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Numerical simulation of cyclic deformation behavior of SLM-manufactured aluminum alloys

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The selective laser melting process has already been developed for many metallic materials, including steel, aluminum, and titanium. The quasi-static properties of these materials have been found to be comparable or even better than their conventionally manufactured counterparts. However, for their reliable application in operational components, their fatigue behavior plays a critical role. This phenomenon is dominated by several process-related features, such as surface roughness, remnant porosity, microstructure and residual stresses. The present contribution shows a model which relies on an assumption for the Helmholtz free energy and the dissipation potential. To be more precise: the phase-field method is applied to simulate the damage evolution, whereas plastic effects are modeled in terms of the isotropic hardening. It is assumed that the damage evolution only occurs in the tension mode of a cyclic load, which is achieved by the decomposition of the stored energy. The numerical results give insight into the evolution of plastic deformations and of damage at a material point and for a chosen mesoscopic sample.

1 Introduction

Selective laser melting (SLM) manufactured aluminum alloys are currently intensively investigated for the purpose of a reliable industrial application. An important aspect of the investigation is fatigue initiated by the mesoscopic porosity at the length scale of a few hundred micrometers [1,2]. The contribution aims at the numerical simulation of crack propagation for samples manufactured under different production conditions.

2 Phase field damage model coupled to the isotropic plasticity

The failure mechanisms in solids are typically modeled on the basis of sharp crack discontinuities. However, this approach suffers in situations with complex crack topologies. This drawback is eliminated by introducing a diffusive crack modeling based on a crack phase-field d, which covers values in the range $[0,1]$, where $d = 0$ describes the unbroken state of the material and $d = 1$ the fully broken state. The model starts with the assumption for the free energy in the form

$$\Psi\left(\boldsymbol{\varepsilon}^{\mathrm{e}}, d\right) = \frac{\omega}{2}\boldsymbol{\varepsilon}^{\mathrm{e}} : \mathcal{C} : \boldsymbol{\varepsilon}^{\mathrm{e}}, \qquad \omega = [1-d]^2 + k_{\mathrm{n}}, \qquad \boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{\mathrm{e}} + \boldsymbol{\varepsilon}^{\mathrm{p}}, \tag{1}$$

where $\mathcal{C}$ is the elasticity matrix and where k_{n} is a small constant required to achieve numerical stability in the case of a fully broken material. The additive decomposition of total strains $\boldsymbol{\varepsilon}$ into an elastic part $\boldsymbol{\varepsilon}^{\mathrm{e}}$ and an inelastic part $\boldsymbol{\varepsilon}^{\mathrm{p}}$ is introduced, as it is typical of the small strain theory.
Equation (1) is furthermore complemented by a relationship governing the evolution of the damage parameter d and plastic deformation $\boldsymbol{\varepsilon}^{\mathrm{p}}$. In contrast to phenomenological methods, the present contribution follows the minimum dissipation potential approach and proposes a model which is based on the assumption for the brittle damage [3] extended by the contribution of plastic deformations:

$$D = \frac{g_{\mathrm{c}}}{l} d\,\dot{d} + g_{\mathrm{c}}\, l \nabla d \cdot \nabla \dot{d} + \omega k_{\mathrm{y}} ||\dot{\boldsymbol{\varepsilon}^{\mathrm{p}}}||, \qquad k_{\mathrm{y}} = k_{\mathrm{y0}} + k_{\mathrm{h}}, \qquad \dot{k_{\mathrm{h}}} = H\,||\dot{\boldsymbol{\varepsilon}^{\mathrm{p}}}||. \tag{2}$$

Here, g_{c} is a threshold value that is related to the critical Griffith-type fracture and l is the length-scale parameter. Furthermore, k_{y} denotes the current yield limit with the evolution depending on the initial yield limit k_{y0} and hardening parameter H. The full formulation additionally requires a Lagrange term stipulating the non-negativity of the damage rate.
In order to limit the damage evolution to the tension mode, an additive decomposition of the total free energy into a tension part $(\Psi^{+}(\boldsymbol{\varepsilon}^{\mathrm{e}}_{+}))$ and a compression part $(\Psi^{-}(\boldsymbol{\varepsilon}^{\mathrm{e}}_{-}))$ is introduced. The corresponding anisotropic energy storage function reads $\Psi(\boldsymbol{\varepsilon}^{\mathrm{e}}, d) = \omega\Psi^{+}(\boldsymbol{\varepsilon}^{\mathrm{e}}_{+}) + \Psi^{-}(\boldsymbol{\varepsilon}^{\mathrm{e}}_{-})$. The definition of the positive and negative part is based on the spectral decomposition of the strain tensor as $\boldsymbol{\varepsilon}_{\pm} = \sum_{a=1}^{3} \boldsymbol{\varepsilon}_{a\pm} \boldsymbol{n}_a \otimes \boldsymbol{n}_a$, where $\{\boldsymbol{\varepsilon}_a\}_{a=1..3}$ are the principal strains and where $\{\boldsymbol{n}_a\}_{a=1..3}$ are the principal strain directions. The ramp function defined as $\boldsymbol{x}_{\pm} = [||\boldsymbol{x}|| \pm \boldsymbol{x}]/2$ separates the positive and negative entries.
For the chosen set-up, the thermodynamic force related to the plastic deformation $(\boldsymbol{\alpha}_{\boldsymbol{\varepsilon}^{\mathrm{p}}})$ is defined according to the Coleman-Noll approach as derivative of the free energy with respect to the internal variable. The corresponding evolution equation is

