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Classification

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Electromagnetic Gauge Study of Laser-Induced Shock Waves in Aluminum Alloys

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Résumé. — Cet article fait la synthèse d'une étude récente sur la caractérisation du comportement sous choc-laser de trois alliages d'aluminium largement utilisés dans l'industrie à travers la méthode dite de la jauge électromagnétique. Cette méthode permet de mesurer les vitesses matérielles induites en face arrière de plaques d'épaisseurs variables par un impact laser. La mise en vitesse de plaques nous a permis, premièrement, de vérifier la validité des pressions d'impact superficielles obtenues en les comparant avec des résultats antérieurs obtenus par des mesures sur capteurs quartz. Sur des plaques d'épaisseurs croissantes, nous avons caractérisé l'atténuation des ondes de choc en profondeur dans les alliages étudiés et mesuré les limites d'élasticité sous choc (pressions d'Hugoniot) des alliages. Les résultats ont été comparés avec succès à des simulations numériques grâce à un code de calcul monodimensionnel Lagrangien. Enfin, les valeurs des pressions d'Hugoniot mesurées ont permis de tracer l'évolution des contraintes d'écoulement plastique en fonction de la vitesse de déformation pour des valeurs comprises entre 10^{-3} s^{-1} et 10^6 s^{-1} .

Abstract. — The laser-shock behaviour of three industrial aluminum alloys has been analyzed with an Electromagnetic Gauge Method (EMV) for measuring the velocity of the back free surface of thin foils submitted to plane laser irradiation. Surface pressure, shock decay in depth and Hugoniot Elastic Limits (HEL) of the materials were investigated with increasing thicknesses of foils to be shocked. First, surface peak pressures values as a function of laser power density gave a good agreement with conventional piezoelectric quartz measurements. Therefore, comparison of experimental results with computer simulations, using a 1D hydrodynamic Lagrangian finite difference code, were also in good accordance. Lastly, HEL values were compared with static and dynamic compressive tests in order to estimate the effects of a very large range of strain rates (10^{-3} s^{-1} to 10^6 s^{-1}) on the mechanical properties of the alloys.

1. Introduction

Among the newly developed surface treatments, Laser Shock Processing (LSP) is one of the most promising ones for many applications such as fatigue resistance (at high cycles, with fretting), stress corrosion or tribological resistance.

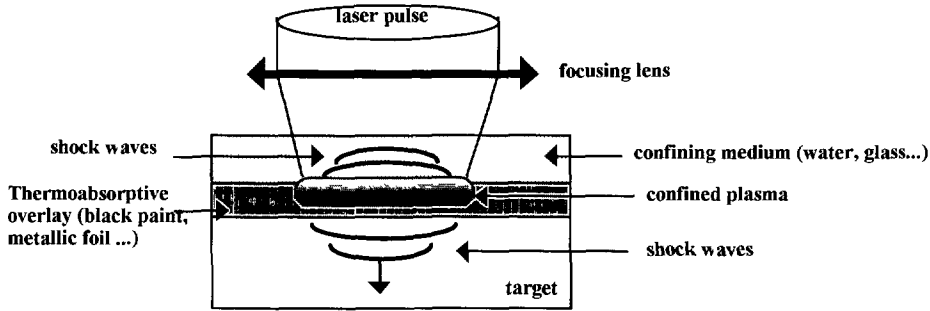


Fig. 1. — Laser Shock Processing (LSP) in a confined ablation mode.

Developed for the first time in the period between 1968 and 1981 at Battelle Columbus (Ohio-USA) laboratories with application to fastener holes [1], the treatment has been extensively studied in France since 1986, supported by French automotive industry (PSA) and other industrial partners. Scientific work has been principally concerned with a precise description of the confined interaction mode [2,3] and of its limiting factors [4], as well as analytical modeling of the mechanical processes involved [5].

Our original results from reference [8] are built upon previous studies on LSP of steels [3,5,6] or nickel base superalloys [7] materials. Three commercial aluminum alloys were chosen to evaluate the effects of LSP. The first two are Al-Si type cast aluminum alloys (Al-12% Si = Al12Si and Al-7%Si = A356-T6) often used in the automotive industry. The third is an aeronautical 7075-T7351 wrought alloy.

Before using laser shock as a new method for processing materials, attention had to be focused on laser-shock wave behavior of the alloys. Preliminary results reported here are based on experimental measurements with an electromagnetic gauge system [9] for monitoring the velocity of back free surfaces of foils accelerated by a 25 ns laser-pulse focused on their front surface. Our overall objective was a characterization of shock-wave decay including shock-compressive yield strength measurements.

