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RESIDUAL STRESSES INDUCED BY LASER-SHOCKS

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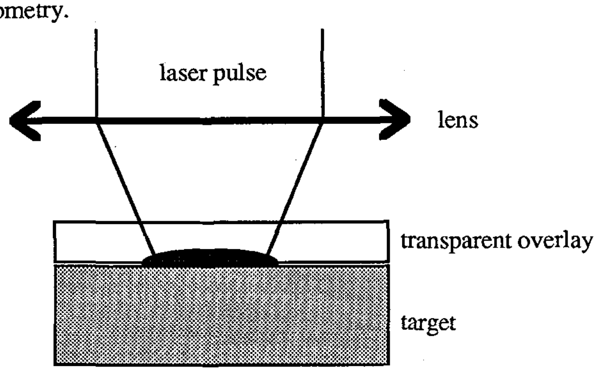
Abstract - *When irradiating a metallic target with a short and intense laser pulse, a high pressure plasma is produced on the surface. An elastic-plastic wave is, then, propagating in the target, creating plastic strains. As a result, a residual stress field is induced. In this paper, by mean of a very simple model, we evaluate the laser produced plasma pressure. The analysis of the resulting wave propagation allows us to compute the plastic strain field. Using these results, we express analytically the induced srface residual stress and the plastically affected depth. We show how this work allows the optimization of the use of laser-shocks as a fatigue surface treatment and an example of application is presented.*

Introduction

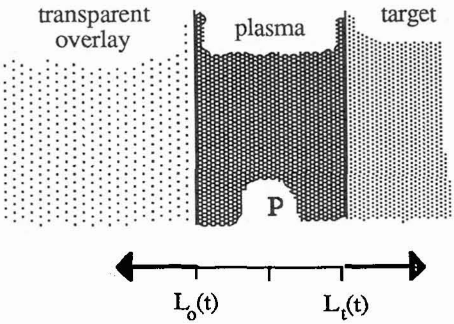
The ability of compressive residual stresses to improve fatigue behaviour of strctures is now well-established and well-understood. These residual stresses can be produced by pure mechanical ways. One example is the shot-peening treatment which is currently used in industry. The object of this work (supported by PSA Etudes & Recherches) is to study in which way laser-shocks could be used to induce compressive residual stresses in order to improve the fatigue behaviour of structures.

1. - Description of laser produced impacts

When irradiating a metallic target with a laser pulse, one can reach a fluence of about 10 GW/cm^2. A high pressure plasma is then formed at the surface of the target. Some previous studies (see for example [1]) have shown that the pressure is higher when a tranparent overlay is put at the surface of the target in such a way that the plasma is formed at the interface of the target and the transparent overlay. This configuration is called confined geometry.



We are going to show that it is possible to evaluate the resulting pressure by mean of a very simple model. We suppose that the laser irradiation on the surface is equivalent to a constant intensity Φ applied while a duration τ. During irradiation, the instantaneous energy on target surface is then Φt. We assume that a part $1-\alpha$ of this energy is devoted to ionize the plasma. The rest $\alpha\Phi t$ is stocked in the plasma, assumed to be a perfect gas, as thermal and mechanical energy.



$$\alpha\Phi t = \frac{3}{2}n(t)kT(t) + P(t)[L_t(t)+L_o(t)]$$

$$\alpha\Phi t = \frac{5}{2}P(t)[L_t(t)+L_o(t)]$$

The transparent overlay is supposed to be an elastic solid and the target an elastic-plastic solid. Under these hypothesis, one can show that the resulting pressure is :

$$P(t) = \frac{(c_e-c_p)\rho_o c_o}{2c_e(\rho_o c_o+\rho c_p)}\left(1+\frac{\lambda}{2\mu}\right)\sigma_Y + \sqrt{\left[\frac{(c_e-c_p)\rho_o c_o}{2c_e(\rho_o c_o+\rho c_p)}\left(1+\frac{\lambda}{2\mu}\right)\sigma_Y\right]^2 + \frac{2}{5}\cdot\frac{\rho\rho_o c_o c_p}{\rho_o c_o+\rho c_p}\alpha\Phi}$$

where : ρ_o is the specific mass of the transparent overlay,
c_o, the speed of elastic longitudinal waves in the transparent overlay
ρ, the specific mass of the target
λ and μ, the elastic Lamé's constants of the target
σ_Y, the uniaxial elastic limit of the target
c_e and c_p, the speeds of elastic and plastic longitudinal waves in the target.

