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

Tillmann Wiegold¹* and Sandra Klinge¹

¹ TU Dortmund University, Institute of Mechanics, Leonhard-Euler-Str. 5, 44227 Dortmund, Germany

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 approach and proposes a model which is based on the assumption for the brittle damage [3] extended by the contribution of the present work. The 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.

\* Corresponding author: e-mail tillmann.wiegold@tu-dortmund.de, phone +00 49 231 7557902

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

\[
\alpha \varepsilon_p = -\frac{\partial \Psi}{\partial \varepsilon_p} = -\omega \frac{\partial \Psi}{\partial \varepsilon_p} = \omega \sigma_+ + \sigma_- = \sigma, \tag{3}
\]

\[
\alpha \dot{\varepsilon}_p = \frac{\partial D}{\partial \varepsilon_p} = \omega k_y \frac{\varepsilon_p}{\sigma} \Rightarrow \dot{\varepsilon}_p = \lambda \frac{\sigma}{||\sigma||}. \tag{4}
\]

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 \( ||\sigma|| = \omega k_y \).

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 \( \mu m \times 100 \mu m \) with the material parameters of AlSi12 is considered in the simulations. It has two voids with diameter of 10 \( \mu m \) 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 \( \mu m \). 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](image)

**Fig. 1:** (a) Change of the stress component \( \sigma_{11} \), b) evolution of the damage variable, c) the crack path for a fully broken sample. Model parameters: \( g_c = 2.7 \times 10^{-3} \) kN/mm, \( l=0.0375 \) mm. Material parameters: Young’s modulus \( E=70 \) GPa, Poisson’s ratio \( \nu=0.3 \), 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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### References

[1] S. Siddique, M. Awd, T. Wiegold, S. Klinge, and F. Walther, Appl. Sci., 8 (10), 1948: 1-18 (2018).
[2] S. Siddique, M. Imran, M. Rauer, M. Kaloudis, E. Wycisk, C. Emmelmann, and F. Walther, Mater. Des., 83, 661-669 (2015).
[3] C. Miehe, F. Welschinger, and F. Hofacker, Int. J. Numer. Methods Eng., 83, 1273-1311 (2010).
[4] S. Klinge, S. Aygün, and T. Wiegold, Int. J. Numer. Methods Eng., (submitted).

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