2. Process and Experimental Environment

Irradiating a metallic target with a short (tenths of ns) and intense ($> 1 \text{ GW/cm}^2$) focused laser pulse generates a vaporization of the first atomic layers of the target. When the partially ionized gas (plasma) blows off, it drives a shock wave by expansion from the irradiated surface. This shock wave propagates into the target, causing plastic deformation to a depth where the peak stress no longer exceeds the Hugoniot elastic limit (HEL) of the metal (= yield strength under a shock condition), and in turn induces residual stresses.

Experimental conditions typically consisted of coating the surface to be treated with a sacrificial material opaque to the laser light (black paint, metallic foil) and a material transparent to the light (water, glass) (Fig. 1). When the energy passes through the water, beam energy is initially absorbed by the opaque overlay, vaporizing ("ablating") a thin layer of that sacrificial material ($< 10 \mu\text{m}$). Consequently, no thermal effects involve the target. The vapor then absorbs the rest of the beam's energy thus heating, ionizing (into a plasma) and expanding the plasma.

As the plasma is confined by the dielectric transparent material, the amplitude and duration of the applied pressure are increased, in a level that depends upon the acoustic impedance Z_{conf} of the confining medium. This effect is called the "confined ablation mode". Compared with direct ablation mode, this configuration allows pressures 10 times greater and durations two or three times longer for the same power densities.

The resulting effect is the generation at the metal surface of a high pressure shock wave, causing plastic deformation and compressive stresses in the target. Consequently, LSP is known to be a pure mechanical treatment inducing negative residual stresses able to improve fatigue behaviour of structures.

A complete model of the confined ablation mode was recently [2] developed, taking into account the heating, adiabatic cooling and final expansion of the plasma for the generation of a pressure. Using this model, and considering the plasma as a perfect gas, the scaling law of the pressure generation is estimated with the following relationship [2]:

$$P(\text{GPa}) = 0.01 \sqrt{\frac{\alpha}{2\alpha + 3}} \sqrt{Z(\text{g cm}^{-2}\text{s}^{-1})} \sqrt{I_0(\text{GW/cm}^2)} \quad (1)$$

where I_0 = incident laser power density, P = pressure, Z = reduced shock impedance between the target and the confining medium $\left(\frac{1}{Z} = \frac{1}{Z_{\text{target}}} + \frac{1}{Z_{\text{conf}}}\right)$, α = efficiency of the interaction (αE contributes to the pressure increase and $(1 - \alpha)E$ is devoted to generate and ionize the plasma).

All the experiments shown in this paper were performed with a water confined mode which is the only industrially convenient one. Formula (1) gives (with $\alpha = 0.12$, $Z_{\text{water}} = 0.165 \times 10^6 \text{ g cm}^{-2} \text{ s}^{-1}$, $Z_{\text{Al}} = 1.5 \times 10^6 \text{ g cm}^{-2} \text{ s}^{-1}$ [4]):

$$P(\text{GPa}) = 1.02 \sqrt{I_0(\text{GW/cm}^2)} \quad (2)$$

Typically, 5 GPa amplitude - 50 ns duration peak pressures could be achieved by 10 GW/cm² laser pulses. Two pulse shapes can be used for LSP: a classical Gaussian and a dissymmetrical Short Rise Time (SRT) pulse [4]. Systematic pressures saturations generally occur over 4 GW/cm² for the Gaussian pulse because of breakdown phenomena that limit the energy pulse transmission through the confinement medium, towards the metallic surface. To avoid these limiting effects, SRT pulses have shown to be efficient by increasing the breakdown thresholds.

All our experiments were performed with the LALP (Laboratoire d'Application des Lasers de Puissance) neodymium glass laser operating at $\lambda = 1.06 \mu\text{m}$ and consisting of an oscillator followed by four amplifier stages. This system is able to emit up to 80 J in a pulse that is semi-Gaussian or has a Short Rise Time (SRT) with a Full Width at Half Maximum (FWHM) of 15-30 ns. During our work, only Gaussian pulses of 25 ns FWHM were used because the maximum peak pressure of 2.5 GPa was large enough to treat any aluminum alloy.

Specimens were water-confined (2 to 5 mm thick) in order to increase the plasma pressure, and submitted to 1-8 GW/cm² irradiations with 5-11 mm spot sizes on the targets.

3. Materials

Three industrial aluminum alloys were investigated to give a general description about their laser shock behaviour [8].

Both Al-Si alloys were chilled-cast, solution treated, quenched and aged to a T6 condition. Age-hardening occurred mainly by fine precipitation of coherent Mg₂Si phase. Weight composition are given in Table I. Each cast alloy exhibited grain size coarsenings to about 300 μm

Table I. — *Weight (%) composition of the 3 aluminum alloys.*

	Si	Cu	Fe	Mg	Mn	Ni	Zn	Cr	Ti
Al12Si	12.2	1.48	0.16	1.3	0.03	1.25	0.03		0.01
A356	7.05	0.05	0.2	0.33	0.03		0.03		0.15
7075	0.08	1.48	0.17	2.6			5.95	0.2	0.04

levels so that residual stresses induced by LSP could no be measurable by conventional X-ray diffraction (X-ray diffraction patterns were not obtained).

