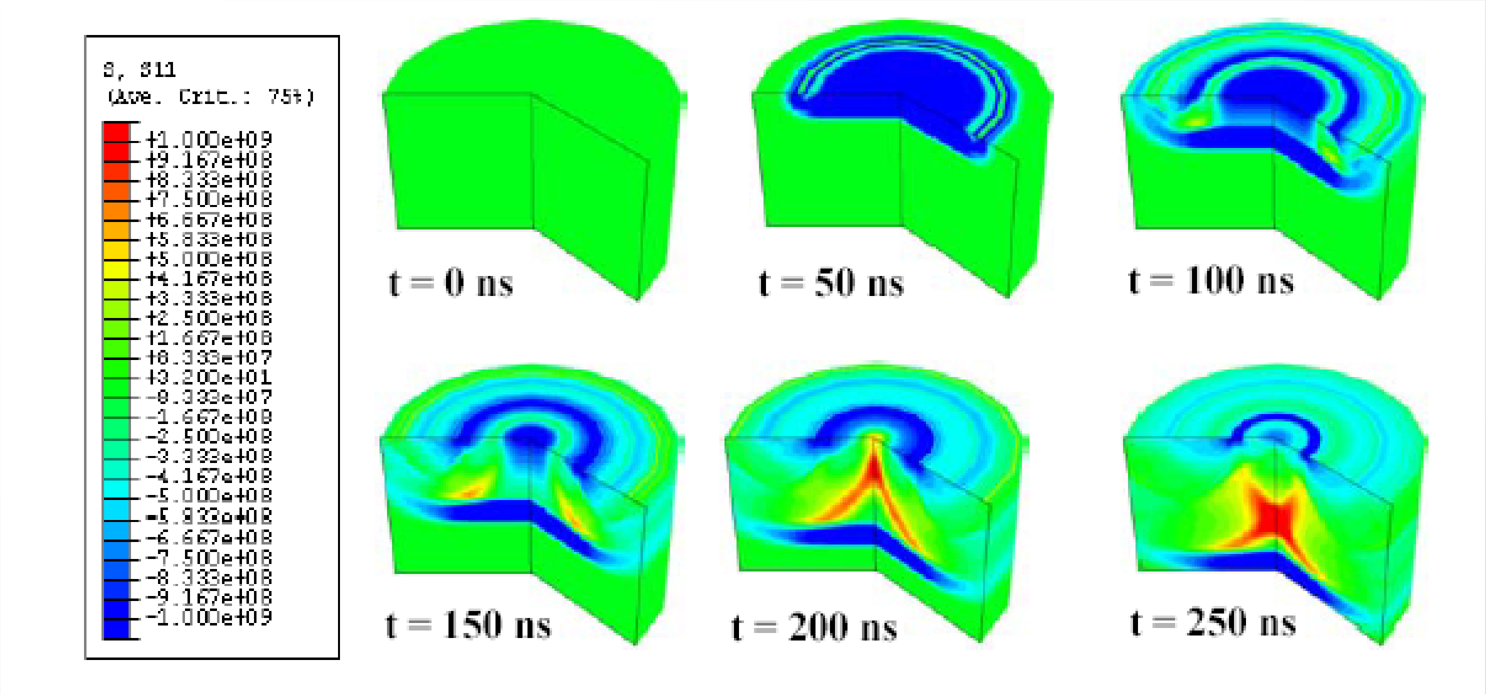
Analysis of plasma for LSP conditions





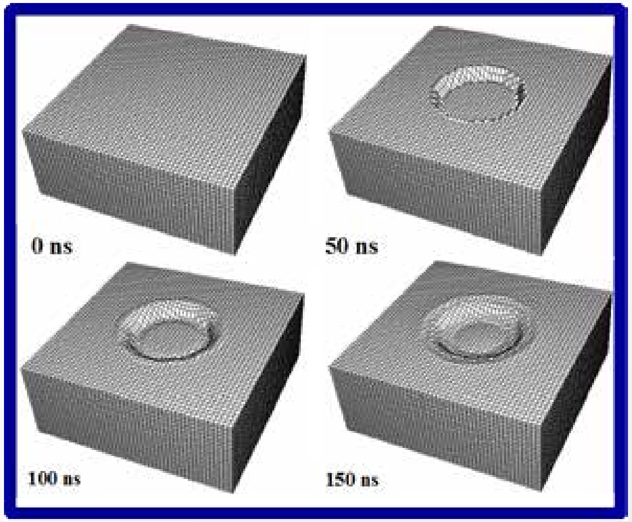


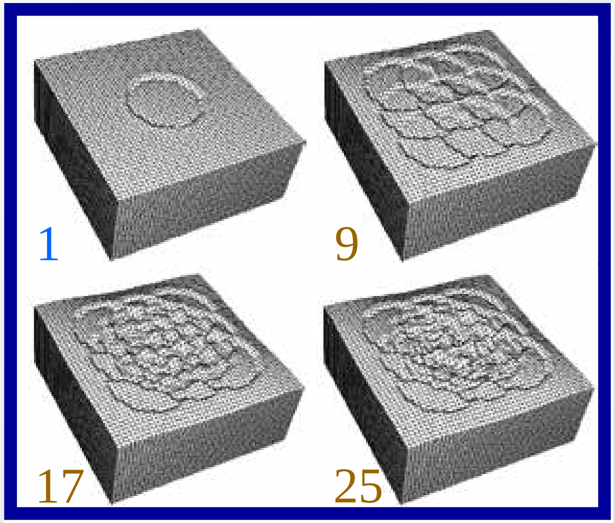
SHOCK PROPAGATION AND DERIVED RESIDUAL STRESSES IN LSP

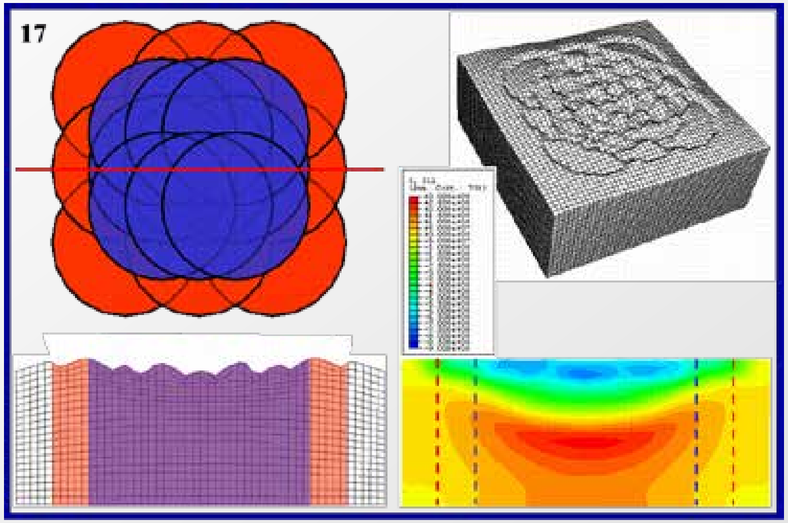


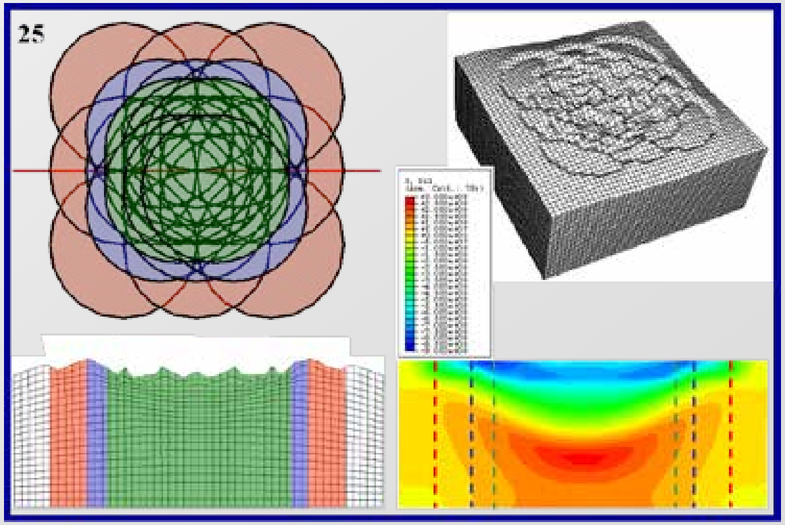
Ocaña, J.L. et al.: "Predictive assessment and experimental characterization of the influence of irradiation parameters on surface deformation and residual stresses in laser-shock-processed metallic alloys". Proc. SPIE 5448, 642-653 (2004)

SHOCK PROPAGATION AND DERIVED RESIDUAL STRESSES IN LSP

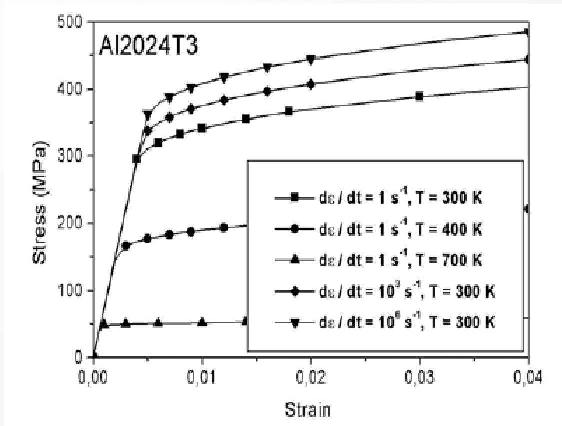


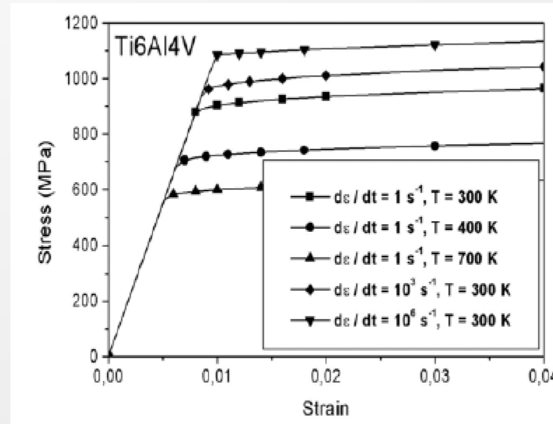


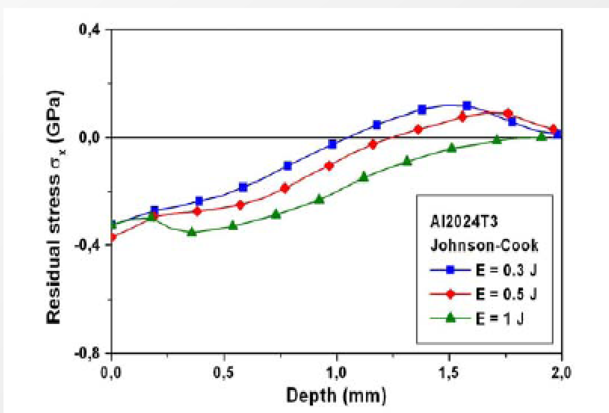


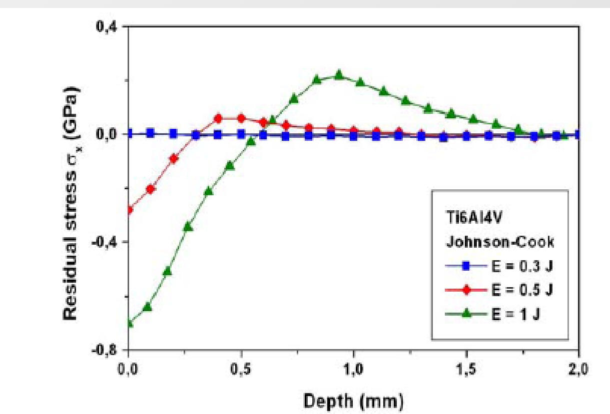


SHOCK PROPAGATION AND DERIVED RESIDUAL STRESSES IN LSP









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". Proc. SPIE 5448, 642-653 (2004)

