Low Cycle Lifetime assessment of Al2024 alloy

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ABSTRACT *A novel ductile-brittle damage law for the numerical simulation of low cycle fatigue of a Al2024-T351 Aluminium alloy in its related S-direction is proposed. To illustrate the predictive capabilities of the brittle damage model, a benchmark example is presented. Some material parameters have been calibrated to Al2024 considering fatigue crack growth.*

INTRODUCTION

High-performance materials play an important role for structural components in transportation vehicles (e.g. aircrafts, automobiles, motorcycles), since they combine superior material properties like high strength or high corrosion resistance with low weight, resulting in higher efficiency. In particular, structures made up of the high-strength and light-weight Aluminium alloy 2024 are often employed in the aerospace industry, e.g. for airframes or the fuselage of airplanes.

For a safe design, the proper characterization of the material properties like fracture toughness or fatigue resistance is very important. Normally, this requires the experimental testing of a number of test samples of various sizes which is costly and time-consuming. The need for realistic material models to replace some of these experimental verifications with predictive numerical simulations of the service life performance is thus of high interest.

The response of the material under cyclic loading is critical, since e.g. aerospace structures are usually subjected to a number of load reversals during lifetime due to recurring landing operations or to repeated pressure loadings in high altitudes which may deteriorate the mechanical properties. For a safer life, the material is usually designed for high cycle fatigue (HCF) assuming relatively low stress levels. However, in bad weather or under extreme service conditions, the components can be subjected occasionally to higher stress levels, where failure is reached after a few number of cycles only. To consider such events with highly stressed components during design, it is necessary to understand and predict the low cycle fatigue (LCF) performance of the material.

To meet these requirements, the current research carried out at the GKSS-Research Centre focuses on the experimental characterization and numerical simulation of the LCF behavior of Al2024-T351. On the experimental side, many different tests on smooth round bars and notched round bars with different strain amplitudes have been analyzed for validation of the numerical models. On the numerical side, a predictive material model based on continuum damage mechanics (CDM) has been used to simulate the observed material response employing the FE method.

It has been found out in earlier analyses [1,2] and during the more recent studies [3,4] that due to the special composition and wrought processing of Al2024-T351 a highly anisotropic microstructure exists with different material properties in the L-(longitudinal), the T-(transversal) and the S-(small transversal)-directions. To analyze this anisotropic material response more closely, test specimens were taken in all three directions of a given block of Al2024-T351. It turned out that the ductility in S-direction is considerably smaller than that in the L- or T-directions and that the fracture process is more localized and quite brittle.

In earlier studies [3,4] it was tried to simulate the aforementioned material response using an anisotropic CDM-model according to [5]. The damage evolution of this particular model depends on the plastic strain rate and the rate of energy release which was sufficient to reproduce the ductile material response closely. Further research was concentrated on the modeling of the rather quasi-brittle material behavior in S-direction. For this purpose, a fully coupled isotropic ductile-brittle damage model was developed. The isotropic ductile damage part of the model is similar to that proposed in [6]. However, the brittle damage model is completely new. By introducing a so-called shift tensor, the simulation of damage growth under cyclic loading is made possible. Some of the material parameters have been defined in advance by means of microstructural considerations, while the remaining parameters can be computed by an inverse analysis. Using an optimal composition of the ductile and the brittle damage contributions, the simulation of the quasi-brittle material behavior in S-direction is made possible.

The present paper is structured as follows: First, the ductile and brittle damage models are outlined. Then, microstructural considerations are presented to calibrate some of the material parameters for the brittle damage law. A benchmark will show the performance of the brittle law.

THE ISOTROPIC DUCTILE-BRITTLE DAMAGE MODEL

In the present section, the ductile and brittle damage models are introduced and are then combined to yield a fully coupled isotropic quasi-brittle constitutive law. For the modeling of ductile damage, a modified approach of LEMAITRE [6] is used where also effective hardening stresses are considered. For brittle damage, a damage indicator function is proposed which simulates a material response defined by fatigue crack growth. A geometrically linearized setting is considered where the global strains $\boldsymbol{\epsilon}$ are decomposed according to $\boldsymbol{\epsilon} = \boldsymbol{\epsilon}^e + \boldsymbol{\epsilon}^p$ with $\boldsymbol{\epsilon}^e$ and $\boldsymbol{\epsilon}^p$ being elastic and plastic strains.

