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Laser shock peening (LSP) is a promising technique to systematically introduce local compressive residual stresses in metal sheets, inhibiting fatigue cracks in these areas. We model fatigue crack growth in these specimen with the help of a phase-field model for fatigue fracture [1]. First, we parametrise the model using untreated aluminium specimens. In a second step, we use the determined parameters to simulate residual-stress-afflicted specimens, qualitatively reproducing the crack inhibition due to LSP.

1 Model framework

Residual stresses, despite their poor reputation, can help to increase the resistance against fatigue crack growth (FCG) if one can ensure the formation of predominantly compressive residual stresses, as it is shown in [2]. With the help of laser shock peening, Keller et al. are able to induce compressive residual stresses locally into metal sheets, effectively reducing the FCG rate in this field. This technique is e. g. especially relevant for critical areas of aircraft fuselages. In order to simulate the phenomenon, we use a phase-field model for FCG [1] which reduces the usually long computional time for cyclic loadings by integrating a renowned fatigue concept from durability analysis.

In order to incorporate residual stresses in the model, the inital residual stress-strain state is assumed to be constant over the lifetime of the specimen and is integrated as an offset to the stress-strain state due to cyclic loading [3]. The energy functional of the phase-field fatigue model therefore reads

$$\Pi_\ell = \int_\Omega g(d)\,\psi^{\mathrm{e}}(\boldsymbol{\varepsilon}_{0,\mathrm{el}} + \boldsymbol{\varepsilon}_{\mathrm{c}})\,\mathrm{d}V + \int_\Omega \alpha(D)\,\mathcal{G}_{\mathrm{c}}\frac{1}{2\ell}(d^2 + \ell^2|\nabla d|^2)\,\mathrm{d}V. \tag{1}$$

The crack is indicated by the phase-field variable $d = 1$ (analogously, intact material by $d = 0$) and driven by the fatigue degradation function $\alpha(D) = (1 - \alpha_0)(1 - D)^\xi + \alpha_0$ with $\alpha(D) \in [\alpha_0, 1]$. Due to $\alpha(D)$, the fracture toughness $\mathcal{G}_{\mathrm{c}}$ is lowered gradually depending on the fatigue damage $D \in [0, 1]$, which is determined from the local strain approach [4] and increases with the cyclic loading. The strain energy density is determined from the superposition of the elastic part of the strain associated with the residual stress $\boldsymbol{\varepsilon}_{0,\mathrm{el}}$ and the strain due to cyclic loading $\boldsymbol{\varepsilon}_{\mathrm{c}}$. Correspondingly, the stress is defined as

$$\boldsymbol{\sigma} = g(d)\,(\boldsymbol{\sigma}_0 + \boldsymbol{\sigma}_{\mathrm{c}}) = g(d)\,(\boldsymbol{\sigma}_0 + \mathbb{C} : \boldsymbol{\varepsilon}_{\mathrm{c}}) \tag{2}$$

with the residual stress $\boldsymbol{\sigma}_0$ as an offset to the stress due to cyclic loading $\boldsymbol{\sigma}_{\mathrm{c}}$.

2 Parametrisation and simulation of LSP-treated specimen

The following studies were performed with a compact tension (CT)-like specimen with the characteristic dimension $W = 100$ mm according to ASTM E647-05 and ASTM E1820-01 and a thickness of 2 mm. For the alumium AA2024-T3 material, the elastic material parameters $E = 74.6$ GPa and $\nu = 0.3$ [5], fatigue parameters $K' = 0.453$ GPa, $n' = 0.201$, $\sigma'_{\mathrm{f}} = 0.314$ GPa, $\varepsilon'_{\mathrm{f}} = 0.162$, $b = -0.091$ and $c = -0.452$ [5] for cyclic stress-strain curve and strain Wöhler curve as an input of the local strain approach, respectively, and the fracture toughness $\mathcal{G}_{\mathrm{c}} = 0.165\,\mathrm{MPa\,m}$ [6] were chosen. The characteristic length ℓ is set to 1 mm, which is three times the minimum element size. The specimens were loaded with a cyclic load characterised by the maximum load $\tilde{F}_{\max} = 1.65$ kN and load ratio $R = \tilde{F}_{\max}/\tilde{F}_{\min} = 0.1$. The simulation is carried out assuming plane stress conditions and with the help of a staggered solution scheme for the coupled problem.

The parameters α_0 and ξ of the fatigue degradation function $\alpha(D)$ are the only model parameters that have to be calibrated. The calibration with unpeened and therefore assumedly residual-stress-free CT specimens yielded $\alpha_0 = 0.0015$ and $\xi = 500$. Results are shown in Fig. 1. The calibrated model is then used to simulate the peened specimen. In the rectangular peened area (Fig. 2a), compressive residual stresses dominate. The measured resdiual stresses [3] are averaged over the thickness and applied to the material points as displayed in Fig. 2b for the residual stress component $\sigma_{0,yy}$ exemplarily. The simulation

