Optimization of the residual stresses induced by laser shock treatment and fatigue life improvement of 2 cast Aluminium alloys

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Introduction

Surface treatments are becoming more and more important in the mechanical industry and their number is yearly expanding. Indeed, besides the commonly used treatments such as shot peening or nitridation, some new techniques are beeing developed like primary explosive [1] or laser shock waves [3,4], particularly to improve fatigue properties of mechanical parts.
In previous studies [2], the effects of laser-shock treatment on the residual stress field and fatigue behaviour of steels were investigated.
The aim of the paper is to present the results of investigations on the effects of laser shock treatment on two cast aluminum alloys used in the automotive industry. In fact, we just tried to demonstrate the feasibility of laser shock waves to strengthen zones in cast aluminium alloys and to give optimized conditions for the treatment.
Residual stress measurements were carried out using the incremental hole-drilling method.

1.Generation of residual stresses with Laser-shock

When an intense laser pulse (80J - 20 nsec) strikes a metallic target , the surface layer is instantaneously vaporized into a high temperature (10000 K) and a high pressure plasma [4]. The expansion of the plasma generates a shock wave in the metal resulting in a uniaxial dynamic strain ($10^6 sec^{-1}$) with no thermal effects if the target has been previously covered with an absorptive overlay. The plastic strain induces compressive résidual stresses in the target.
The mechanism of generation of residual stresses is shown on figure 1 : during the interaction (a) the impact plane is put into a tensile state and when the laser pulse stops (b) the surrounding matter (besides and below the impact) reacts to the change of volume by inducing a biaxial compressive stress field.

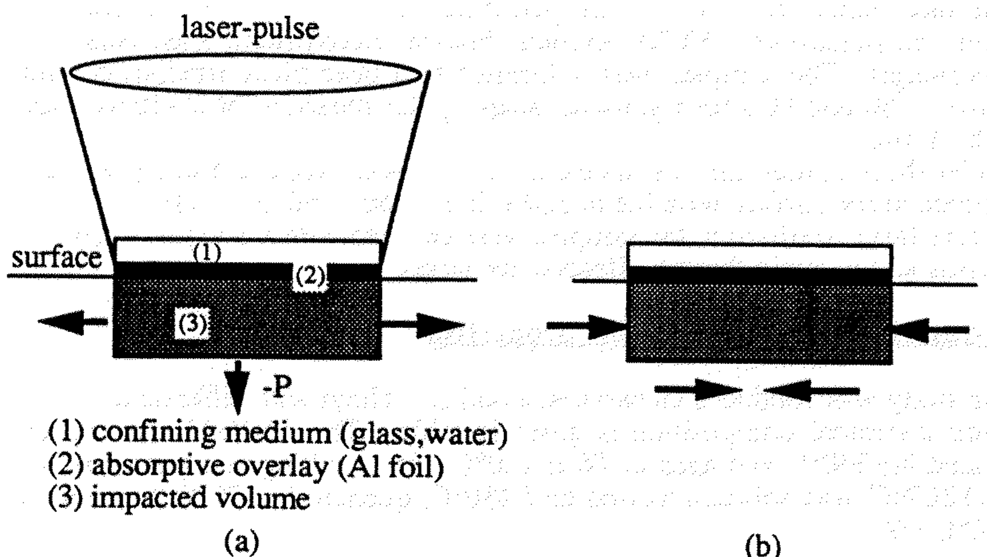

figure 1 : generation of compressive stresses by laser-shock treatment

One of the particular drawbacks of the shock-induced residual stress-fields is the presence of a lack of stresses at the center of impacts , mainly for circular spots.

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The reason for this non-homogeneity of the compressive stress field at this particular point may be attributed to radial relief waves coming from the edges of the impact after the interaction and focalizing simultaneously to its center (fig 2). This focalization results in a reverse strain state and a stress drop.
Using squared shape impacts (achieved with some particular optical lenses) and optimized pressures avoids the simultaneous focalisation of relief waves and the lacks of residual stresses. All our residual stresses measurements were performed at the center of squared shape spots for different impact pressures in order to determine the optimized condition of treatment (which induces a maximum surface stress with no focusing effects).