The ductile damage model

For the description of ductile damage, an evolution law for the damage variable according to LEMAITRE [6] is used which is linear in the plastic strain rate and the rate of energy release, i.e.,

$$\dot{D} = \sqrt{\frac{2}{3}\,\dot{\boldsymbol{\epsilon}}^p : \dot{\boldsymbol{\epsilon}}^p}\;\frac{Y}{1.3}\;. \tag{1}$$

For the computation of the energy release rate $Y = -\rho\,\frac{\partial\Psi}{\partial D}$, the complete elasto-plastic strain contributions are considered. More precisely, the HELMHOLTZ free energy is defined by

$$\rho\,\Psi(\boldsymbol{\epsilon}^e, \boldsymbol{\alpha}_{k\,j}, \alpha_i, D) = (1-D)\left(\frac{\boldsymbol{\epsilon}^e : \mathbb{C} : \boldsymbol{\epsilon}^e}{2} + \sum_{j=1}^{3} H_{k\,j}\,\frac{\boldsymbol{\alpha}_{k\,j} : \boldsymbol{\alpha}_{k\,j}}{2} + H_i\,\frac{\alpha_i^2}{2}\right)\;, \tag{2}$$

where $\mathbb{C}$ is the isotropic elastic stiffness matrix and $H_{k\,j}$ and H_i are the hardening moduli related to the plastic kinematic and isotropic hardening strains $\boldsymbol{\alpha}_{k\,j}$ and α_i, respectively. For the simulation of kinematic hardening, a sum of three back stress tensors $\mathbf{Q}_{k\,j} = -\rho\,\frac{\partial\Psi}{\partial\boldsymbol{\alpha}_{k\,j}}$ is used to improve the approximation of the experimentally observed plastic hysteresis. The yield function is described totally in effective stresses which are defined by

$$\tilde{\boldsymbol{\sigma}} = \frac{\boldsymbol{\sigma}}{(1-D)}\;,\quad \tilde{\mathbf{Q}}_{k\,j} = \frac{\mathbf{Q}_{k\,j}}{(1-D)}\;,\quad \tilde{Q}_i = \frac{Q_i}{(1-D)}\;, \tag{3}$$

where $\boldsymbol{\sigma} = \rho\,\frac{\partial\Psi}{\partial\boldsymbol{\epsilon}^e}$ is the CAUCHY stress and $Q_i = -\rho\,\frac{\partial\Psi}{\partial\alpha_i}$ describes the growth of the initial elastic limit Q_0^{eq} (isotropic hardening). In what follows, a yield function of von Mises type is considered, i.e.,

$$\phi^p = \sqrt{\frac{2}{3}\,\mathrm{dev}(\tilde{\boldsymbol{\sigma}} - \tilde{\mathbf{Q}}_k) : \mathrm{dev}(\tilde{\boldsymbol{\sigma}} - \tilde{\mathbf{Q}}_k)} - (\tilde{Q}_i + Q_0^{eq}) \ . \tag{4}$$

The brittle damage model

To describe brittle material degradation, the damage indicator function

$$\phi^d = \frac{|Y^N - \Gamma|}{S_2} - Q_{d0} \ , \tag{5}$$

is proposed, where Γ is the so-called shift tensor and Q_{d0} is a constant threshold value defining damage nucleation. N and S_2 are material parameters. Y is the energy release rate and is defined according to the ductile damage model. Hence, also the brittle damage evolution is driven by the elasto-plastic strain accumulation.

Considering the framework of generalized standard materials, cf. [7], the evolution equations are derived from a convex damage potential. More precisely,

$$\dot{D} = \lambda^d \,\frac{\partial \bar{\phi}^d}{\partial Y} \ , \quad \dot{\alpha}_\Gamma = \lambda^d \,\frac{\partial \bar{\phi}^d}{\partial \Gamma} \ , \tag{6}$$

where α_Γ is the dual variable to Γ and where the damage potential is defined by

$$\bar{\phi}^d := \phi^d + \frac{B_\Gamma}{H_\Gamma}\,\frac{\Gamma^2}{2}. \tag{7}$$

Accordingly and in line with the plastic material model, the shift tensor is governed by an Amstrong-Frederick-type hardening model considering two material parameters H_Γ and B_Γ.