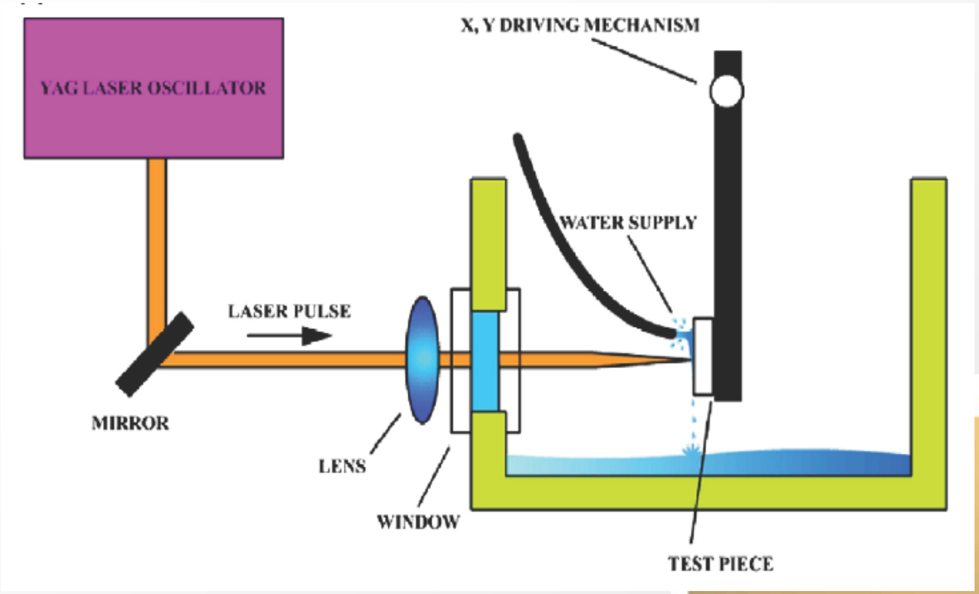
PROCESS EXPERIMENTAL SETUP

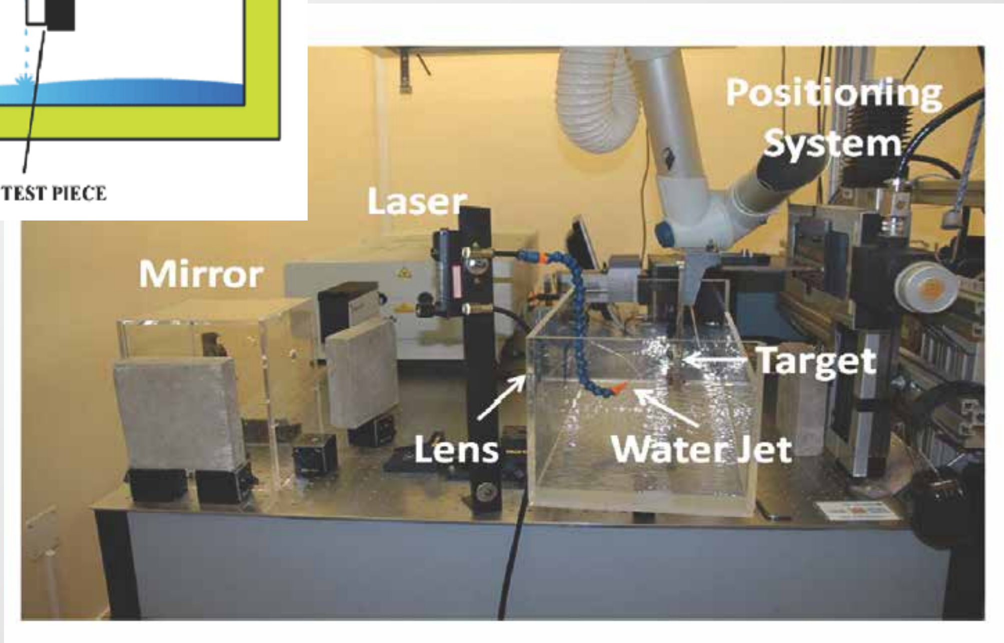
Q-SWITCHED Nd:YAG LASER

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

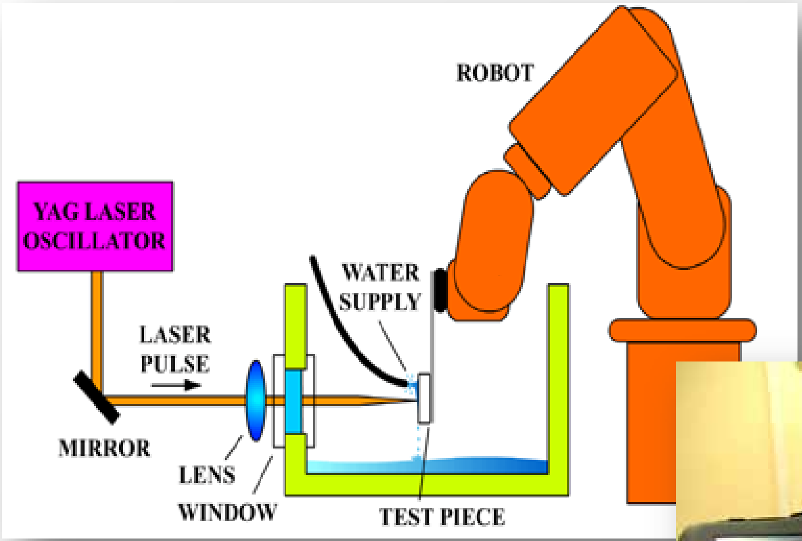
$t = 10$ ns; $f = 10$ Hz

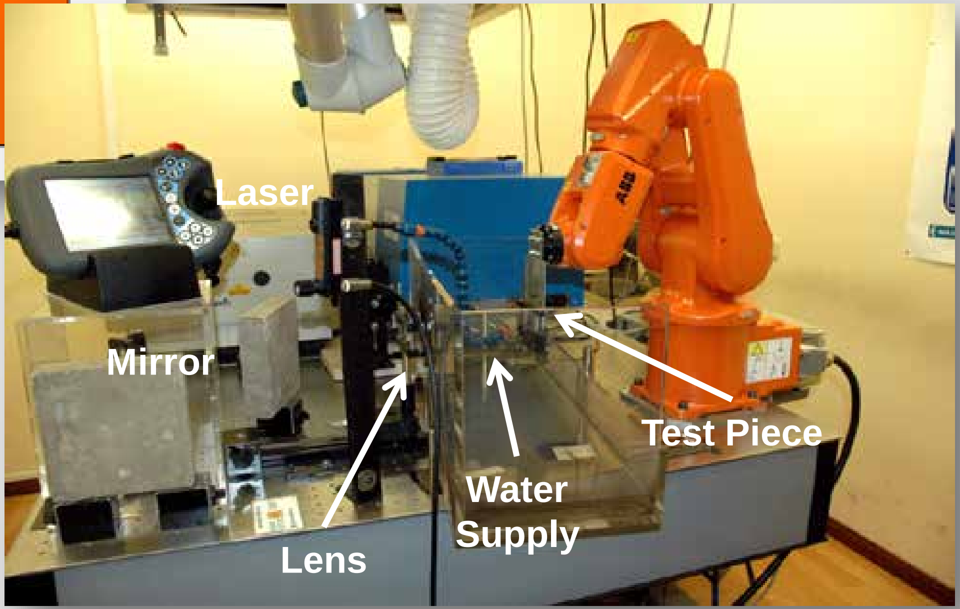
PROCESS EXPERIMENTAL SETUP





PROCESS EXPERIMENTAL SETUP

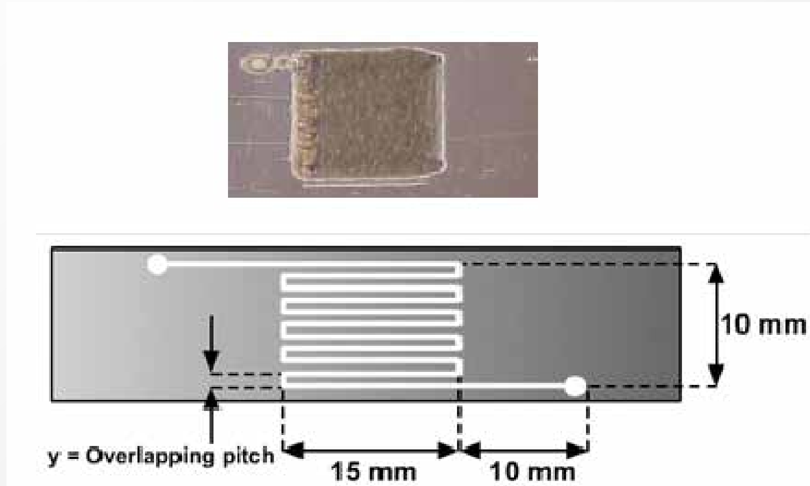




PROCESS EXPERIMENTAL SETUP

PROCESS EXPERIMENTAL SETUP

EXPERIMENTAL PROCEDURE



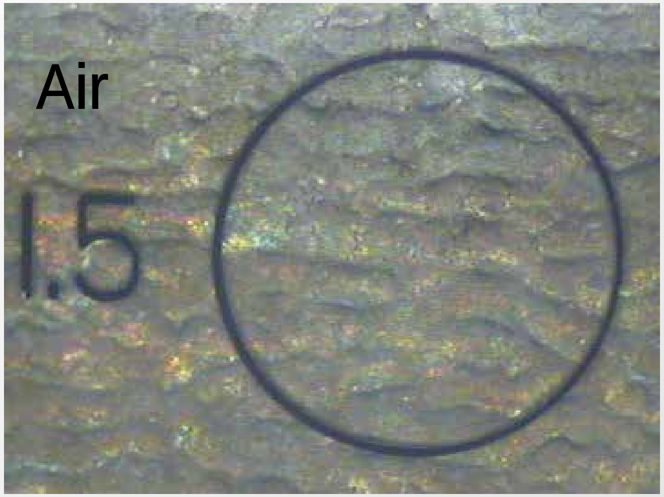
$$\text{Equivalent Overlapping Density} \equiv EOD = \frac{\text{Nº of pulses}}{\text{Total treated surface}} = \frac{\frac{x}{\Delta x}\,\frac{y}{\Delta y}}{\Delta s} = \frac{\frac{x}{d}\,\frac{y}{d}}{xy} = \frac{1}{d^2}$$

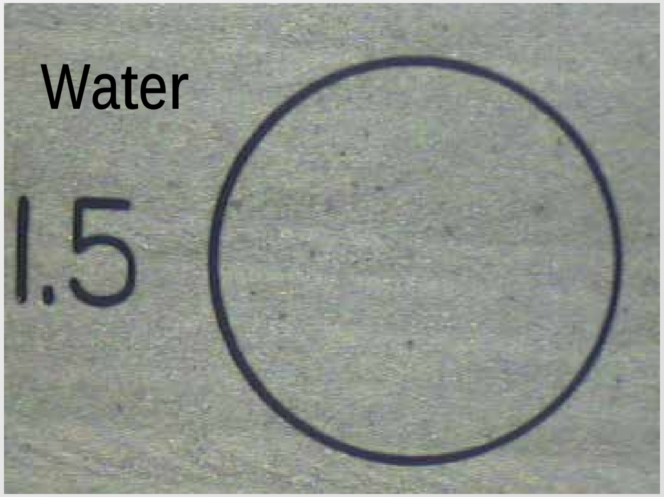
$$\text{Equivalent Energy Density} \equiv EED = \frac{\text{Nº of pulses} \times \text{Pulse Energy}}{\text{Total treated surface}} = \frac{\frac{x}{\Delta x}\,\frac{y}{\Delta y}}{\Delta s}E = \frac{\frac{x}{d}\,\frac{y}{d}}{xy}E = \frac{E}{d^2}$$

$$\text{Equivalent local overlapping factor} \equiv ELOF = \frac{\text{Nº of pulses} \times \text{Pulse Area}}{\text{Total treated surface}} = \frac{\frac{\pi}{4} f^2}{d^2} = \frac{\pi}{4}\left(\frac{f}{d}\right)^2$$

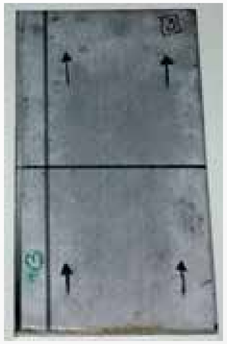
EXPERIMENTAL RESULTS

Material:	Al2024 T3
Pulses:	Æ=1,5 mm; **t** =10 ns; f=10 Hz;
	E=1 J/pulse; I=1,41 GW/cm^2
Swept Area :	15x15 mm^2; 2500 pulses/cm^2





Fatigue Life enhancement of AISI 316L specimens



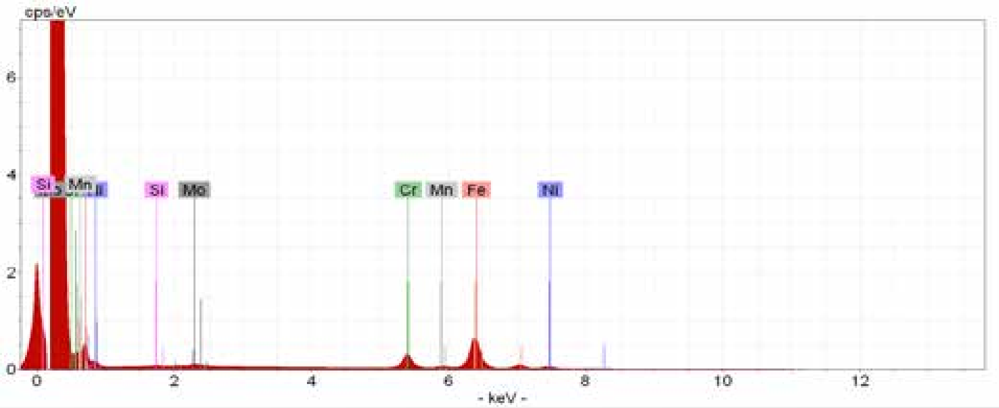


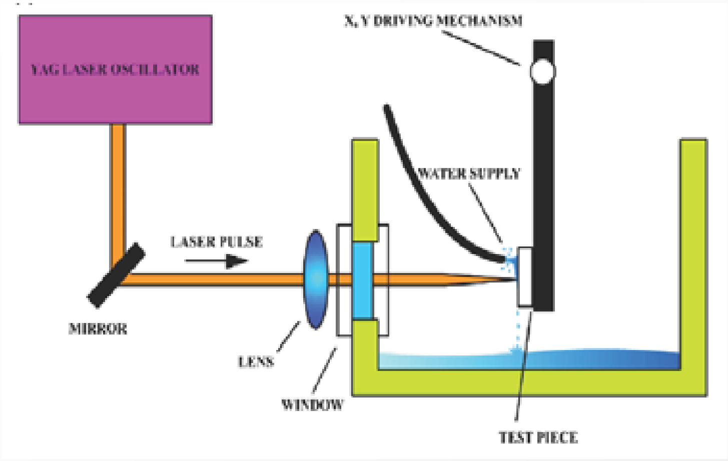
Table 1: Percent Composition of AISI 316L Steel Used in the Reported Experiments

Element	C	Cr	Ni	Mo	Mn	Si	N	P	S	Fe
% wt	0.018	16.815	10.086	2.044	1.294	0.458	0.047	0.032	0.003	Bal.

Table 2: Initial Mechanical Properties of AISI 316L Steel Used in the Reported Experiments

Property	Value
Elastic Modulus [GPa]	177.2
Offset Tensile Yield Strength [MPa]	355.4
Ultimate Tensile Strength [MPa]	633.6

EXPERIMENTAL RESULTS. Fatigue life enhancement of AISI 316L



Process parameters	
Wavelength (nm)	1064
Frecuency (Hz)	10
Energy (J/pulse)	2.0
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 pulses/cm^2

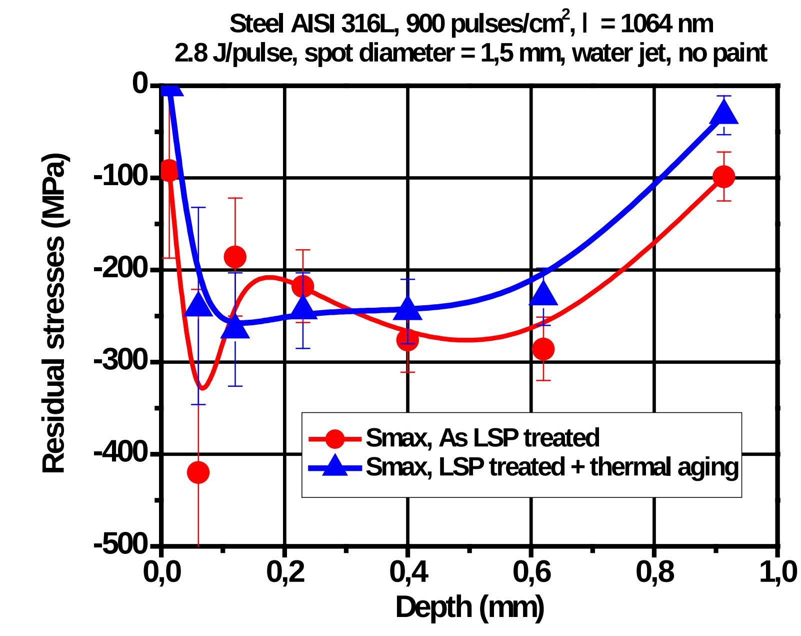
1600 pulses/cm^2

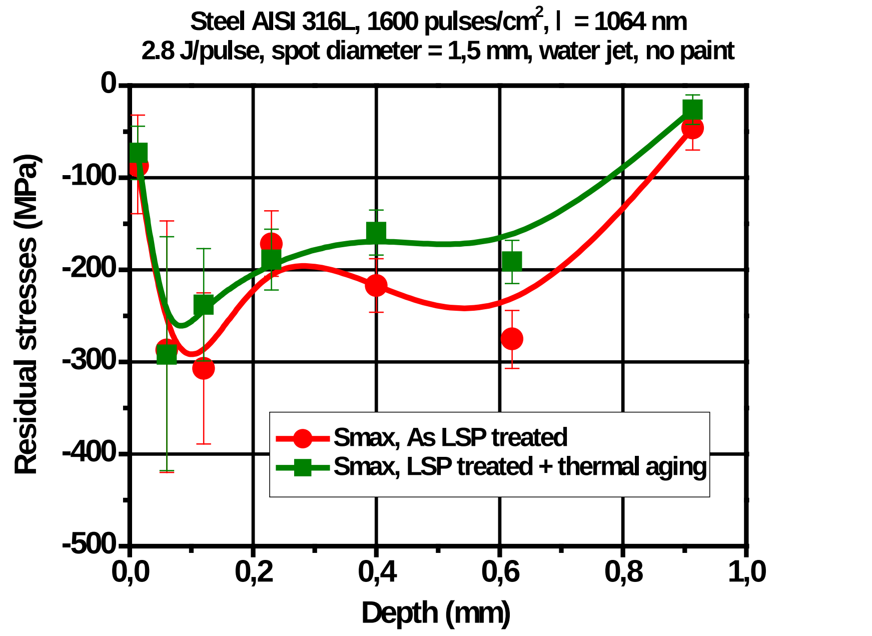
900 pulses/cm^2 +
Heat treat.: 500 ˚C, 8h

1600 pulses/cm^2 +
Heat treat.: 500 ˚C, 8h

EXPERIMENTAL RESULTS. Fatigue life enhancement of AISI 316L

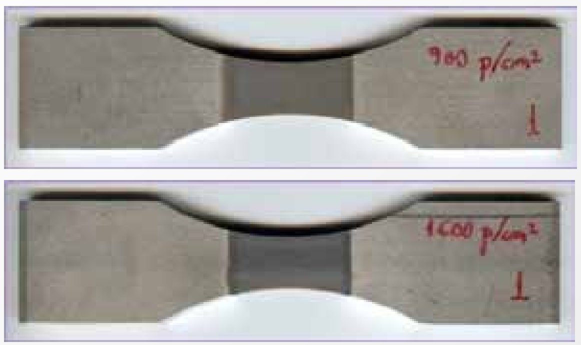
Residual Stresses:

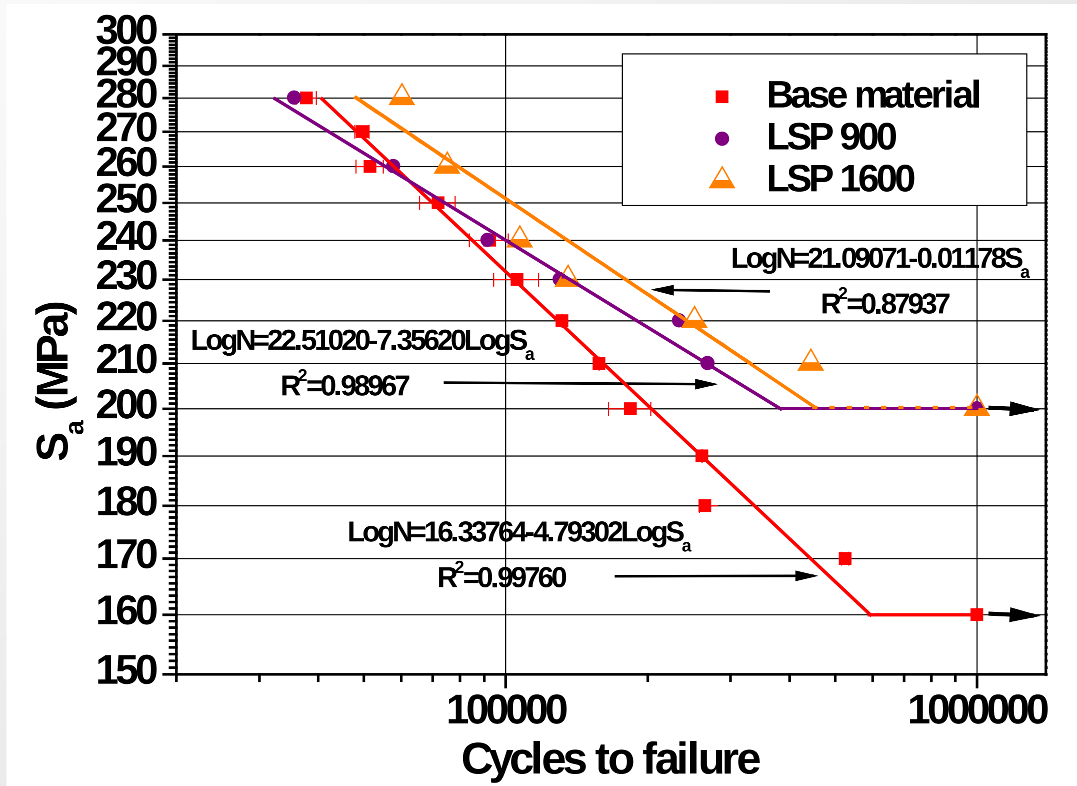




EXPERIMENTAL RESULTS. Fatigue life enhancement of AISI 316L

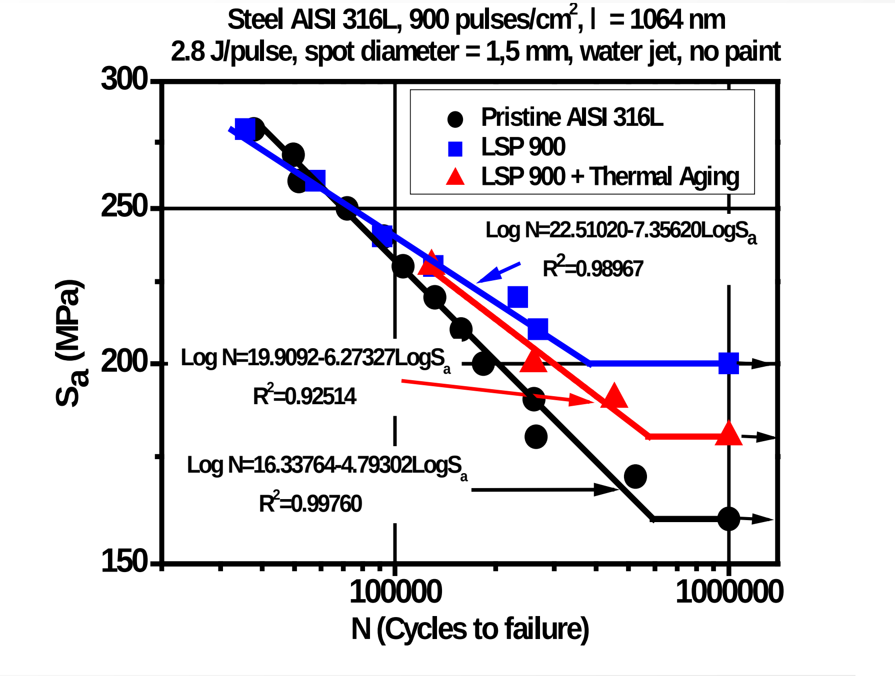
Fatigue Tests:

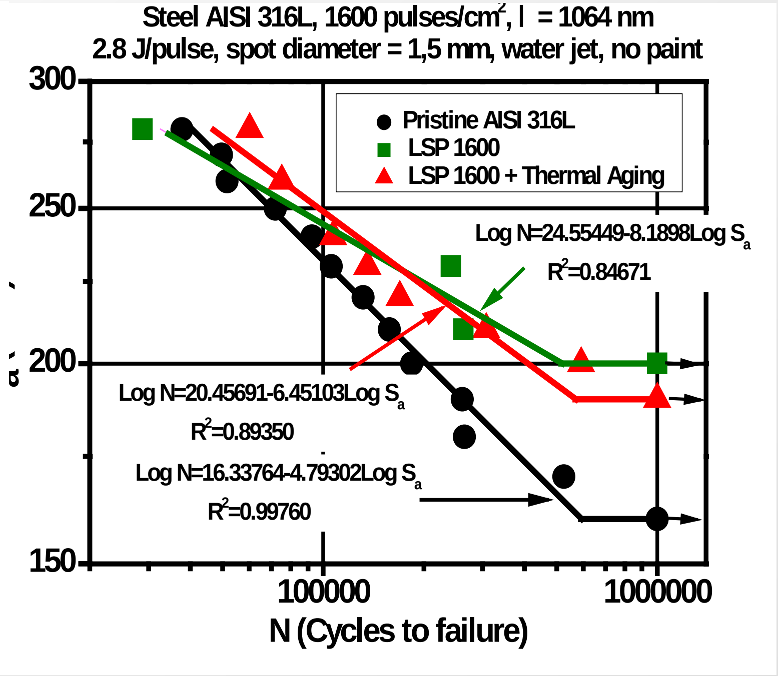




EXPERIMENTAL RESULTS. Fatigue life enhancement of AISI 316L

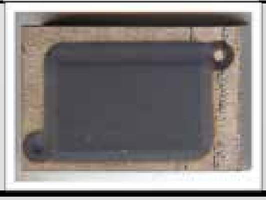
Fatigue Tests:





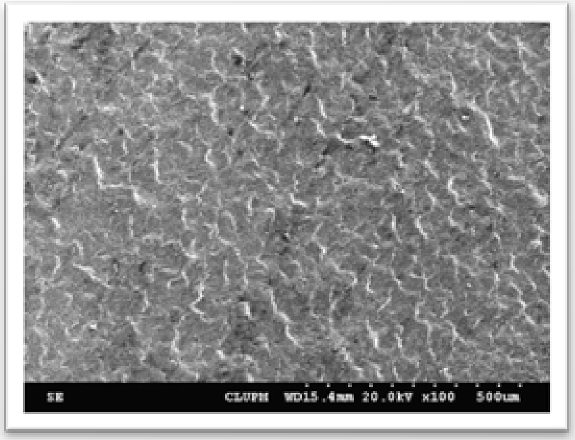
EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples

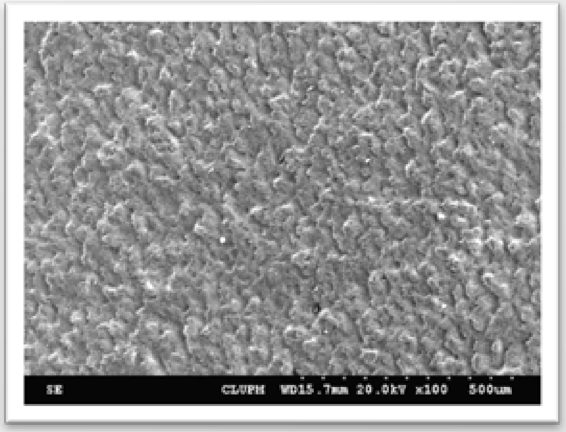
Reported Analysis

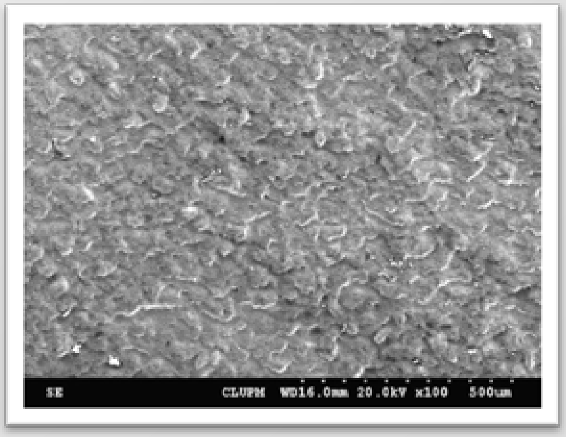
	Al2024-T351 30x20x8 mm³	Ti6Al4V 30x20x10 mm³
900 pulses/cm²		
1600 pulses/cm²		
2500 pulses/cm²		
5000 pulses/cm²		

EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples

Surface Roughness (Microscopy): Al2024-T351



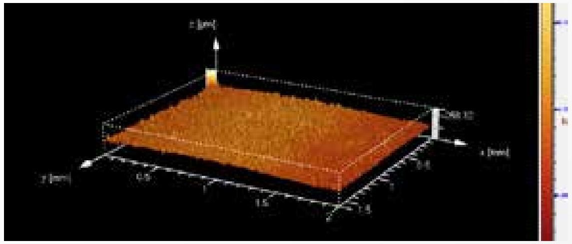


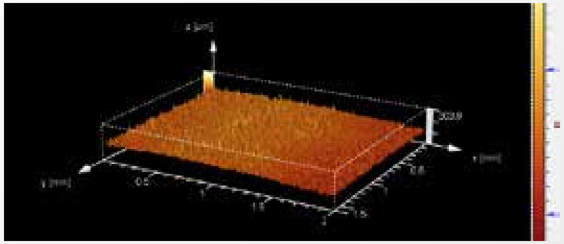


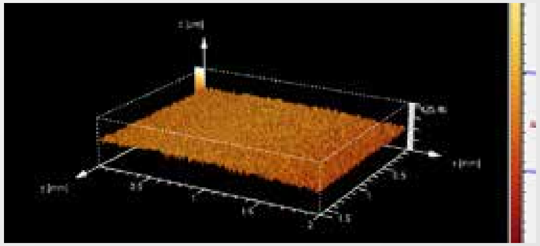
900 pulses/cm^2 | 1600 pulses/cm^2 | 2500 pulses/cm^2

EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples

Surface Roughness (Topographic Confocal microscopy): Al2024-T351



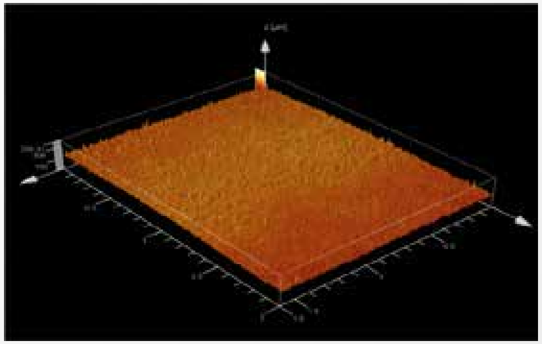


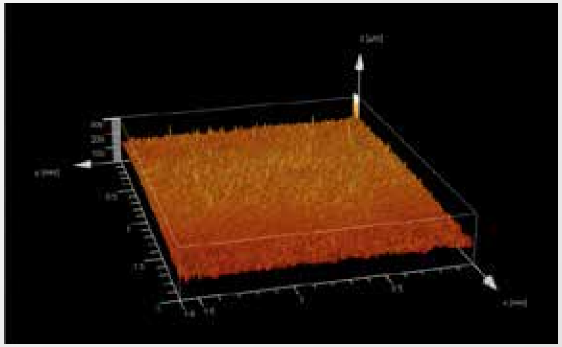


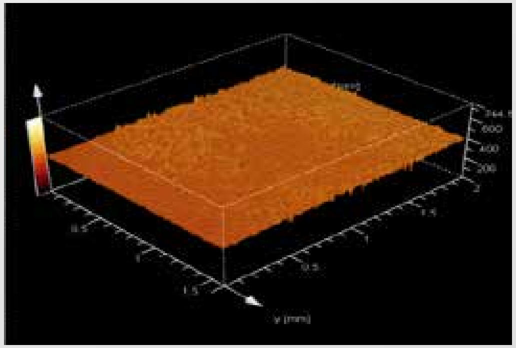
900 pulses/cm^2

1600 pulses/cm^2

2500 pulses/cm^2



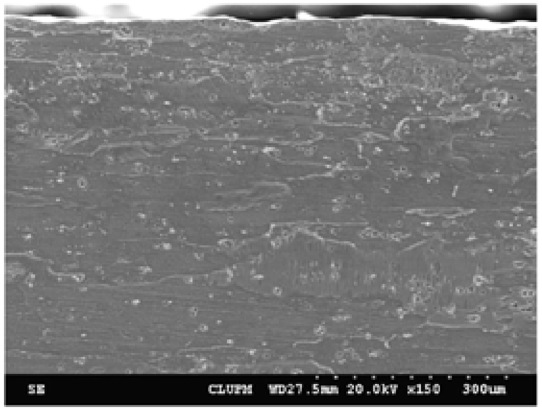


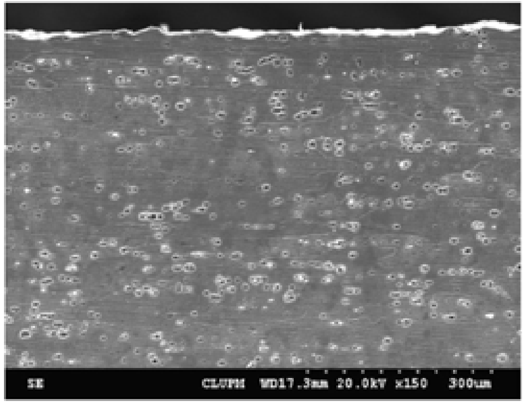


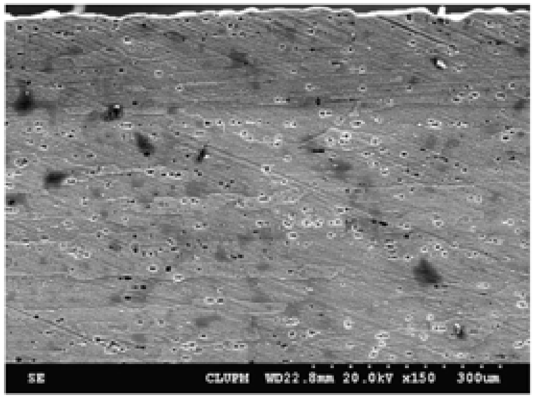
	No treatment	900 pulses/cm^2	1600 pulses/cm^2	2500 pulses/cm^2
Pa (mm)	7.96	5.23	4.82	4.96
<Dz>	----	10.30	20.00	26.82

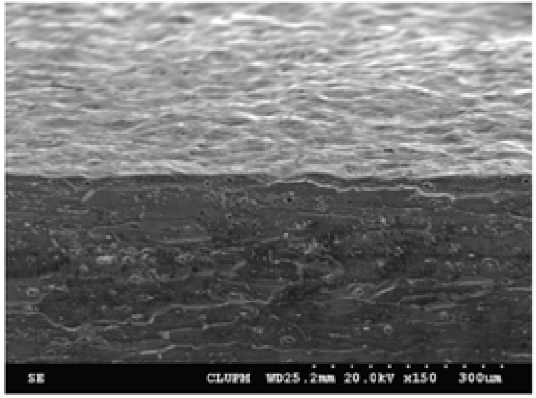
EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples

