Analysis of Short Crack Growth for Two Representative Light Metals

B. Oberwinkler[1], C.Oberwinkler[1], S. Redik[1], H. Leitner[1]
[1]*University of Leoben, Franz-Josef-Straße 18, 8700, Leoben, Austria*

1. Abstract
To estimate the lifetime of flawed components with the aid of fracture mechanics it's essential to know the short crack growth behavior. Therefore the crack growth was characterized for short and long cracks in two different light metals, namely Ti-6Al-4V and AlSi9Cu3, respectively.
The measurement of long crack propagation was done on single-edge-bending specimens with potential drop method to determine the crack length. To investigate the short crack growth two different methods were implemented for the measurement of microstructurally and physically short cracks, respectively. First test results confirmed the applicability of these different short crack growth measurements. Short crack growth below the long crack threshold and faster crack propagation were determined. The collected crack growth data will be used for the lifetime estimation of components made of Ti-6Al-4V or AlSi9Cu3, respectively. Thereby fracture mechanical material models will be used.

2. Introduction
The crack growth behavior of two representative light metals (Ti-6Al-4V and AlSi9Cu3) was observed. These alloys have entirely different main applications namely aviation and automotive engineering. Furthermore the shape forming is forging for Ti-6Al-4V and casting for AlSi9Cu3. According to this, different types of initial failures can occur within a component. For titanium forgings surface flaws caused by forging or foreign object damage during the application play a major role whereas for aluminum high pressure die cast alloys casting inhomogeneities (especially pores) dominate. But for components made of Ti-6Al-4V or AlSi9Cu3 respectively damage tolerant design is increasingly requested. For such a fracture mechanical approach the formation and the propagation behavior of cracks play a major role. The crack growth behavior of so-called long cracks is well documented in literature but the mechanisms causing variations in the crack propagation of short cracks compared with long cracks are not clearly clarified until yet.

Corresponding author: B. Oberwinkler, Institute of Mechanical Engineering,
University of Leoben, Franz-Josef-Straße 18, 8700 Leoben, Austria
e-mail: bernd.oberwinkler@unileoben.ac.at

In 1975 Pearson [1] observed the abnormal behavior of short cracks in commercial aluminum alloys for the first time. Short cracks already propagate beneath the stress intensity range threshold ΔK_{th}. Furthermore they possibly show significant higher crack growth rates at equivalent stress intensity ranges ΔK compared with long cracks. The crack growth behavior of short cracks is often explained by the absence of crack closure mechanisms [2, 3]. But Nalla et al. [4] report that short cracks propagate also beneath the effective stress intensity range threshold $\Delta K_{th,eff}$ which is corrected regarding crack closure effects.

Analyses of the fatigue behavior of Ti-6Al-4V show that the crack initiation site and the proceeding crack propagation path depend primarily on the microstructure. Numerous authors [5-8] analyzed the short crack growth in Ti-6Al-4V and found the typical short crack effects mentioned before. But for mill-annealed microstructure detailed information regarding short crack propagation is missing.

The literature [9] shows for Al-Si cast alloys that a crack initiates in absence of coarse pores at micro porosities or at damaged Si-particles within the eutectic phase. At low stress intensities – typical for short cracks – the crack propagates through the α-aluminum matrix. The stress intensity increases with growing crack length whereby the crack propagation mode changes at a certain material dependent value of the stress intensity. Then the crack growth occurs preferred through the eutectic. This change in the crack growth mode indicates the transition from short to long crack growth. Caton et al. [10] analyzed the crack growth behavior of a 319 aluminum cast alloy and found a distinct short crack effect too.

In the present research work two different methodologies for measuring the short crack growth are implemented. The crack growth behavior of mill-annealed Ti-6Al-4V and high pressure die cast AlSi9Cu3 is analyzed for long cracks, physically and microstructurally short cracks respectively. The results are reported as follows.