A356 was solution treated 6 h at 480 °C, water quenched (20 °C) and aged 6 h at 160 °C. The tensile failure behaviour studied with scanning electronic microscopy was half ductile-half fragile.

Al12Si (French name = AS12UNG) was obtained by solution treating 6 h at 480 °C, water quenching at 70 °C, and aging 6 h at 220 °C. The microstructure of the as-received Al12Si-T6 consisted of Mg₂Si phase (like A356) with also Al₂Cu partially coherent precipitates. Alloying Al with 12% Si has two opposite effects on the mechanical behaviour. First, it reduces strongly its plasticity (less than 1%) and then it increases strengthening coefficients for tensile or compressive tests.

The starting 7075 material was 4 cm thick sheet oriented with the direction parallel to the hot-rolling direction. It was delivered at T7351 thermal state consisting in quenching, tensile stress relieving and two stages ageing (8 h at 135 °C and 1 h at 190 °C).

Even though texturation was obvious on the grain shapes, X-ray diffraction could be used for residual stress measurements on 7075.

LSP can be considered as a high strain rate (10^6 s^{-1}) uniaxial compression, creating surface layers' stretching during the interaction. So mechanical properties had to be measured first with monotonic tensile and compressive tests (strain rate: 10^{-3} s^{-1}) and also with dynamic compressive tests (10^3 s^{-1}) using the Split-Hopkinson Pressure Bar system (SHPB). However, as SHPB monitors information only over 2% plastic strain, dynamic yield strengths were extrapolated from the first 2 – 5% of plastic strain. Resulting mechanical properties are summarized in Table II.

Compressive measurements on cylindrical samples (5 mm radius, 15 mm height) show that strain rate sensitivities between 10^{-3} s^{-1} to 10^3 s^{-1} drive to +20 to +30% enhancements on the elastic limits σ_Y of each material. The observed difference between static and dynamic behaviours are typical of previous investigations on Al alloys [10].

4. Experimental Results: Study of Laser Shock Wave Propagation in the Alloys

The main objective of our study was devoted to some experimental and numerical descriptions of laser-shock waves propagations in-depth. Our interest was stimulated by the need to determine Hugoniot Elastic Limits (HEL) and to predict the shock waves decay for each alloy.

Results reported here are based on experimental measurements with an electromagnetic (EMV) gauge for particle velocity measurements at the back free surface of thin foils. This method permitted an estimation of pressure attenuation in a semi-infinite body.

4.1. THE ELECTROMAGNETIC GAUGE METHOD. — Developed in the case of LSP at the ENSMA (Ecole Nationale Supérieure de Mécanique et d'Aéronautique) of Poitiers [9], the electromagnetic gauge method (EMV) deals with the measurements of back free surface velocity u_f of aluminum foils, accelerated by shock waves induced at the front surface.

Table II. — Physical and mechanical properties of the alloys with $\rho_0 =$ density; $E =$ Young modulus; $HV =$ Vickers hardness; $A =$ Elongation (tensile tests); $\sigma_Y^{comp} =$ Compressive Yield strength; $\sigma_Y^{tensile} =$ Tensile Yield strength.

Material	ρ_0 (kg m ⁻³)	E (GPa)	σ_Y^{comp} static (MPa)	σ_Y^{comp} dynamic (MPa)	$\sigma_Y^{tensile}$ static (MPa)	A (%)	HV (25 g)
Al12Si-T6	2770	77	-238	-310	170	0.7	120
A356-T6	2620	70	-218	-260	225	8	110
7075-T7351	2880	72	-450	-550	415	11	170