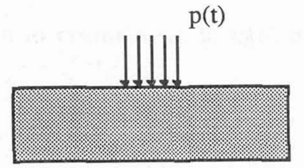
We have the relations (see [2]) :

$$c_e = \sqrt{\frac{\lambda+2\mu}{\rho}} \qquad c_p = \sqrt{\frac{\lambda+{}^{2\mu}/_{3}}{\rho}}$$

This result has been compared with piezo-electric quartz pressure measurements. It appears that the value of the parameter α seems to be independant of the intensity and the duration of the laser pulse (at least in the range of 1 to 100 GW/cm^2 and 3 to 30 ns). In all cases, α is about 0.25.

2. - Description of the response of the target to the impact

We are dealing, here, with the dynamic response of a metallic target submitted to a laser impact. It is possible to show (see [2]) that laser induced pressures are such as the Small Strain Hypothesis is satisfied. As far as laser pulse duration is greater than 1 ns, one can also prove that viscous effects in materials such as steels or aluminium alloys are negligeable. Then, we make the following assumptions :



- the applied pressure is uniform on the impacted surface

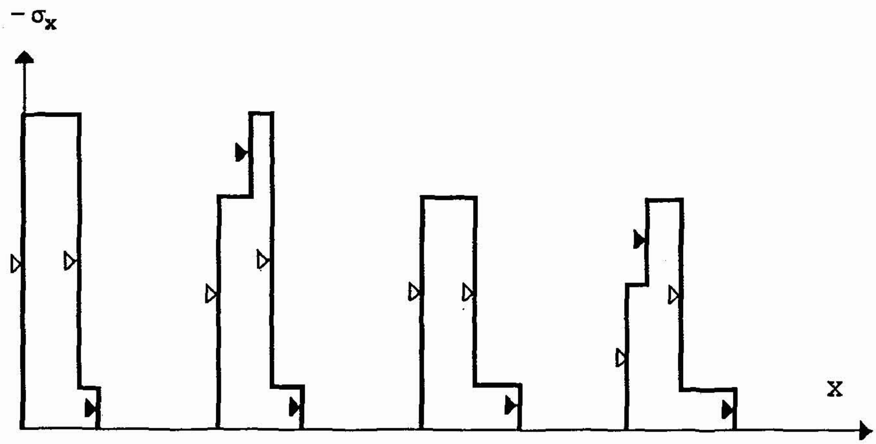
- the target is made with a perfect elastic-plastic material

In a first step, we assume the impact to be geometrically circular. Its radius is r_0. If the duration of the impact is sufficiently small, satisfying the relationships :

$$\tau \ll r_0 \sqrt{\frac{\rho.(\lambda + 2\mu)}{4\mu(\lambda+\mu)}}$$

then, one can admit that the total strain in the induced wave remains uniaxial. Such an impact will be called a fast impact. This analysis is acceptable only for a wave propagation distance small in front of the impact diameter. In this case, induced waves are longitudinal and plane.

In case of a temporally rectangular impact (constant pressure P applied while a duration τ), the propagation analysis can be analytically made using the characteristic method. In a first approximation, the propagation phenomenology can be synthesized in the following scheme :



▶ elastic wave propagating at c_e

▷ plastic wave propagating at c_p

This analysis allows to evaluate analytically the plastically affected depth :

$$e_p = \frac{c_p c_e \tau}{c_e - c_p}.E\left(\frac{P + \sigma_Y.\left(1+\lambda/2\mu\right)}{2\sigma_Y.\left(1+\lambda/2\mu\right)}\right)$$

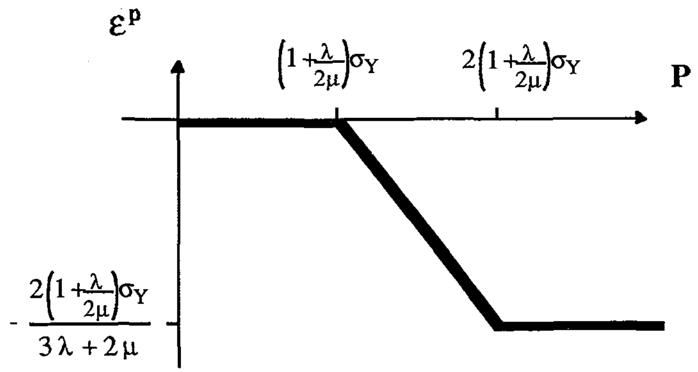
where E() is the integer part function.
This formula can be applied only if e_p remains small in front of the diameter of the impact.

