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LASER SHOCK PEENING: Laser explosion and shear wave propagation

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Abstract: *The movement of dislocations can be characterized by the viscosity depending on the rate of deformation. In this way, the material strengthening is explained by overcoming atomic bonds, which coressponds to the hardening work. The movement of dislocations can be modeled by shear waves, which are strongly dispersive. In areas of high viscosity (before the shock wave) they precede the pressure shock wave. The concept of shear waves allows to describe with some accuracy the strengthening of the material due to extremely fast compression. The presented analysis shows, that to achieve a higher residual stress at the same laser energy, it is more advantageous to use a pulse of shorter length. For greater depth of reinforcement, it is necessary to use a longer pulse. Currently, an experiment is always needed to model Laser Shock Peening (LSP). The experimental residual stress data used were provided by the HiLASE Center of the Institute of Physics of the CAS. After the calibration, the LSP process can also be used to determine the properties of the material under extremely fast loads.*

Keywords: Metal Reinforcement, Laser Shock Peening, Shear Waves, Dislocation.

1. Introduction

Surface improvement of materials has become an integral part of industrial processes; it serves to improve mechanical and metallurgical properties such as fatigue life, corrosion resistance as well as wear and erosion resistance. One of the advanced coating techniques is laser shock peening (LSP), see (Peyre, 1996), see Fig.1. The mathematical modeling of this process presents a number of problems related to both the course of the pressure pulse and the properties of materials exposed to such high strain rates. The laser explosion itself is unknown, even if the parameters of the laser pulse are known: the total light energy (5 J), the beam diameter (2.45 mm) and the pulse length (14 ns). As a consequence of the high pressure magnitude (3-7 GPa) and the high expansion rates ($10^6 - 10^9$ s^{-1}), shock waves are generated in both water and steel. Due to the existence of these waves, which propagate at a speed greater than the corresponding speed of sound, the pressure reaches extreme values and causes strong deformation of the material. From the point of view of the subsequent strengthening of the material, the dynamics of the shock wave propagation in the steel is decisive. Modeling the consequences of a shock wave is, in addition to the standard elasticity, dependent on the plasticity model of the steel, see (Wang, 2019). The Bodner-Parton dislocation movement model is presented in the contribution, see (Bodner, 1975).

2. Energy balance for LSP

The supply of energy by the laser pulse $J_q = \dot{Q} = AI(t)$ leads to a change in the internal energy

$$\dot{U} = A\dot{\overline{L(t)u(t)}} = A\dot{\overline{p(t)L(t)}}/(\kappa_{H_2O} - 1)\,,$$

see Fig. 1 and the superheated steam equation of state (6). The required expansion power is $W_{exp} = Ap(t)\dot{L}(t)$. Energy necessary for evaporation will be included in the $\dot{Q}_{evap}$ member and the energy radiated due to ionization will be taken into account by including the $\dot{Q}_{ext}$ member. The energy balance is

$$\dot{U} = J_q - \dot{W}_{ext} - \dot{Q}_{evap} - \dot{Q}_{ext} \tag{1}$$

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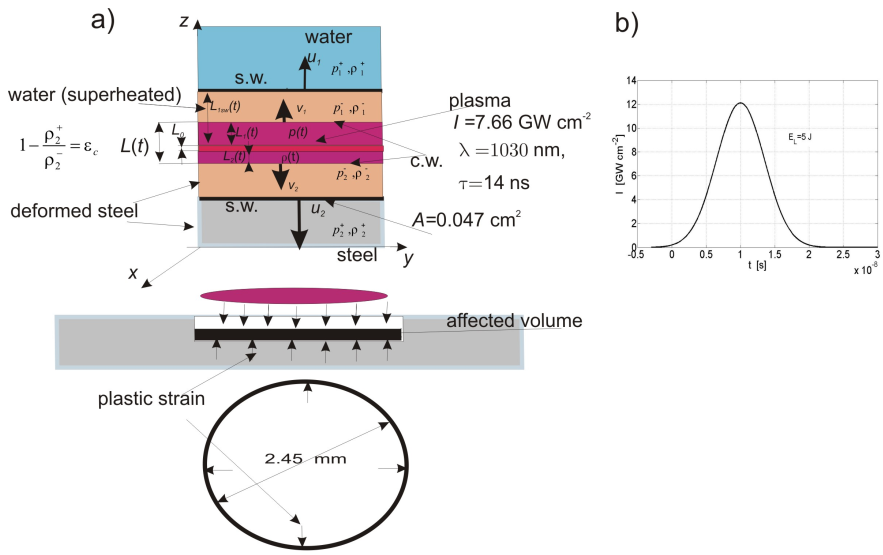

