Scientific and Technological Issues on the Application of High Intensity Lasers to Material Properties Modification: The case of Laser Shock Processing of Metallic Alloys

J.L. Ocaña, M. Morales, J.A. Porro,
C. Molpeceres, A. García-Beltrán

Centro Láser UPM. Universidad Politécnica de Madrid
Campus Sur UPM. Edificio La Arboleda.
Ctra. de Valencia, km. 7,300. 28031 Madrid. SPAIN
Tel.: (+34) 913363099. Fax: (+34) 913363000.
email: jlocana@etsii.upm.es

Scientific and Technological Issues on the Application of High Intensity Lasers to Material Properties Modification: Laser Shock Processing of Metallic Alloys

OUTLINE:

- Introduction
- Physical Principles of LSP
- Numerical Simulation. Model Description
- Simulation Results
- Experimental Validation. Diagnosis Setup
- Discussion and Outlook

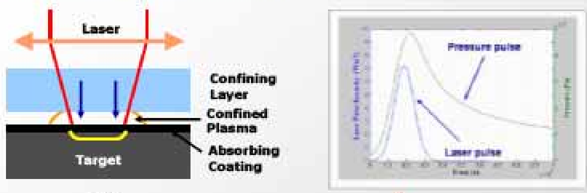
CENTRO LÁSER UNIVERSIDAD POLITÉCNICA DE MADRID
Exploratory Meeting ELI- A New Impetus for Multidisciplinary Scientific Research
September 16-18, 2008 BUCHAREST (RUMANIA)

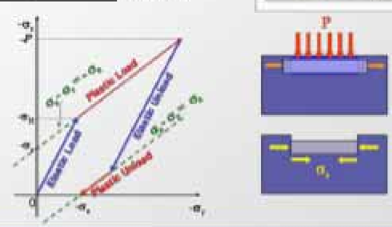
1. INTRODUCTION

- Laser Shock Processing (LSP) has been practically demonstrated as a technique allowing the effective induction of residual stresses fields in metallic materials allowing a high degree of surface material protection. Experimental results obtained with commercial Q-switched lasers prove complete feasibility at laboratory scale
- Depending on initial material mechanical properties, the remaining residual stresses fields can reach depths and maximum values providing an effectively enhanced behaviour of materials against fatigue crack propagation, abrasive wear, chemical corrosion and other failure conditions. This 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.
- However, according to the inherent difficulty for prediction of the shock waves generation (plasma) and evolution in treated materials, the practical implementation of LSP processes needs an effective predictive assessment capability
- A physically comprehensive calculational tool (SHOCKLAS) has been developed able to sistematically study LSP processes

CENTRO LÁSER UNIVERSIDAD POLITÉCNICA DE MADRID
Exploratory Meeting ELI- A New Impetus for Multidisciplinary Scientific Research
September 16-18, 2008 BUCHAREST (RUMANIA)

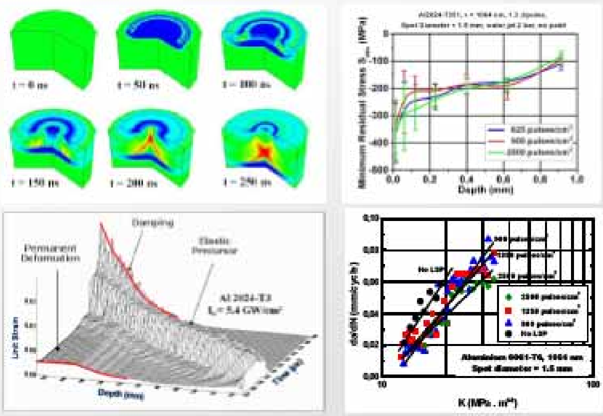
2. LSP PHYSICAL PRINCIPLES



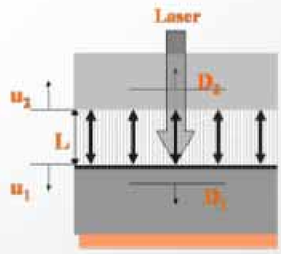


CENTRO LÁSER UNIVERSIDAD POLITÉCNICA DE MADRID
Exploratory Meeting ELI- A New Impetus for Multidisciplinary Scientific Research
September 16-18, 2008 BUCHAREST (RUMANIA)