3. Material characterization

The Ti-6Al-4V for this research work has been provided by Böhler Schmiedetechnik GmbH & Co KG in form of V-shape forgings. Subsequent a mill-annealing heat treatment has been done. A detailed characterization of the thermo-mechanical treatment is given in [11]. Mill-annealing doesn't cause complete recrystallisation and leads therefore to a distinct texture of the primary α-grain shapes in respect of the forging process (cf. Fig.1 left). Due to the missing recrystallisation step the costs of thermomechanical processing of components are reduced but the microstructure is not as well defined as for solution treated or recrystallisation annealed components. The long crack growth direction is marked in Fig.1 left with an arrow and will be discussed later on. Due to the forming temperature no crystallographic texture occurs in the microstructure [12]. This has been shown with X-ray diffraction (XRD) measurements.

AlSi9Cu3 is a hypoeutectic Al-Si alloy and represents the most widely used alloy for high pressure die casting (hpdc). The microstructure with the α-Al dendrites, plate-like eutectic silicon and intermetallic phases is shown in Fig.1 right. Due to the different cooling rates in the hpdc-component the eutectic phase in the surface regions shows only a coarse distribution of the eutectic silicon phase. The specimens for the short crack growth experiments have been manufactured from this area because of the absence of casting defects.

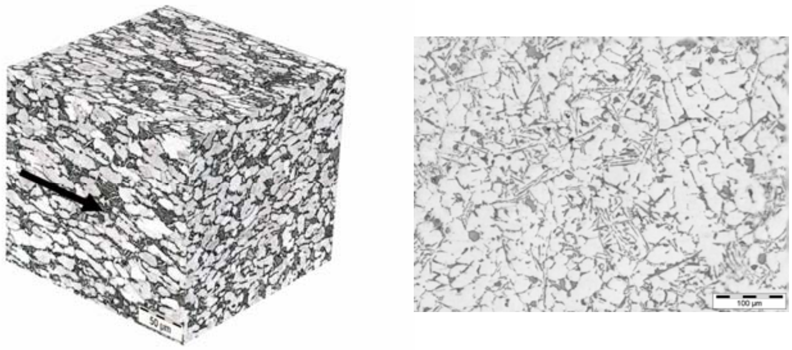


Fig.1: Micrographs of Ti-6Al-4V – the arrow depicts the direction of long crack propagation – (left) and AlSi9Cu3 (right)

4. Long crack growth

The characterization of the long crack growth was done with V-notched single edge bending (SEB) specimens under four point bending loading at room temperature and ambient air with a resonant testing rig. Thereby the crack length was measured with the potential drop method. Temperature compensation was done with a Pt100 resistance temperature sensor fixed at the specimens near the crack. The measurements were performed for four different stress ratios *R* (ratio of minimum and maximum stress or stress intensity respectively) for Ti-6Al-4V (3 specimens per stress ratio, cf. Fig.2 left) and AlSi9Cu3 (2 specimens per stress ratio, cf. Fig.3 left). For a stress ratio of zero the stress intensity range threshold for Ti-6Al-4V is approximately 4.8 MPa√m and for the aluminum cast alloy 3.6 MPa√m. Due to limitations of the maximum testable stress intensity range (80 MPa√m) the critical stress intensity range was not reached for Ti-6Al-4V for stress ratios smaller 0.7.