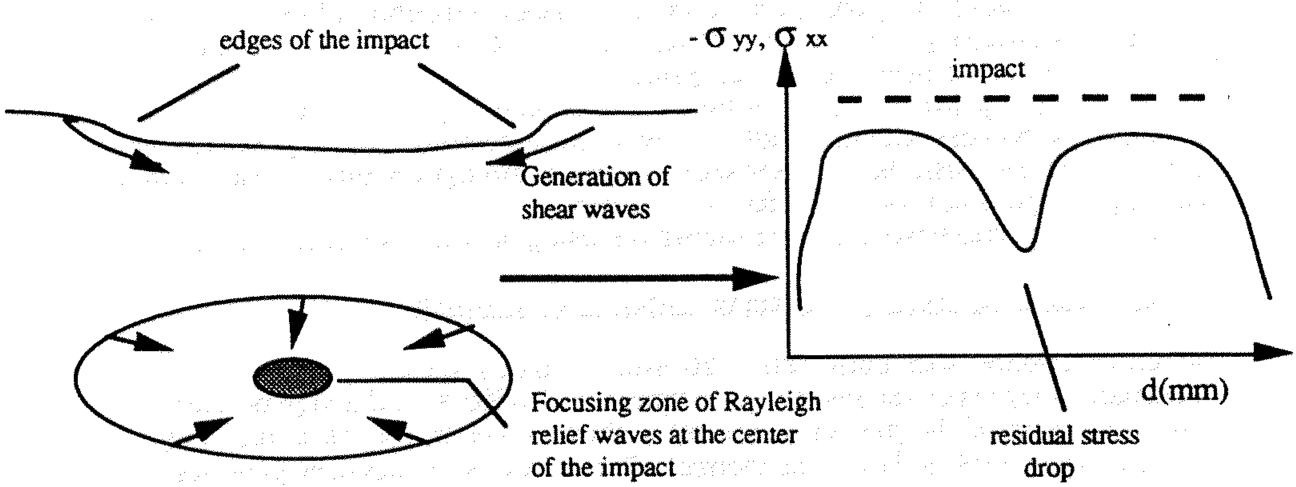

fig 2 : Heterogeneities at the center of circular laser-shocks

2.shock-conditions

The laser-shock treatments were performed using the LALP (Laboratoire d'application des lasers de puissance - ETCA Arcueil -France) neodymium-glass laser operating at 1,06µm wavelength. The samples were submitted to a laser plane irradiation with energies ranging between 60 and 80 J for a gaussian shape, pulse durations of 20-30 nsec and focals diameters of 8-10 mm.
Under these conditions , the incident fluences were about 0,5 to 6 GW/cm2 and the pressures reached at the surface were 0,8 to 3GPa in a water confined mode.
Before laser irradiation, the samples were covered with a 100 µm Al foil in order to form the plasma and to avoid thermal effects in the target.

3.Materials and mechanical properties

The study was conduced on two cast aluminum alloys with different Silicon rates.
Their chemical composition is given in table 1.The AS7G03 was chilled casted , solution treated 8h/540°C and aged to T6 at 160°C / 6h resulting in a grain size of about 300µm.The AS12UNG was solution treated 6h / 480°C, quenched at 70°C then aged to T6 condition at 220°C / 6h.
Plane samples irradiated were milled to a roughness of 0,7 µm.

	Si	Cu	Ni	Mg	Zn	Ti	Mn
AS7G03	7,03	0,05	---	0,33	0,03	0,15	0,03
AS12UNG	12	1,3	1,3	1,3	0,2	0,1	<0,5

table 1 : chemical composition (wt %) of the 2 cast aluminium alloys

The mechanical characterization of the alloys was conduced with quasi-static ($10^{-3}sec^{-1}$) compressive σ_y^{sc} and tensile tests σ_y^{st} and also dynamic (10^3 sec^{-1}) compressive tests σ_y^{dc} using the split Hopkinson pressure bar system (table 2).The main objective of the compressive dynamic tests was to correlate the yield strengths of both the alloys with the optima conditions of laser-shock treatment.

