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Two-step simulation approach for laser shock peening

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Laser shock peening (LSP) is a surface modification technique to introduce compressive residual stresses (RS) with a high magnitude in the near surface region of the material. Due to non-linear interactions (e.g. laser absorption by plasma, shock wave propagation, etc.) and a high number of parameters, it is difficult to study and optimize the process based on experiments alone. Therefore, a two-step simulation approach is proposed in this paper, where two models are combined, because one model of the complete process is difficult to derive, due to the different characteristics of the plasma formation and the shock wave propagation in the material. On one hand, a global model including plasma and shock wave descriptions is applied for the LSP of an aluminium sample with water confinement. The numerical solution of this model, applied for a 3×3 mm^2 focus size, 5 J and 20 ns (full width at half maximum (FWHM)) laser pulse, allows to determine the temporal plasma pressure evolution on the material surface. On the other hand, a finite element simulation is used to calculate the RS distribution within the target material, where the plasma pressure is applied as a surface loading for the aluminium alloy AA2198-T3. The simulated residual stresses are fitted to measurements via parameter variation of the global model. The identified values and the two-step simulation approach can be used in future work to predict stress states of materials after LSP for various process parameters variations.

1 Introduction

LSP can be used to improve the fatigue performance of metallic structures by fatigue crack retardation via inducing compressive residual stresses. In laser peening short-time high energy laser pulses are used to vaporize a surface layer of the target. The vaporised material is turned into a high temperature and high pressure plasma (Fig. 1**a**). An increase of the obtained pressure can be reached by the usage of a laser-transparent overlay (e.g. water or glass). The rapid expansion of plasma induces a mechanical shock wave within the material, which causes local plastic deformations and grain reorientations. After the elastic relaxation of the deformed system, RS remain as a result of the plastic deformation gradients within the material. The process is highly non-linear and difficult to optimize based on experiments alone due to a high number of process parameters and non-linear interactions (e.g. shock wave propagation, plasma formation). Therefore, a two-step simulation approach is proposed in this paper, where two models are combined. The global model describes the plasma formation and shock waves propagation in water and metal. Based on the time-dependent laser intensity profile, a temporal plasma pressure evolution is determined. The finite element simulation is used to calculate the in-depth RS distribution using the plasma pressure as a surface loading.

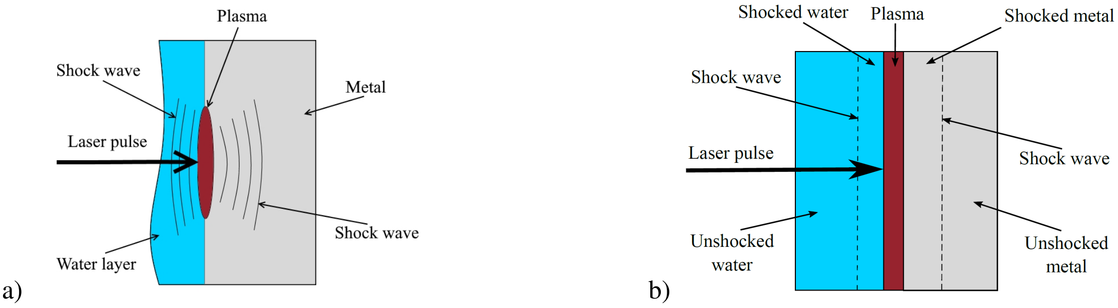

Fig. 1: a) Schematic of laser shock peening process with a water layer. **b)** Schematic of the global model of the water-confined LSP, where every region is assumed to be uniform.

2 Global model

Due to the almost uniform spatial intensity distribution of the used laser system, the global model of Zhang et al. [1] with the assumption of one-dimensional motion in the direction of laser beam propagation is applied, see Fig. 1**b**. Within this model all physical quantities for each region are assumed to be only time-dependent and uniform. Rankine-Hugoniot relations for the mass, momentum and energy conservation across the shock waves in water and metal are combined with the mass and momentum conservations at the interfaces (water-plasma and plasma-metal). The mass exchange between water layer, plasma

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and metal is also taken into account and results in energy exchange. Plasma energy and mass balance equations consider the plasma as an ideal gas with the assumption that it directly absorbs only a constant fraction of the laser energy during the pulse. The advantage of the current model, compared to the widely used model of Fabro et al. [2], is the separation between directly absorbed energy by the plasma and phase change energies to generate the mass flow from water and surface layer into the plasma. After the laser pulse vanishes a plasma relaxation process is taken into account, which results in a rapid pressure decrease.