Fig. 1: Conversion of pulse energy into internal energy of water vapor and subsequently pressure energy. a) In a limited space about the initial size L_0, the superheated steam expands in the z direction. The space between contact surfaces (c.w.*) is of size $L(t)$ and it expands with velocities* v_1, v_2*. The shock waves (* s.w.*) propagate at speeds* u_1, u_2*. We assume that the pressure $p(t) = p_1^- = p_2^-$. b) Laser pulse distribution $I(t)$ with the average duration τ.*

The explicit time dependence of the pressure in the expanding region on the laser power and losses caused by water evaporation and radiation is

$$\dot{p} = \overbrace{\frac{\tilde{\alpha}(\kappa_{H_2O}-1)}{L} I(t)}^{\text{laser beam}} - \overbrace{[1+\tilde{\alpha}(\kappa_{H_2O}-1)]\frac{\dot{L}}{L}p}^{\text{expansion work}} - \overbrace{\frac{\tilde{\alpha}(\kappa_{H_2O}-1)\rho_l h_{lv} L_0}{L}\delta_{ev}(t-t_{ev})}^{\text{evaporation}} \tag{2}$$

$$- \underbrace{\frac{\varepsilon_e \sigma_B L^3}{\tilde{\alpha}^3(\kappa_{H_2O-1})^3(c_{vH_2O}\rho_v)^4}\left(\frac{p}{L_0}\right)^4}_{\text{radiation}} \quad \cdots \text{balance of energy}$$

$$\dot{L} = \mathrm{v}_1 + \mathrm{v}_2, \quad L = L_1 + L_2 = \int_0^t (\mathrm{v}_1+\mathrm{v}_2)\mathrm{d}t' \quad \text{expansion area}$$

The evaporation occurs at the very beginning of the pulse at a very short interval $t \in (t_{ev\,m}-\delta, t_{ev\,m}+\delta)$, where δ is around time $t_{ev\,m}$ in which the maximum evaporation occurs. The evaporation can be described by the Dirac delta function, which we approximate using the normal distribution

$$\dot{Q}_{evap}(t) = Q_{0\,ev}\delta_{ev}(t-t_{ev}) \quad \text{kde } \delta_{ev}(t-t_{ev}) = \frac{1}{\sqrt{2\pi}\sigma_{ev}}\exp\left(-\frac{(t-t_{ev\,m})^2}{2\sigma_{ev}^2}\right) \tag{3}$$

$$Q_{0\,ev} = m_{h_2O}h_{lv} = \rho_l h_{lv} A L_0 \quad \text{for evaporation heat } h_{lv} = h_v - h_l = 2255.9\,\mathrm{kJ\,kg^{-1}}$$

The superheated steam (plasma) temperature is

$$T = \frac{pAL}{\tilde{\alpha}(\kappa_{H_2O}-1)m_{H_2O}c_{v\,H_2O}} = \frac{p}{\tilde{\alpha}(\kappa_{H_2O}-1)\rho_l c_{v\,H_2O}}\left(\frac{L}{L_0}\right) \tag{4}$$

$$\tilde{\alpha} = \frac{\kappa_{id}-1}{\kappa_{H_2O}-1}\alpha \quad (=4.09\alpha)$$

The relevant part of the absorbed energy is expressed by the absorption coefficient $\alpha \in (0.1, 0.5)$. A certain amount of evaporated water $m_{H_2O} = \rho_l A L_0$ is necessary for the LSP function. Although this amount is un know, we consider it to be constant, but its magnitude can affect the course of the generated pressure. The time for which the stated amount of water evaporates is approximately equal to $\sigma_{ev} = 1.5\,\mathrm{ns}$.

$$\tilde{u}^{\mathrm{e}} = const T^4, \quad \text{the radiant flux is } j^{rad} = c\tilde{u}^{\mathrm{e}} = \varepsilon_e\sigma_B T^4 \tag{5}$$

$$\text{where } \sigma_B = 5.670373\cdot 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}} \text{ is the Stefan-Boltzmann constant}$$

$\varepsilon_e \in (0.01; 0.95)$ is emissivity coefficient. A value close to zero corresponds to an explosion with a thick layer of water or some protective layer (confinement). The speed of propagation of the radiant energy (light) is c.