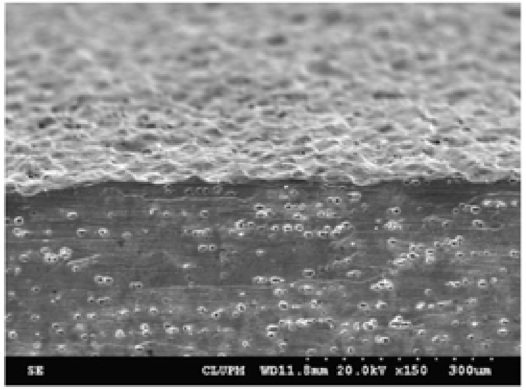
Microscopic material compactation: Al2024-T351

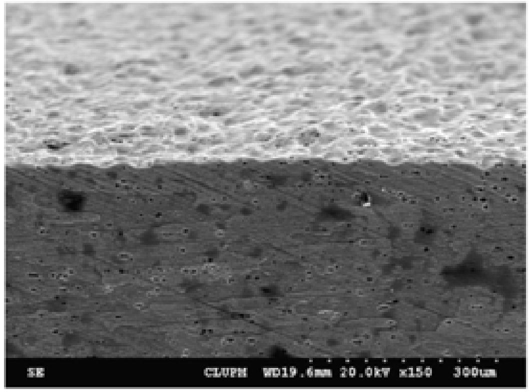








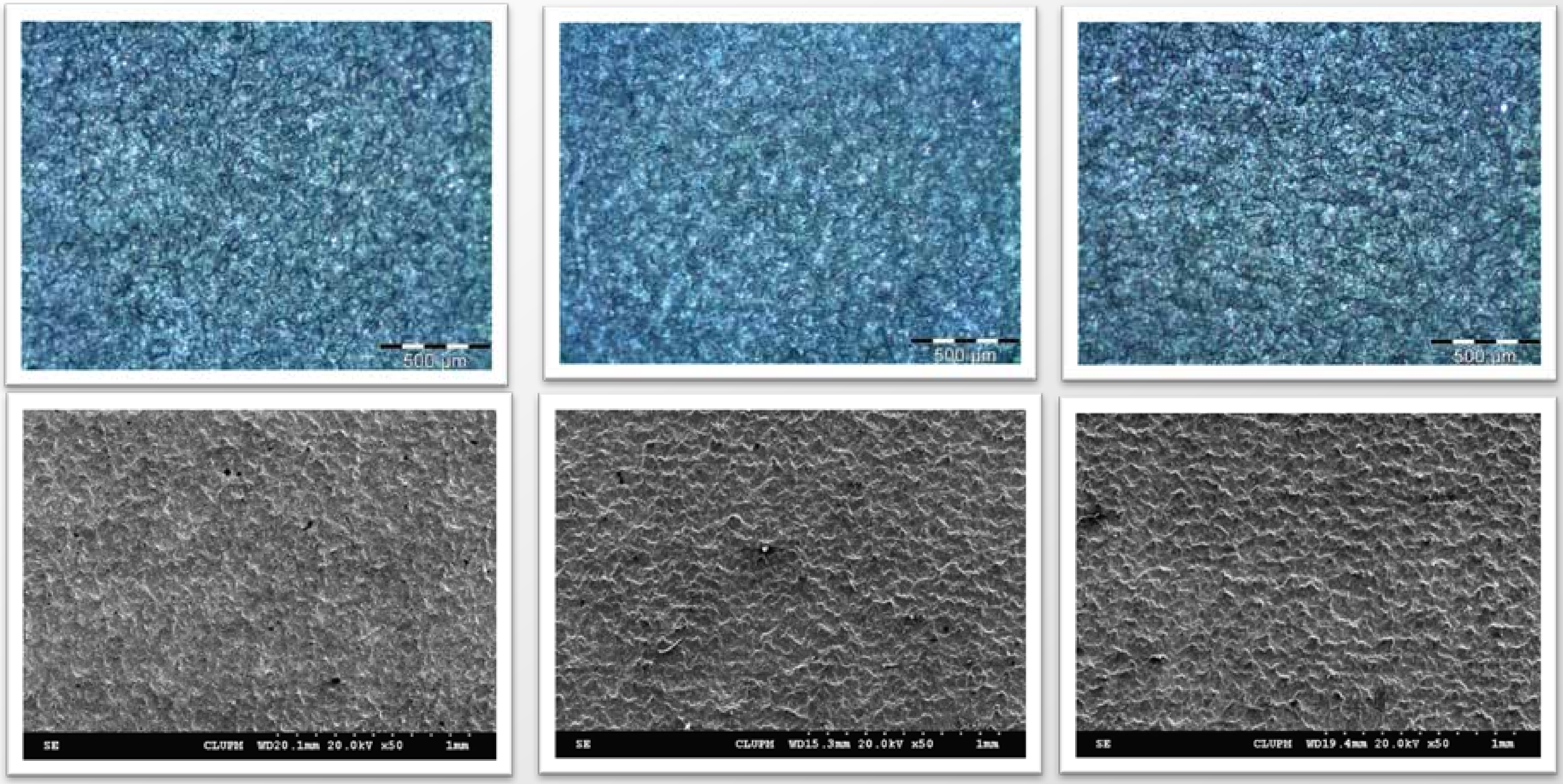




900 pulses/cm^2 **1600 pulses/cm^2** **2500 pulses/cm^2**

EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples

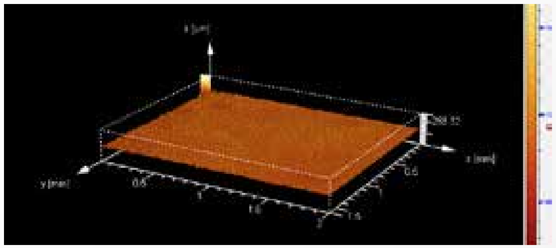
Surface Roughness (Microscopy): Ti6Al4V

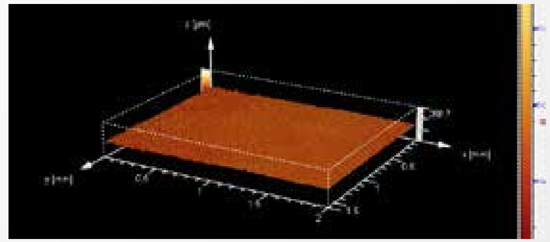


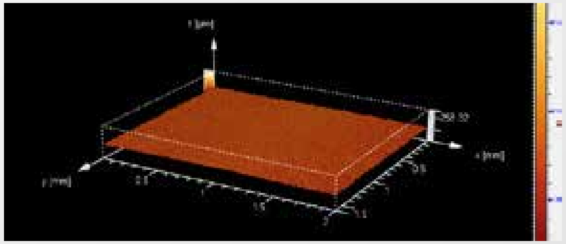
900 pulses/cm^2 | **2500 pulses/cm^2** | **5000 pulses/cm^2**

EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples

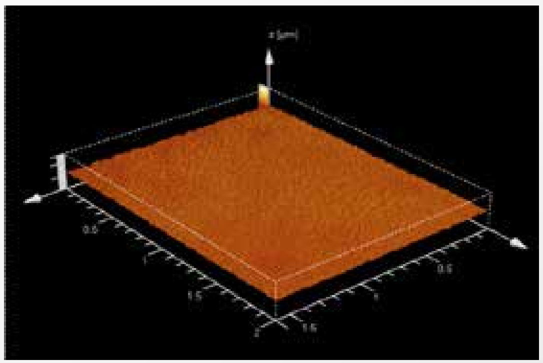
Surface Roughness (Topographic Confocal microscopy): Ti6Al4V

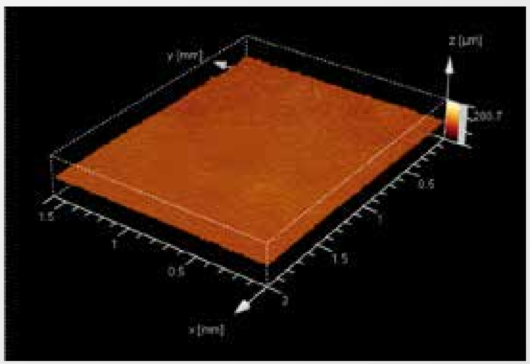


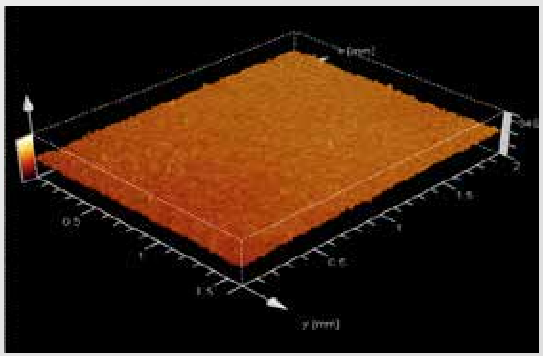




900 pulses/cm² | **2500 pulses/cm²** | **5000 pulses/cm²**



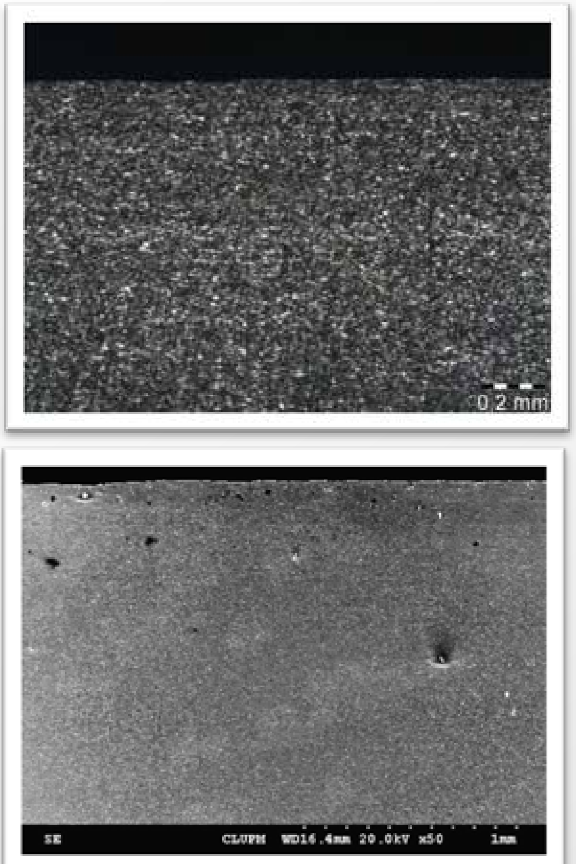




	No treatment	900 pulses/cm²	1600 pulses/cm²	2500 pulses/cm²
Pa (mm)	9.98	3.62	3.87	3.87
<Dz>	----	2.81	7.40	5.80

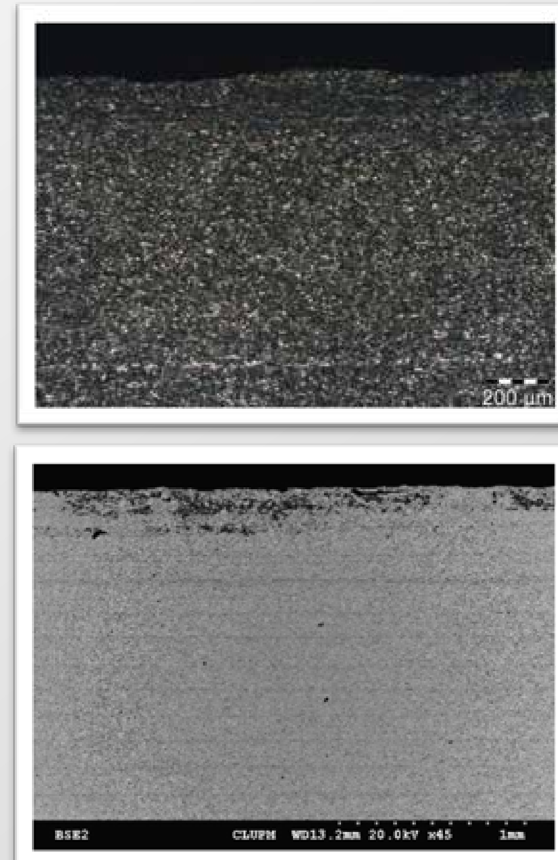
EXPERIMENTAL RESULTS

Microscopic material compactation: Ti6Al4V



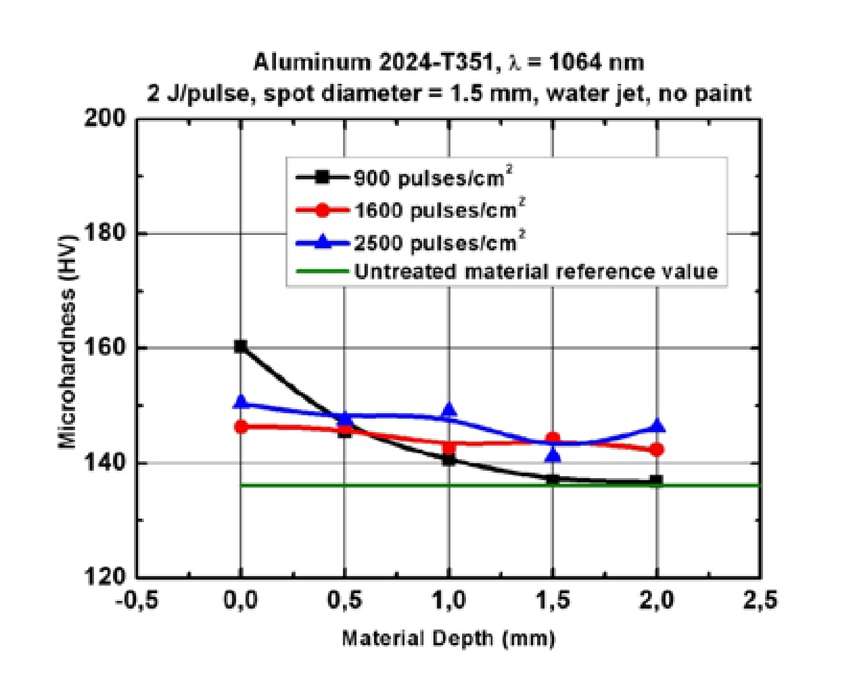
900 pulses/cm²

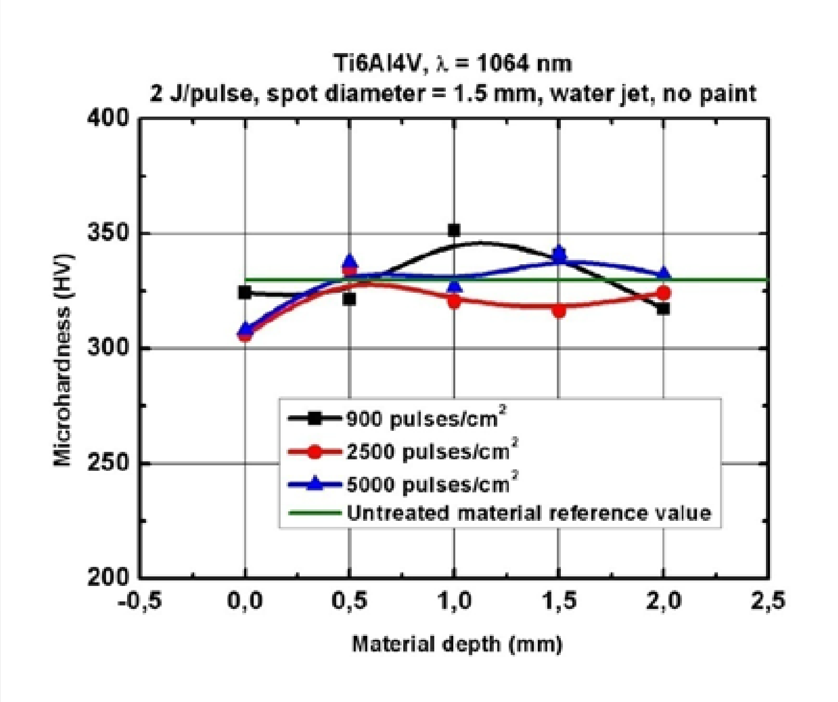
2500 pulses/cm²



5000 pulses/cm²

Microhardness (HV)