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then obtain from the expression relating the driving force to the derivative of the dissipation potential:

$$\boldsymbol{\alpha}_{\varepsilon^{\mathrm{p}}} = -\frac{\partial \Psi}{\partial \varepsilon^{\mathrm{p}}} = -\omega \frac{\partial \Psi_{+}}{\partial \varepsilon^{\mathrm{p}}} - \frac{\partial \Psi_{-}}{\partial \varepsilon^{\mathrm{p}}} = \omega \boldsymbol{\sigma}_{+} + \boldsymbol{\sigma}_{-} = \boldsymbol{\sigma}, \tag{3}$$

$$\boldsymbol{\alpha}_{\varepsilon^{\mathrm{p}}} = \frac{\partial D}{\partial \dot{\varepsilon^{\mathrm{p}}}} = \omega k_y \frac{\dot{\varepsilon^{\mathrm{p}}}}{||\dot{\varepsilon^{\mathrm{p}}}||} \qquad \Rightarrow \qquad \dot{\varepsilon^{\mathrm{p}}} = \lambda \frac{\boldsymbol{\sigma}}{||\boldsymbol{\sigma}||}. \tag{4}$$

Here, $\lambda \geq 0$ denotes the plastic multiplier to be calculated from the consistence condition. The form of evolution equation for plastic deformations does not change, compared to the case of pure plasticity, however, the stresses are calculated in a different manner. Moreover, the yield surface is influenced by the damage state as defined by the yield surface condition $||\boldsymbol{\sigma}|| = \omega k_{\mathrm{y}}$. The model is numerically implemented at the global level for the calculation of total deformations and of damage, whereas the inelastic deformations are calculated locally at Gauss points by using the predictor-corrector scheme [4].

3 Numerical Results

A plate with dimensions of 100 μm $\times$ 100 μm with the material parameters of AlSi12 is considered in the simulations. It has two voids with diameter of 10 μm which simulates the mesoscopic porosity typical of SLM-manufactured materials. The plate is discretized by a mesh with $\approx$ 7000 elements such that a fine discretization is performed in the areas where the crack propagation is expected. The plate is fixed on its left edge and a prescribed displacement is applied to its right edge. The chosen displacement increment amounts to 0.001 μm. Fig. 1 shows stress and damage evolution at a single point for a cyclic load as well as the crack shape for a fully broken sample. The damage and stresses are monitored at a Gauss point in a relevant area near one of pores. The stress diagram (Fig. 1 a) shows an elastic material response in the beginning of the process. Once plasticity occurs, the slope of the stress changes as expected for the processes with hardening. The stress decreases to zero for the fully broken material. The damage evolution (Fig. 1 b) firstly shows an exponential behavior and then an abrupt growth to the limiting unit-value. The crack path (Fig. 1 c) starts perpendicular to the load direction at the top and bottom points of the holes. Furthermore, the upper and lower cracks evolve in a straight line toward the edges of the sample whereas the cracks between the holes change their initial directions and merge towards each other.

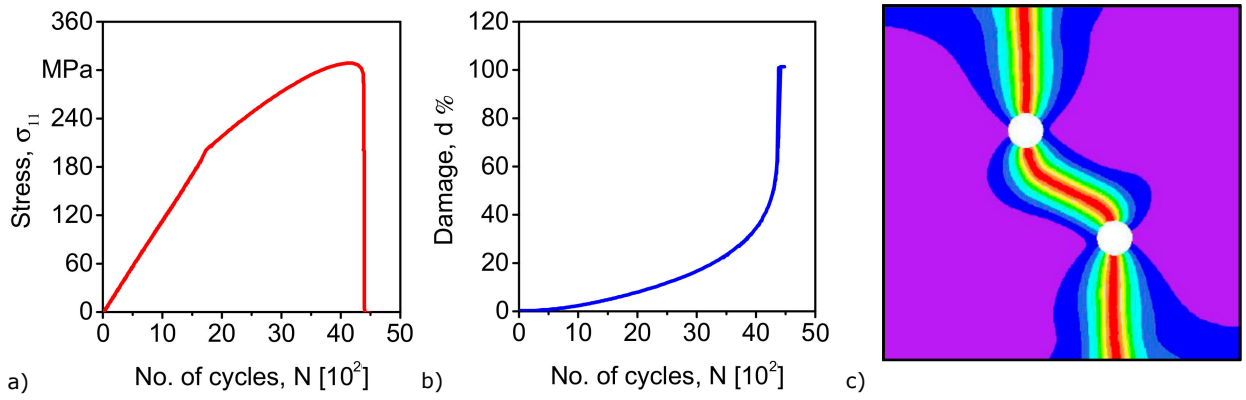

Fig. 1: (a) Change of the stress component σ_{11}, b) evolution of the damage variable, c) the crack path for a fully broken sample. Model parameters: $g_{\mathrm{c}} = 2.7 \times 10^{-3}$ kN/mm, l=0.0375 mm. Material parameters: Young's modulus E=70 GPa, Poisson's ratio ν=0.3, initial yield limit K_{y0}=218 MPa, hardening constant H=123 GPa.

4 Conclusion

This contribution deals with the simulation of the damage evolution in SLM aluminum alloys under cyclic loading by using the phase-field method coupled to plasticity with isotropic hardening. The energy split is introduced in order to distinguish the tension, and the compression state and the minimum principle of dissipation potential is used for the derivation of evolution equations for inelastic deformations. In the next step, the model will be extended by implementing the kinematic hardening and the results achieved will be compared to the experimental observations.

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