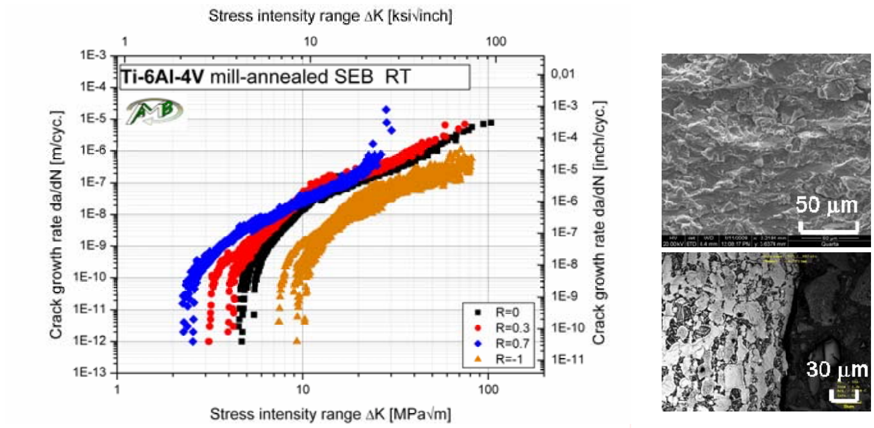


Fig.2: Long crack growth behavior of Ti-6Al-4V and fracture surface and transect

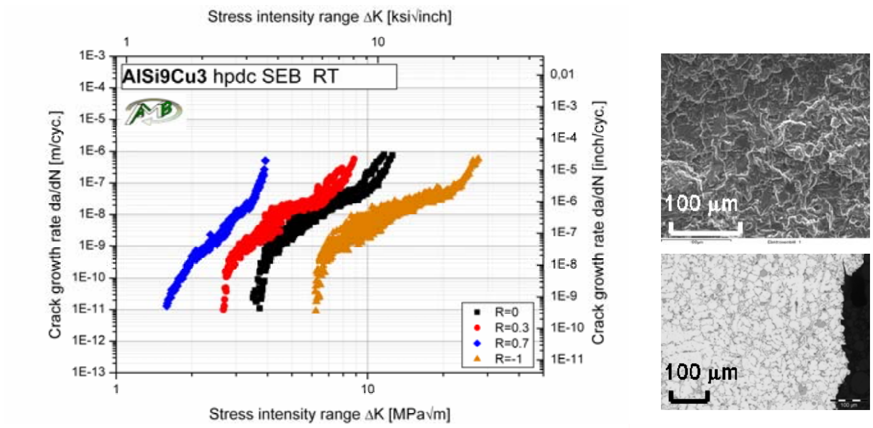


Fig.3: Long crack growth behavior of AlSi9Cu3 and fracture surface and transect

Fig.2 and Fig.3 right hand depict the crack surface (scanning electron microscopy SEM) and transect (light optical microscopy) from the middle of the SEB specimens (plane strain state) resulting from a stress ratio of 0.7 and a loading in the Paris region (growth direction from top to bottom). The crack propagation seems to be transcrystalline for Ti-6Al-4V and intercrystalline for AlSi9Cu3. Furthermore the texture – from left hand to right hand side in the SEM micrograph – of the primary α-grain shapes in the mill-annealed Ti-6Al-4V can be identified in the fracture surface.

5. Short crack growth

All measurements of short crack growth (SCG) were done at ambient air and at room temperature. Two different methodologies of short crack growth characterization were applied in the present work.

For Ti-6Al-4V naturally grown short cracks are observed, cf. [8]. Therefore electrolytically polished round hourglass specimens (gauge diameter 6 mm) were loaded under rotating bending (R = -1) in the finite life region (constant stress amplitude 750 MPa).

The expected lifetime at this stress level is approximately 16,000 load cycles. About 25 % of the lifetime is consumed for crack initiation. After this crack initiation phase an etching has been done to visualize the microstructure and to accent the initiated cracks. Due to the dimensions of the cracks – they approximate the primary α grain size – they can be classified as microstructurally short. Then the fatigue tests were continued at the same stress level and interrupted after a given number of cycles. For evaluation of the crack length with a confocal laser scanning microscope (LEXT) crack opening was necessary. Therefore a loading rig was designed for static loading of the round specimens during the microscopy. The width to depth ratio of the surface cracks, approximately 0.25, was also evaluated with the LEXT. The stress intensity factors F_I were determined for a round bar containing a semi-elliptical surface crack under rotary bending according to Murakami [13]. The stress intensity ranges ΔK_I of the surface cracks were then calculated appropriate to Eq.(1) where $\Delta\sigma_0$ is the applied stress range and s is the half arc length of the crack (approximately equivalent to the crack length for small cracks).