	σ_y^{st} (MPa)	σ_y^{sc} (MPa)	σ_y^{dc} (MPa)	A %
AS7G03-T6	233	-216	-260	7
AS12UNG-T6	155	-248	-310	0,5

table 2 : mechanical properties (compressive and tensile yield strengths) of the alloys

4.Optimization of the residual stress-field induced

4.1.The incremental hole drilling method [5]

As X-ray diffraction could not be used because of the grain sizes (300μm) of our cast alloys , residual stress distribution on each sample was determined by a modified step by step hole drilling method (special finite elements software CETIM-metro) developped at the CETIM.

The radial surface strains could be measured in 3 directions ε' , ε'', ε''' by a three gauge rosette .The determination of the in depth residual stresses distribution was possible by using coefficients A_{in} and B_{in} corrélating surface strains to the redistribution of stresses during the incremental drillings of the hole.

Strains related to the different layers removed are expressed by :

$$\varepsilon_{in}' = [\ A_{in}(\sigma_{1hi} + \sigma_{2hi}) + B_{in}\ (\sigma_{1hi} - \sigma_{2hi})\cos(2\theta_i)]\ \Delta_{hi} \qquad (1)$$

where : Δ_{hi} = removed layer

A_{in},B_{in} = coefficients (calculated by finite éléments)

σ_{1hi} , σ_{2hi} = increments of stresses redistributed during a drilling step

θ_i = angle between σ_{11} and the reference gauge

Each measurement was performed at the center of impacts as we can see in fig 3.

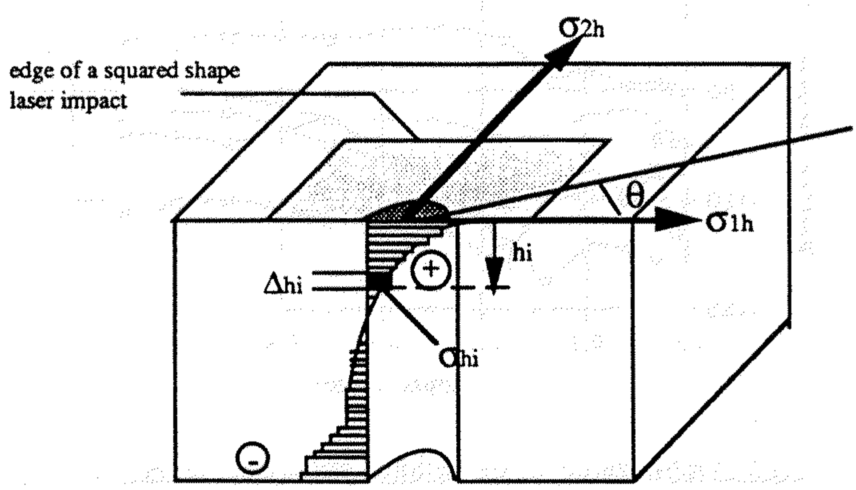

figure 3 : distribution of residual stresses with depth during a hole-drilling on a squared-shape laser shock

4.2.Residual stresses measurements on AS7G03 and AS12UNG

On figures 4 and 5 we show the results of the optimization of the treatment by measuring in-depth profiles at the center of 10 mm squared shape impacts for different fluences and impact pressures.

