LEUPHANA
UNIVERSITÄT LÜNEBURG

Simulation of fatigue crack growth in residual-stress-afflicted specimen with a phase-field model

Seiler, Martha; Keller, Sören; Kashaev, Nikolai; Klusemann, Benjamin; Kästner, Markus

Published in:
PAMM

DOI:
10.1002/pamm.202100210

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Link to publication

Citation for pulished version (APA):
Seiler, M., Keller, S., Kashaev, N., Klusemann, B., & Kästner, M. (2021). Simulation of fatigue crack growth in residual-stress-afflicted specimen with a phase-field model. *PAMM*, *21*(1), Article e202100210. https://doi.org/10.1002/pamm.202100210

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 09. Juli. 2025

Check for updates

Received: 25 June 2021 | Accepted: 21 August 2021

DOI: 10.1002/pamm.202100210

Simulation of fatigue crack growth in residual-stress-afflicted specimen with a phase-field model

Martha Seiler[1,*], **Sören Keller**[2], **Nikolai Kashaev**[2], **Benjamin Klusemann**[2,3], and **Markus Kästner**[1]

[1] Chair of Computational and Experimental Solid Mechanics, TU Dresden, Germany
[2] Institute of Materials Mechanicss, Helmholtz-Zentrum Hereon, Germany
[3] Institute of Product and Process Innovation, Leuphana University of Lüneburg, Germany

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.

© 2021 The Authors. *Proceedings in Applied Mathematics & Mechanics* published by Wiley-VCH GmbH.

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

* Corresponding author: e-mail martha.seiler@tu-dresden.de

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2021 The Authors. *Proceedings in Applied Mathematics & Mechanics* published by Wiley-VCH GmbH.

(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.

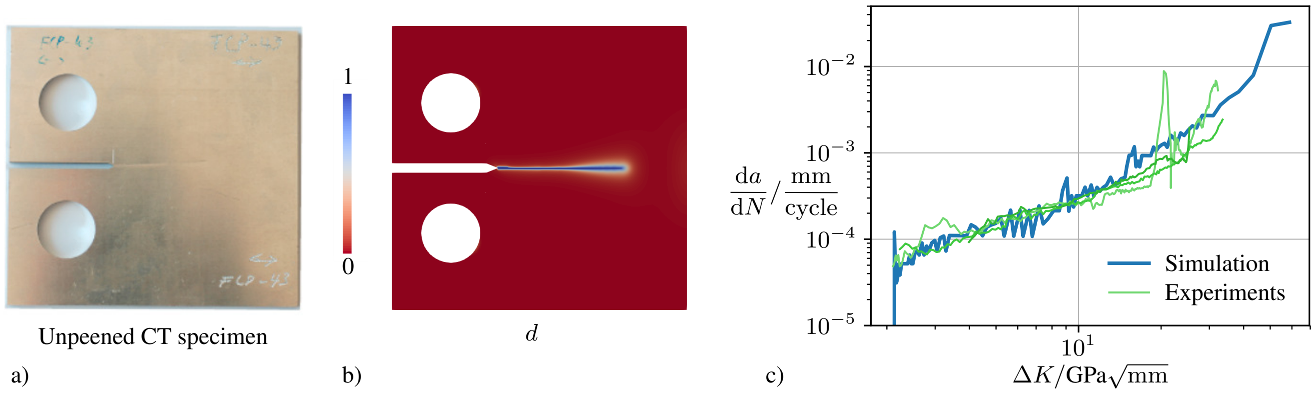

Fig. 1: **(a)** Aluminium specimen of 2 mm width (untreated, mostly residual-stress-free). **(b)** Phase-field variable after ≈ 251 000 load cycles. **(c)** Paris plot of crack propagation rate in experiments and simulation. A fit yielded the model parameters $\alpha_0 = 0.0015$ and $\xi = 500$.

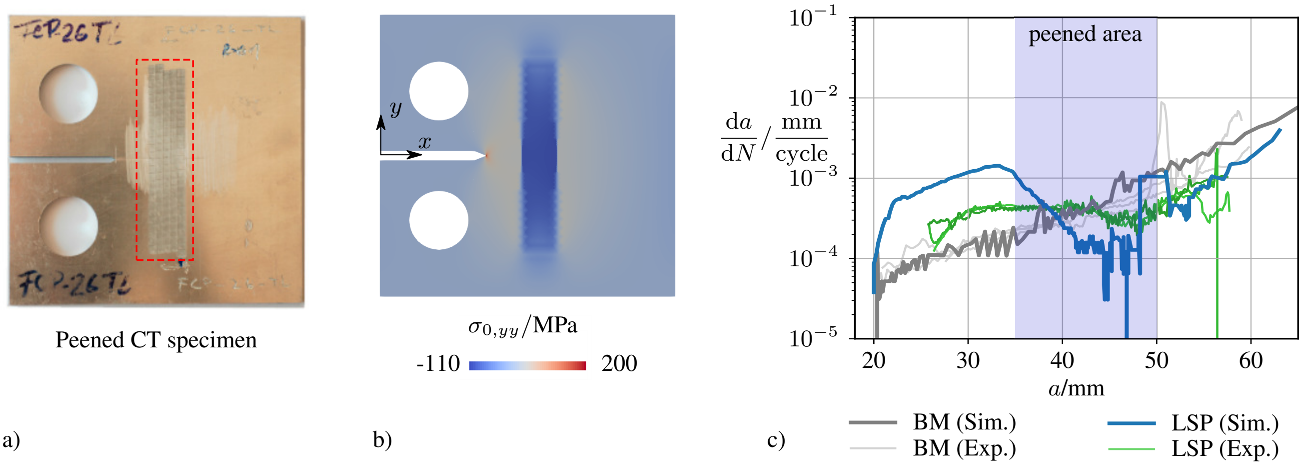

Fig. 2: **(a)** Aluminium specimen treated with laser shock peening (LSP). Procedure applied to the rectangular field marked in red, inducing compressive residual stresses there. **(b)** Initial residual stress distribution due to LSP (yy-component) shows the compressive residual stresses in the peened 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.

Acknowledgements This work was supported by the German Research Foundation DFG within the Priority Programme 2013 *Targeted Use of Forming Induced Residual Stresses in Metal Components* grant number KA 3309/7-2. The authors are grateful to the Centre for Information Services and High Performance Computing TU Dresden for providing its facilities for high throughput calculations. Open access funding enabled and organized by Projekt DEAL.

References

[1] M. Seiler et al., Eng. Frac. Mech. **224** (2020), DOI 10.1016/j.engfracmech.2019.106807.
[2] S. Keller et al., Int. J. Fat. **124** (2019), DOI 10.1016/j.ijfatigue.2018.12.014.
[3] M. Seiler et al., Arch. Appl. Mech. (2021), DOI 10.1007/s00419-021-01897-2.
[4] D. Radaj and M. Vormwald, Ermüdungsfestigkeit für Ingenieure (2007), ISBN 978-3-540-71458-3.
[5] C. Boller and T. Seeger, Materials science monographs **842** (1987), ISBN 978-0-444-42873-8.
[6] J. Kaufmann, Fracture resistance of aluminum alloys (2001), ISBN 978-0-87170-732-1.

© 2021 The Authors. *Proceedings in Applied Mathematics & Mechanics* published by Wiley-VCH GmbH.

16177061, 2021, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/pamm.202100210 by Universitaet Lueneburg Zeitsch, Wiley Online Library on [25/04/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License