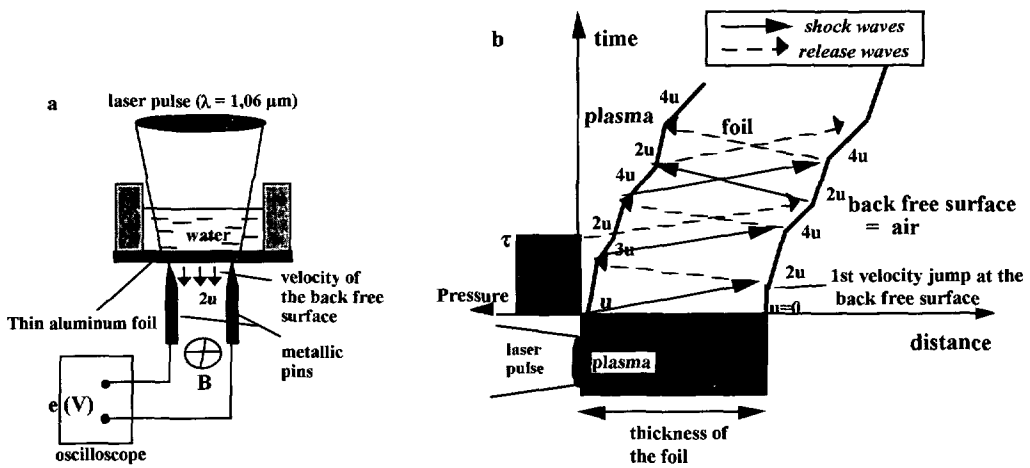


Fig. 2. — a) Scheme of the electromagnetic gauge system; b) Acceleration of a thin foil with a laser-shock-reverberations of successive shock and release waves on the front and back free surfaces.

Metallic foils to measure the back free surface velocities were $100 \mu\text{m}$ to 2 mm thick, for 6 mm diameter spots, in order to ensure a pure uniaxial configuration. As back surface of the foils stands on two parallel metallic pins ($l = 2 \text{ mm}$ distant) and in a constant magnetic induction environment (close to $B = 0.2 \text{ T}$), a voltage is induced when laser-shock waves emerge from the back free surface (Fig. 2a) and accelerates it. Therefore, the voltage e is given by a Laplace's Law $e = u_f B l$ so that voltage recordings $e(t)$ allow free surface velocities recordings as a function of time, $u_f(t)$.

As known from the examination of air and aluminum Hugoniot curves, back free surface velocity is about twice the material velocity value u behind the shock front. So we can develop a general formula giving u as a function of voltage recordings e as

$$u(\text{m/s}) = \frac{e(\text{V})}{2.1(\text{m})B(\text{T})} \tag{3}$$

Classical reverberations of shock and release waves from the front and back free surfaces (Fig. 2b) are obvious on the oscillating aspects of $u = f(t)$ curves, especially with thin foils. For instance, a typical recording for a $150 \mu\text{m}$ thick 7075 foil (Fig. 3a) shows a first velocity

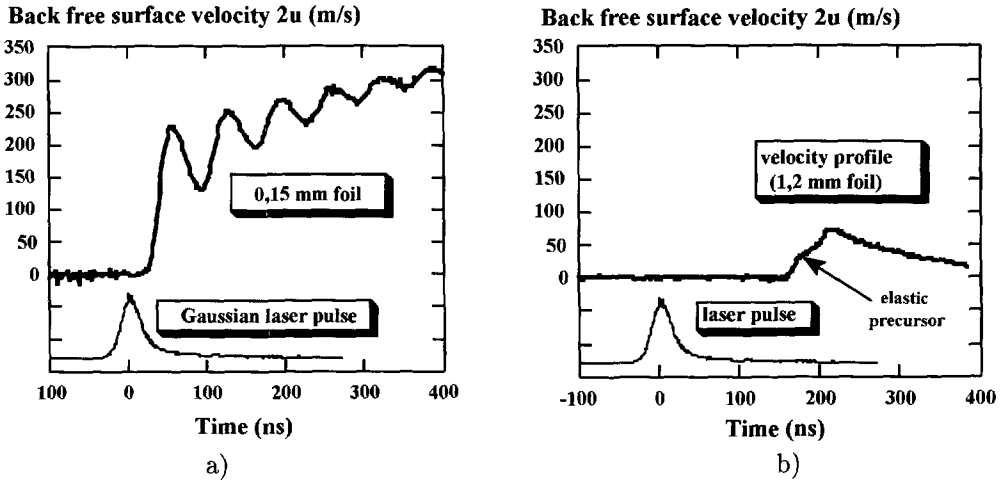


Fig. 3. — Back free surface velocity measurements as a function of time with electromagnetic gauge system on 7075 alloy (irradiation = 3.8 GW/cm², water confined): a) Thin 0.15 mm foil; b) 1.2 mm foil.

emergence of about 230 m/s followed by numerous secondary shocks occurring every 70 ns (= duration of double-transit time through the foils).

Based on the conservation of momentum relation $P = \rho_0 D u$ where D is the wave speed. For many materials $D = C_0 + S u$ where C_0 is the bulk sound velocity and S a material constant. For simple elastic plastic behaviour, the elastic contribution to P is $\frac{2}{3} \sigma_Y$.

$$P = \rho(C_0 + S u)u + \frac{2}{3} \sigma_Y \tag{4}$$

with $S = 1.38$ on Al alloys

In the first part of our study, experimental values of P determined behind thin aluminum foils (100 μm) were compared with quartz measurements at the same peak power densities. The determination of these gauge pressures was required for the validation of our experimental measurements. Great part of our work was dedicated to a precise characterization of shock wave decay, using foils of increasing thicknesses (from 0.15 to 2 mm) to determine peak pressure attenuation in depth.

