In-situ observation of initiation and propagation of (short) microstructural crack growth using a rotating bending machine

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ABSTRACT. *For a comprehensive understanding of the fatigue behaviour of engineering materials fatigue crack growth experiments are needed in addition to conventional fatigue tests. Besides the experimental determination of the crack growth fatigue behaviour of long cracks especially the phase of crack initiation and behaviour of microstructurally short cracks are important for materials characterisation. This methodology needs adequate testing machines which allow the observation of all stages of crack growth. Conventionally, testing machines do not allow a combined characterisation of multiple short crack initiation and propagation phase up till fracture of specimens. Furthermore, experiments are limited to the observation of one crack and require special preparation of testing specimens.*

For the purpose of characterization of multiple cracks in the stage of crack initiation, on the Chair of Mechanical Engineering the special rotating bending machine was designed. Based on a 3-point bending system the testing device is able to operate under a confocal laser microscope allowing in-situ observation of short crack growth using typical fatigue specimens. During fatigue process multiple short cracks initiate and propagate on the specimen's surface. These short cracks can be analyzed by the aid of the microscope up till fracture of the specimen.

In this contribution the short crack growth investigations were done on the casting material austempered ductile iron (ADI). Microstructural cracks initiate at the surface of the specimen and within 10% of the fatigue process related to the number of cycles to failure.

It shows that microstructural cracks are initiated on the nodular graphite at the surface within the initial 10% of the load to rupture. With progressing fatigue, the sub-surface cracks which primarily originate in vicinity of the graphite nodules below surface, began to appear on the surface.

INTRODUCTION

For characterisation of fatigue behaviour of a material, cyclic tests with standardised round specimens at different loading levels are done. The end of fatigue tests is defined as the failure of the fatigue specimen or achievement of a defined number of cycles. For a comprehensive understanding of fatigue behaviour the influence of microstructure on crack initiation and propagation in addition to conventional fatigue strength are important for estimate fatigue life. Therefore, information of the microstructural sites of crack initiation and the characteristics of crack path in the different stages of crack growth is needed. Conventional (rotating bending) fatigue tests provide only incomplete information of crack initiation after fatigue test and require extensive fractographic analysis.

An analysing method to characterise the short crack growth is presented in [1]. The fatigue specimens were tested on a conventional rotating bending machine and crack were analysed on a light microscope, separately. After declamping from the testing machine the crack behaviour can analysed with the aid of a light microscope with a special bending clamping rig which opens the cracks during crack observation, shown in Fig. 2. After reaching the a certain number of cycles on the conventional rotating bending fatigue testing rig this procedure of analysing the fatigue cracks is repeated till fracture of the specimen. The great disadvantage of this method is the time consuming and extensive test procedure.

Fig. 1 Conventional rotating bending machine for high cycle fatigue (HCF) tests designed by AMB (Chair of Mechanical Engineering)

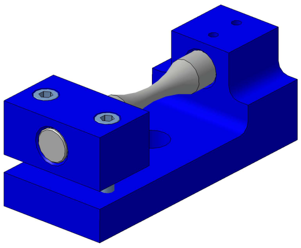

Fig. 2 Bending clambing rig for crack obersvation of specimens tested on conventional rotating bending testing machine

In the following a new testing machine designed on the Chair of Mechanical Engineering is described which operates directly under the light microscope using conventional specimens for rotating bending fatigue tests. This method allows the characterisation of the short cracks on the specimen's surface without demounting.

MINIATURE ROTATING BENDING MACHINE (MINI-UB)

For short crack observation the testing device has to combine fatigue testing process (crack initiation and crack propagation) and the observation of crack growth and crack length with the aid of a light microscope. For analysis crack initiation and propagation the test machine applies bending moment for a defined number of cycles directly under the light microscope. The observation of crack propagation due to loading with the light microscope the testing machine provides the possibility of access precisely the position of the different cracks of interest.

The microscope of analysis is a laser-confocal LEXT OLS2000 (LEXT) with maximum loading weight of 10 kg and a very limited space at the object holder. Furthermore, the testing machine should provide the possibility of only crack analysis with scanning electron microscope (SEM).

