The influence of ageing on fatigue and fracture-related material parameters for an aluminum cast alloy

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Abstract

To meet the requirements of modern lightweight design in automotive engineering, a continuously increasing use of aluminum alloys is observed. If precipitation-hardening aluminum alloys are to be used in internal combustion engines, the accelerated ageing of the material due to the elevated temperatures of locally up to 250 °C must be taken into account.
To describe the influence of temperature and ageing on the parameters of the material's stress-strain behavior, several models (such as the one by Shercliff & Ashby [7, 8]) have been proposed. Similar ideas have been pursued for the fracture mechanics parameters. The present contribution deals with possible analogies as well as with some fundamental differences between these concepts from damage and fracture mechanics.
Using results from tensile, fatigue and fatigue crack growth tests, some simple engineering estimates are proposed for describing the influence of ageing on the material parameters.

1 Introduction

In recent years, lightweight design has become increasingly important in the automotive industry. There exist several approaches for performing a fatigue life assessment of components in the context of lightweight design. The classical method, which has been used for decades with success, is based on the use of S/N curves. These curves are obtained from standardized smooth, defect-free specimens. A lifetime assessment under varying load amplitudes using S/N curves is possible via the Pålmgren-Miner linear damage accumulation hypothesis.
Another approach stems from fracture mechanics, which is gaining more and more importance in the automotive industry. The presence of a crack in the material is assumed, its size being estimated from the non-destructive testing (NDT) detection limit. Under cyclic loading, the crack may grow until final rupture occurs. This approach is based on the use of fatigue crack growth (FCG) curves.

For the chassis frame or other components of the vehicle which are not subjected to elevated temperatures, a lot of material data is available for calculations based on damage accumulation as well as for FCG-based estimates.
As precipitation-hardening aluminum alloys are used for combustion engines, also the ageing behavior due to the elevated temperatures has to be taken into account.
For stress-based approaches, a damage model accounting for the effects of ageing on the strength of aluminum alloys was proposed by Shercliff and Ashby [7, 8]. Although it is possible to estimate the lifetime of an ideal component without flaws with this approach, the model is not suited for an assessment of the behavior of flawed components.
The aim of this contribution is to introduce a phenomenological model for describing the evolution of the parameters of the crack growth curve of an AlSi7Mg alloy throughout different states of ageing. The connection between the damage mechanics and the fracture mechanics approaches will be discussed.

2 Influence of ageing on the damage parameters

The process model of Shercliff and Ashby [7, 8] allows to describe the ageing behavior of precipitation-hardening aluminum alloys. The ageing-dependent yield strength $\sigma_y(t)$ is the sum of three different contributions as follows (Eq. 1): the strength of the aluminum matrix σ_i is independent of the age; the strength contributions of the solid solution $\Delta\sigma_{ss}$ and the precipitations $\Delta\sigma_{ppt}$, respectively, depend on the age of the material (Fig. 5).

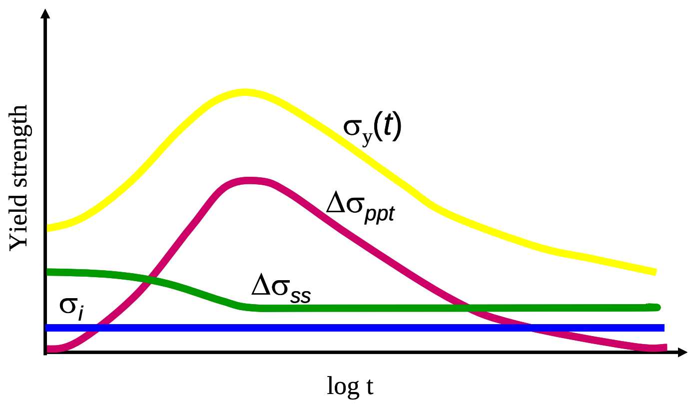

Fig. 1 Process model according to Shercliff and Ashby [7, 8]

$$\sigma(t) = \sigma_i + \Delta\sigma_{ss} + \Delta\sigma_{ppt} \qquad \textit{(Eq. 1)}$$

In Fig. 2, the results obtained with the process model for the AlSi7Mg alloy aged for different times at 200°C are shown. For this temperature, the maximum yield strength is found at an ageing time of about 8h.