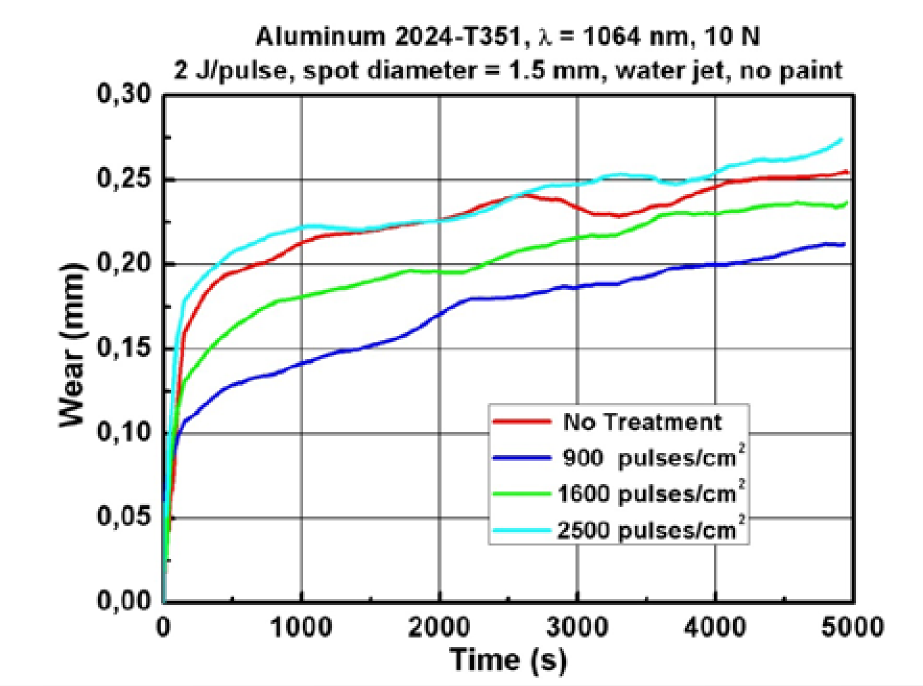
Slight increase in microhardness in Al2024-T351
Higher for higher LSP treatement intensity

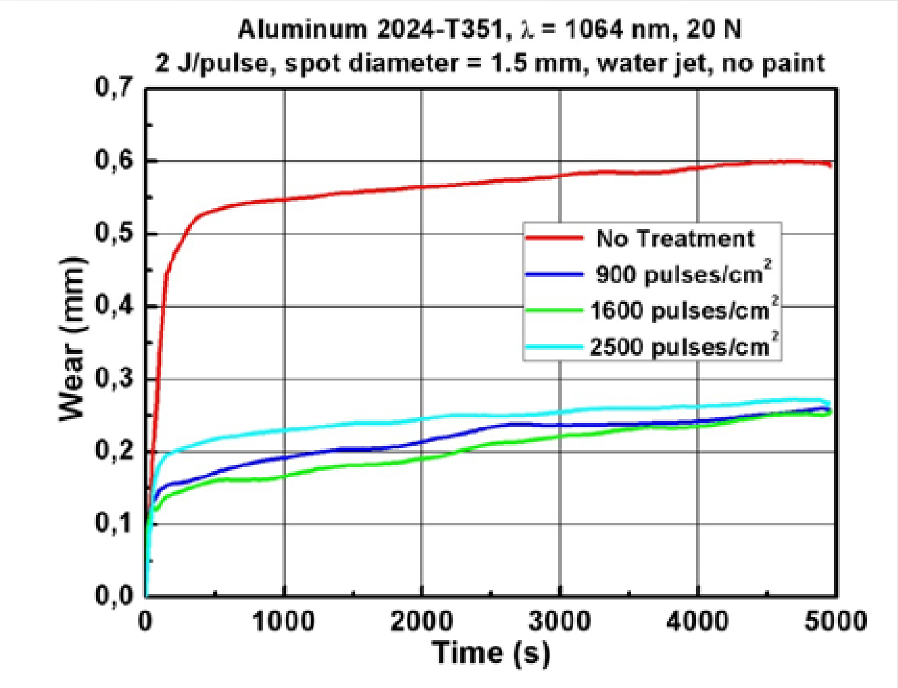
No apparent hardening effect in Ti6Al4V.

EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples

Wear resistance (According to ASTM G99-04)

Al2024-T351



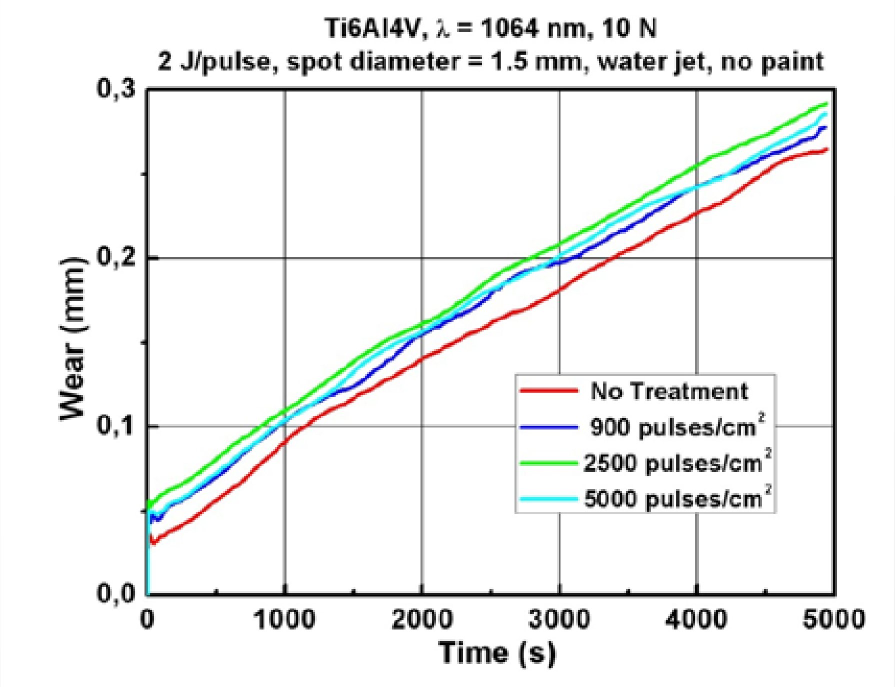


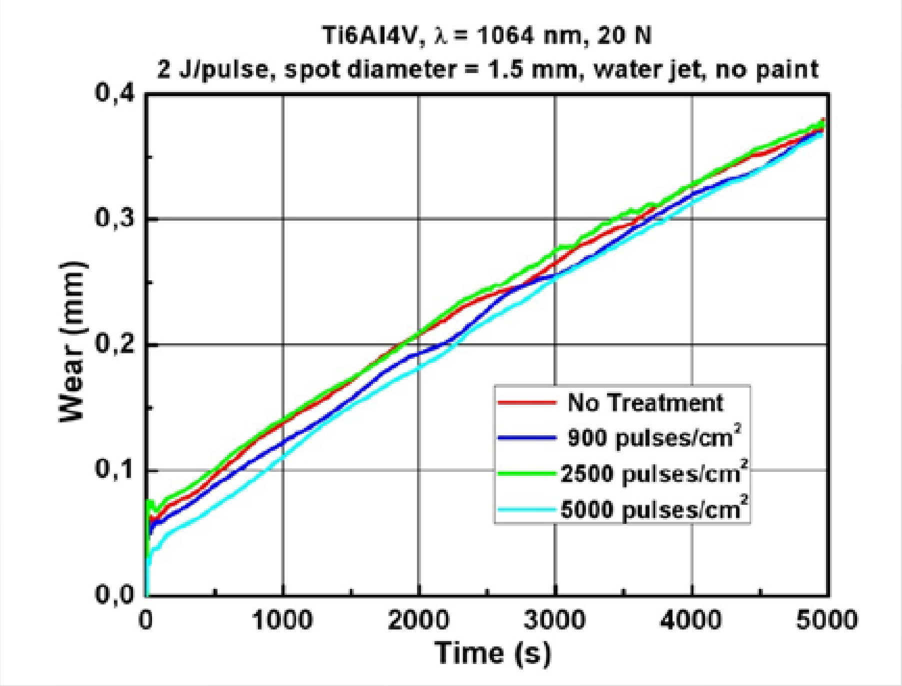
Slight wear improvement in Al2024-T351 at low loads

Considerable wear improvement in Al2024-T351 at moderate loads

Wear resistance (According to ASTM G99-04)

Ti6Al4V



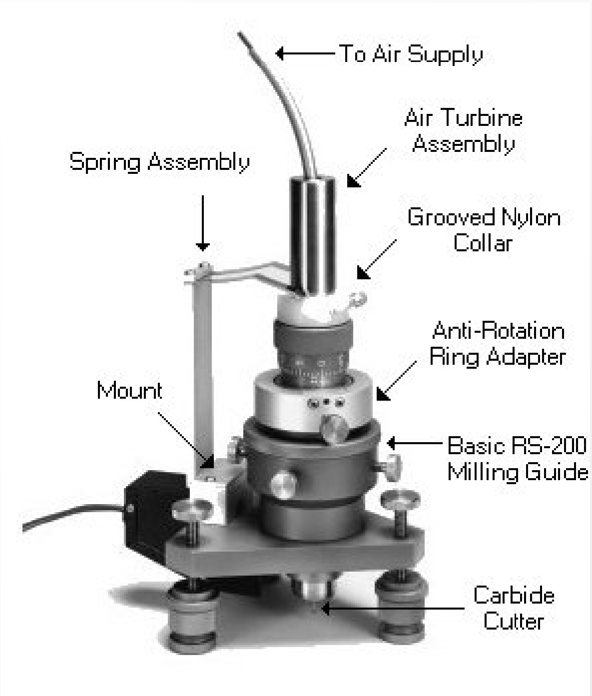


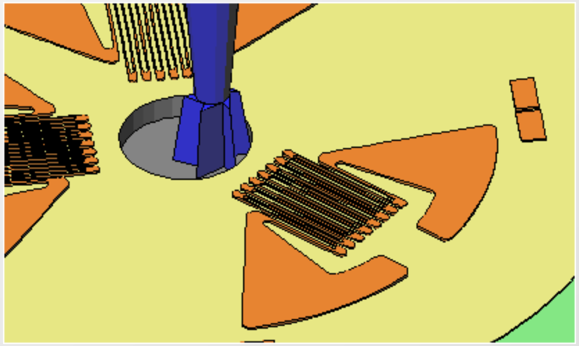
Slight negative wear impact in Ti6Al4V at low loads

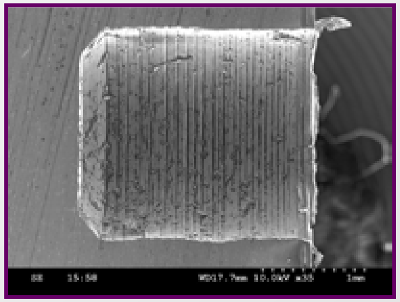
Inappreciable wear improvement in Ti6Al4V at moderate loads

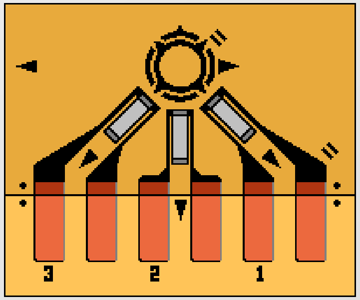
EXPERIMENTAL RESULTS. Compressive RS's fields induced in Ti6Al4V

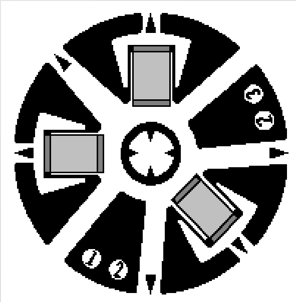
Residual Stresses Measurement Equipment (According to ASTM E837-08)









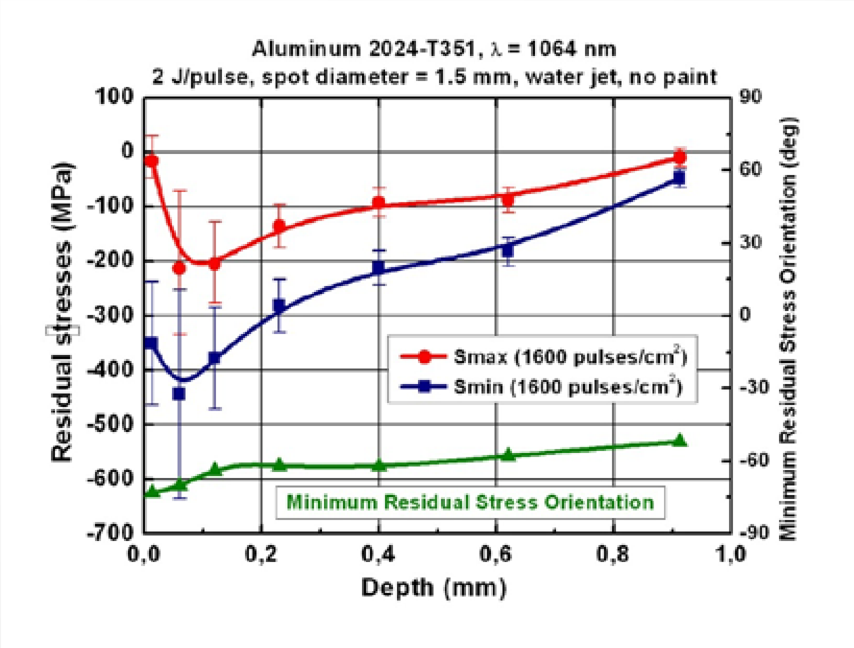


CEA-XX-062UM-120 EA-XX-062RE-120

EXPERIMENTAL RESULTS. Compressive RS's fields induced in Ti6Al4V

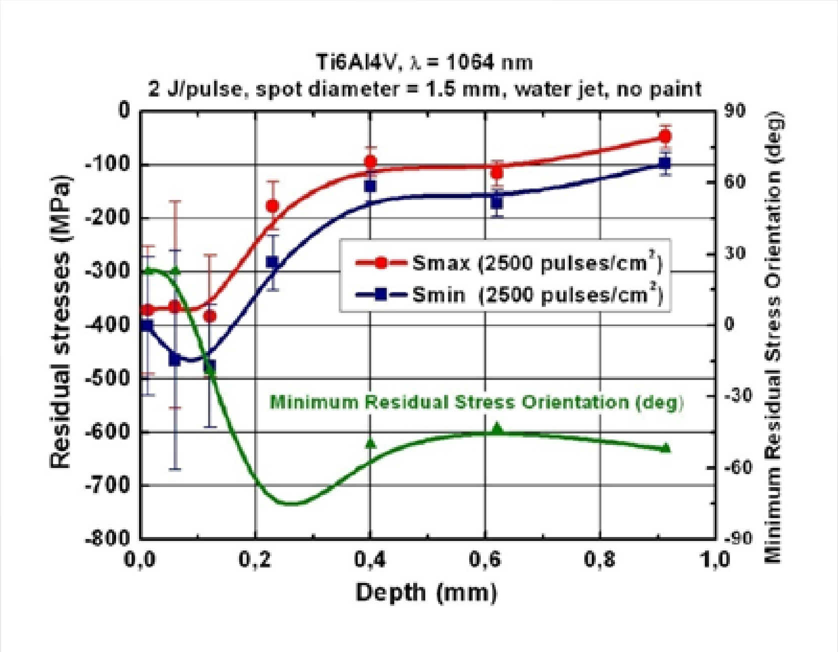
Residual Stresses (According to ASTM E837-08)