The model results in a large system of non-linear equations, which are numerically solved in Wolfram Mathematica 11.2 with the Newton-Raphson method. The initial parameters for the time-dependent variables are based on unshocked properties of the water layer, metal and plasma from [1, 3].

3 Finite Element Simulation

A finite element simulation is used to predict the resulting RS after the LSP-treatment as described by Keller et al. [4]. The resulting plasma pressure from the global model is assumed to be constant in space and applied as surface pressure on the material over the area of the laser focus. The shock wave propagation is simulated using an explicit solver (ABAQUS/Explicit) followed by an implicit simulation of the RS prediction (ABAQUS/Standard) after all laser pulses are applied. The simulation approach contains a stress averaging scheme to enable the comparison to experimentally measured RS via the incremental hole drilling technique. The shock wave propagation is assumed as a purely mechanical process, as the short time of plasma formation restricts thermal effects to the surface of the material. In this work, the Johnson–Cook model [5] is used to model the strain rate dependency of the material during the shock wave propagation.

4 Simulation results and comparison with experiments

Simulation results of the global model are highly dependent on two unknown parameters: initial approximation of the plasma density and the fraction of the laser pulse energy adsorbed by the plasma. Therefore, for a constant set of process parameters (laser pulse energy of 5 J, spot size 3×3 mm^2, pulse duration of 20 ns FWHM), the mentioned model parameters were fitted via the two-step simulation approach to experimentally measured RS for AA2198-T3, see Fig. 2. Taking into account the identified plasma pressure, a comparison of the measured plasma density of Wu and Shin [3] with the maximum plasma density in the simulations allowed to determine the direct energy absorption of the laser in the plasma to be about 17%. Knowing the absorption coefficient yields an initial plasma density of 2 kg/m^3.

The pressure reaches its maximum ($\approx$ 1.5 GPa) after the laser intensity maximum and the duration of the pressure pulse is approximately three times larger than the laser pulse duration, see Fig. 2**a**. This can be explained by a mass flow from the water curtain to the plasma region, which is still present although the laser pulse decreases. The fitted simulated RS (Fig. 2**b**) indicate that the described models can be finely adjusted with only two plasma parameters. Based on the quantified energy absorption in the plasma, the global model allows to gain physical insight into the behaviour of the plasma. The identified values should be applicable for different LSP cases in future work and the shown two-step simulation approach can be used to predict RS profiles in order to study the influence of initial parameters changes and to optimize the process.

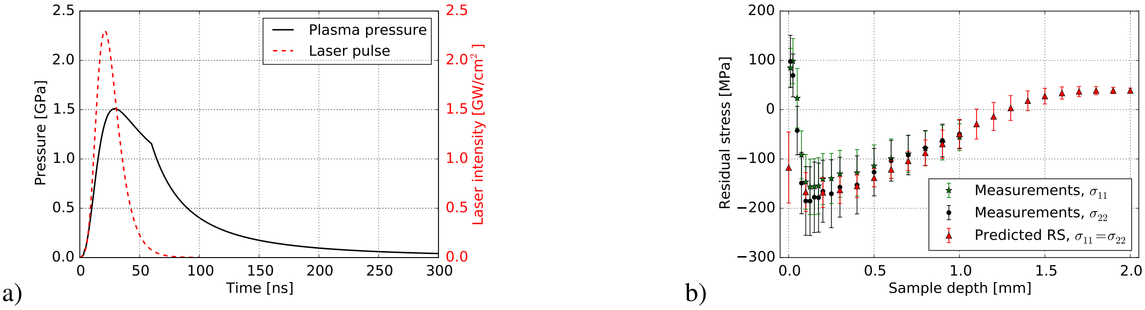

Fig. 2: a) Plasma pressure distribution and temporal profile of the laser pulse with 20 ns FWHM. The plasma relaxation process is assumed after the laser pulse vanishes. **b)** The comparison of measured [4] and simulated RS after LSP of AA2198-T3 with 3×3 mm^2 laser focus size using the calculated pressure pulse.

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