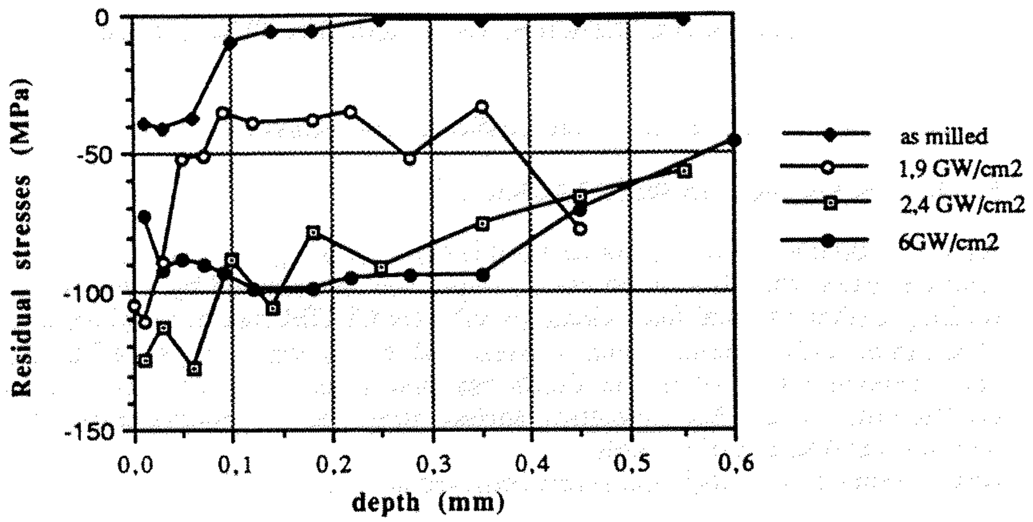

fig 4 : Optimization of the residual stress field on AS12UNG-T6
(with Residual stresses = $(\sigma_x+\sigma_y)/2$)

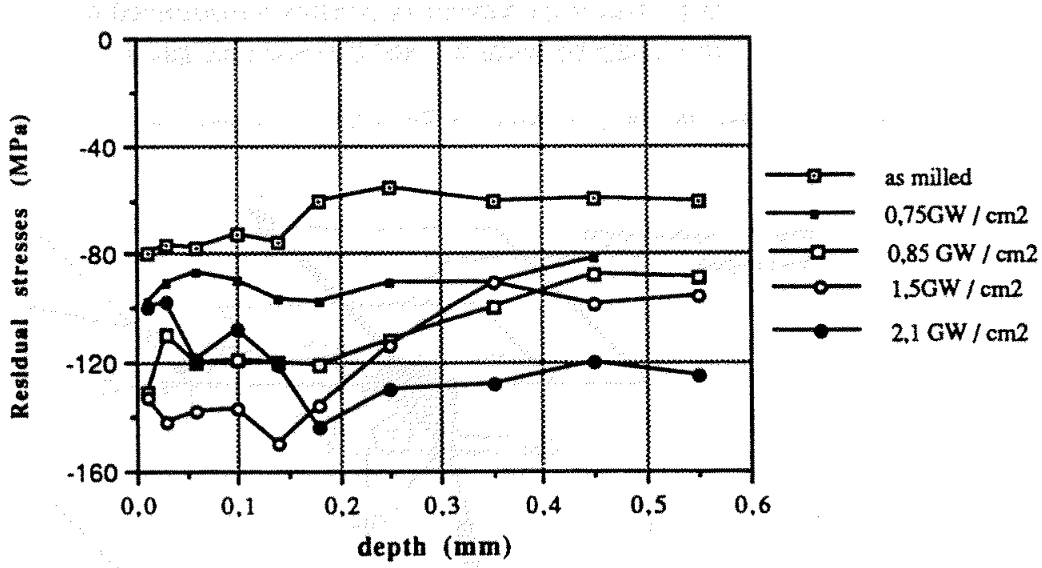

fig 5 : Optimization of the residual stress field on AS7G03-T6
(with Residual stresses = $(\sigma_x+\sigma_y)/2$)

The optimized conditions are 2,4 GW/cm^2 for AS12UNG-Y33 and 1,5 GW/cm^2 for AS7G03-Y33 because they generate the maximum surface stress. These fluences are equivalent to impact pressures of P_{opt} (AS12UNG)=17 Kbars and P_{opt} (AS7G03) =13 Kbars in a water confined mode.They give superficial stresses of -135 MPa for AS7G03 and -125 MPa for AS12UNG.

Below the optima conditions , shock waves do not induce plastic strain enough to generate a high level of residual stresses.
Above the optimized fluences (for instance 6GW/cm2 for AS12UNG and 2,1 GW/cm2 for AS7G03), radial relief waves become efficient by creating a reverse strain and a surface stress decrease.