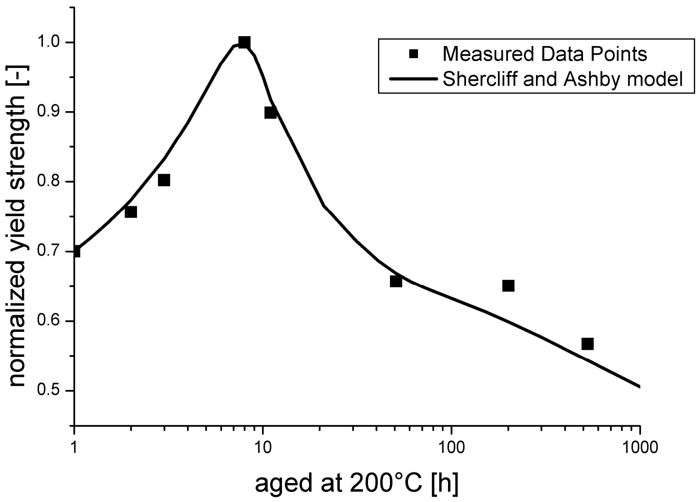

Fig. 2 Ageing behavior of AlSi7Mg

3 Experimental assessment of the influence of ageing on fatigue crack growth

In order to obtain fatigue crack growth (FCG) parameters, tests were performed on Single Edge Notched Bending (SENB) specimens on resonant testing equipment under frequencies of approximately 100-130 Hz, depending on the crack length. The crack length was measured with the Direct Current Potential Drop (DCPD) method, see [9] and Fig. 3. The testing was performed according to ASTM [10].

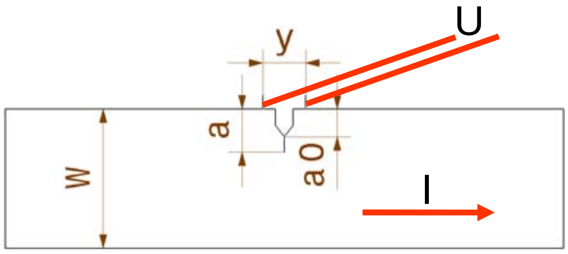

Fig. 3 SENB specimen for DCPD method (U … potential drop, I … constant current)

In the literature, a significant number of studies on the effect of under-ageing and over-ageing on the mechanical properties of aluminum alloys can be found, e.g. [4-6]. However, only very few studies deal with the entire range of ageing [1-3]. Investigations by Bray et al. [1] show that in the case of two different aluminum alloys investigated only the threshold region of the fatigue crack growth curve is affected by ageing, whereas the region of constant crack growth remains virtually unchanged. Similar results were found for the AlSi7Mg alloy, which was tested at four different states of ageing (0h, 10h, 50h, 500h) and four different stress ratios (0, 0.2, 0.4, 0.6).
The data plotted in Fig. 4 shows the results for fatigue crack growth obtained in the present study. It is clearly seen that the threshold region is influenced by

ageing, whereas in the region of constant crack growth no significant influence larger than the data scatter can be found, which is again consistent with the findings obtained by Bray et al. [1] for their material grades.