The fully coupled ductile-brittle damage model

In order to simulate a quasi-brittle damage, both damage models are coupled. For that purpose, the composition factors γ^d and $\gamma^b = (1 - \gamma^d)$ are introduced. The total damage variable is postulated to be

$$D = \gamma^d\, D^d + \gamma^b\, D^b \ , \tag{8}$$

where the rates of D^d and D^b are defined by Eqs. (1) and $(6)_1$, respectively. Analogously, the total energy release rate Y can be consistently separated into two components $Y^d = \gamma^d\, Y$ and $Y^b = \gamma^b\, Y$.

Calibration of the brittle damage law to Al2024

For the calibration of the brittle damage model it is assumed that the long crack growth behavior can be extrapolated into the small crack growth regime, cf. [8]. It is well-known that the growth of long cracks can be described by the PARIS law

$$\frac{da}{dN} = C\,(\Delta K)^{\eta}\ , \tag{9}$$

where C and η are material parameters. According to [9], $\eta = 3.0$ for Al2024. Without going too much into details, it is mentioned that the material parameter N defining the damage evolution $(6)_1$ can be computed by a comparison to PARIS law leading eventually to

$$\dot{D} = \frac{1.25\,\sqrt{Y^b}\,\dot{Y}^b}{B_\Gamma\,(\Gamma_\infty - \Gamma)}\ . \tag{10}$$

Γ_∞ is a threshold value for Γ which defines an accelerating damage growth for Γ approaching Γ_∞. Γ_∞ is defined by

$$\Gamma_\infty = \frac{H_\Gamma\,\mathrm{sign}(Y^{b\,N} - \Gamma)}{N\,B_\Gamma}\ . \tag{11}$$

BENCHMARK

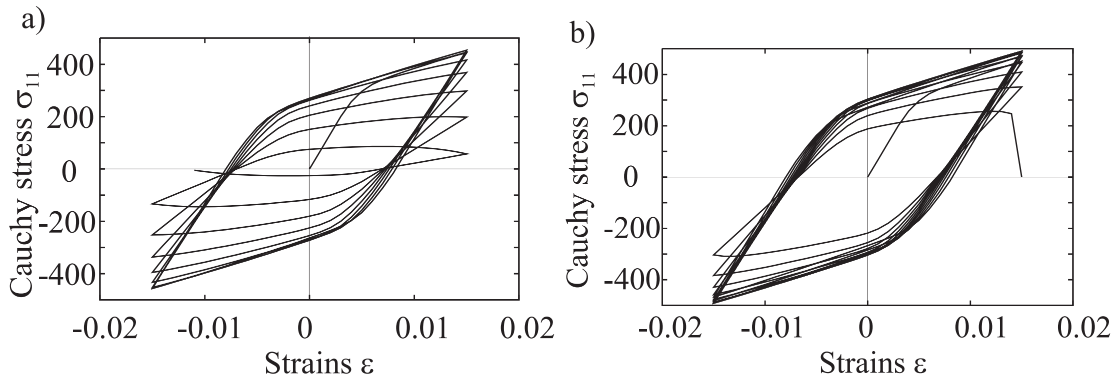

Figure 1: Uniaxial tension test: Stress-strain response as predicted by the novel brittle damage law (3D-computation), a) (H_Γ,B_Γ) = (250.0,10.0), b) (H_Γ,B_Γ)= (1250.0,50.0).

To illustrate the performance of the brittle damage model, a uniaxial tensile test has been analyzed with a strain range of $\Delta\epsilon = 0.03$ considering the optimized plastic hardening and saturation parameters derived from an experimental hysteresis curve of Al2024. For the computational assessment, Q_{d0}=0.010629 and Γ_∞=20.0 have been assumed.

As can be observed in Figure 1, the material parameters H_Γ and B_Γ with Γ_∞ being constant can be adjusted to fine-tune the softening and failure behavior. For small H_Γ the softening process is not rapid and the failure point is reached later for small CAUCHY stresses. For larger H_Γ the damage evolution is slower and also the final failure is very abrupt almost within one single time step.

CONCLUSION

A new approach for the low cycle lifetime assessment of an Al2024 alloy using a novel ductile-brittle damage model has been presented. The brittle damage model has been calibrated to small crack growth of Al2024 considering the PARIS law. A FE-simulation has been performed to show the performance of the model. In summary, the proposed damage model seems to be very promising for the intended purpose.

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