Al2024-T351



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

Ti6Al4V

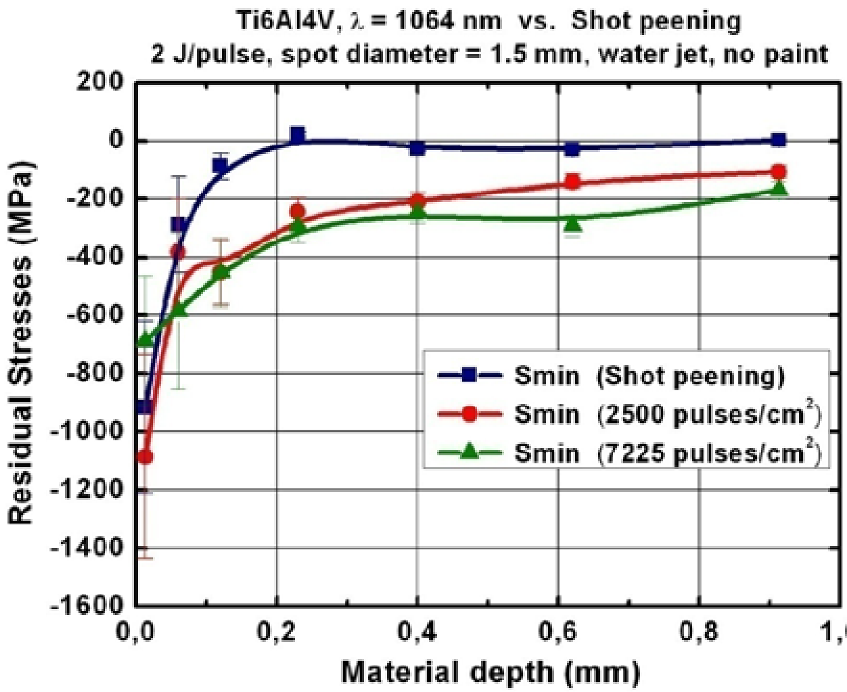


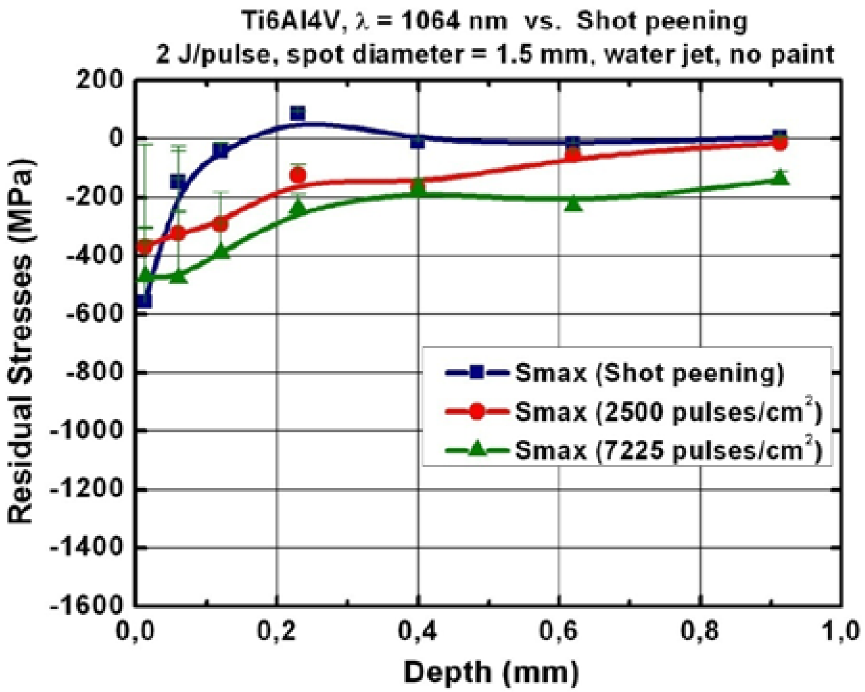
Relatively small difference between S_{max} and S_{min} in Ti6Al4V

EXPERIMENTAL RESULTS. Compressive RS's fields induced in Ti6Al4V

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. Compressive RS's fields induced in Ti6Al4V

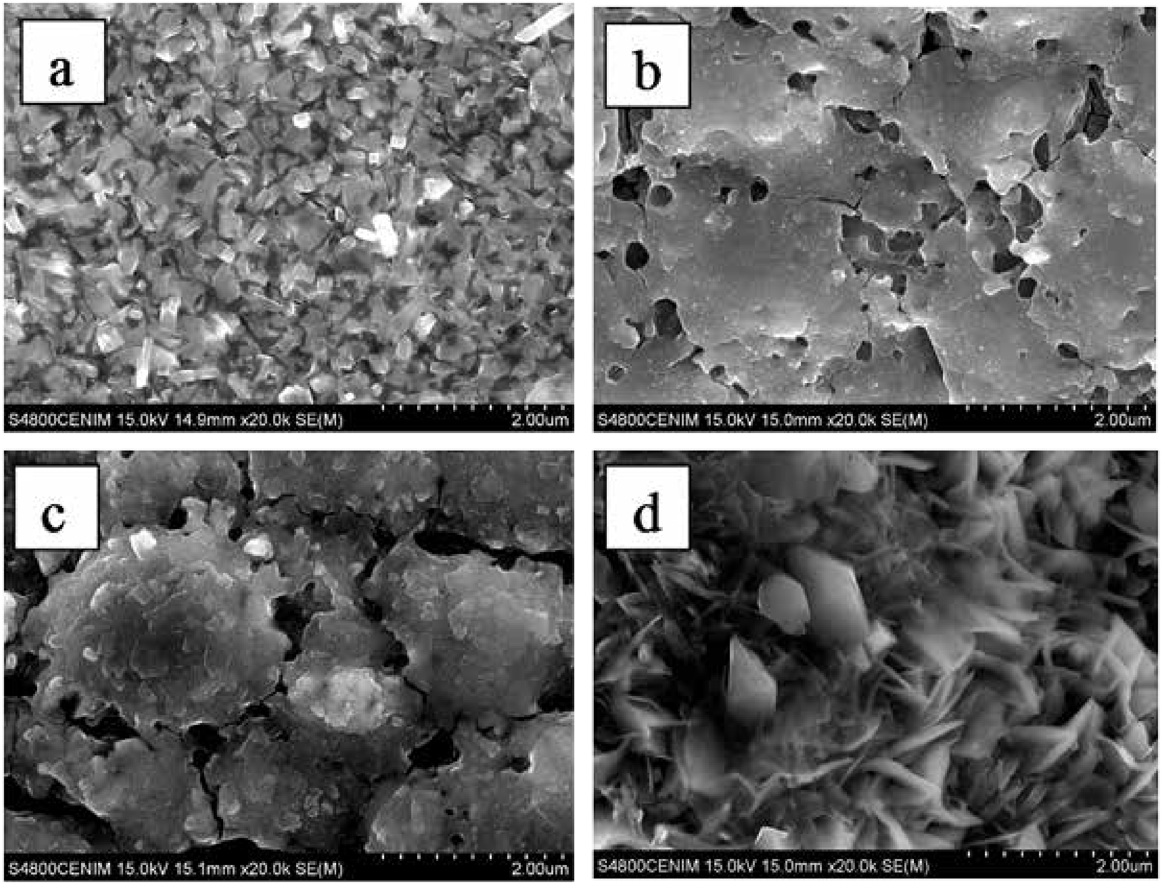
Table 1. Ti6Al4V specimens composition

Element	Al	V	C	O	N	Ti
Weight percentage	6.1	4.2	0.01	0.12	0.006	Bal.

Table 2. Samples designation and processing conditions

Sample	**Initial treatment (pre LSP)**	**LSP treatment EOD (cm^{-2})**	**Thermal aging treatment (post LSP)**
T	710ºC / 2h	No	No
T-LSP	710ºC / 2h	5000	No
T-LSP5	710ºC / 2h	5000	595ºC / 1h
T-LSP7	710ºC / 2h	5000	710ºC / 2h

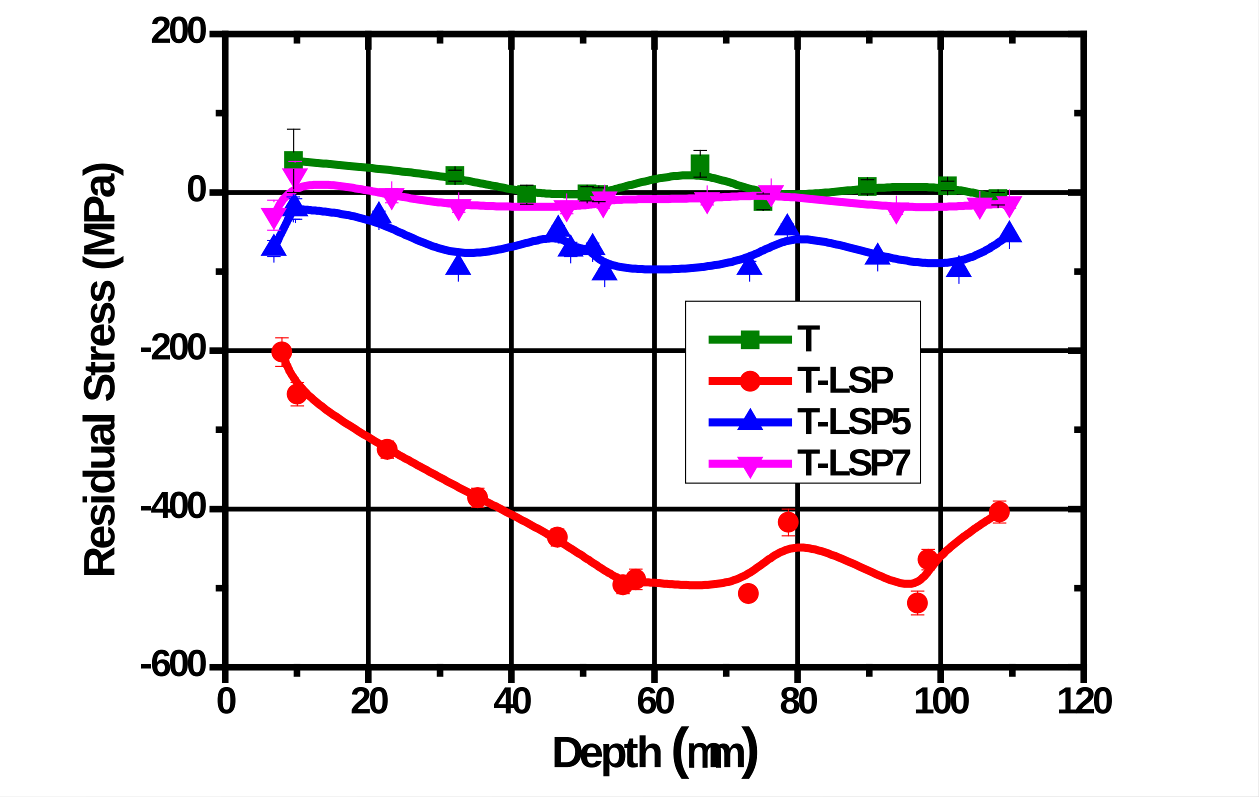
EXPERIMENTAL RESULTS. Compressive RS's fields induced in Ti6Al4V



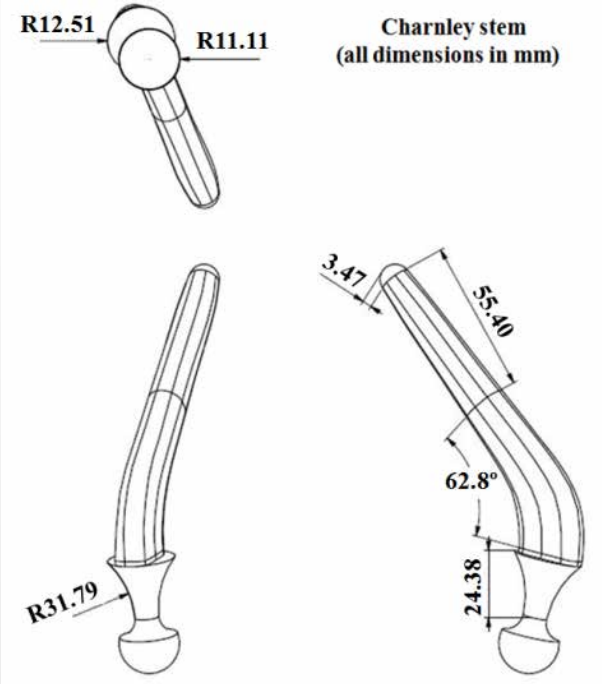
Typical SEM views of surfaces on T (a), T-LSP (b), T-LSP5 (c), and T-LSP7 (d) specimens.

Residual Stresses Fields for the Different Conditions

(Measured by energy-dispersive diffraction using synchrotron X-ray radiation at the EDDI beam line of BESSY II (Berlin, Germany); 10-150 keV; 2q =16º)

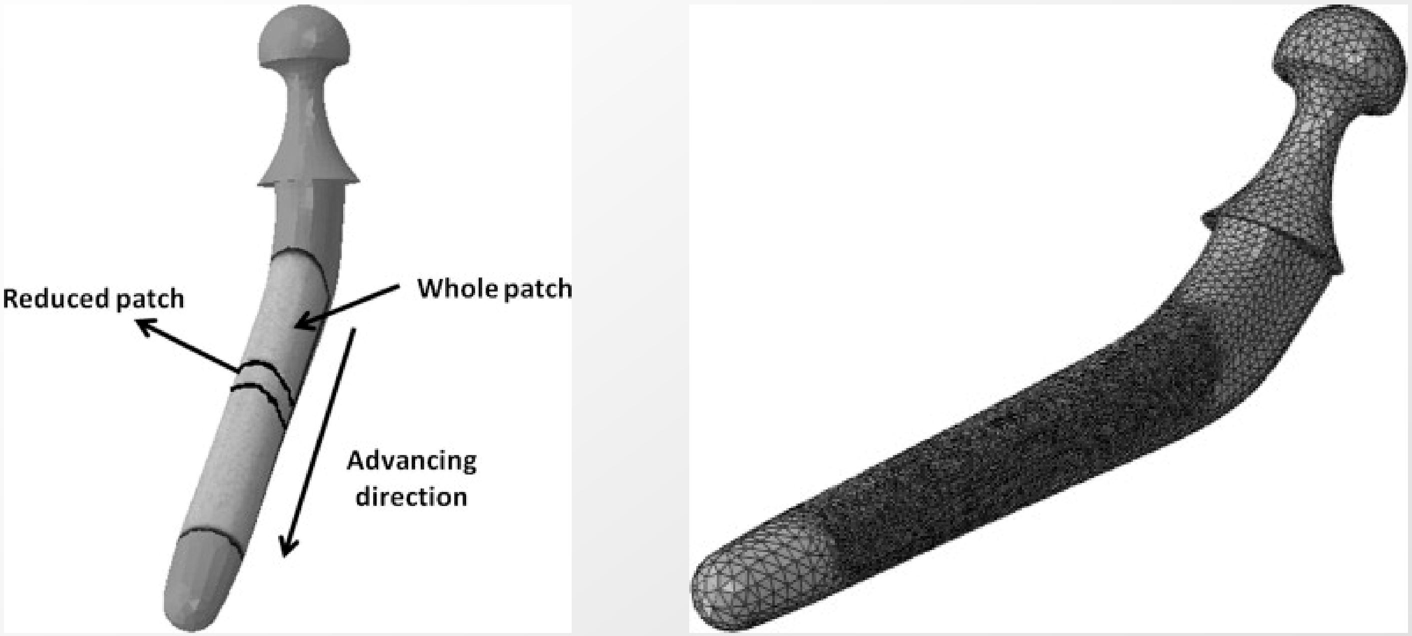


Computational Design of LSP Treatment for a Ti6Al4V Hip Prosthesis



Typical geometry of a Charnley hip replacement prosthesis (adapted from Charnley, 1977)

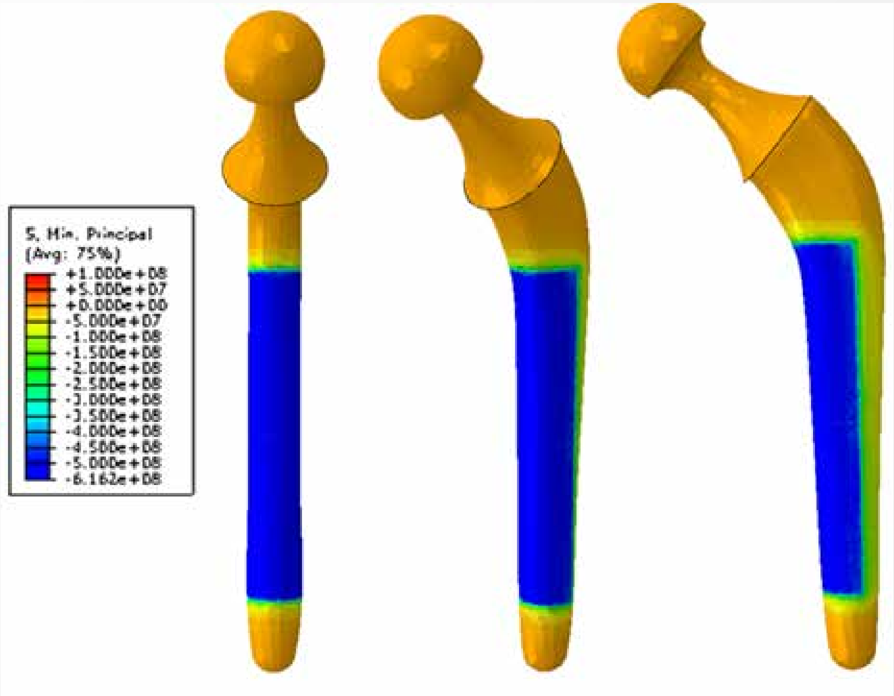
Computational Design of LSP Treatment for a Ti6Al4V Hip Prosthesis



Treatment geometry and FEM mesh used in the treatment of the considered hip replacement by LSP.