A correlation with the dynamic ans static compressive yield strengths of both the alloys shows a linear dependance of the optimized pressures :

$$P_{opt} = 5 \times \sigma_y^{dc} = 6 \times \sigma_y^{sc} \tag{2}$$

4.3.Comparison with the analytical model [2]

4.3.1. Optima shock-conditions

An analytical model was proposed by Ballard and al [2] to evaluate the mechanical response of a metallic target to a laser-impact.
According to this model , the compressive yield strength under a purely uniaxial strain (a shock wave for instance) which is called the Hugoniot limit P_h has the following expression :

$$P_h = (1 + \lambda/2\mu)\sigma_y \tag{3}$$

where λ , μ are the Lame's élastic constants of the target
and σ_y is the static yield strength

Then the condition for inducing the highest as possible surface residual stress , which is also the bounding condition of the plastic strain induced by a laser-shock.must be :

$$P = 2{,}25.P_h = 4\ .\sigma_y \qquad \text{for a squared shape impact}$$

So the calculated optima pressures are :
Popt = 0,9 GPa = 9Kbars for AS7G03
Popt = 1 GPa = 10 Kbars for AS12UNG

Consequently , the model slightly underestimates the impacts conditions but the differences may be ascribed to pressures heterogeneities in the plasma.

4.3.2.Surface Residual stresses

The model also allows us to calculate the surface residual stresses induced by the treatment.by considering a parallelepipedic inclusion in a elastic semi-infinite body.

$$\sigma_{surf} = \mu\ .\ \varepsilon_p^0\ .\ (\frac{1+\nu}{1-\nu}).\left[1\frac{4\sqrt{2}}{\pi}.(1+\nu).\frac{L_{plast}}{a}\right] \tag{4}$$

where : L_{plast} = plastically affected depth (experimentally determined to 1,5mm for AS7G03-13Kbars and to 2 mm for AS12UNG-17Kbars)
a = edge of the impact
and ε_p^0 = bounded plastic strain rate = $(- 2\ Ph / (3\lambda+2\mu))$

The calculated residual stresses are -140 Mpa for AS7G03 impacted with 13 KBars and -130 MPa for AS12UNG impacted with 17 Kbars. The comparison with experimental results (-135 MPa for AS7 and -125 MPa for AS12UNG) gives a very good agreement.

5.Juxtaposition effects

The effects of juxtaposing (fig 6) 2 impacts (n° 2 and 3) close to a pre-existing one (n°1) were investigated on AS12UNG.
The three impacts had the same shock-conditions and the residual stresses were determined at the center of the impact n°1 before and after juxtaposition.

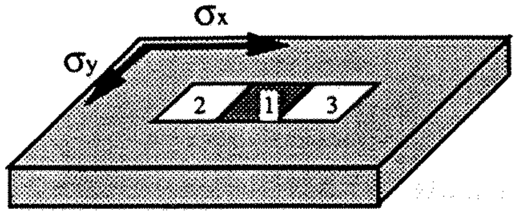

fig 6 : juxtaposition of squared-shape laser- impacts

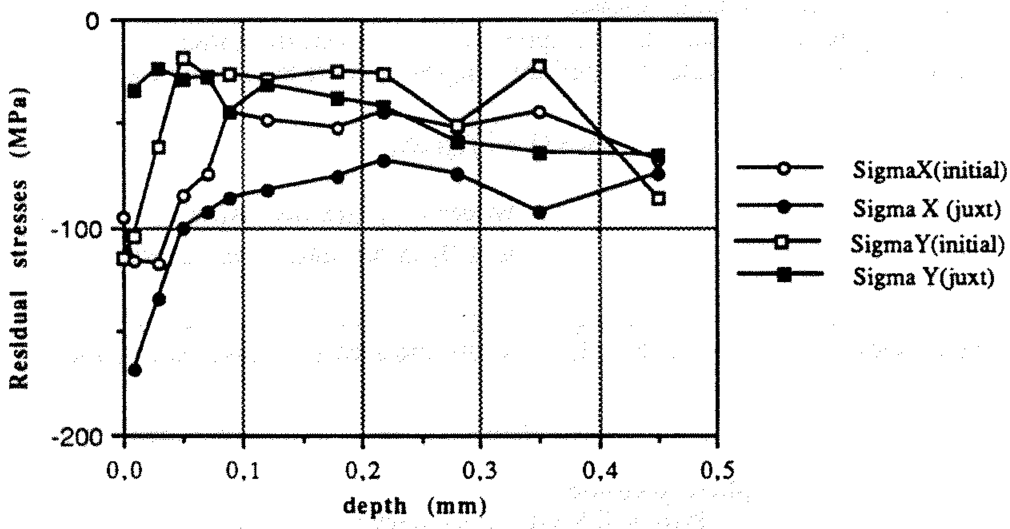

fig 7 : Juxtaposition of impacts- effects on the residual stress field (AS12UNG-1.9 GW/cm2=16 Kbars)