Thin foils (100 – 150 μm) allowed determination of peak pressures at the very surface of the alloys where hydrodynamic attenuation has not already occurred. HEL of the three alloys was determined from the observal of the elastic precursors. Because of their higher wave speed, elastic precursor waves have been found to “break away” from the plastic wave as the pressure pulse propagates through the material. Their magnitude could only be evaluated with the use of more than 1 mm foils. For instance, we report in Figure 3b a material velocity profile measurement for 1.2 mm thick 7075 foil submitted to 3.8 GW/cm²-water confined Gaussian irradiation. The resulting profile exhibits two characteristics: a 30 m/s elastic precursor and a 70 m/s peak velocity.

4.2. COMPARISON OF PIEZOELECTRIC QUARTZ AND ELECTROMAGNETIC GAUGE MEASUREMENTS. — The ablation pressures are usually determined with synthetic X-cut quartz crystals, 1 mm thick and 5 mm in diameter, plated with 0.5 μm thick gold electrodes.

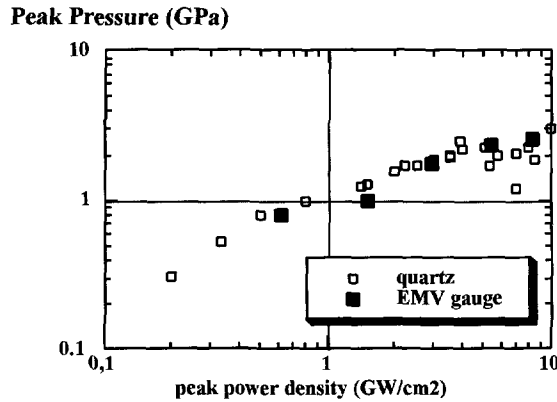


Fig. 4. — Comparison of piezoelectric quartz and Electromagnetic gauge system (0.1 to 0.15 mm foils) measurements.

In the 0-3 GPa range, quartz response is known to be almost linear. So, pressures are achieved from the measurement of the current output I of the gauge with:

$$\sigma = \left(\frac{t_0}{A}\right) \left(\frac{I}{f}\right) \tag{5}$$

where σ is the stress in GPa, A is the area of the collecting electrodes, t_0 the transit time of the pressure pulse through the gauge ($= 0.15 \mu\text{s}$) and f is the piezoelectric coefficient depending on the quartz geometry ($= 2 \times 10^{-7} \text{ C/cm}^2/\text{GPa}$) [11].

We reported in Figure 4 a comparison between quartz and electromagnetic gauge measurements over the 0.5 – 10 GW/cm^2 range in a water confined mode.

EMV measurements were performed on 0.1 to 0.15 mm thick Aluminum foils with a 2 mm water confinement and without thermo-absorptive overlay. Formula (4) was used to calculate peak pressures from the particle velocity values u .

As shown in Figure 4, in the 0.5 – 10 GW/cm^2 range, a good agreement was found between gauge and quartz measurements. This confirms the validity of our gauge measurements.

4.3. HUGONIOT ELASTIC LIMIT DETERMINATION. — Considering the mechanical effects of a laser-shock wave propagating in a metal, HEL values P_H permit us to predict plastically affected depths and residual stresses induced in the target. As shown by previous studies [5], analytical formulation of P_H , in a pure, linearly elastic, rate independent uniaxial strain configuration, is as follows:

$$P_H = \left(\frac{1 - \nu}{1 - 2\nu}\right) \sigma_Y^{\text{compressive}} = 1.75 \sigma_Y^{\text{compressive}} \tag{6}$$

with $\nu =$ coefficient of Poisson = 0.3 \tag{7}

Experimental determination of HEL was motivated by the need to give a better prediction of elastic-plastic mechanical effects induced by LSP. The equation of P_H , as a function of material velocity of the precursor u_H , is written in the elastic part of the shock wave as:

$$P_H = \rho_0 C_{el} u_H \tag{8}$$

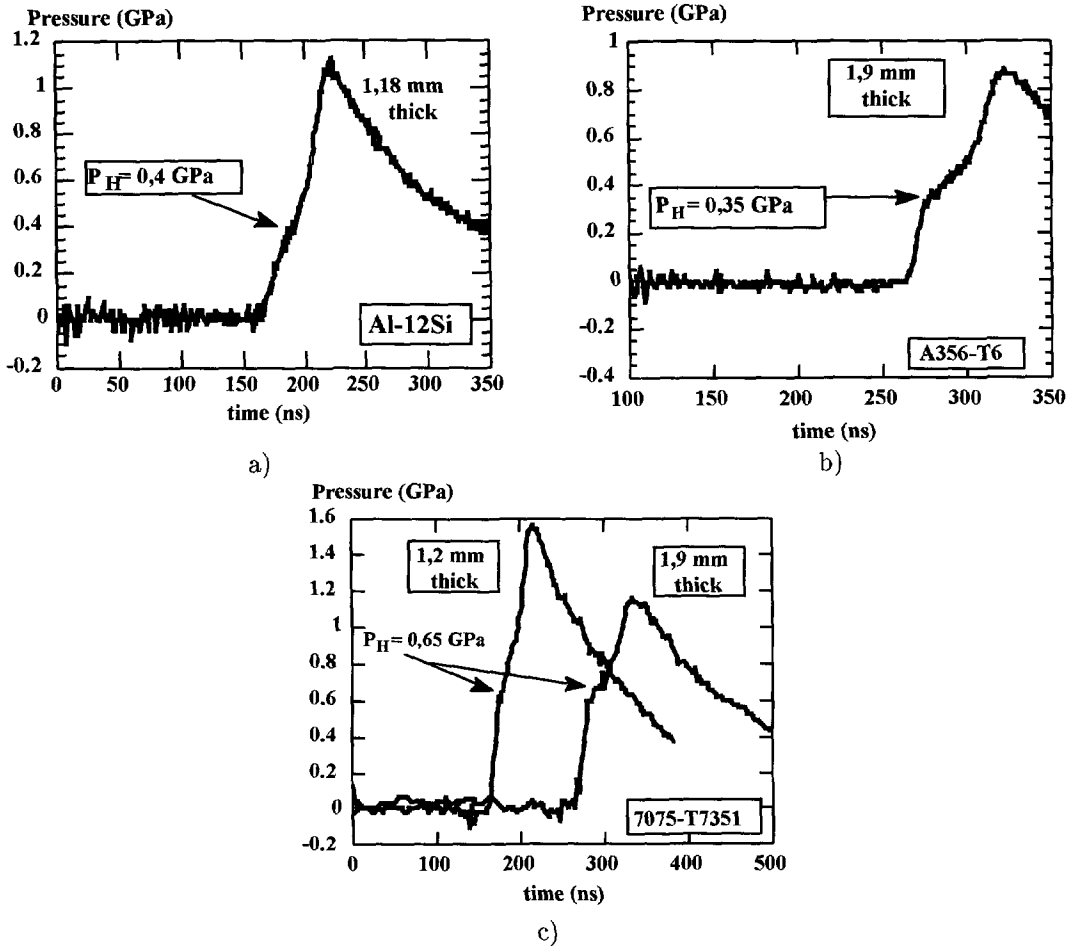


Fig. 5. — Determination of Hugoniot limits (HEL) using elastic precursor measurements; a) Al12Si-T6 aluminum alloy 2.6 GW/cm²; b) A356-T6 aluminum alloy - 2.4 GW/cm²; c) 7075 aluminum alloy - 4 GW/cm².

Considering $C_{el} = \sqrt{\frac{E(1-\nu)}{\rho_0(1+\nu)(1-2\nu)}}$ as the speed of the longitudinal elastic waves in the target [5], calculated values of C_{el} for Al12Si, A356 and 7075 give respectively: 6110, 6000 and 5850 ms⁻¹. These values were used in formula (7) for the determination of P_H from u_H measurements. Figures 5a, 5b and 5c highlight the elastic precursors determination for Al12Si, A356 and 7075 alloys. The three profiles are based on formula (7); that is to say that pressure environments as a function of time are only valid in the elastic parts of the curves (from 0 to P_H). Over P_H , stress levels are overestimated by formula (7). The determination of P_H through different thicknesses of foils allowed us to check the good reproducibility of our gauge results.

Based on the $P = f(t)$ profiles shown in Figure 5, the measured values of P_H for Al12Si, A356 and 7075 are reported as about 0.4 GPa, 0.35 GPa and 0.65 GPa, respectively. As shown from Table III, good agreement was found between calculated and experimental values of P_H ,

Table III. — Comparison between calculated and measured values of HEL.

Material	$\sigma_{Y\text{compressive}}$ (GPa)	P_H calculated (GPa)	P_H measured (GPa)
Al12Si-T6	-0.238	0.42	0.4
A356-T6	-0.218	0.36	0.35
7075-T7351	-0.450	0.79	0.65