Subsequently the boundary conditions of the test machine can be summarized as:

- Rotating bending for crack initiation on surface
- Operation under microscope
- Specimens has to be compatible to conventional rotating bending machine
- Test frequency > 5 Hz
- Angle resolution during rotation for positioning of < 1°
- Mounting on LEXT and SEM
- Easy handling

After virtual design a 3-point bending system with force application emerges from the other design concepts. With an appropriate specimen shape design, the asymmetric momentum distribution due to 3-point-bending is then changed in an axially symmetric stress distribution over the specimen.

Force application is linked with an on-line monitoring and can apply a maximum force of 250 N which e.g. will cause an maximum elastic stress level at the specimens surface with a testing diameter of 5.5 mm of 765 MPa.

The drive is a special combination of closed loop stepper motor and an planetary gear (1:5 ratio) to achieve the combination of high stepping resolution (< 0,1°/step) and moderate test frequency of 10 Hz.

The construction achieves all of the requirements. The dimension of the machine are 335 x 65 x 58 mm with a weight of 3.2 kg including a steel specimen.

It consists of 4 modules:

1. Drive module
2. Specimen support 1
3. Specimen support 2
4. Force application.

These modules are marked in Fig. 3 by different colouring. For SEM application the first listed module can be extracted while the remaining modules were bending-resistant connected. Hence each component is special designed for high vacuum operations with special features[1] except the drive module. In Fig. 3 also the SEM-mounting and the manufactured prototype is shown. Furthermore, to improve the safety handling, an operation appraisal was done according to the safety regulations EN ISO 13849:2003 and EN ISO 12100:2003.

The operating Mini-UB under the confocal light microscope LEXT and the individual programmed easy handling user-interface is shown in Fig. 4 [2].

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[1] For example one feature is using full ceramic bearings and ultrasonic resistant (for cleaning) force measuring box for online monitoring.

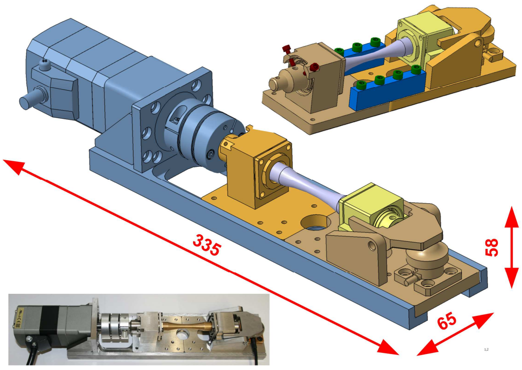

Fig. 3: Miniature rotating bending machine; middle: construction with motor and main dimensions in mm, right upper corner: manufactured prototype; right upper corner: Mini-UB for SEM use.


max Spannung (MPa) 502
aktuelle Position (°) 0,000
aktuelles Lastwechselspiel (1) 0
Probendurchmesser 4,5
Probendrehzahl (Upm) 0,000
fahre zu Position 0
gewünschte Lastwechselzahl 0
Kraftmessdose (N) 89,9

Fig. 4: Operating Mini-UB under LEXT and user interface.

RESULTS OF SHORT CRACK GROWTH EXPERIMENTS WITH THE MINI-UB

The first observations for the short crack growth analyses were done with an austempered ductile iron (ADI), according to DIN-EN-1564:1997.

Experimental Setup

Material selection

The fatigue specimens made out of austempered ductile iron with a tensile strength of 1000 MPa (EN-GJS-1000-5; short: ADI 1000) were tested. Austempered ductile iron is produced by a special heat treatment out of conventional casted ferritic/pearlitic ductile iron and exhibits higher strength and ductility related to the base material. The microstructure after heat treatment is shown in Fig. 5 and consists of graphite nodules and acicular ausferrite.

Dependent on the austempering temperature the material can be used for applications requiring high wear resistance or average strength and good ductility [3,4].

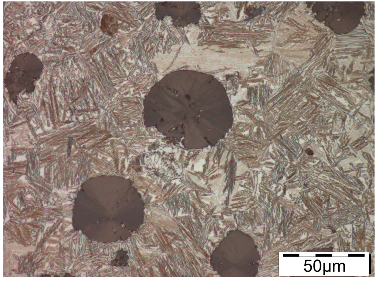

Fig. 5 Etched metallographic grinding of ADI 1000 graphite nodules and acicular ausferrite nodular graphite and ausferritic matrix

General microstructural crack growth

For an appropriate choice of a fracture mechanics approach to describe the crack growth behaviour the following three main influences which have to be taken into account:

- Kind of material,
- Crack length and the
- Local and global loading situation.