The results pointed out in fig 7 confirm the predictions of the analytical model .
Indeed, the juxtaposition of impacts increases the compressive stresses of the first impact in the sense of juxtaposition (-110 MPa -->-170 MPa) and diminishes them in the transverse direction (-120 --> -40 MPa).
Similarly , rectangular or ovoïds mono-impacts should induce more compressive stresses in the longitudinal sense than in the transverse one.

6.Repetition effects

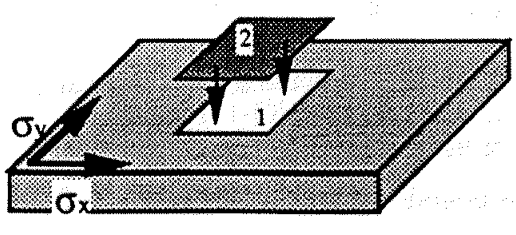

fig 8 : Repetition of squared shape laser-impacts

We're dealing here with the effects of repeating impacts , in terms of the residual stress field induced.We show on fig 9 that , beyond the condition of strain bounding , repeating impacts has no to little effect on the surface stress but increases the in-depths compressive stresses. This confirms previous studies showing that the plastically affected depth increased almost linearly with the number of impacts [2,3] .

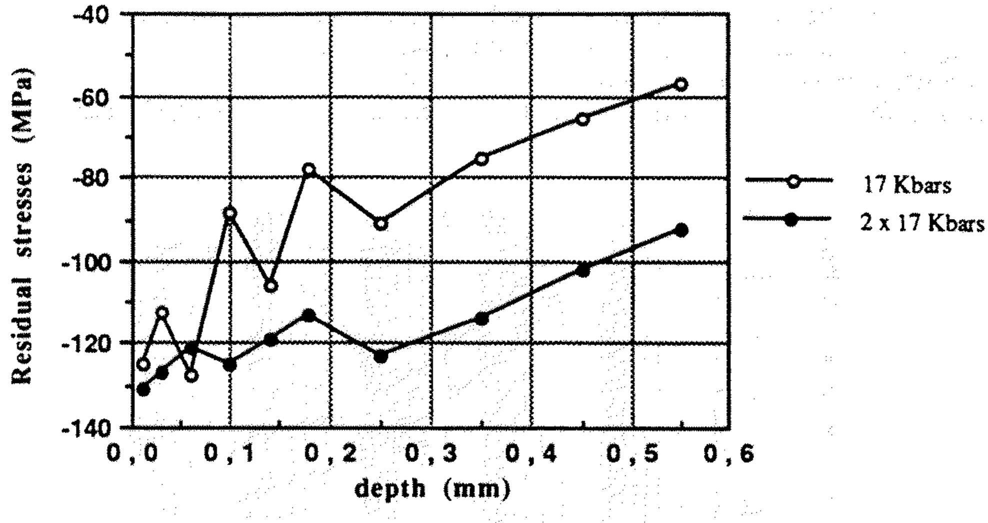

fig 9 : In depths residual stress-fields after 1 or 2 impacts 2.4 GW/cm2 (=17 Kbars) on AS12UNG-T6 (with Residual stresses = (σ_x+σ_y) /2)

7.Application to Fatigue behaviour improvement

In order to demonstrate the efficiency of the treatment to improve the fatigue behaviours of our cast alloys , comparative tests were conduced on notched samples (Kt=1,63) laser shocked or not.
Laser-shock treatment was conduced by using overlapping of squared shape impacts on the notches.
All the samples were tested in bending fatigue with a stress ratio R=0,1 and a frequency of 50 Hz using a servo-controlled hydraulic machine with a maximum capacity of 16 kN.
A total of 12 shocked and 12 unshocked specimens were tested for each lot . The fatigue strength at 10^7 cycles was recognized as the endurance limit and statistical approach of Bastenaire developed at IRSID (ESOPE software) was used to plot the curves.