3. - Evaluation of the induced plastic strain

We choose a cylindrical coordinate system (r, θ, x) where x is the depth in the target. Since the total strain in a fast impact induced wave is assumed to be uniaxial, then the plastic strain field has the following form :

$$\underline{\varepsilon}^p = \begin{pmatrix} -\frac{\varepsilon^p}{2} & 0 & 0 \\ 0 & -\frac{\varepsilon^p}{2} & 0 \\ 0 & 0 & \varepsilon^p \end{pmatrix}$$

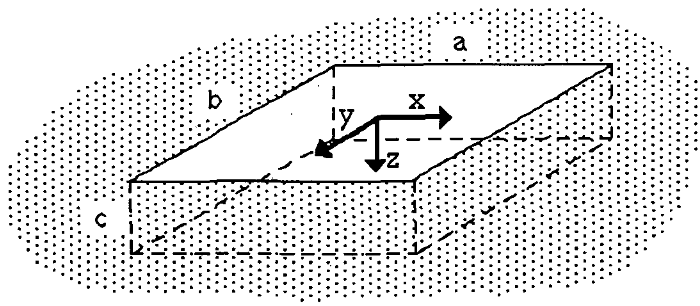
Below the impact, ε^p depends only on the depth x. The absolute value of ε^p is a decreasing function of x. At the surface of the target, ε^p depends only on the amplitude P of the applied pressure. We find :



The main consequence of this result is that the induced plastic strain field is bounded.

4. - Determination of the surface residual stress induced by laser impact in a semi-infinite body

As far as the plastic strain field is known, the determination of resulting stresses is a structure problem. In many cases, the geometrical configuration is not very far from the case of a semi-infinite body. Moreover, the case of a semi-infinite body can undergo an analytical treatment. Let us consider a parallelepipedic inclusion at the surface of an elastic semi-infinite body :



We assume that there is an homogeneous plastic strain field in the inclusion. This plastic strain has the form :

$$\underline{\varepsilon}^p = \begin{pmatrix} -\frac{\varepsilon^p}{2} & 0 & 0 \\ 0 & -\frac{\varepsilon^p}{2} & 0 \\ 0 & 0 & \varepsilon^p \end{pmatrix}$$

Then, it is possible to compute the resulting residual stress field (see [2] for complete solution). In case of a square cross section inclusion (whose thickness is e_p and side is a), one can show that the stress in the inclusion is not very different from :

$$\underline{\sigma} = \begin{pmatrix} \sigma_{surf} & 0 & 0 \\ 0 & \sigma_{surf} & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \text{with} \qquad \sigma_{surf} = \mu\varepsilon^p\left(\frac{1+\nu}{1-\nu}\right)\left[1 - \frac{4\sqrt{2}}{\pi}(1+\nu)\frac{e_p}{a}\right]$$

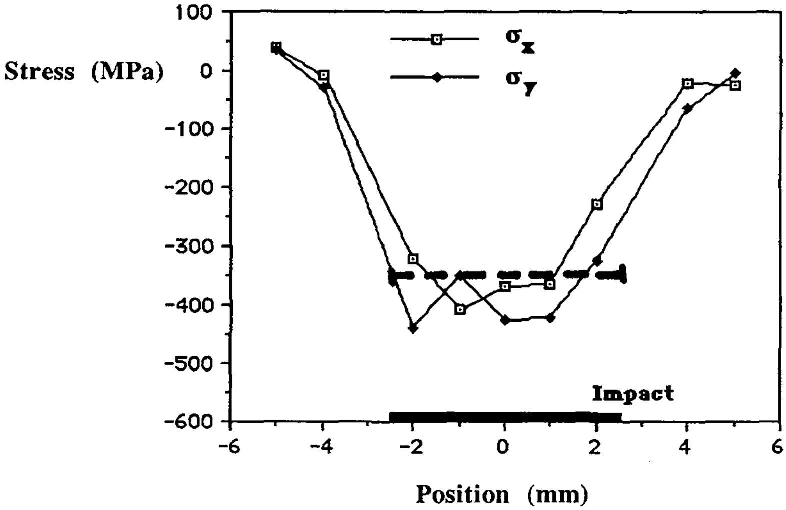
where ν is the Poisson's ratio of the material.

As far as ε^p et e_p have analytically be determined in the previous sections, this formula gives an analytical evaluation of the residual stress induced by laser impact at the surface of a semi-infinite body.

