Method for efficient optical crack path observation and deformation measurement and its usage

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ABSTRACT. *The observation of cracks which curved crack path has to be done optically. It is shown that a modified commercial flat bed scanner and a combination of high-resolution scanner camera system with 10,000 x 10,000 pixels with telecentric lens are appropriate for high-resolution (up to 8 µm / Pixel) optical registration of multiple crack ends on sample areas up to 210 mm x 290 mm. The registered high-resolution images are suitable for determination of crack length. It is also possible to measure crack paths or geometrical crack tip parameters and strain fields by image correlation. The method is used to determine crack resistance and crack growth curves on CCT- and biaxial cruciform samples.*

INTRODUCTION

For fracture mechanical investigations it is important to measure the propagation of cracks. The direct optical observation of the crack is the safest measurement method to determine the position of the crack tip and to calculate the crack length. Nevertheless, it can hardly be automated and the detection of small changes in crack size needs high magnification. Therefore, in the past indirect methods has been developed. Among these the potential drop method where the electric potential over the crack tip is measured while a constant currend is sent through the sample is widely used. Another common method is the measurement of small changes in stiffness of the sample (compliance method). These methods are well established for standard testings in particular because its signals are recordable easily. Each method has its own additional sources of error - for instance the local change of electric conductivity by plastic deformation. In addition these indirect measurement methods for crack length give only a projection of the crack length. Changes in crack direction are not determined. So the most standards demand a calibration of these methods with optical measurements and give restrictions for the tolerable change of crack direction such as [1].

The optical crack observation is usually done by a (video-) microscope which can be moved by linear actuators with integrated length measurement system. For the measurement the test is paused, the crack tip positions are located and measured with the microscope. With this method it is possible to observe cracks on curved paths [2] or to measure geometrical crack tip parameters like the crack tip opening angle (CTOA) or δ_5 which are used especially for testing plates with low constraint [3,4]. The major problem to automate this procedure is that a self acting crack tip detection within a digitalized picture is up to now not reliable. So an operator has to be present during the whole test. To overcome this, the complete area of interest should be saved in a high resolution picture. The main handicap of the existing practice is the small image section which can be viewed in a high magnification.

MODIFIED FLAT BED IMAGE SCANNER FOR CCT-TESTING

A commercial flat bed scanner with CCD line sensor *CANON Canoscan 4200F* which gives a resolution up to 3,200 dots per inch was modified for the high magnification observation of areas up to 210 mm x 290 mm. The modifications consist mainly of the removal of the transmitted light unit together with the cover. For the vertical usage reinforcements of the body with fixing holes were adapted. The frame of the glass pane was changed that the latter can contact directly the specimen. The distortion was determined by measuring a sheet of millimeter paper against the coordinate measurement table to be smaller than 0.02 mm.

Sample applications

Measurement of cyclic crack growth curves using CCT-Specimen

The tests were done using CCT-Samples (400 mm x 160 mm x 5 mm) made of aluminium alloy 7175 in T 7451 condition with a 3 mm EDM starting notch on a

Figure 1. Test set-up with modified flatbed scanner and 160 mm CCT-sample

servohydraulic universal testing unit MTS 880. Figure 1 show the test set-up.

Crack growth curves were performed in load-control with a constant stress range of 90 MPa and a stress ratio R = 0.1 at a frequency of 3 Hz. The measurement areas of the samples were polished mechanically. Crack length from the compliance measurement and cycle counter was used to trigger to take a picture. When the calculated crack extension from the compliance measurement extended 0.7 mm or the cycle counter exeeded 2,000 cycles the test was interrupted and a picture of the defined measurement area (165 mm x 32 mm) was taken at a resolution of 3,200 dpi. The freeware script interpreter *runcmd* was used to automate the control of the scanning software. With this script also the sample identification and the actual cycle counter or servo cylinder stroke were included in the file name of the picture. The measurement of crack length was done with the free available image processing system *ImageJ* offline after the test. In this procedure the crack tips were marked by hand. Figure 2 shows an image of a 160 mm CCT sample with two crack tips of each approximately 50 mm in length. A magnification of the right crack tip from the same picture is shown in Figure 3. In a direct comparison there was no significant difference between the scanner measurements and a measurement with video microscope. Figure 4 shows a typical crack growth curve measured with this set-up. The typical scatter of fatigue crack propagation measurements with the secant method can be smoothed using the 7-point polynomial method according to ASTM E 647-08 [1].