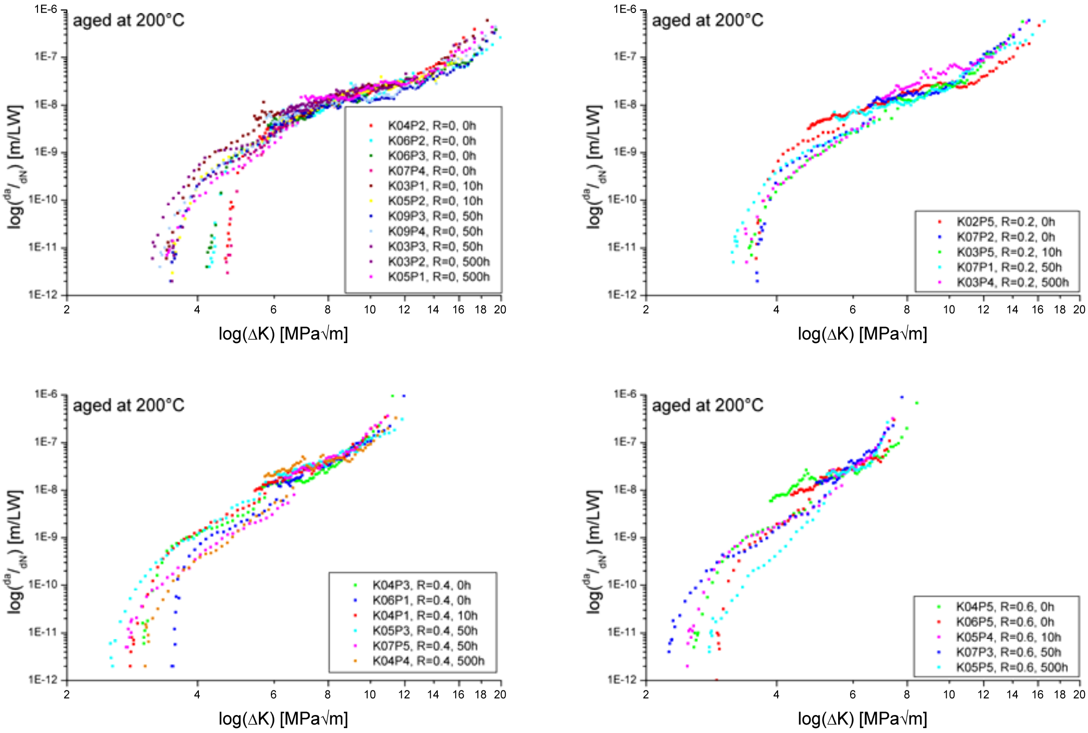

Fig. 4 Fatigue crack growth curves for different ageing states and stress ratios

4 Phenomenological modeling of the influence of ageing on the fatigue crack growth threshold

In Fig. 5, the normalized threshold stress intensity factors are compared. It can be seen that, for all stress ratios tested, the minimum crack growth rates are found for an ageing time of 50h. From a literature survey [1-6] it has become clear that, as of now, no consensus regarding the physical mechanisms responsible for the effects of ageing on the FCG threshold has been reached yet. Therefore, the following preliminary phenomenological model is proposed for describing the dependence of the FCG threshold ΔK_{th} on the stress ratio R and the ageing time t for the purpose of engineering computations, (Eq. 2):

$$\Delta K_{\mathrm{th}}(R,t) = \Delta K_{\mathrm{th,ua}}\left(1-R\right)^{\gamma_{\mathrm{ua}}} e^{-D_{\mathrm{ua}}t} + \Delta K_{\mathrm{th,oa}}\left(1-R\right)^{\gamma_{\mathrm{oa}}}\left(1-e^{-D_{\mathrm{oa}}t}\right) \qquad \textit{(Eq. 2)}$$

Here, the parameters $\Delta K_{th,ua}$ and $\Delta K_{th,oa}$ correspond to the FCG threshold at a stress ratio of R = 0 in un-aged (subscript “ua”) and over-aged (subscript “oa”) conditions, respectively.

The influence of the stress ratio is taken into account by the factor $(1-R)^{\gamma}$, which is also used in Kohout's fatigue crack growth equation [11]. However, comparing the thresholds at zero and 500h ageing time in Fig. 5, it can be seen that the influence of the stress ratio on the FCG threshold becomes smaller for the over-aged material. To include this behavior into the phenomenological model, (Eq. 2), two different exponents γ_{ua} and γ_{oa}, corresponding to the un-aged and over-aged conditions, respectively, have been introduced.

A tentative physical explanation for this behavior could be based on a decreasing influence of crack closure for the aged material as follows: after 500h of artificial ageing, the material becomes more ductile compared to the non-aged material, facilitating plastic deformation of the crack flanks in contact and thereby reducing their surface roughness contributing to crack closure.

In fact, the formal structure of (Eq. 2) corresponds to a split of the constitutive description into the response of the un-aged material (parameters $\Delta K_{th,ua}$ and γ_{ua}) and the response of the over-aged material (parameters $\Delta K_{th,oa}$ and γ_{oa}). The behavior at intermediate ageing conditions is obtained by means of the empirical matching functions exp $(-D_{ua}\ t)$ and $[1 - \exp(-D_{oa}\ t)]$, with the parameters D_{ua} and D_{oa} determining both the position and the value of the minimum FCG threshold.

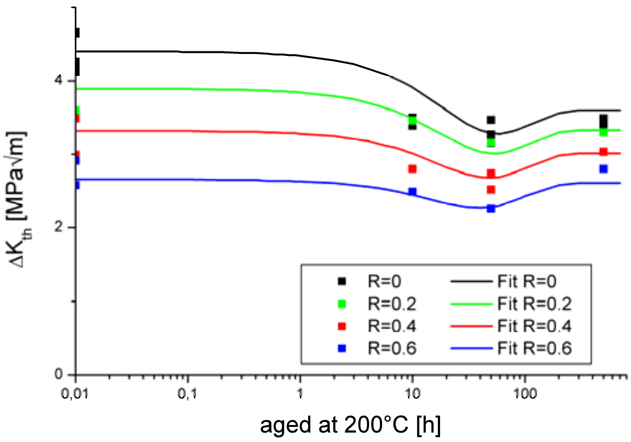

Fig. 5 Influence of ageing on the fatigue crack growth threshold

5 Fatigue lifetime estimation from fatigue crack growth data

For estimating the fatigue life of a flawed component from FCG data, the following (Eq. 3) can be used:

$$N_f = \frac{1}{A\left(2\sigma\sqrt{\pi}\,1{,}12\right)^m}\frac{2}{2-m}\left[a_f^{\,1-\frac{m}{2}} - a_0^{\,1-\frac{m}{2}}\right] \qquad \textit{(Eq. 3)}$$

For considering the ageing behavior, this equation can be extended to a two-stage crack growth curve (Fig. 6).