2.1. Constitutive relation for water and steam

The equation of state of the superheated vapour is

$$pv = (\kappa_{H_2O} - 1)u, \quad \text{where} \quad u = c_{vH_2O}T, \ \kappa_{H_2O} = \frac{c_{pH_2O}}{c_{vH_2O}} = 1.163 \tag{6}$$

and the dynamic resistance of water is given by

$$\begin{aligned} \varepsilon_{1c} &= \frac{L_{1sw} - L_1}{L_{1sw}} = 1 - \left[1 + n\left(\frac{p - p_0}{K_0}\right)\right]^{-1/n}, \\ L_1 &= L_{1sw}(1 - \varepsilon_{1c}) \quad \text{for}\, n = 7.15, \ K_0 = 21.64 \cdot 10^8 \text{Pa} \\ \dot{L}_{1\,sw} &= u_{(1)} = \sqrt{\frac{(p - p_0)}{\rho_l \varepsilon_{c1}}} \quad \text{speed of the shock wave in water} \\ \dot{L}_1 &= \mathrm{v}_1 = \frac{p - p_0}{\rho_l u_{(1)}} = \sqrt{\frac{(p - p_0)\varepsilon_{c1}}{\rho_l}} \quad \text{speed of the contact surface} \end{aligned} \tag{7}$$

2.2. Constitutive relation for reinforced material (304L austenitic steel). Shear wave propagation

The dynamic resistance of steel is based on the Bodner-Parton constitutional relationship, see Bodner (1975)

$$\begin{aligned} \varepsilon_{2c} &= \frac{L_{2sw} - L_2}{L_{2sw}}, \\ L_2 &= L_{2sw}(1 - \varepsilon_{2c}), \quad \text{position of the contact surface} \\ \dot{L}_{2\,sw} &= u_{(2)} = \frac{c_{l\,BP}}{(1 - \Gamma\varepsilon_{2c})} \qquad \text{for}\ ,\ \Gamma = 1.51 \quad \text{speed of the shock in steel} \\ \dot{L}_2 &= \mathrm{v}_2 = \frac{c_l \varepsilon_{c2}}{1 - \Gamma\varepsilon_{c2}} \quad \text{is equal to the speed of the contact surface of the steel} \\ \dot{\varepsilon}_{2c} &= 3^{m/2}\tilde{c}_0 \left(\frac{p}{\sigma_{HEL}}\right)^m \quad \text{steel deformation rate, for } m \in (4; 20), \\ & \tilde{c}_0 \in (1; 2 \cdot 10^4)\,\mathrm{s}^{-1}, \ \sigma_{\mathrm{HEL}} = \frac{1 - \sigma}{1 - 2\sigma}\sigma_Y = 612.50\,\mathrm{MPa} \end{aligned} \tag{8}$$

The propagation of the shear wave c_{vis} is determined by the magnitude of the viscosity, which depends on the strain rate (or the pressure profile $p(t)$) and on the material parameters $\tilde{c}_0, m$. The viscosity ν_{00} before the pressure wave (shock) is very hight and the decisive factor for the sher wave attenuation is the ratio $c_M/c_{vis0} \ll 1$, see Fig. 2 a). The velocity of the pressure wave $c_M = u_{(2)}$ depends mainly on the magnitude of the pressure pulse. The general relationship for the shear wave propagation is

$$p_{res}(t) = \exp\left[-\frac{\pi t}{\tau_{cor}}\left(1 - \frac{c_M}{c_{vis0}}\right)\right][p(t) - \sigma_{HEL}]\Big|_{t=z/c_{vis0}} = p_{res}(z) \tag{9}$$

$$c_{vis0} = \sqrt{2\pi\nu_{00}/\tau} = \sqrt{\frac{2\pi\sigma_{HEL}}{\sqrt{3}^{m_0}\rho_0\tilde{c}_{00}\tau}\left(\frac{p(t)}{\sigma_{HEL}}\right)^{1-m_0}} \quad \text{for } \nu_{00} = \frac{\sigma_{HEL}}{\sqrt{3}^{m_0}\rho_0\tilde{c}_{00}}\left(\frac{p(t)}{\sigma_{HEL}}\right)^{1-m_0}$$

3. Comparison of numerical solution with experiment

Numerical solution (MATLAB) of equations (2), (7) and (8) gets the pressure profile $p(t)$ and by substituting into the relation (9) we get the residual stress distribution $p_{res}(z)$. $\tau_{cor} \simeq 2\tau/\pi \leq \tau$ is the fitted effective time of creep, see Fig. 2.