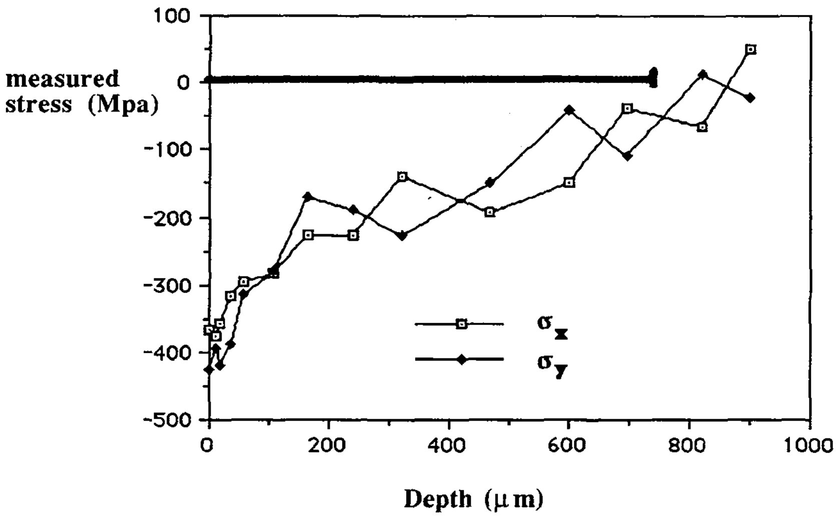
5. - Experimental results and practical applications

In order to validate these results, we have laser impacted some steel samples and measured the induced residual stresses by mean of X-ray diffraction.

A 35CD4 50 HRC steel (σ_Y=1250 MPa) was irradiated with a 30 ns laser pulse. The plasma was confined with water and the laser fluence was 8 GW/cm^2 (on a 5 mm side square). Then, we have measured the surface residual stress distribution by mean of X-ray diffraction. The plastically affected depth has been also evaluated using successive electrolytical polishing and X-ray diffraction. Theoritical predictions (using the previously discussed model) have been superposed (using the discontinuous thick line) to the experimental results.



Residual stress distribution on a line at the surface



Plastically affected depth

The agreement between our model and experiments appears as being very good.

We are going to show now that the modelling results allow to optimize the use of laser-shocks as a surface treatment on a given material. We suppose that the aim is to get the highest possible surface residual stress. Then, the impact pressure must be :

$$P = 2\left(1+\frac{\lambda}{2\mu}\right)\sigma_Y$$

To get that impact pressure, the laser fluence must be :

$$\Phi = 20.\left(1+\lambda/2\mu\right)^2\sigma_Y^2\left[\frac{c_e+c_p}{\rho c_e c_p}+\frac{2}{\rho_t c_t}\right]$$

Then, the plastically affected depth is :

$$e_p = \frac{c_e c_p \tau}{c_e - c_p}$$

and the surface residual stress is :

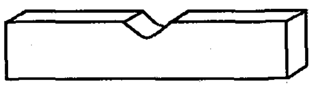
$$\sigma_{surf} = -\sigma_Y\left[1-\frac{4\sqrt{2}}{\pi}(1+\nu)\frac{c_e c_p \tau}{(c_e - c_p)a}\right]$$

6. - Application to fatigue behaviour improvement

In order to demonstrate the ability of laser-shocks to improve the fatigue behaviour of structure, we made a comparative fatigue test on knotched samples. The test was designed in the following way :

Material : 35CD4 50 HRC steel

Geometry : knotched samples ($K_t = 1.56$)



Treatment : the samples were subdivised into three parts. One part was kept as a reference. The second part was shot-peened and the third part was treated by mean of laser-shocks (duration : 30 ns, laser fluence : 10 GW/cm^2, transparent overlay : water).

Applied loading : ondulated bending was applied on the samples and we measured the fatigue strength in the three cases of treatment.

Results : For each lot (reference, shot-peening and laser shock) of samples, we have reported the surface residual stress (measured by mean of X-ray diffraction) and the fatigue strength (expressed in maximum nominal stress).

	σ_{res}	σ_D
Reference		680 MPa
Shot-peening treatment	- 650 MPa	720 MPa
Laser-shocks treatment	- 550 MPa	900 MPa

We can notice that in this case, although the laser induced residual stress is smaller than shot-peening one, the fatigue limit is far greater. The reason is probably that laser-shocks preserve the surface state wheras shot-peening does not.

Conclusion

We have shown the technical interest of using laser-shocks as a surface treatment to improve the fatigue behaviour of structures. We have built an analytical model able on one hand to draw a physical interpretation of the involved phenomena and on the other hand to predict laser parameters to optimize the treatment on a given material.

References

[1] R. Fabbro, J. Fournier, P. Ballard, D. Devaux, J. Virmont, 'Physical Study of Laser procded Plasma in Confined Geometry', J. Appl. Phys., Vol. 68, No 2, July 1990.

[2] P. Ballard, 'Contraintes Résiduelles induites par Impact Rapide - Application au choc-laser', Thèse de doctorat de l'Ecole Polytechnique, 22 Avril 1991.