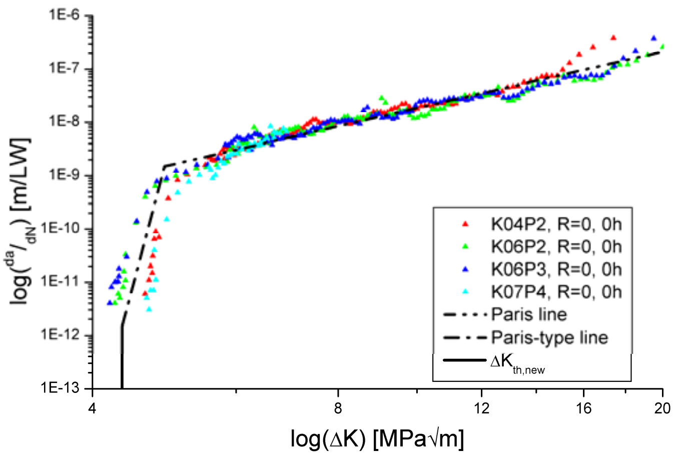

Fig. 6 Two-stage model for FCG

The parameters A_{II} and m_{II} characterize the linear part (stage II) of the fatigue crack growth curves. As noted above, these parameters do not depend on ageing. However, the influence of ageing enters through the parameters $A_I(t)$ and $m_I(t)$ defining the crack growth curve in stage I, i.e., in the near-threshold region. The two stages are integrated separately from the initial crack length a_0 to the crack length at their intersection a_i, and from a_i to the crack length at failure a_f. The sum of both integrals gives the number of cycles at failure.

The initial crack length a_0 is either given by the length of detected pre-existing flaws, or by the non-destructive testing (NDT) detection limit, or by the intrinsic crack length as defined by El Haddad's approximation to the Kitagawa-Takahashi diagram via the endurance limit stress and the fatigue crack growth threshold stress intensity factor (Eq. 4):

$$a_0 = \frac{1}{\pi} \cdot \left(\frac{\Delta K_{th}}{\Delta \sigma_0 \cdot Y(a)} \right)^2 \qquad \textit{(Eq. 4)}$$

To find the crack length at the intersection a_i, the applied stress σ and the intersection stress intensity factor $K_i(t)$, which depends on the ageing, are needed. The crack length at fracture a_f can be calculated by use of K_{IC} and the yield strength σ_y, similarly to a_0 and a_i.

6 Discussion and Conclusion

Experimental investigations on the fatigue crack growth behavior of a precipitation-hardening aluminum alloy have shown that the threshold region is affected by ageing, whereas in the region of constant crack growth no significant influence is found.
For the dependence of the FCG threshold on the stress ratio and the ageing time, a split constitutive relation has been proposed combining the constitutive descriptions of the un-aged and the over-aged material via an empirical matching function.
While the FCG threshold gives the endurance limit (i.e., the fatigue limit for infinite lifetime) for a flawed component, the FCG curve itself forms the basis for the assessment of the finite life regime. In contrast to the threshold, the remaining parts of the FCG curve do not depend significantly on ageing; this means that the effect of ageing in the finite life regime is expected to be rather small, at least for situations where linear-elastic fracture mechanics can be applied reliably, i.e., the high cycle fatigue (HCF) regime. In order to describe the influence of ageing on the HCF regime, a two-stage model must be used instead. Investigations on the correlation between measured and calculated HCF data, derived from FCG curves, are currently in progress.
The present approach for accounting for the influence of ageing on the fatigue properties of flawed components is complementary to a plasticity/damage mechanics approach for un-flawed components based on the Shercliff/Ashby model published elsewhere [12], which is applied preferably in the low cycle fatigue (LCF) regime.
It is interesting to note that the yield strength reaches a *maximum* at an ageing time of 10h, whereas the FCG threshold reaches a *minimum* at an ageing time of 50h. In other words, the static and fatigue threshold behavior at intermediate ageing conditions do not correlate. As of now, an explanation for this discrepancy is still missing, due to a lack of a physical model for the FCG threshold behavior. Work along these lines is underway. Once the effect of ageing on the FCG and HCF behavior is completely understood, it should become possible to merge the approaches presented in order to get a complete description of the influence of ageing on the LCF, HCF and FCG response.

7 References

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