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(blue) yields qualitatively the same evolution of the fatigue crack growth rate as experimental results (green), see Fig. 2c: Compared to the unpeened specimen (grey), the crack growth rate decreases when the crack passes the peened area with compressive residual stresses whereas it increases infront and after the peened area where tensile residual stresses dominate due to equilibrium. In order to improve the quantitative agreement, a 3D simulation is a needed, since measurements show a significant gradient of the residual stresses over the thickness of the specimen [3], leading to curved crack fronts. Furthermore, explicit modelling of crack closure can be included as well to take crack closure induced stress redistribution at minimum load $F_{\min}$ into account.
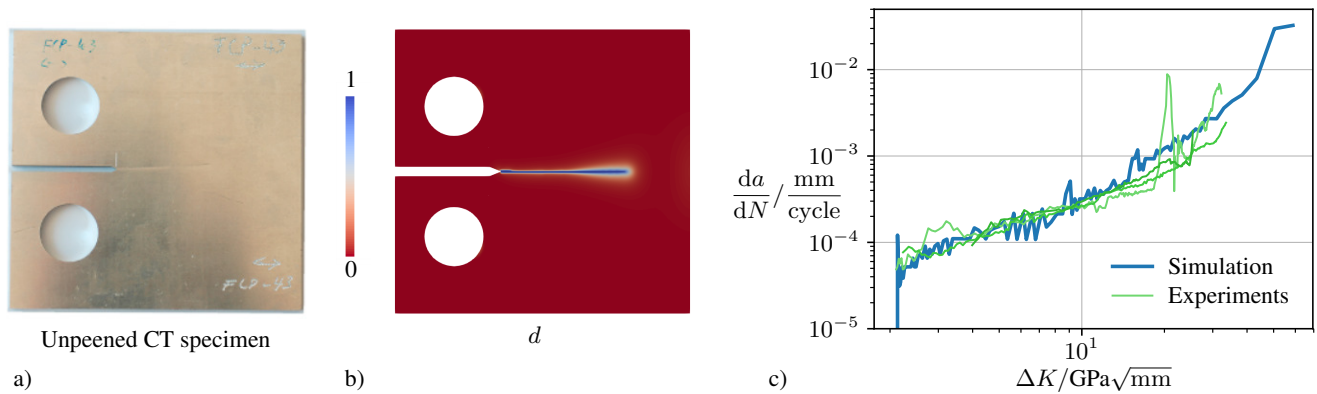

Fig. 1: (a) Aluminium specimen of 2 mm width (untreated, mostly residual-stress-free). **(b)** Phase-field variable after $\approx 251\,000$ load cycles. **(c)** Paris plot of crack propagation rate in experiments and simulation. A fit yielded the model parameters $\alpha_0 = 0.0015$ and $\xi = 500$.
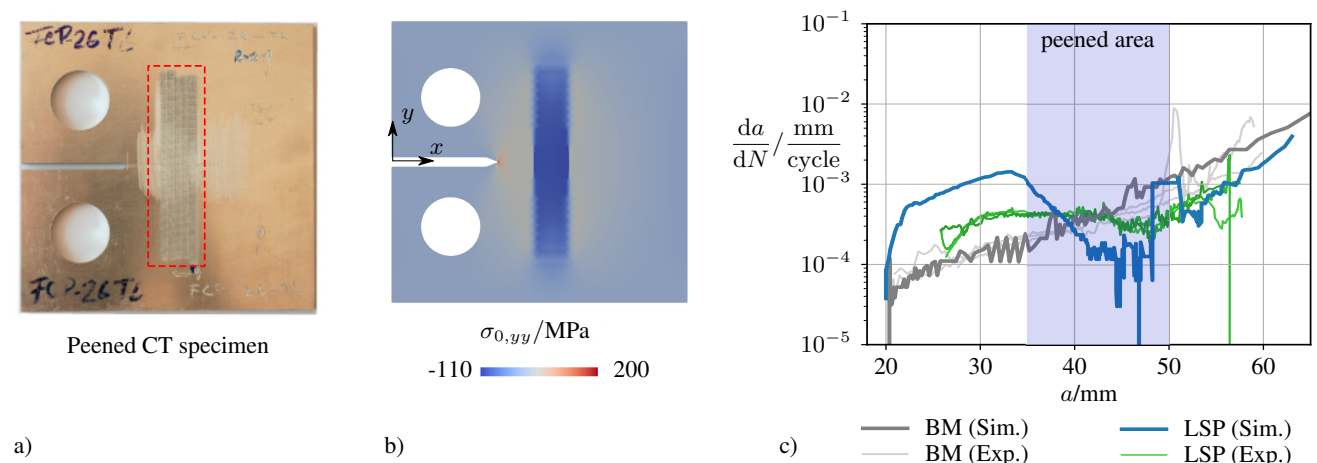

Fig. 2: (a) Aluminium specimen treated with laser shock peening (LSP). Procedure applied to the rectangular field marked in red, inducing compressive residual stresses there. **(b)** Initial residual stress distribution due to LSP (yy-component) shows the compressive residual stresses in the peened area and tensile residual stresses in the surroundings. **(c)** Crack propagation rate plotted over crack length a, showing experimental (Exp.) and simulative (Sim.) results of the peened specimen (LSP) and the untreated basis material (BM) for comparison. The simulation can reproduce the drop of the crack propagation rate in the peened area qualitatively.

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