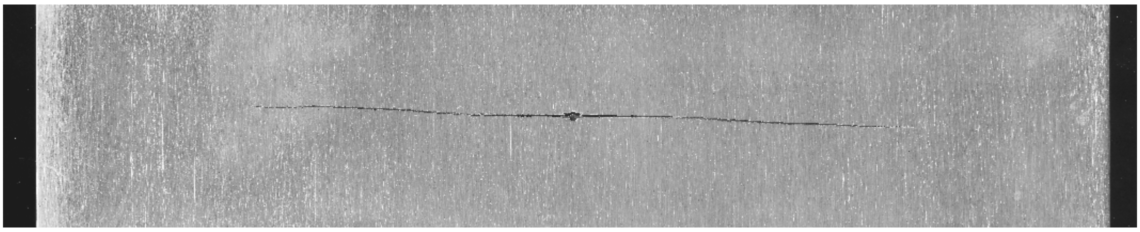

Figure 2. Picture of the measurement area of a 160 mm CCT sample

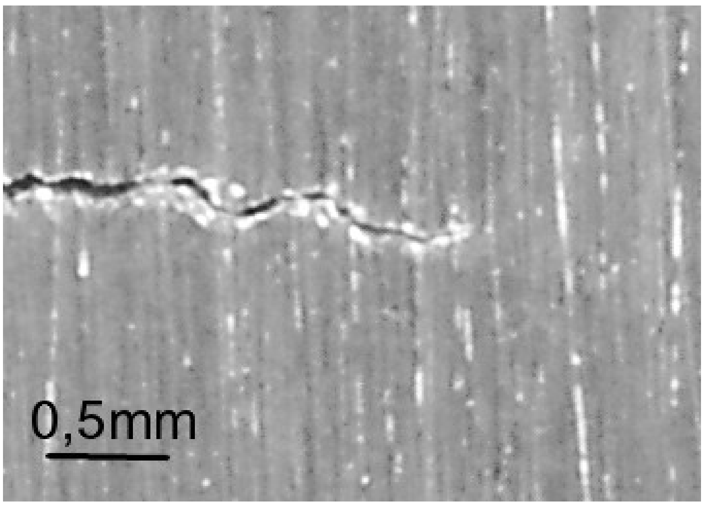

Figure 3. Zoom of Figure 2

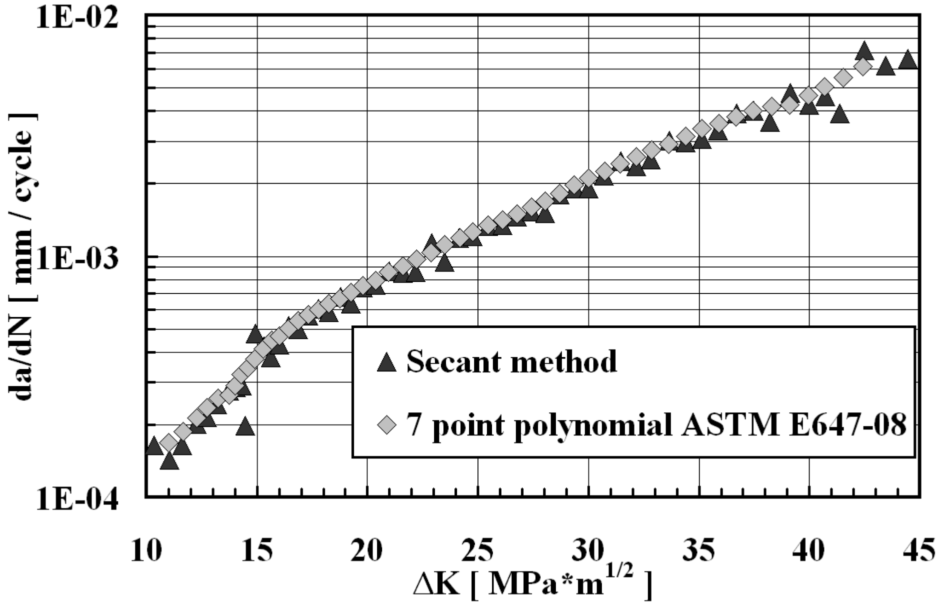

Figure 4. Typical crack growth curve

Measurement of crack resistance curves using CCT-Specimen

The measurement of crack resistance curves is done in a similar way. After precracking the sample by fatigue load two hardness indentations were inserted in 2.5 mm distance to the crack tip. During the static test a tensile load was applied by cylinder stroke control. Every 0.1 mm enhancement the test was stopped to take an image of the measurement area. The crack extension and the movement of the hardness marks were measured in the pictures. Figure 5a shows a propagated crack tip and Figure 5b shows a crack resistance curve measured with this set-up.

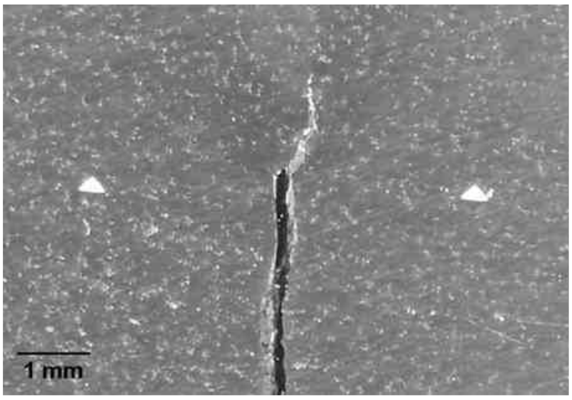