2. LSP PHYSICAL PRINCIPLES



3. NUMERICAL SIMULATION. MODEL DESCRIPTION



Solid/Liquid $D = C + S u$

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

LSPSIM

Interface thickness

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

Shock wave relation

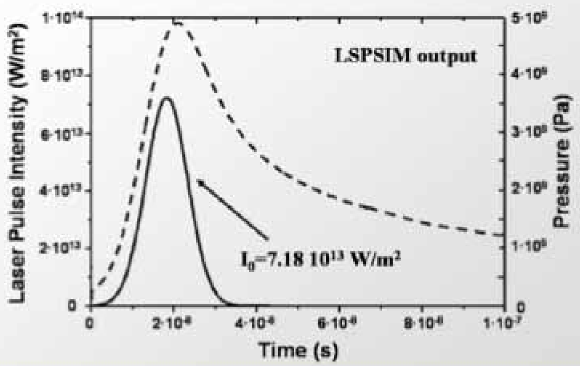
$$P = \rho_i D_i u_i$$

Heating phase

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

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

3. NUMERICAL SIMULATION. MODEL DESCRIPTION



3. NUMERICAL SIMULATION. MODEL DESCRIPTION

HARDSHOCK

- 1D Motion: Mass, Momentum, Energy
  (Method of characteristics)
- Hydrodynamic/elastic-plastic (Von Mises yield criterion)
- Ideal gas/Grüneisen E.O.S.

$$\rho_1 u_1 = \rho_0 u_0$$

$$P_1 + \rho_1 u_1^2 = P_0 + \rho_0 u_0^2$$

$$\varepsilon_1 + \frac{P_1}{\rho_1} + \frac{u_1^2}{2} = \varepsilon_0 + \frac{P_0}{\rho_0} + \frac{u_0^2}{2}$$

$$|\sigma_r - \sigma_t| < -YS$$

$$P = P_h + \Gamma\rho(W - W_h)$$

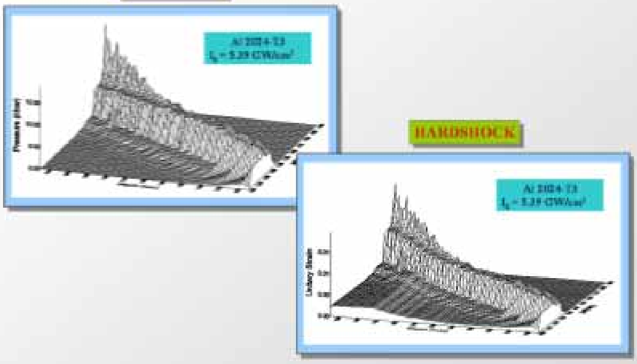
$$W_h = \frac{P_h\varepsilon}{2\rho_0} \quad P_h = \frac{\rho_0 C_0^2 \varepsilon}{(1 - S\varepsilon)^2}$$

$$U_s = C_0 + S U_p$$

3. NUMERICAL SIMULATION. MODEL DESCRIPTION

HARDSHOCK

HARDSHOCK

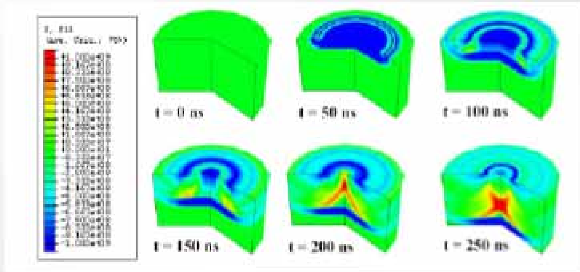


3. NUMERICAL SIMULATION. MODEL DESCRIPTION

HARDSHOCK-2D Semi-infinite

Ti6Al4V

Radial stress dynamic analysis

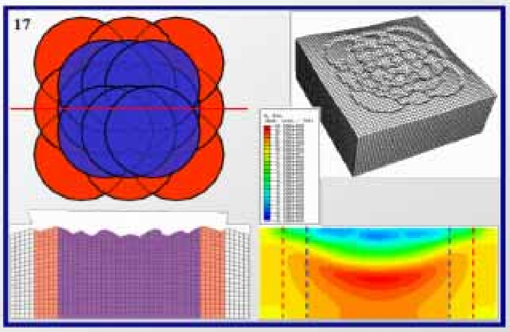


3. NUMERICAL SIMULATION. MODEL DESCRIPTION

HARDSHOCK-3D (full scope)

Ti6Al4V

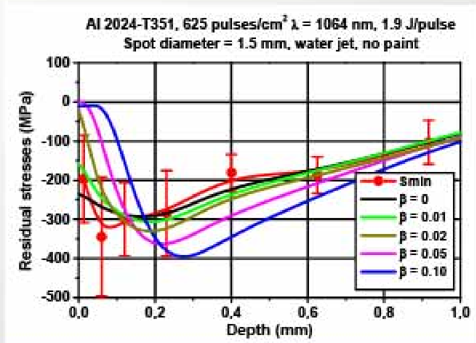
Nd:YAG (1064 nm)
P_{av}= 5,7 W/cm²
Spot radius = 0.75 mm
FWHM = 0 ns
α= 0.15
Overlapping = 900/cm²