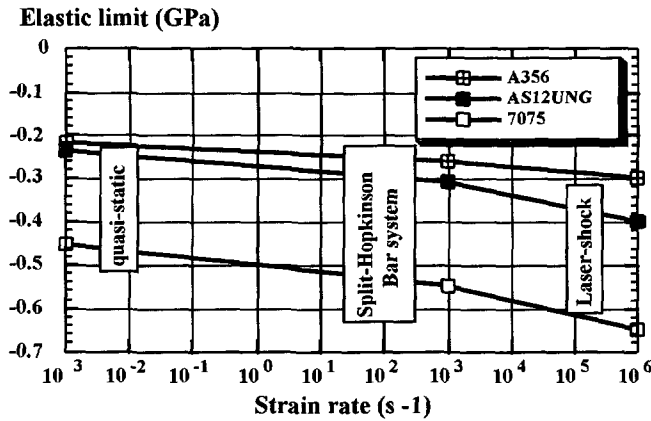


Fig. 6. — Strain rate sensitivity of Aluminum alloys over the 10^{-3} to 10^6 s^{-1} range.

except on 7075 which seems to have 20% lower magnitudes than those calculated by a uniaxial model. Previous results with quartz measurements [12] on 5086 aluminum alloy confirm that experimental values of P_H are often inferior to theoretical predictions. This result may perhaps result from biaxial stress attenuation occurring into 7075 and reducing the magnitude of P_H . However, no differences were found in P_H values between 1.2 and 1.9 mm 7075 foils although a biaxial stress environment would be expected to give higher attenuation on P_H for 1.9 mm foils than for 1.2 mm. Differences may also result from the value of ν which could possibly be inferior to 0.3 because of a slight texturation of 7075.

Lastly, Figure 6 shows the strain rate dependence of the compressive elastic limits of the alloys. No real difference of strain sensitivity could be pointed out between the three alloys over the $10^{-3} s^{-1}$ to $10^6 s^{-1}$ range even though their chemical compositions and static properties were different.

4.4. MEASURED AND SIMULATED SHOCK WAVES DECAY. — A one dimensional Lagrangian computer code called SHYLAC [13] (Simulation HYdrodynamique LAgrangienne des Chocs) which is based on the method of finite differences was used to simulate the elastoplastic and hydrodynamic response of materials irradiated by a pulsed laser beam. This code includes a Mie Grüneisen equation of state with reference to the Hugoniot curves of the materials and an elastic-plastic behaviour for solid materials. At low pressures (< 5 GPa), hydrodynamic effects could be neglected in comparison with elastic-plastic ones. The only parameters used for the simulations were: the incident energy density deposition E_i (J/cm^2), the efficiency of the interaction α , and lastly the monotonic mechanical properties of the alloys (E = Young modulus, ν = coefficient of Poisson, σ_Y). α parameter was optimized to a value of 0.13 in