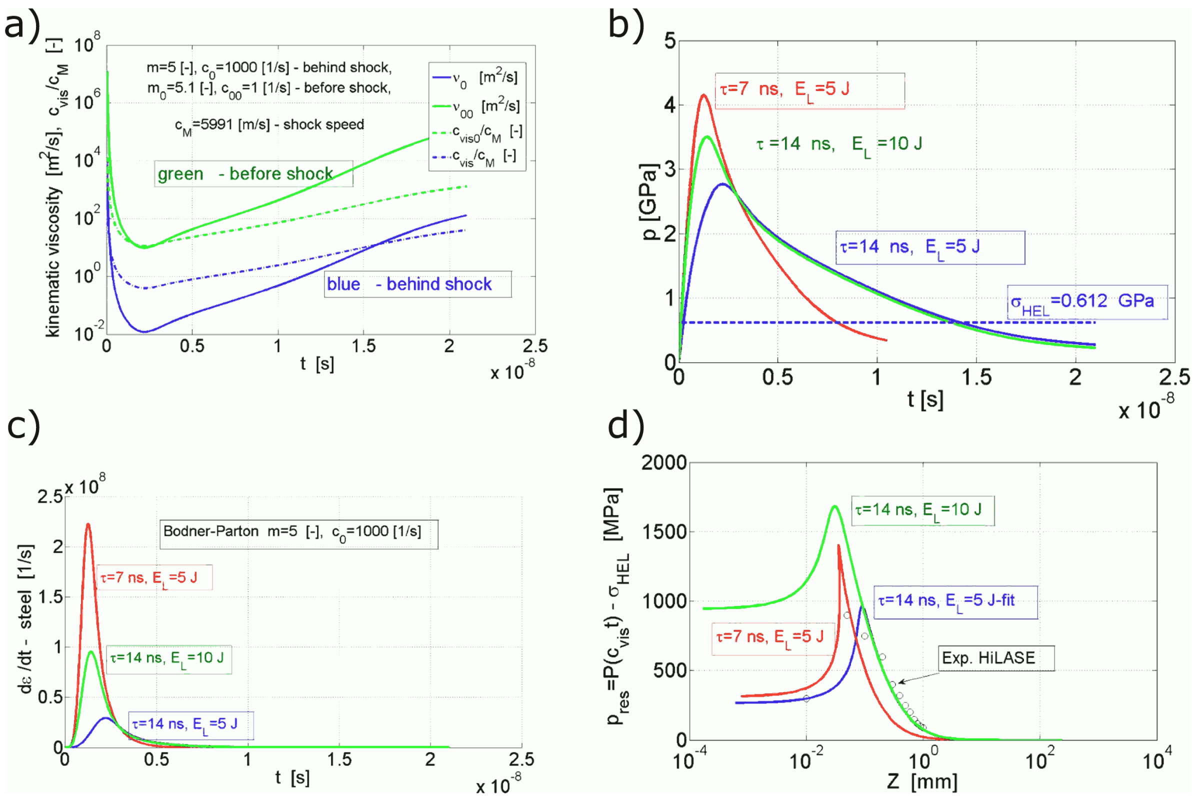

Fig. 2: Sensitivity analysis: a) Change in viscosity and velocity of viscous waves in the material before the shock wave (green curves) and behind the shock wave (blue curves). b) The course of pressure $p(t)$ during the deformation of steel is fitted for $m = 5$, $\tilde{c}_0 = 1000$ [s^{-1}], see (8). c) Deformation rate of steel. d) Residual stress. The velocity of the shear wave propagation before the shock c_{vis0} is fitted by values $m_0 = 5$, $\tilde{c}_{00} = 1.0$ [s^{-1}] see (9).

4. Conclusions

The parameters of the laser explosion dynamics are unknown because the underlying processes are so fast they could not be, until recently, studied experimentally. Based on our physical analysis and numerical simulations we can conclude the following:

i) it is always necessary to fit the LSP model with the experimental data;

ii) to achieve higher residual stresses for the same energy of the laser pulse it is more favourable to use a shorter pulse length;

iii) to achieve a greater depth of reinforcement it is necessary to use a longer pulse;

iv) the LSP process can be used to determine material properties at extremely fast loads.

Acknowledgments

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