$$\Delta K_I = \Delta\sigma_0 \sqrt{\pi\, s}\, F_I \tag{1}$$

The first results show that the initial cracks grow at stress intensity levels beneath the threshold of long cracks (cf. Fig.4 left). Thereby every data point stands for one initial crack after 1,000 additional load cycles. The averaging over 1,000 load cycles is the reason for the low (sub-angstrom) crack growth rates. Fig.4 right shows two initial cracks and their growth due to 1,000 load cycles (confocal laser scanning microscopy). The regions of interest are marked with circles. Thereby the thick black lines are the initiated cracks (enlarged due to the etching). The cracks nucleate in α grains at slip bands as well as in α+β phase. The crack propagation takes preferentially place in α grains. Interconnected α grains lead therefore to an acceleration of crack growth. In α phase the crack propagation is transcrystalline whereas in (α+β) phase the crack grows intercrystalline.

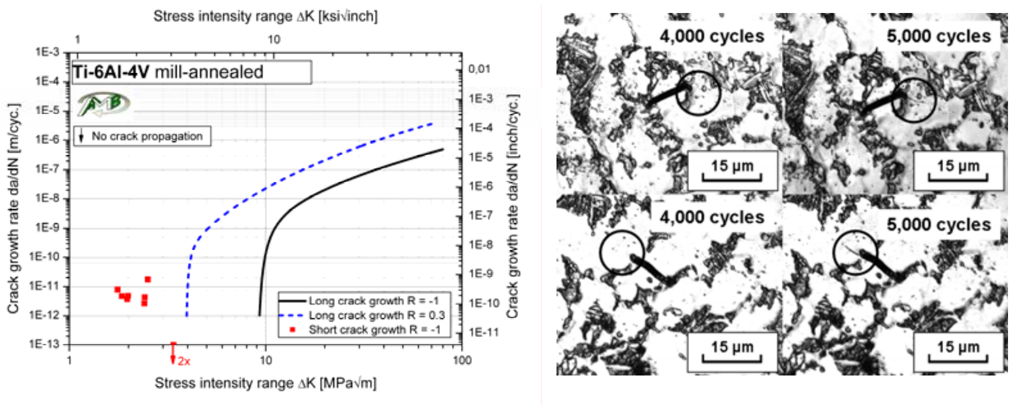
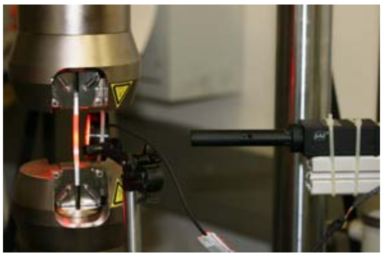


Fig.4: Crack growth rates of short cracks (left) and microscopy results, regions of interest are marked with circles (right)

The second type of measurement of the short crack growth has been done on plane tension/compression specimens provided with initial cracks. The initial cracks with a length of 0.4 mm were produced by wire-cut electrical discharge machining. The crack width corresponds with the thickness of the plane specimens (8 mm). Due to this dimensions the cracks can be classified as physically short. Uniaxial short fatigue crack growth tests were conducted in load control at a frequency of 30 Hz on a servo hydraulic testing machine. Tests were performed at different stress levels. Crack length was measured optically by a purpose designed camera system (cf. Fig.5 left).
The camera system consists of a digital CCD monochrome area scan camera with objective lens (eightfold magnification) and a dark field illumination. In dark field illumination technique the light which illuminates the sample is not collected by the objective lens; only diffusion on irregular surface texture leads to reflection of a small portion of light. Therefore dark field illumination produces a dark almost black background where cracks appear bright. For a better visibility of the cracks the specimens were polished and ultrasonic-cleaned before testing. To monitor crack growth the tests were interrupted after a defined number of cycles and a picture was taken by the camera system. Crack length was measured from the picture and the crack growth rate and the according stress intensity range were calculated. The procedure was repeated several times until failure. Each interruption produced a data point of the crack growth diagram.
Currently the short crack growth behavior of AlSi9Cu3 is analyzed with this method. Further research work will be done on mill-annealed Ti-6Al-4V to compare microstructurally and physically short crack propagation. Fig.5 right hand shows the first test results for three different stress amplitudes and a stress ratio of -1. It can be observed that the small cracks propagate at lower stress intensity factors than long cracks and they propagate faster, cf. Fig.3. Fig.6 depicts the dark field pictures of a crack at different load cycles.