Adapted from: C. Correa et al.: Materials & Design, 79, 106 – 114 (2015)

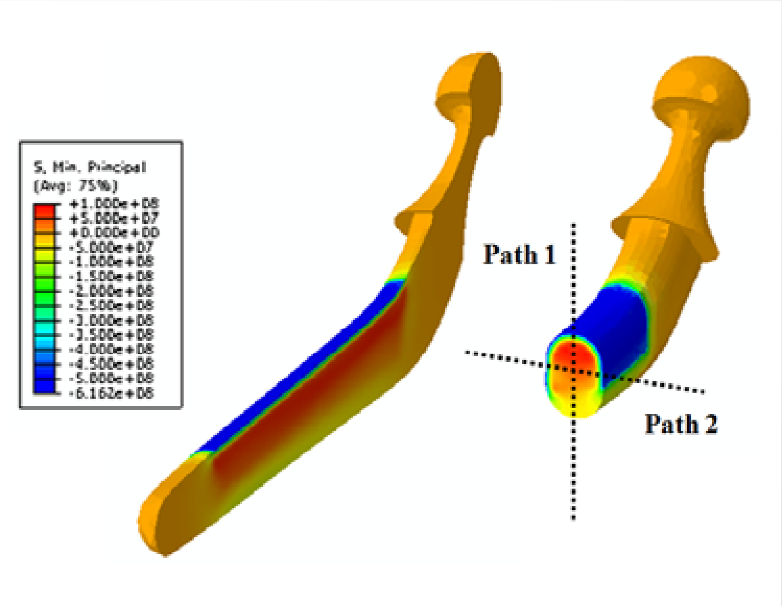
Computational Design of LSP Treatment for a Ti6Al4V Hip Prosthesis



Colour scale presentation of the minimum principal superficial residual stresses induced in the considered hip replacement by LSP.

Adapted from: C. Correa et al.: Materials & Design, 79, 106 – 114 (2015)

DESIGN CASE STUDY: Ti6Al4V HIP PROSTHESIS



Sample result showing the internal residual stresses fields induced in a hip replacement prosthesis by LSP.

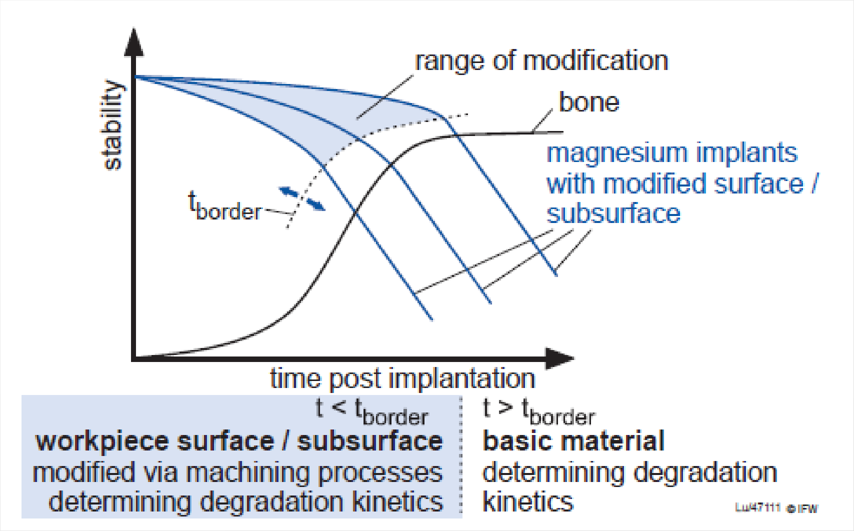
Adapted from: C. Correa et al.: Materials & Design, 79, 106 – 114 (2015)

DISCUSSION AND OUTLOOK

- **Important surface resistance and life cycle extension improvements in critical high reliability components by LSP have been experimentally demonstrated. The associate predictive assessment capabilities needed for adequate process design have also been developed and used for theoretical-experimental contrast.**
- **In view of the important improvements reached in wear behaviour, surface roughness (precursor of improved corrosion resistance) and fatigue life (all of them resulting from the deep compressive residual stresses fields introduced by the process), the LSP technique has to be recognized as a key technology for the enhancement of materials and systems durability and reliability.**
- **Important technological implementations of LSP in the aerospace, automotive, nuclear and biomedical sectors are under course, anticipating relevant improvements in service reliability and in material preservation and (eco-friendly) efficient use.**
- **Of special interest is the LSP treatment of new/advanced materials of biomedical interest as a means of improving the effective life of high risk/reliability components (i.e. prosthetic replacements in aged persons).**

DISCUSSION AND OUTLOOK

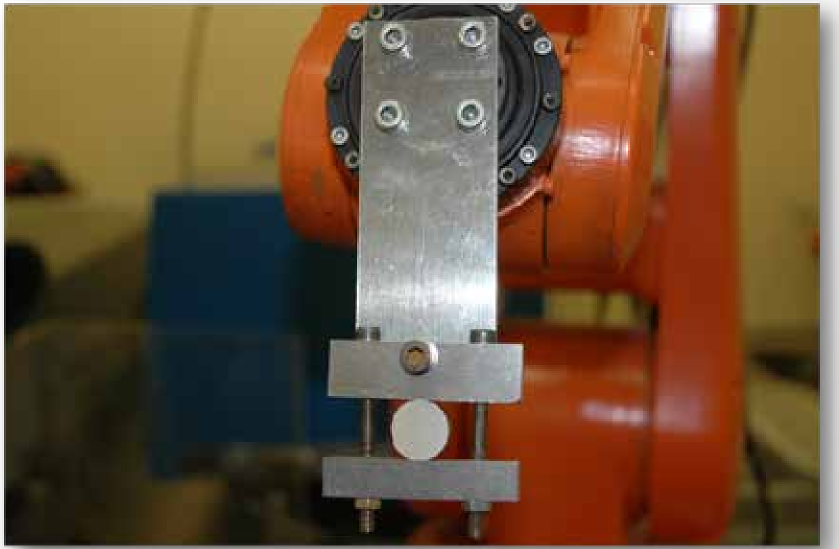
Due to their excellent biodegradability characteristics, Mg and Mg-based alloys have become an emerging material in biomedical implants, notably for repair of bone as well as coronary arterial stents. However, the main problem with Mg-based alloys is their rapid corrosion in aggressive environments such as human body fluids



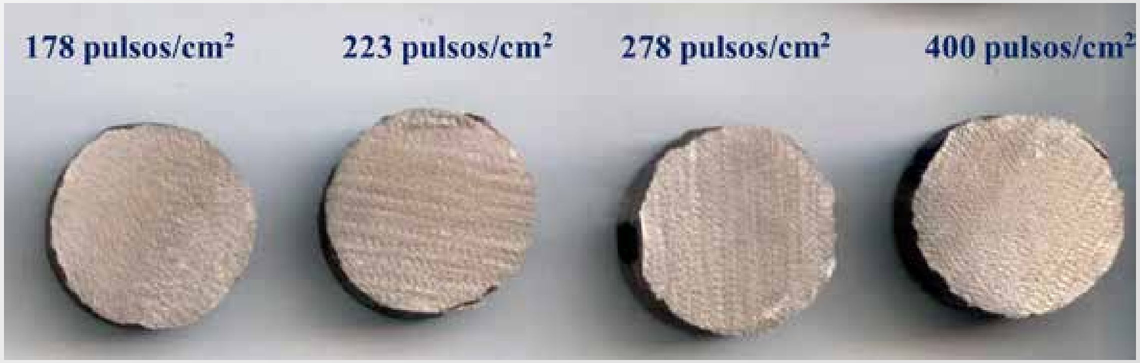
(M. Peuster et al.: doi: 10.1017/S1047951106000011)

(B. Denkena, A. Lucas.: doi:10.1016/j.cirp.2007.05.029)

DISCUSSION AND OUTLOOK



Ø=2.5 mm



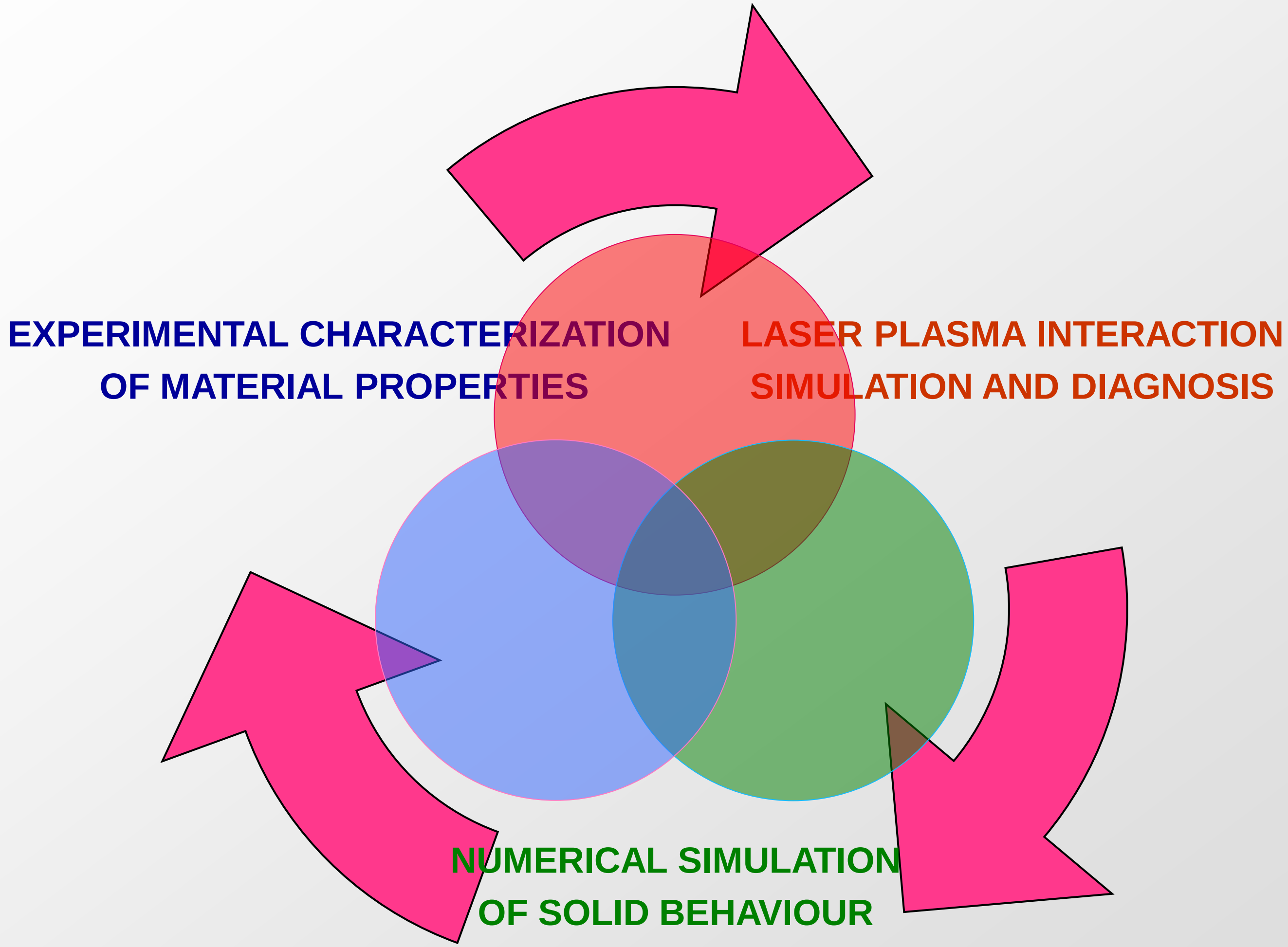
ACKNOWLEDGEMENTS

Work partly supported by MINECO (Spain; Projects MAT2012-37782 and MAT2015-63974-C4-2-R).

REFERENCES

1. 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)
2. Ocaña, J.L. et al.: Materials Science Forum, 539-543, 1116-1121 (2007)
3. Morales, M. et al.: Surfaces and Coating Technology, 202 , 2257-2262 (2008)
4. Morales, M. et al.: Applied Surface Science, 255, 5181–5185 (2009)
5. Ocaña, J.L. et al.: "Design Issues of Engineered Residual Stress Fields and Associate Surface Properties Modification by LSP in Al and Ti Alloys". Proceedings of the Fifth International WLT-Conference on Lasers in Manufacturing 2009. Munich, June 2009. A. Ostendorf et al. Eds.. pp. 387-392 (2009)
6. Ocaña, J.L. et al.: "Laser Shock Processing of Metallic Materials: Coupling of Laser-Plasma Interaction and Material Behaviour Models for the Assessment of Key Process Issues". In International Symposium on High Power Laser Ablation 2010, C.R. Phipps, Ed. AIP Conference Proceedings, Vol. 1278, pp. 902-913 (2010)
7. Morales, M. et al.: Materials Science Forum, 638-642, 2682-2687 (2010)
8. Morales, M. et al.: International Journal of Structural Integrity, 2, 51-61 (2011)
9. Correa, C. et al.: International Journal of Fatigue, 70, 196–204 (2015)
10. Correa, C. et al.: Materials & Design, 79, 106–114 (2015)

The UPM Laser Centre Approach to LSP Development



Thank you very much for your attention !


jlocana@etsii.upm.es

CENTRO LÁSER
UNIVERSIDAD POLITÉCNICA DE MADRID

Centro Láser U.P.M.