Especially at the crack front, the forming and size of the plasticity zone plays an important role in analysing short crack behaviour. Only when the plasticity zone is small enough in relation to the microstructural short cracks the application of the linear elastic fracture mechanic (LEFM) is justified. Eq. 1gives an approximation of the dimension of the plasticity zone at the crack tip [5].

$$r_{pl} = \frac{K}{2\pi\sigma_y^2}(1-2\upsilon)^2 \tag{1}$$

where ν is the poisson's ratio, σ_y the yield stress and K the stress intensity factor. The yield strength for ADI 1000 is about 700 MPa.

The LEFM connects the crack propagation to the loading situation with the stress intensity factor range ΔK, defined by Eq. 2.

$$\Delta K = Y\Delta\sigma\sqrt{\pi a} \tag{2}$$

where Y is the geometry factor, $\Delta\sigma$ the outer load range and a the crack length.

In the case of the presented austempered ductile iron the LEFM (linear elastic fracture mechanics) is applicable only when mode 1 cracks appears and the plasticity zone doesn't exceed half of the grain size.

Surface preparation method of the fatigue specimens

To indentify small cracks under the microscope clearly, the specimen's surface has to be prepared with special methods. The geometry for the short crack growth experiments was a 140 x 12 mm round specimen with a test diameter of 4.5 mm (Fig. 6) and was taken out of a heat treated Y-block according to DIN-EN-1564:1997.

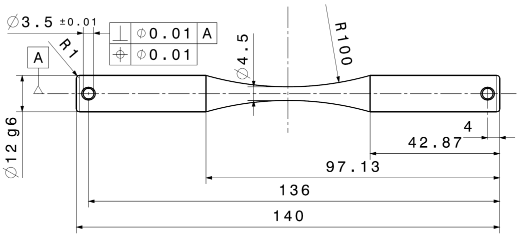

Fig. 6: CNC drafting of a 4,5 mm Mini-UB specimen

The surface finishing comprehends several steps of grinding and polishing. After the last polishing step the average surface roughness (R_Z) measured and was about 11 µm. An additional etching technique to uncover the microstructure was not applied on the fatigue specimen’s surface becaue etching process cause undesired sites of small crack initiation.

The specimen was loaded with a maximum stress level of 550 MPa during the whole testing procedure. At this stress level the specimen failed at 45000 cycles by rotating bending loading.

Results

First small cracks initiate at about 4500 cycle or 10% of the number of cycles to failure. The cracks sized after initiation from 10 to 30 µm and were orientated between 60 to 90 degrees to the uniaxial stress direction.

Every 2000 cycles till the number of cycles to fracture the crack development was analysed in several section on the specimen’s surface. To characterise the short crack growth behaviour the increasing size measured by light microscopy (LEXT) and especially the microstructural sites of crack initiation were observed.

The results of these investigations indicate that the graphite nodules play an important role in short crack growth behaviour of austempered ductile iron. In this context two different cases could be observed:

1. When a crack initiates at the matrix, any in the direction of propagation lying graphite nodule severs into two pieces;
2. Initiates the crack at the vicinity of a graphite nodule; first the direction of propagation leads from the graphite nodule away. But with increasing lifetime (about 70% of the numbers of cycles to failure) the crack propagates also into the nodule and slices it also transnodular, like in case 1 was described.

Fig. 7 shows a continuous of the crack growth at several stages of the analysing process at the specimen’s surface. At the beginning cracks initiates at surface nodules. When the lifetime increases cracks also initiates at the matrix.