Figure 5a. Crack tip with hardness indentation for optical δ_5 measurement

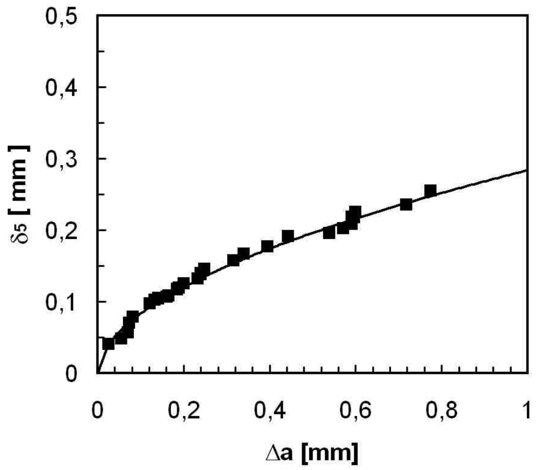

Figure 5b. Crack resistance curve – optical crack length and δ_5 measurement with flatbed scanner

Measurement of crack path

The system was also used successfully for the determination of curved fatigue crack paths under biaxial planar load. Figure 6 shows such a path starting on an excentric notch in Y-direction while the load ratio between the loading axes was $\lambda = F_X / F_Y = 2$. To determine the crack growth rate the test was interrupted to mark the crack tip position on the sample and to record the related cycle counter. After finishing the test the measurement area was machined out of the sample and scanned. The crack path and the crack growth rate were measured in the image. The investigated crack paths had good accordance to curves predicted with the PCCS-2D FEA Program [2].