3. NUMERICAL SIMULATION. MODEL DESCRIPTION

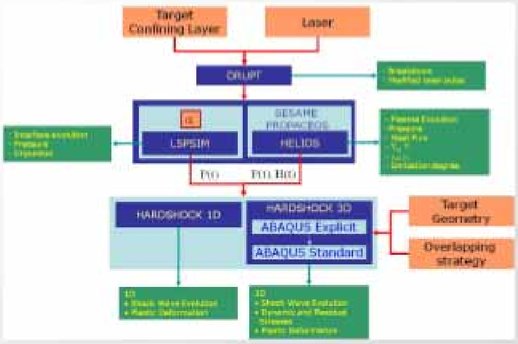
Analysis of relative influence of thermal and mechanical effects

Al2024-T351



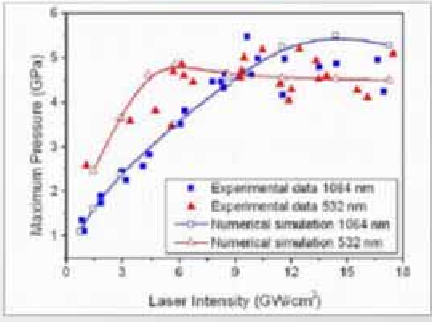
3. NUMERICAL SIMULATION. MODEL DESCRIPTION

The SHOCKLAS Calculational System



3. NUMERICAL SIMULATION. MODEL DESCRIPTION

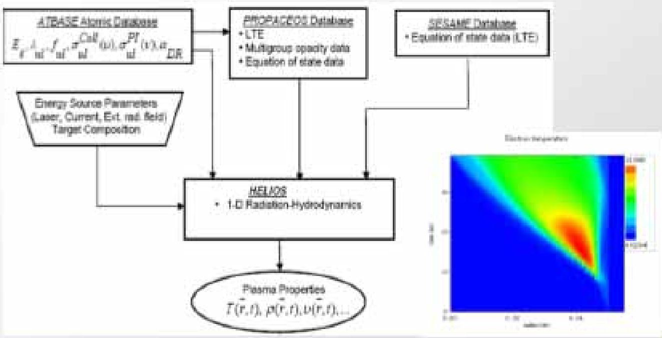
DRUPT



CENTRO LÁSER
UNIVERSIDAD POLITÉCNICA DE MADRID
Exploratory Meeting
ELI- A New Impetus for Multidisciplinary Scientific Research
September 16-18, 2008
BUCHAREST (RUMANIA)

3. NUMERICAL SIMULATION. MODEL DESCRIPTION

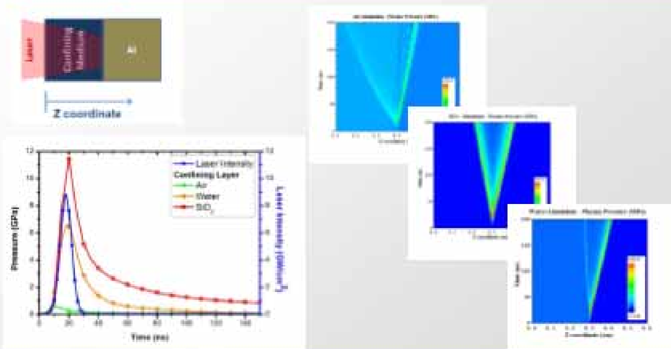
HELIOS



CENTRO LÁSER
UNIVERSIDAD POLITÉCNICA DE MADRID
Exploratory Meeting
ELI- A New Impetus for Multidisciplinary Scientific Research
September 16-18, 2008
BUCHAREST (RUMANIA)

4. NUMERICAL SIMULATION RESULTS

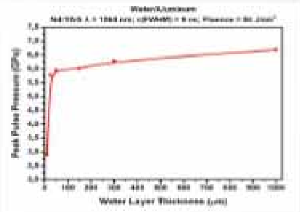
HELIOS Analysis of relative influence of confining material