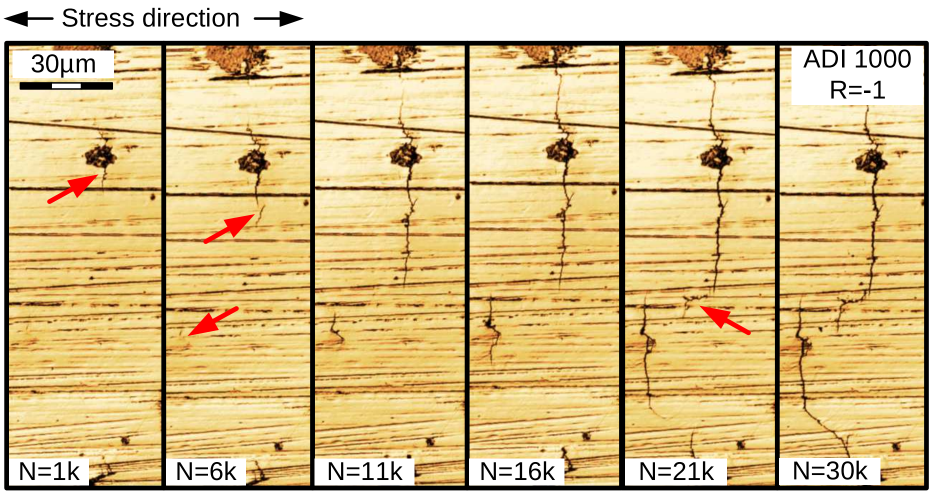

Fig. 7: Collection of the crack initiation and propagation of ADI 1000 at different numeber of cycles, fracture occurs at 45000 cycles; Each arrow shows a new crack initiation, stress level 550 MPa, rotating bending

DISCUSSION

Material specific tests

At the beginning graphite nodules are proofed places where cracks initiate. Advancing damage also leads to initiation of cracks on the matrix, due to graphite nodules which are situated direct below the surface. Finite element and metallographic investigations done by the authors of [6] confirms that assumption.
Considering the evaluation, first the plasticity zone at the crack tip was approximated with Eq. 1. The diameter then is calculated for the observed microstructural cracks between 2 µm and 25 µm, so it fulfils the LEFM condition defined above because the grain size which was measured was about 50 µm. Also all of the observed cracks propagated in mode 1 condition, like these one shown in Fig. 7, so that the evaluation of the crack propagation rate could be done by Eq. 1. The crack propagation curve for some microstructural short cracks is shown in Fig. 8. In accordance with [1] the geometry factor was set to 0,75 considering the arithmetic average of the recommendation by the authors of [7] and [8]. Microstructural short crack behaviour affects in irregular propagation rates because the inhomogeneous microstructure acts as irregular barriers. A comparison of the microstructural short and long crack growth is shown in Fig. 9. The long crack growth was tested by another system and specimen geometry [2]. Here in this investigation none of the selected cracks reached the transition from short to long crack growth and stopped before reaching the threshold.

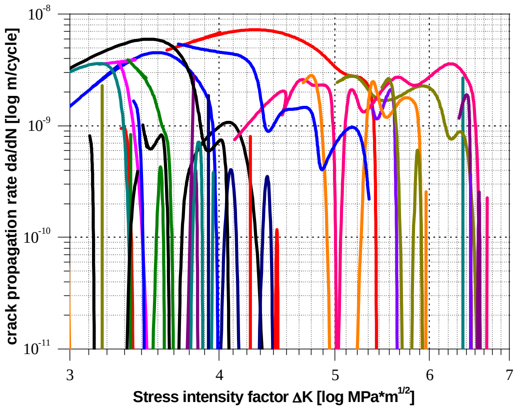

Fig. 8: Microstructural short crack growth of ADI 1000 at R=-1, evaluated by LEFM

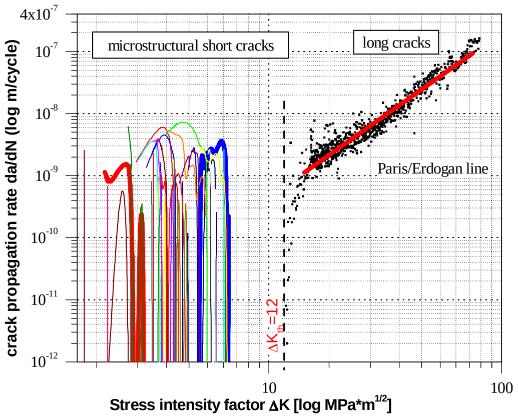

Fig. 9: Short and long crack growth of ADI 1000 at R=-1, evaluated by LEFM; Threshold located at 12 Mpa√m

Experiences of the test machine (Mini-UB)

The mechanical construction was high reliable and there was no evidence of low stiffness which may could arise because of the small construction. Now with this testing machine the time effort reduces to one third and simplifies the complete procedure significantly than the test routine presented in [1].

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