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An Investigation on Low Cycle Lifetime of Al2024 Alloy

A. Vyshnevskyy[1, a], S. Khan[2, b] and J. Mosler[3, c]

[1, 2, 3] GKSS Research Centre GmbH, Max-Planck Strasse 1, 21502 Geesthacht, Germany

[a]andriy.vyshnevskyy@gkss.de, [b]shehzad.khan@gkss.de, [c]joern.mosler@gkss.de

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Abstract. One of the important considerations in the design of components is the estimation of cyclic lifetime and analysis of the critical regions of a construction. The local approach of lifetime estimation using continuum damage mechanics (CDM) has shown a great potential in predicting material failure not only for monotonic, but also for fully reversed loadings. In this paper, the CDM model of Desmorat-Lemaitre [1] was investigated regarding the prediction of cyclic lifetime. A series of experiments on tension specimens with different geometries were performed. The latter were used for the determination of model parameters as well as for the validation of the predictive capability of the model.

Introduction

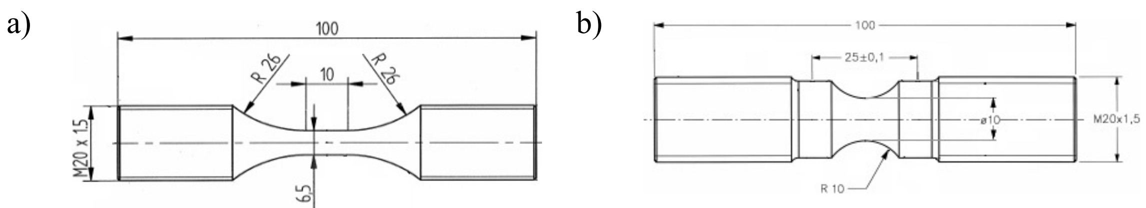
Fatigue analysis is an essential aspect in design of engineering structures, since most of them are subjected to cyclic loadings. Research on fatigue life as a function of multiaxial stress/strain state dates back to the last century [2] and many multi-axial fatigue life prediction models have been proposed [3, 4]. Low cycle fatigue (LCF) which results, for instance, from repeated take-offs and landings of aircrafts is considered one of the major life limiting factors in performance of aircraft engine components such as impellors, compressor and turbine discs, etc. Usually, those components are modeled by assuming an isotropic constitutive response. Since most engineering materials exhibit some degree of mechanical anisotropy, it is important to include the material anisotropy effect in multiaxial fatigue life prediction models so as to improve the safety design methods. Aluminium alloys of the 2000 series, Al-Cu, are one of the most widely used materials in aerospace industry. This class of alloys owes their good mechanical properties to the presence of small dispersoid Al_2Cu particles in its microstructure, <0.01 μm, which impart mechanical strength to the material through a precipitation hardening mechanism [5].

Damage mechanics may be applied to predict the mechanical deterioration of structural materials under cyclic conditions [6]. Damage evolution throughout the fatigue life of a specimen or component may be expressed by applying the framework of CDM.

Experiments

The alloy under investigation is Al-2024-T351 (solution heat treated, air-quenched, and stress relieved by cold stretching). The material was supplied in form of 100 mm thick plate. The peculiar thickness of the investigated plate gives the unique possibility to study the mechanical properties also in S (thickness) direction. Previous mechanical investigations on this material for the S direction show a fracture surface perpendicular to the loading direction for smooth round-bar specimens [7].

Two types of specimens were tested (see Fig. 1). Initially, a so-called DLC-specimen (Damage Low Cycle), was designed for tension-compression tests showing a stress state close to the uni-axial one (see Fig. 1a). Subsequently, a circumferential round notch was designed to achieve the variation of the stress state in the middle cross section of the specimen (see Fig. 1b,c). All specimens were cut from the same plate of Al-2024-T351 in S direction. The entire specimens were grinded and mechanically polished in the direction of loading. The final polishing was performed with a diamond paste showing 1μm grains.