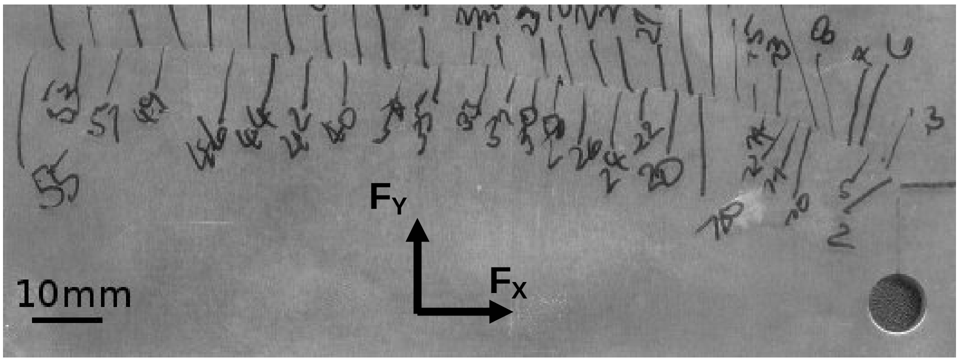

Figure 6. Crack path under biaxial load, $\lambda = F_X / F_Y = 2$

MEASUREMENT ASSEMBLY WITH CAMERA SCANNER

Especially the small amount of depth of focus limits the usage of the flat bed scanner system for instance, if anti-buckling devices are used or if samples for biaxial crack growth tests with reduced thickness in the middle area are investigated. This kind of sample is shown in Figure 7.

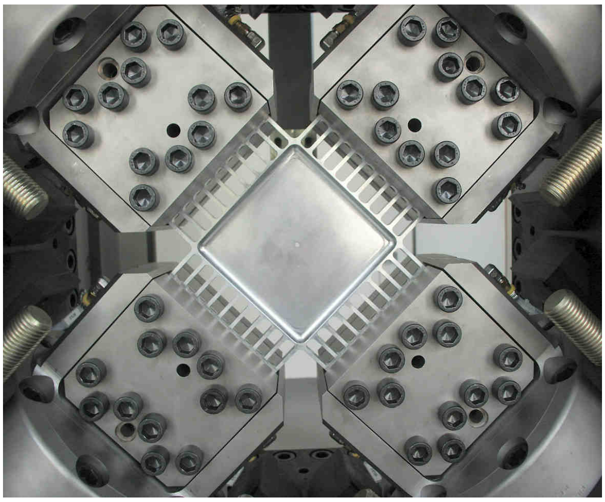

Figure 7. Biaxial planar sample for fracture mechanics investigations fixed in test rig

To enhance the field of application for such cases a system with a camera scanner *Pentacon SCAN 6000* is used. It consists of a 40 mm trilinear CCD line which is moved over an image field of 40 mm x 40 mm. Pictures with a resolution of up to 10,000 x 10,000 pixels can be taken from this area. The scan time for the whole image field is

Figure 8. Scanner camera system consists of: Pentacon scan 6000, telecentric lens, LED ring light and alignment kit

approximately 120 s. A telecentric lens is used to get an object field of 120 mm x 120 mm with negligible distortion for a lens-specimen distance of 400 mm. The depth of focus is approximately 4 mm. The resolution of this system was measured with a reticule of lines to 45 line pairs per millimeter. This is in the range of the pixel size on the object side. Figure 8 shows the camera system together with the alignment and positioning kit and the LED ring light. With this system the incident light goes nearly rectangular to the specimen surface. The telecentric lens select mainly the rectangular light direction again. So cracks in all directions appear black. An image of a biaxial sample made of 6061 T6 aluminium alloy and tensile tested made with the camera scanner is shown in Figure 9. The initial crack was EDC machined under 45° according to the loading axes. In addition a starting crack was extended under fatigue loading conditions. The load ratio between the axes was $\lambda = F_X / F_Y = 1$. Four shear cracks are formed. Two of them grow in the rolling direction, the other two cracks which should