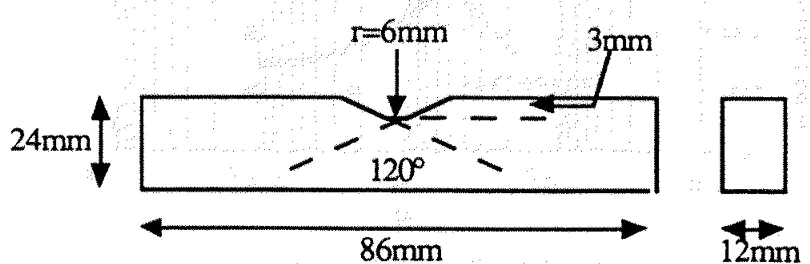

figure 10 : Three points bending-fatigue samples

As we can see in fig 11 and 12 , the results exhibit clearly the significant improvements obtained for the shocked specimens compared with the basic-materials.
The fatigue strength of AS12UNG increased from 107 MPa to 128 MPa i.e an improvement of 20 % and the fatigue strength of AS7G03 increased from 109 to 151 MPa resulting in a gain of 38 %.

The reason for these large improvements may be ascribed to the residual stress field induced, its deepness (about 1,5-2 mm) and its stability at R = 0,1 stress ratio.
Current acoustic emission studies show that the benefit derived from shock-waves treatment mainly concerns the crack-propagation stage.
Indeed , our first investigations tend to point out that the crack propagation is slowed dramatically in the laser-shocked area, resulting in a prolonged propagation stage although the crack initiation stage is not extended very much by the treatment.
So, it seems that a laser-shock induced compressive stress field acts more to inhibit crack propagation than to inhibit the opening of surface cracks.
However, a lot of scatter could be observed in the fatigue results. This was attributed mainly to casting defects (gas porosities) of the basic materials where the cracks easily originated.