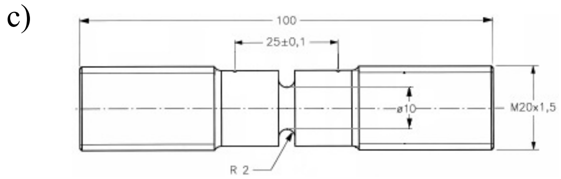


Fig. 1: *Specimens geometries: a) DLC-specimen; b) and c) specimens with circumferential notches 10 mm and 2 mm respectively.*

The entire experiments were conducted on a 60 KN servo-hydraulic testing machine. Specially designed gripping of the testing setup and shoulders of the specimens allow for tension-compression reverse loading. The loading in all cases was performed displacement-controlled. The displacement was measured using extensometer, attached to the working distances of specimens. A triangular wave shape symmetric cycle ($R = -1$) was imposed with various amplitudes and identical time period $T = 100\,s$. The amplitudes were varied to achieve different life times (number or cycles to failure). All of the tests were conducted until complete rupture. Time-force-displacement responses during the tests were recorded with a digital acquisition device.

Experimental and simulation results

Similar to many metallic materials subjected to cyclic loading, the stabilization of the mechanical response is achieved for Al2024 after several cycles. After the stabilization stage, the mechanical degradation is observed (see Fig. 2a, Pt. 1). Following [1] this is usually related to a critical value of the stored plastic energy. The subsequent degradation of mechanical properties results in a decrease of the maximum stress. Evidently, it is associated with the evolution of damage (see Fig. 2a, from Pt. 1 to Pt. 2). The experimental observations show that visible macro cracks appear on the surface of DLC-specimens after Pt. 1 during a relatively small number of cycles. This is associated with the rupture of specimen (see Fig. 2a, Pt. 2).

Within the computations based on the model presented in [1], it was assumed that the stage of cyclic damage (between Pt. 1 and Pt. 2, Fig. 2a) is short compared to the plastic regime (from beginning up to Pt. 1). Finally, for the prediction of the cyclic life time of Al2024 the function of the plastic stored energy [8]

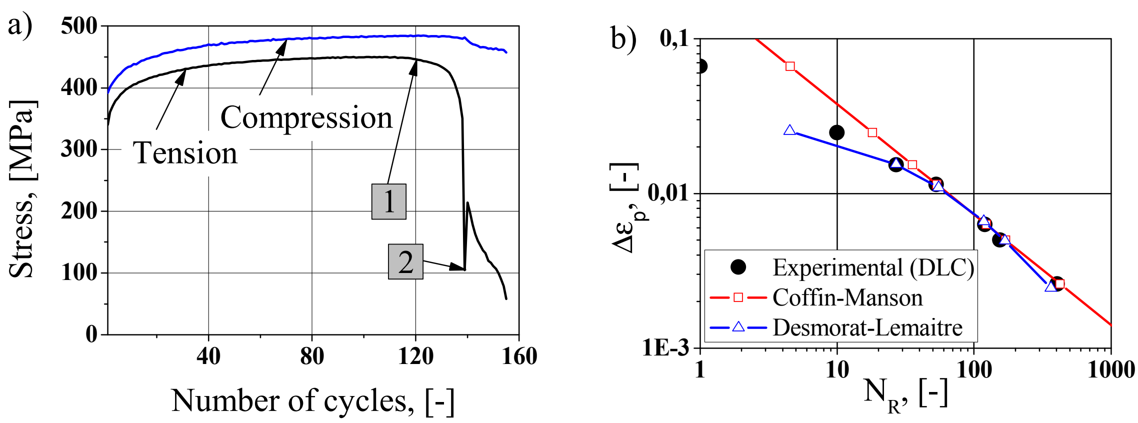


Fig. 2: *Mechanical response of DLC specimens: a) absolute maximum value of tension and compression stresses in a particular cycle ($\Delta\varepsilon_p = 0.0063; N_R = 120$); b) amplitude of plastic strains $\Delta\varepsilon_p$ versus number of cycles to rupture N_R.*