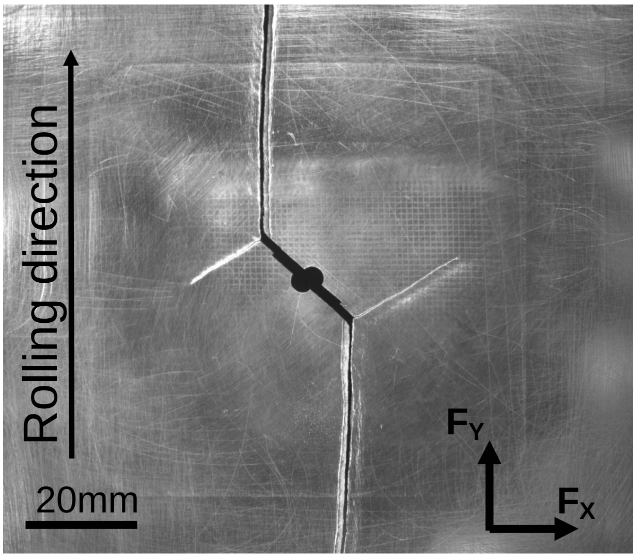

Figure 9. Measurement area of tensile tested cruciform sample

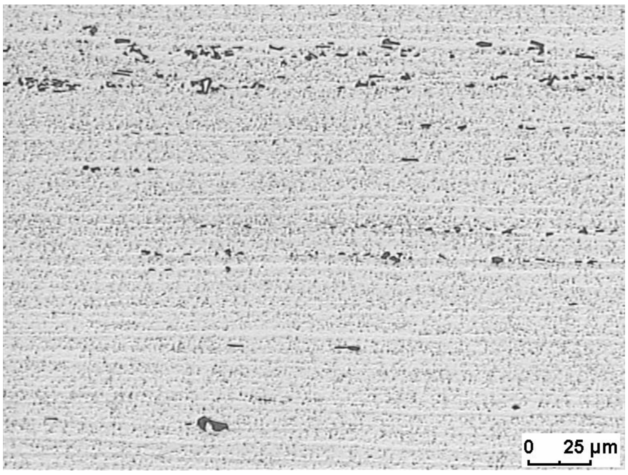

Figure 10. Microstructure of the 6061 T6 alloy with wrought structure

run 90° to the rolling direction prefer a path app. 60° to this direction. This is mainly caused by materials anisotropy which is shown in Figure 10. If a measurement grid or a statistic pattern is applied to the surface then the images can be used for deformation field investigations using image correlation.

SUMMARY AND CONCLUSIONS

With the presented method it is possible to get high resolution images to determine the crack and deformation development on the complete measurement area of biaxial planar samples and 160 mm CCT-samples. Curved crack propagation can easily be observed automatically without the need of an operator due to the possibility to evaluate images after the tests. There is no information lost if additional cracks occur and the complete primary data are stored for additional investigations. A calibration of the system can be done with marks on the sample. The pictures can be used to determine geometrical crack tip parameters like δ_5 or CTOA and to measure deformation fields using image correlation if a stochastic or regular pattern is applied to the sample. The high resolution of the scanning devices applied in the present study are necessary for the detection of details on the samples surfaces. However the high number of pixels does not give proportional higher precision in deformation measurement because of the movement of the CCD line. In [5] the accuracy of a kamera scanner was determined to 1/7 pixel while a camera with fixed CCD area chip reached 1/30 pixel. In all cases a fix set-up and specimen are necessary during the scan. The digital image size of 50 to 100 Mb can easily be handled by actual computer equipment.

ACKNOWLEDGMENT

Special thanks go to AMAG Austria Metall AG for providing test material and to DFG (German Research Foundation) for purchasing the equipment and supporting our research within the collaborative research center 799 Trip Matrix Composites.

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