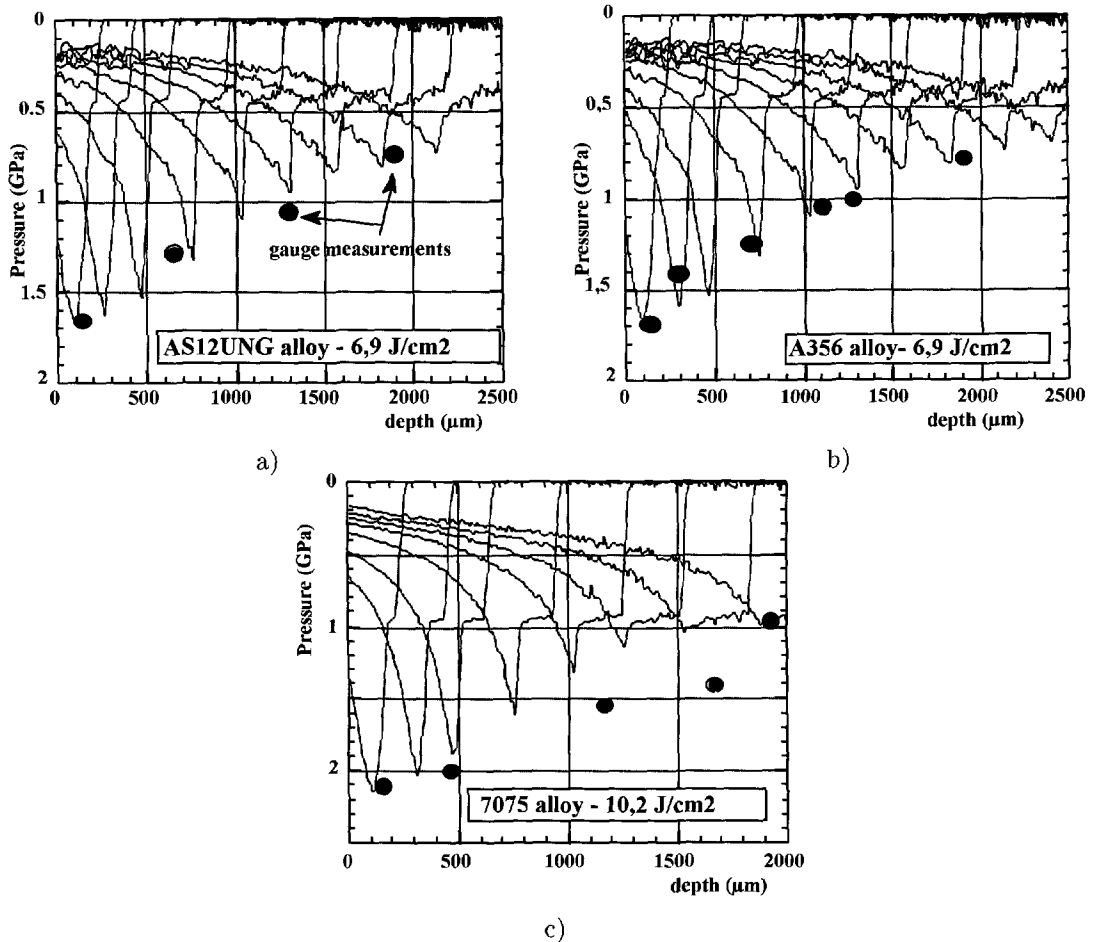


Fig. 7. — Shock wave decay in depth. Comparison of simulated (SHYLAC= Simulation HYdrodynamique LAgrangienne des Chocs) and measured (gauge) values. a) Aluminum alloy Al/12Si (AS12UNG) - 2.4 GW/cm² (simulation of 6.9 J/cm² energy deposition); b) Aluminum alloy A356 (AS7G03) - 2.4 GW/cm² (simulation of 6.9 J/cm² energy deposition); c) Aluminum alloy 7075 - 3.8 GW/cm² (10.2 J/cm² energy deposition).

order to give a good fitting with peak pressures measurements made with piezoelectric quartz in the 1 – 5 GW/cm² range.

Electromagnetic method measurements were made in a water confined mode with foil thicknesses ranging between 0.15 mm (almost equal to the surface peak pressure) and 1.9 mm. Figure 7 illustrates the comparison between experimental values and predicted shock waves decay on two aluminum alloys irradiated with power densities driving to the higher residual stress levels as shown in reference [8]. Corresponding energy depositions αE were simulated to 6.9 J/cm² for A356 and Al/12Si and 10.2 J/cm² for 7075-T7351.

As can be seen from Figure 7a and 7b, a very good agreement could be observed between experimental and numerical values for the case of A356 and Al/12Si irradiated with about 2.5 GW/cm² (= 1.7 GPa peak pressure). On 7075, significantly higher pressures were measured with gauge than simulated with SHYLAC (Fig. 7c). This is expected to come from the value

of the elastic release waves coming back from the front surface and governing the attenuation of pressures: when overestimating HEL, the magnitude of release waves (close to 2 HEL) also increases, and pressure decay seems more pronounced (7075 simulation).

Shock decay profiles shown in Figure 7 are consequent with magnitudes of measured P_H : on 7075 the reason the computed profile underestimates pressures in-depth can be attributed to lower values of P_H evidenced in Figure 5c: as the elastic release waves magnitude ($2P_H$) decreases, plastic waves may persist up to depths higher than those simulated. More over, elastic-plastic approximation might not be realistic for the case of 7075 (analytical calculations of residual stresses induced do not give a good agreement with measurements [8]).

5. Application of LSP to Fatigue Behaviour Improvements

As shown in previous papers [14], HEL measurements and shock decay characterization using the electromagnetic gauge approach allowed a better optimization of the process in terms of the shock conditions inducing maximum residual stress levels in the alloys. Indeed, shock conditions investigated in this paper were used on fatigue notched samples and generated some +20 to +40% enhancements on the fatigue limits of the alloys [14]. These improvements were due to the depth –more than 2 mm– of the residual stress fields induced and, most of all, to the preservation of the initial surface state. In comparison, conventional surface treatments like shot-peening are known to generate a detrimental surface roughness and lower fatigue improvements.

6. Conclusion

A new method for characterizing the in-depth laser stress wave environment was used on three industrial aluminum alloys. This method is based on free surface velocity measurements behind thin metallic foils in a magnetic induction environment. The main conclusions of the study may be summarized as follows:

(1) Back free surface velocity measurements on thin aluminum foils allowed a precise determination of surface peak pressures induced by a pulsed laser irradiation in a water confined mode over the 0.5-10 GW/cm² peak power density range.

(2) Shock decay in depth was estimated on the three aluminum alloys using foils of increasing thicknesses. Comparison with a one dimension hydrodynamic Lagrangian code gave good agreement, especially on cast Al-Si alloys.

(3) Hugoniot elastic limits, from the elastic precursor determination on thick foils, were found to be in quite good accordance with theoretical predictions based on static strength in pure uniaxial strain. However, the 7075 alloy seems to exhibit lower experimental than calculated HEL values based on static strength.

(4) Results achieved allowed a better prediction of mechanical effects induced by the treatment in terms of the residual stress fields induced

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