Fatigue crack propagation influenced by laser shock peening introduced residual stress fields for thin aluminum specimens

S. Keller [1], M. Horstmann [1], N. Kashaev [1], B. Klusemann [1,2]
[1] *Helmholtz-Zentrum Geesthacht, Institute of Materials Research, Materials Mechanics, Geesthacht, Germany*
[2]*Leuphana University of Lüneburg, Institute of Product and Process Innovation, Lüneburg, Germany*

Laser Shock Peening (LSP) is a promising surface treatment, which allows the introduction of high compressive residual stresses in metallic components. LSP draws interest from the aerospace industry, where a damage tolerant design permits the crack initiation and propagation within components. High compressive residual stresses, as induced by LSP, are able to retard the fatigue crack growth and, therefore, to increase the fatigue life of the component. However, tensile residual stresses are always generated as well. These tensile residual stresses might accelerate the Fatigue Crack Propagation (FCP), which counteracts the fatigue life enhancement. Thus, the exact knowledge of the induced residual stress field and the fatigue crack retarding or accelerating mechanisms is necessary to apply LSP efficiently. In this work a step-wise simulation [1], predicting the FCP-rate, is utilized to study these fatigue crack retarding or accelerating mechanisms. The step-wise simulation, as shown in Figure 1, includes (i) a LSP-process simulation, (ii) a residual stress transfer between LSP-process model and FCP-model based on the eigenstrain-method, (iii) calculation of the crack driving stress concentration factors and (iv) FCP-prediction using empirical FCP-laws, in particular the NASGRO-equation. Step (i) and (iii) are based on the finite element method in our work. The different steps are shortly described in the following:

(i) LSP uses short-time laser pulses to vaporize material of the radiated surface. The vaporized material turns into plasma and expands rapidly. The heat expansion of the plasma causes a pressure at the surface of the solid material, which induces a mechanical shock wave traveling into the material. This shock wave deforms the material plastically. The gradient of the plastic deformations leads to elastic distortions of the material causing the residual stresses after the relaxation of the system. The LSP-process simulation takes the plasma pressure, acting at the material surface, as input and predicts the material response. The plasma pressure is adjusted for one-sided LSP using 5 J and 20 ns laser pulses with a square 3x3 mm² laser focus for AA2198-T3 and is applied to AA2198-T8 with a 3x3 mm² focus as well as AA2198-T3 and T8 for a 1x1 mm² square laser focus. The predicted residual stresses are experimentally validated [2]. In this work, a LSP-process simulation of a two-sided LSP-treatment is performed in AA2024-T3. The number of simulated laser pulse impacts is reduced based on a periodicity assumption of the plastic deformations. Hence, the aim of the LSP-process simulation is the prediction of the plastic deformations in a representative area.

(ii) Predicted plastic deformations of the LSP-process simulation are transferred to the FCP-simulation using the eigenstrain-method. Therefore, plastic strains of the LSP-process simulation are applied as thermal strains to the crack propagation model of the C(T)-specimen. The plastic deformations, predicted with the LSP-process simulation, were extended to a larger area based on the periodicity-assumption, already assumed in (i). Resulting residual stresses in the C(T)-specimen were validated with residual stress measurements using the incremental hole drilling method with electronic speckle pattern interferometry of peened specimens.

(iii) Crack driving stress concentration factors are calculated using a C(T)-specimen model and assuming an interaction of residual and applied stresses. The calculation is based on the virtual crack closure technique, where the energy release rate after the crack extension by a finite length is linked to the stress concentration factor. The stress concentrations at the minimum and maximum applied load used to calculate the crack driving stress concentration factor range ΔK_{cd} and the crack driving stress concentration factor rate R_{cd}. ΔK_{cd} and R_{cd} are identified as main crack driving quantities, by applying ΔK_{cd} and R_{cd} to an unpeened specimen using specific external loadings. The FCP-rate of the unpeened specimen in this test set-up is in a good agreement with the experimentally measured FCP-rate of a peened specimen.

(iv) The NASGRO-equation is used to predict the FCP-rate. While ΔK_{cd} and R_{cd} are the inputs of the NASGRO-equation, material parameters were identified by experiments of unpeened material.

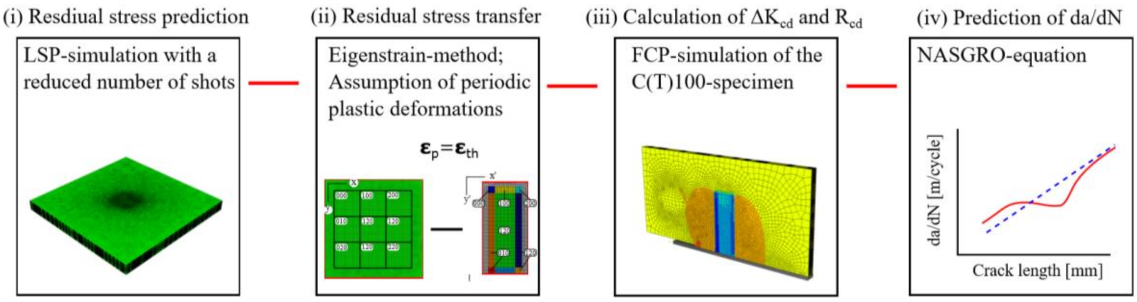

Figure 1. Multi-step simulation approach. The multi-step simulation takes the plasma-pressure as input and predicts the plastic deformations after the LSP-treatment (i). These plastic deformations are transferred to FCP-simulation based on the eigenstrain-method (ii). The FCP-simulation calculates the crack driving stress concentration factors (iii), which are used as input for the NASGRO equation (iv). Figure 1 is depicted and adopted from [1].

The experimentally validated step-wise simulation to predict the FCP-rate based on the LSP-induced surface pressure is used to study the crack retarding and accelerating mechanisms [3]. One of the most important mechanisms is crack closure, which occurs, if the external load is not able to open the crack completely due to compressive residual stresses. It is found, that the location of crack closure depends strongly on the position of the compressive residual stresses and does not have to be linked to the crack tip. This crack closure is interpreted as a change in geometry of the cracked C(T)-specimen, which strongly changes the stress distribution. Crack closure is able to reduce ΔK_{cd} which reduces the FCP-rate. The simulations and experiments showed that the fatigue crack retardation is dramatically reduced if no crack closure occurs. Furthermore, it is shown, that tensile residual stresses in front of the peened area are accelerating the fatigue crack while tensile residual stresses behind the fatigue crack do not lead to an acceleration of the crack propagation. Consequently, LSP should be applied as close as possible to areas were fatigue crack can be initiated, e.g. close to a weld.

Keywords: Laser shock peening, fatigue crack propagation, residual stresses, finite element simulation, stress concentration factor

References:

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