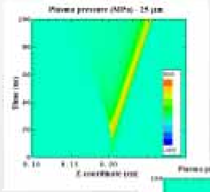


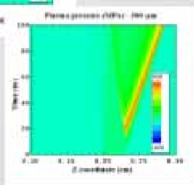
CENTRO LÁSER
UNIVERSIDAD POLITÉCNICA DE MADRID
Exploratory Meeting
ELI- A New Impetus for Multidisciplinary Scientific Research
September 16-18, 2008
BUCHAREST (RUMANIA)

4. NUMERICAL SIMULATION RESULTS

HELIOS — **Analysis of influence of water layer thickness**

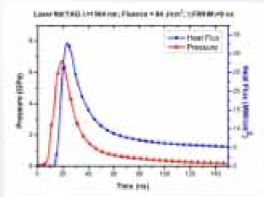


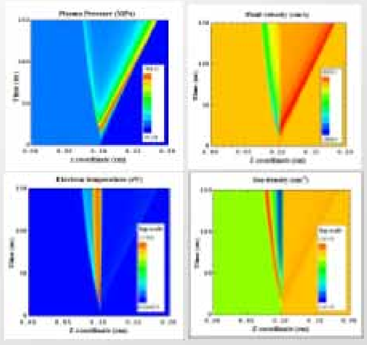




4. NUMERICAL SIMULATION RESULTS

HELIOS — **Analysis of plasma for LSP conditions**





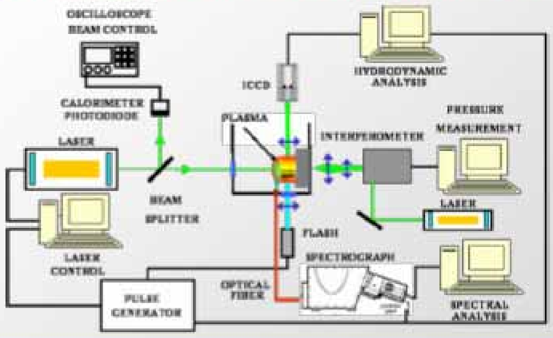
5. EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

Summary of correlated experimental observations and simulation results defined for plasma monitoring and process design

PLASMA EXPLORED CHARACTERISTICS	EXPERIMENTAL OBSERVATION NEEDED	MATCHING SIMULATION RESULTS
Average plasma ionization energy in interaction region	Line Spectroscopy (integrated spectrum energy)	HYDRA ionization model results
Average plasma density and temperature in interaction region	Line Spectroscopy (collisional line broadening)	HYDRA hydrodynamic simulation
Space resolved plasma density	Shadowgraphy + Schlieren photography	HYDRA hydrodynamic simulation
Shock wave generation and plasma expansion speed	Shadowgraphy + Schlieren photography	HYDRA (short times) + LSPSIM free surface evolution simulation
Breakdown in confining medium	Line spectroscopy	Dielectric breakdown evaluation module in LSPSIM

5. EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

CONCEPTUAL INTERRELATED DIAGNOSTICS SYSTEM

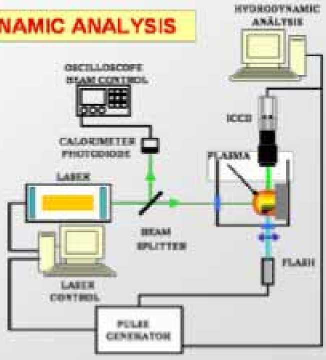


5. EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

CONCEPTUAL INTERRELATED DIAGNOSTICS SYSTEM

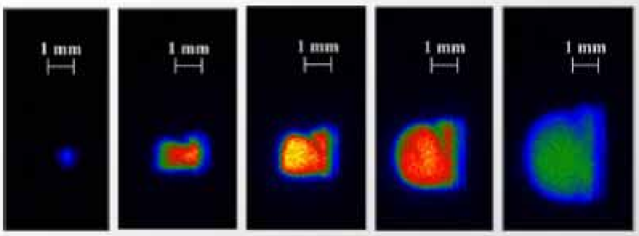
5. EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