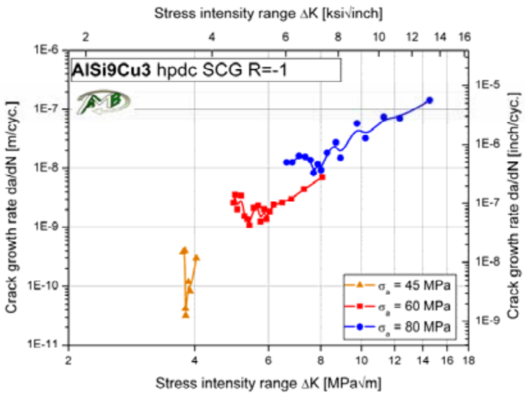


Fig.5: Short crack growth measurement setup with camera system (left) and crack growth results (right)

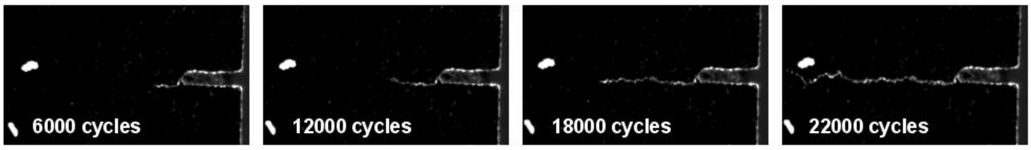


Fig.6: Crack lengths for different load cycles

6. Discussion

The single edge bending tests show distinct differences in the long crack growth behavior of Ti-6Al-4V and AlSi9Cu3. Among the expected differences in the absolute values of the stress intensity range thresholds the scatter shows also varieties depending on the material. Although Ti-6Al-4V is a high-purity material the results show a huge scatter in the near threshold region independent of the stress ratio. This behavior may be caused by the mill-annealed microstructure, cf. [14]. By contrast AlSi9Cu3 shows a low scatter in the near-threshold region as well as in the Paris regime.

The analysis of the crack growth of microstructurally short cracks in Ti-6Al-4V shows that some of them (crack lengths 10 – 20 μm) propagate at stress intensity ranges below the threshold of long cracks. Two relative large cracks (initiated in $\alpha+\beta$ phase) with a length of approximately 50 μm were found after the initiation phase. They were not growing during additional 1,000 load cycles. Assuming that the short cracks are not affected by crack closure their propagation behavior may be compared with the long crack growth curve for a stress ratio of 0.3 (cf. Fig.4 left). Then the thresholds of the long cracks and for the initial short cracks match well.

The physically short cracks in AlSi9Cu3 also show crack propagation at stress intensity ranges below the threshold of long cracks. At higher stress intensity ranges they show a faster crack propagation compared with long cracks.

7. Conclusion and Outlook

Long crack growth measurements were performed for mill-annealed Ti-6Al-4V and for high pressure die cast AlSi9Cu3. Distinct differences were found for stress intensity thresholds and scatter in the near-threshold region.

Physically short crack growth measurements were done for AlSi9Cu3. The crack length has been measured with a purpose designed camera system. Distinct differences in the growth behavior of short and long cracks were found. The aim of the presented research work is to derive a fracture mechanical based material model linking the casting defect size to fatigue strength. This will help to drastically reduce testing time and consequently costs as it is required for an existing stress based material model [15]. This knowledge can be directly linked to the estimated defect distribution in the component [16] to compute the life time of hpdc-components.

For Ti-6Al-4V naturally grown microstructurally short cracks were observed. Thereby the crack length was measured with a laser scanning microscope. The crack growth behavior of these short cracks exhibits distinct differences compared with long crack propagation. Further measurements at physically short cracks in Ti-6Al-4V will be done with the camera system mentioned before. The collected crack growth data will be used for the lifetime estimation of components made of mill-annealed Ti-6Al-4V. Thereby a combination of safe life and fail safe approaches will be implemented [11, 17].

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