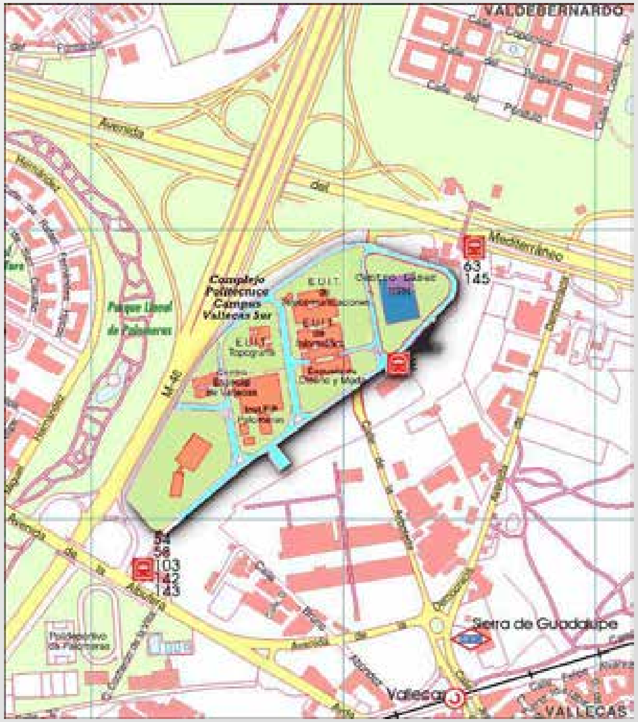
Campus Sur U.P.M.
Edificio Tecnológico "La Arboleda"
Carretera de Valencia km. 7,300
28031 Madrid - SPAIN

Tel. : (+34) 91 336 30 99

Fax.: (+34) 91 336 55 34

Email: claser@etsii.upm.es

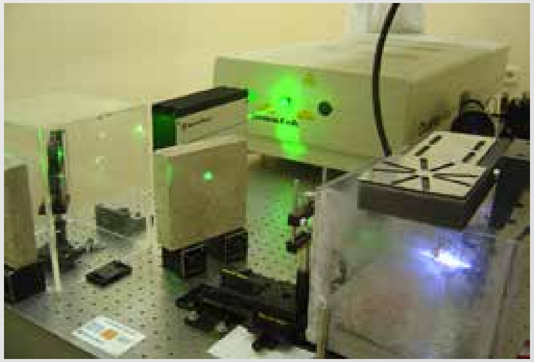
jlocana@etsii.upm.es



CENTRO LÁSER
UNIVERSIDAD POLITÉCNICA DE MADRID

Major Facilities (1/2)

Major Facilities (2/2)

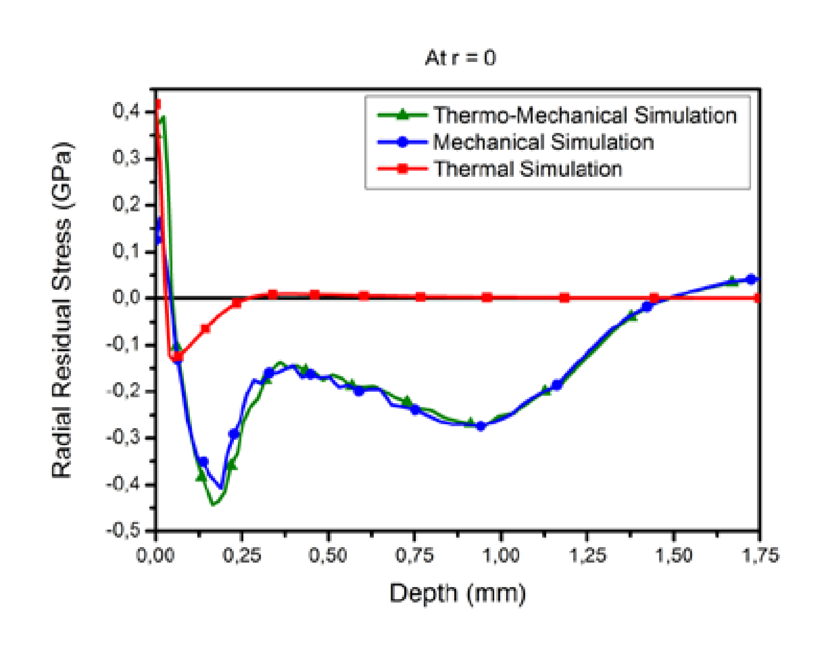


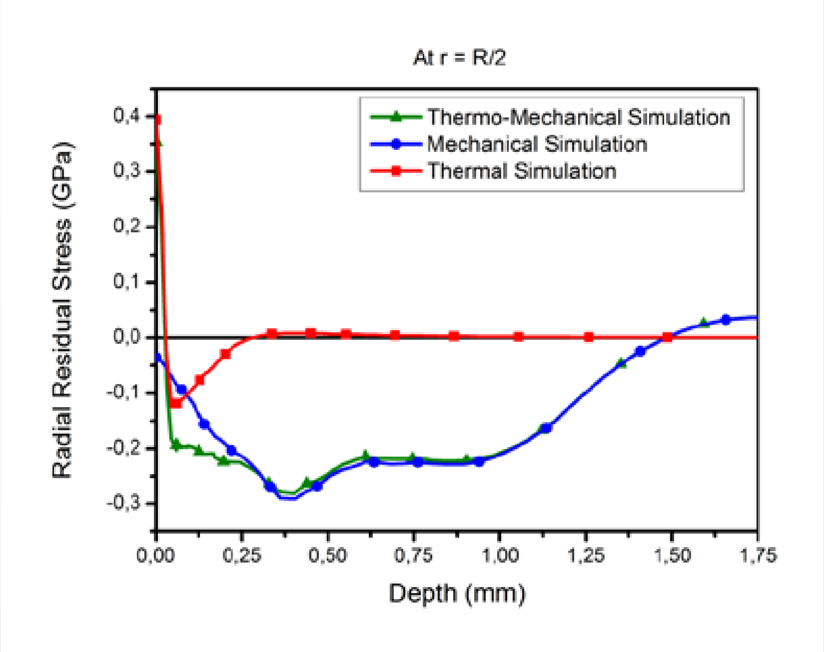
SHOCK PROPAGATION AND DERIVED RESIDUAL STRESSES IN LSP

Evaluation of relative effects of thermal and mechanical waves on shocked material

Water / Aluminium; Nd:YAG (1064 nm),

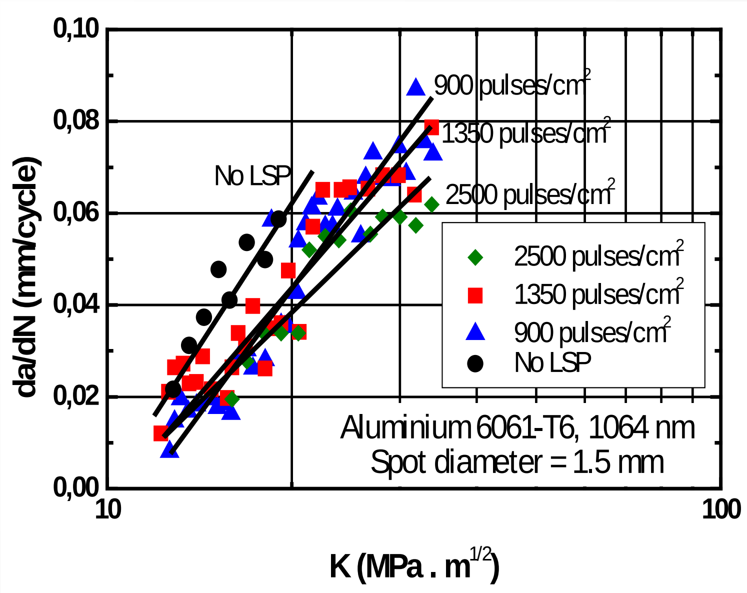
t= 9 ns, F= 84 J/cm^2, radius = 1.5 mm

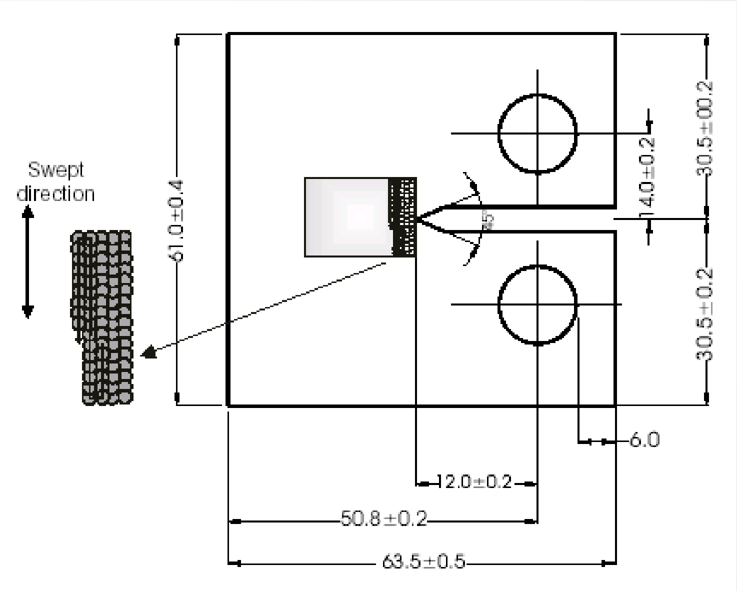




Morales, M. et al.: Materials Science Forum, 638-642, 2682-2687 (2010)

EXPERIMENTAL RESULTS



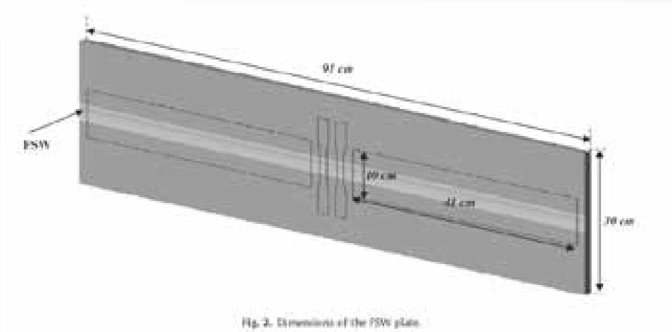


$$\frac{da}{dN} = C.K^{m}$$

Pulse density (cm^{-2})	C (mm/cycle)	M (dimensionless)
0 (No LSP treatment)	$4x10^{-13}$	7.664
900	$8x10^{-13}$	6.818
1350	$2x10^{-11}$	5.733
2500	$3x10^{-10}$	4.723

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

A typical prospective LSP application to welding technology



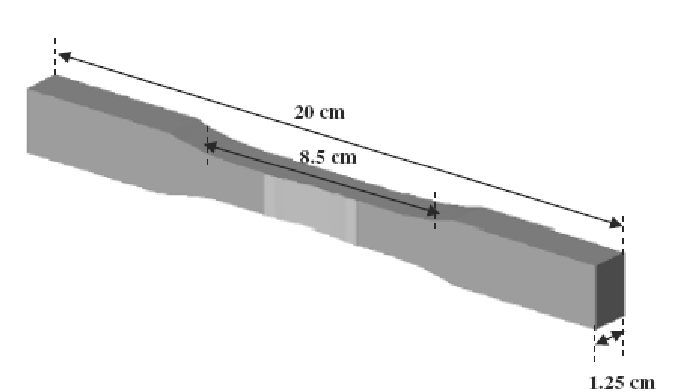
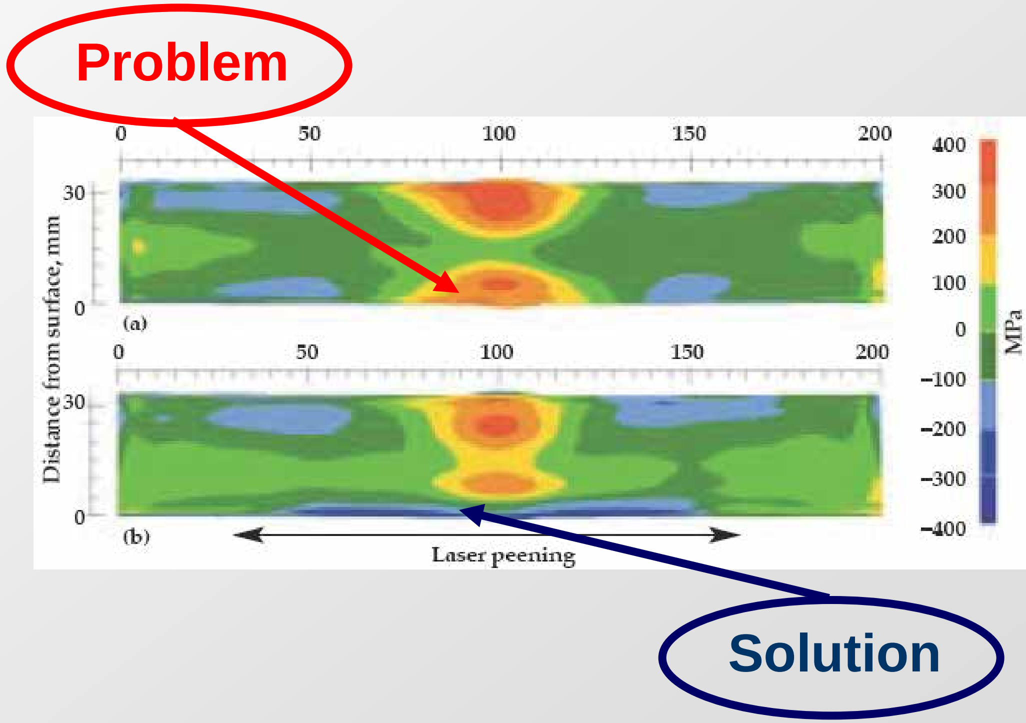


Fig. 4. Dimensions of the tensile specimen.



DISCUSSION AND OUTLOOK

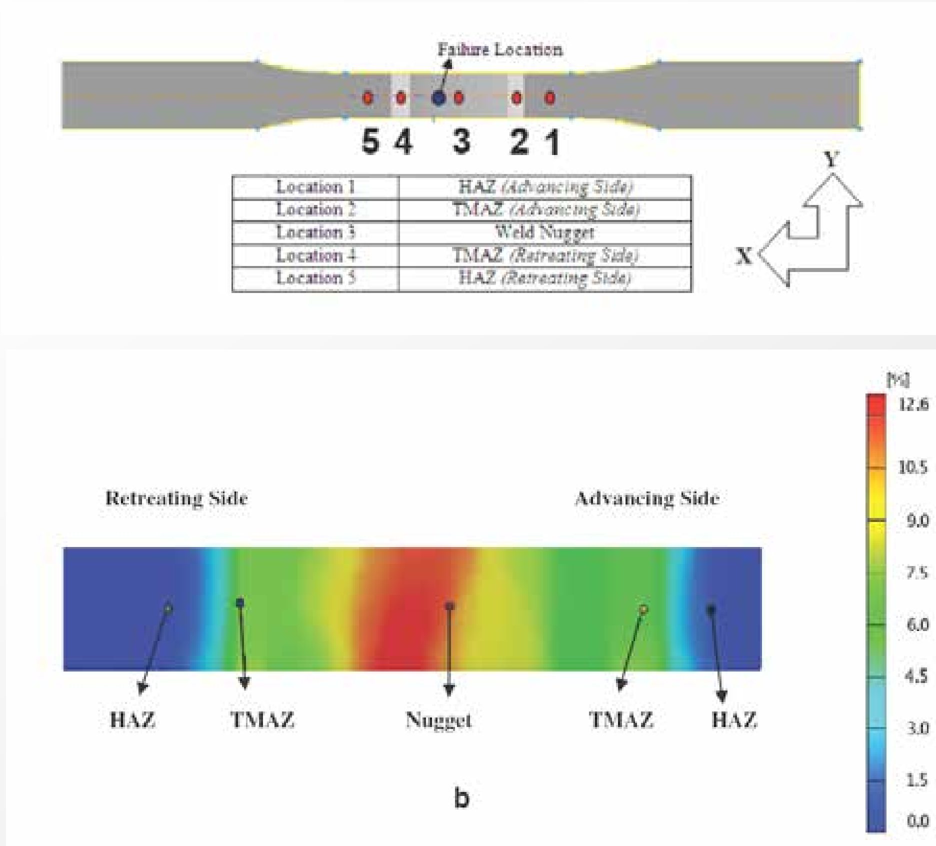


Fig. 10. (a) Tensile properties at different regions of the weld (b) Strain fields in the x-direction for the specimen before failure.

O. Hatamleh / **International Journal of Fatigue 31 (2009) 974–988**

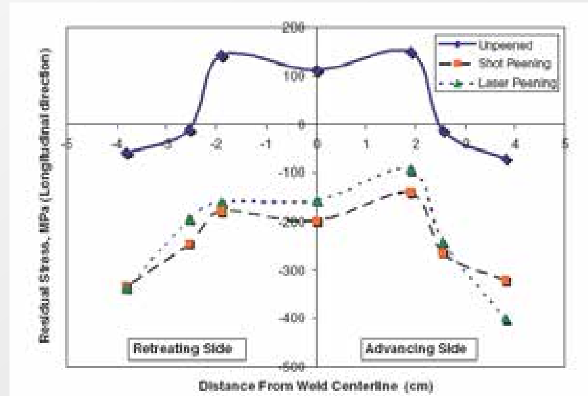


Fig. 11. Residual stresses for the various peened FSW specimens.

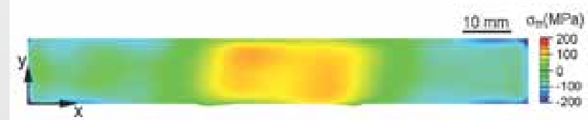


Fig. 12. Two-dimensional map of the measured residual stress for the unpeened FSW specimen.

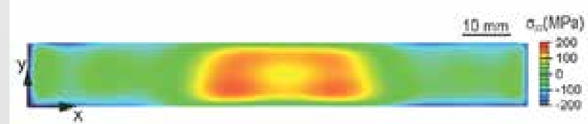


Fig. 13. Two-dimensional map of the measured residual stress for the shot peened FSW specimen.

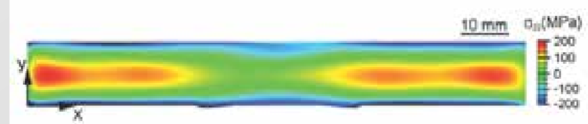


Fig. 14. Two-dimensional map of the measured residual stress for the laser peened FSW specimen.