DIRECT IMAGING - HYDRODYNAMIC ANALYSIS



5. EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

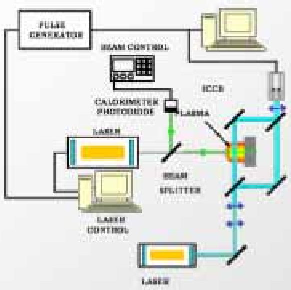
DIRECT IMAGING - HYDRODYNAMIC ANALYSIS

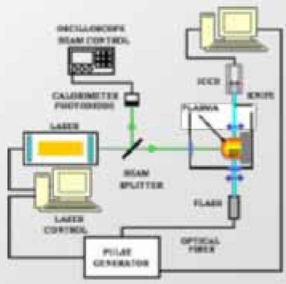


t = 10 ns t = 25 ns t = 50 ns t =100 ns t =200 ns

5. EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

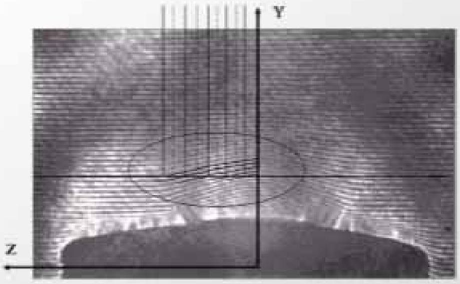
IMAGING TECHNIQUES – SCHLIEREN / INTERFEROMETRY





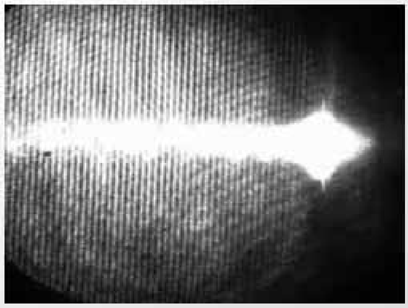
5. EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

IMAGING TECHNIQUES – SCHLIEREN / INTERFEROMETRY



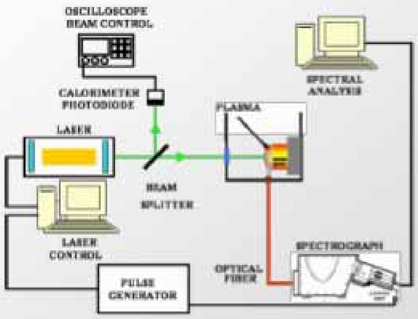
5. EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

IMAGING TECHNIQUES – SCHLIEREN / INTERFEROMETRY



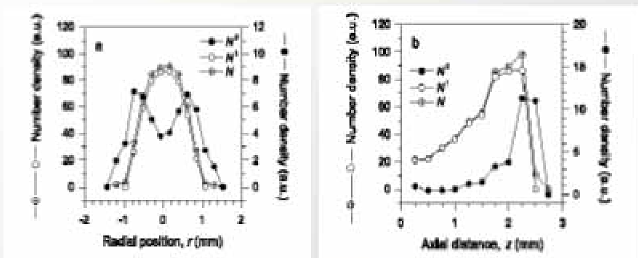
5. EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

EMISSION SPECTROSCOPY



5. EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

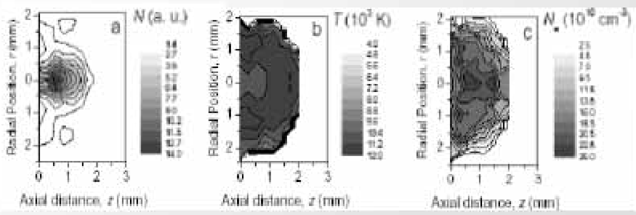
EMISSION SPECTROSCOPY



J.A. Aguilera, C. Aragón / Spectrochimica Acta Part B 59 (2004) 1861–1876

5. EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

EMISSION SPECTROSCOPY



6. DISCUSSION AND OUTLOOK

- The need for a practical capability of LSP process control in practical applications has led to the development of comprehensive theoretical/computational models for the predictive assessment of the complex phenomenology involved.
- High intensity laser-plasma interaction has revealed itself as a critical point for a proper process understanding and predictive assessment.
- A physically comprehensive calculational model (SHOCKLAS) has been developed able to systematically study LSP processes starting from laser-plasma interaction. The integrated laser-plasma analysis routine, based in realistic material EOSs, provides a unique capability for process coupled theoretical/practical characterization
- The development of the appropriate experimental diagnosis facilities enables a reliable process predictive assessment capability in view of process industrial implementation.

CENTRO LÁSER UNIVERSIDAD POLITÉCNICA DE MADRID
Exploratory Meeting ELI- A New Impetus for Multidisciplinary Scientific Research
September 16-18, 2008 BUCHAREST (RUMANIA)

CENTRO LÁSER UNIVERSIDAD POLITÉCNICA DE MADRID
Exploratory Meeting ELI- A New Impetus for Multidisciplinary Scientific Research
September 16-18, 2008 BUCHAREST (RUMANIA)

ACKNOWLEDGEMENTS

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

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

CENTRO LÁSER UNIVERSIDAD POLITÉCNICA DE MADRID
Exploratory Meeting ELI- A New Impetus for Multidisciplinary Scientific Research
September 16-18, 2008 BUCHAREST (RUMANIA)