$$w_s = \int_0^t R_\infty (1-\exp(-br)) \frac{A}{m} r^{(1-m)/m} \dot{r} dt + \frac{3}{4C} \mathbf{X}^2 \le w_D \tag{1}$$

has to be calibrated. Here, r is the accumulated plastic strain, $\mathbf{X}$ is the back stress tensor, A, m are parameters defining the plastic stored energy function, R_∞, b, C are additional parameters describing the cyclic plasticity model and w_D is the threshold value when damage occurs.

For the simulation of the cyclic mechanical response, a combined isotropic-kinematic hardening plasticity model is used, cf. [1]. The material parameters were adjusted using experimental cyclic stress-strain curves of DLC-specimens. The resulting material parameters are summarized in Table 1.

Elasticity		Plasticity					Stored plastic energy		
$E,[MPa]$	ν	$\sigma_y,[MPa]$	$R_\infty,[MPa]$	b	γ	$C,[MPa]$	m	A	$w_D,[MJ/m^3]$
$7\cdot10^5$	0.3	284	150	4	80	$1.7\cdot10^4$	3.9	0.0113	0.897

Table 1: *Parameters of the model.*

They are based on an optimization algorithm implemented in MATLAB. The objective function to be minimized reads:

$$\{A, m, w_D\}^* = \underset{\{A,m,w_D\}\in R_+^3}{\arg\min} \left(\sum \left(\log N_R^{\exp} - \log N_R^{sim}(A, m, w_D) \right) \right). \tag{2}$$

The results of the simulations are compared to the experimental data and to the well-known Coffin-Manson function (see Fig. 2b).

10 mm notch			2 mm notch		
$\Delta l,[mm]$	$N_R^{\exp}$	N_R^{sim}	$\Delta l,[mm]$	$N_R^{\exp}$	N_R^{sim}
0.375	8	12	0.20	24	20
0.200	370	350	0.18	45	41
0.150	1900	- *	0.16	90	75

Table 2: *Comparison of the simulation results with the experimental data for the notched specimens. * - stopped after 2000 cycles.*

The calibrated parameters were used for FE simulations of notched specimens. For these simulations, an axis-symmetric FE model was designed for each specimen geometry. The simulations were performed by using the FE-program Abaqus combined with the material library Z-Mat. The results of the simulations are shown in Table 2.

Two distributions of the stored energy at the rupture time point $w_s = w_D$ are shown in Fig. 3. The maximum stored plastic energy is concentrated in the notch root for both notch geometries.

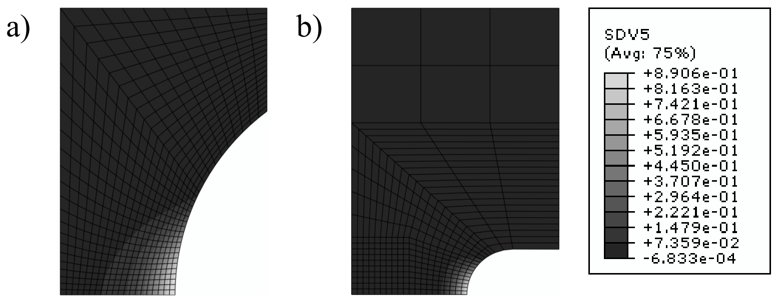


Fig. 3: *Distribution of stored plastic energy: a) notch radius* $10\,mm$, $N_R = 350$; *b) notch radius* $2\,mm$, $N_R = 41$.

Conclusions

The proposed modeling method is in good agreement with experimental observations for DLC-specimens. This agreement has been confirmed even for specimens with a relatively complex geometry. All important physical quantities, such as the number of cycles to rupture or the location of crack initiation, are realistically predicted.

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