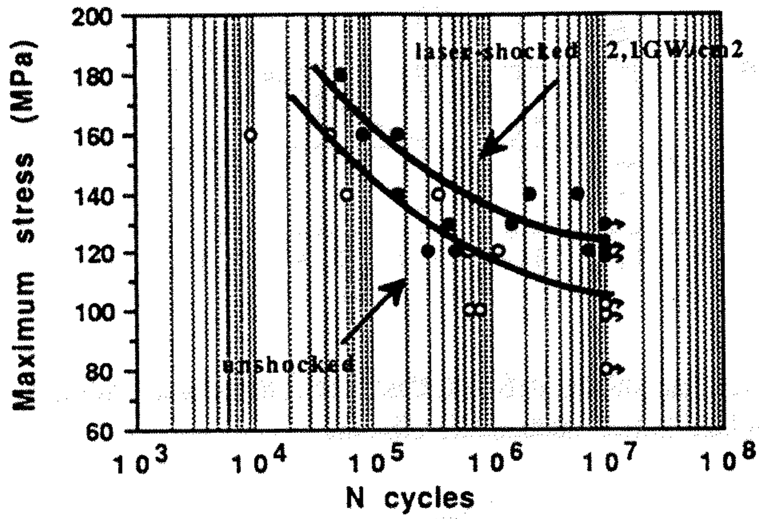

fig 11 : S-N curves for AS12UNG-T6 shocked 2,1 GW/cm^2 and unshocked specimens

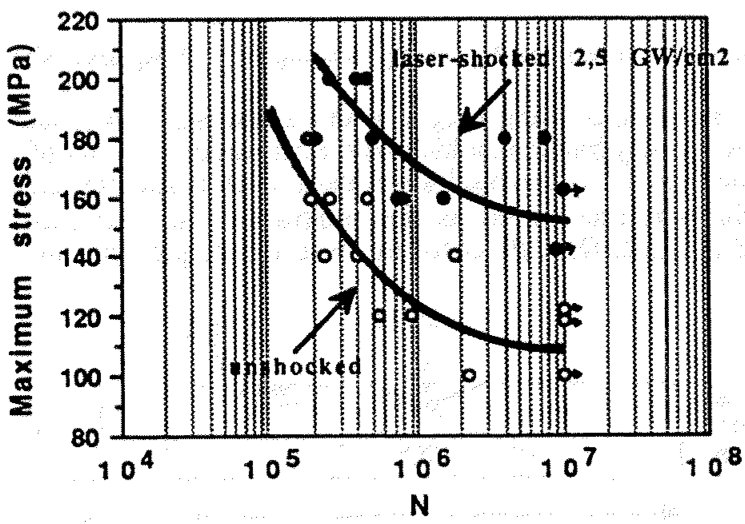

fig 12 : S-N curves for AS7G03-T6 shocked 2,5 GW/cm2 and unshocked specimens

8.Comparison with shot-peening

Laser-shock was firstly developed in order to compete against shot-peening in some particular applications of the mechanical industry. Then , logically, it seemed of interest to compare the effects of the two mechanical treatments.

On the following figure (13) we show the comparative effects of laser-shock and shot-peening on the residual stresses of AS7G03-T6.
It appears that shot-peening induces a higher level of residual stresses (- 200 MPa against -130 MPa) . However, the shot-peening strengthened depth is limited (0,4 mm) compared with laser shock (about 1,5 mm).

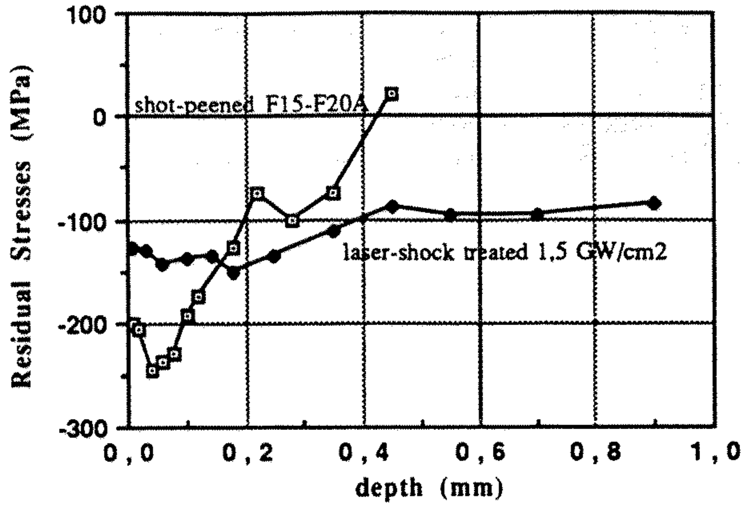

fig 13 : In-depth residual stress fields on AS7G03-T6 after shot-peening F15-F20 A (steels beads) and laser-shock treatment (1,5 GW/cm2)

Fatigue tests on shot-peened notched specimens were conduced. The determination of the fatigue limit was made on 6 specimens using the stair-case method.
Results showed an increase of + 32 % after shot-peening. The loss of gain compared with laser-shock could be attributed mainly to the detrimental surface state induced by the treatment although laser-shock preserves entirely the initial roughness.

9.Conclusion

As in all surface treatments, optimum conditions must be found for the laser-shock treatment of materials.
The main purpose of this article was to show the optimization of the residual stresses induced by laser-shock in a water-confined mode on two cast aluminium alloys : AS7GO3-T6 and AS12UNG-T6.
Results pointed out that the optimum condition of treatment could be correlated with the static or dynamic compressive yield strengths of the metals with factors of 6 or 5.
Maximum Residual stresses induced were about 0,6 σ_y^{SC} (where σ_y^{SC} is the static compressive yield strength) for plastically affected depths of 1,5 to 2 mm.
Bending fatigue tests at R=0,1 on notched specimens showed that the fatigue limit of both the alloys could be increased strongly with laser-shock (+19% and + 38%).
These improvements are mainly attributed to an increase in the cracks propagation stage.
In this article, we demonstrated the feasibility of laser-shock to strengthen cast Aluminum alloys. However , at the present time , the industrialization of the process for high-cost structures depends on the ongoing development [6] of high frequences (1 Hz) pulses lasers.

Acknowlegments

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