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Kay A. Weidenmann, Eberhard Kerscher, Matthias Merzkirch

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In Situ Damage Detection With Acoustic Emission Analysis During Cyclic Loading of Wire Reinforced EN AW-6082**

By *Kay André Weidenmann*, *Eberhard Kerscher* and *Matthias Merzkirch**

In the field of lightweight construction, hybrid structures such as reinforced metal matrix composites are highly qualified materials. The direct composite extrusion process allows for continuous manufacturing of wire reinforced aluminum matrix profiles. The aim is to increase the stiffness and specific strength in a way that the composite material shows better mechanical properties than the single matrix material. To determine and locate damage evolution during cyclic loading of spring steel reinforced EN AW-6082 matrix the acoustic emission analysis is used. Furthermore it allows for getting more information about the damage mechanisms during fatigue of the matrix and the final failure of the reinforcing element. The current work also includes the determination of damage evolution using strain measuring methods.

For the production of aluminum profiles with endless reinforcement a 10 MN extrusion press with modified porthole dies are used to feed the reinforcing elements from the outside of the pressing tool. In order to embed them inside the material flow during the extrusion process, Figure 1 (left), the conventional billet in front of the cover plate is split into upper and lower strands which join again in the welding chamber of the die with the reinforcing element in between. Figure 1 (right) shows the design of a composite extrusion tool for a flat profile.

The reinforcing element bonds to the billet material under high temperature (400–550 °C) and pressure. During the extrusion process there is no external force needed to feed-in the reinforcing wires because the billet flow applies a tensile force to the wire in the direction of the extrusion.[1]

Experimental

Specimen Material and Geometry

The matrix material was the aluminum alloy EN AW-6082 (AlMgSi1) in heat treatment state T4 (F) which was realized by quenching with air after the extrusion process. The composite specimens were made from the same matrix material and additionally reinforced during composite extrusion with a spring steel wire (X10CrNi 18-8). The gauge length of the cylindrical specimen was 10 mm with a diameter of 3 mm. The centric placed wire has a diameter of 1 mm resulting in a volume fraction of 11% in the gauge length (see Fig. 2, left).

Experimental Setup

The tests were carried out with an electro-dynamic testing machine Instron E3,000 with specially designed clamps allowing for hydraulic mounting of the specimen as well as attaching the acoustic sensors to the specimen (see Fig. 2, right) [2]. The stress-controlled fatigue tests were carried out at a stress ratio of $R = -1$ with a loading frequency of 10 Hz.

The strain was measured with a capacitive extensometer (3 in Fig. 2, right). The evolution of the mechanically determined parameter D indicates crack growth via loss of the stiffness of the specimen (increase of compliance) [3,4]. D is defined by the following equation:

$$D_i = \frac{S_{\mathrm{unl(ave1-100)}} - S_{\mathrm{unl}(i)}}{S_{\mathrm{unl(ave1-100)}}} \tag{1}$$

where S_{unl} characterizes the unloading stiffness in tension, the index i stands for the current cycle, and (ave1–100) for the average value of the first 100 cycles as reference for the start value.

The acoustic emission system was a Vallen AMSY 5 with AEP3 preamplifiers featuring integrated high pass filters of 95 kHz and a variable gain to amplify the relatively low voltage of the sensors. Broad-band sensors Digital Wave B1025 were used for the investigations of the background noise [5]. The gain was held constant at 49 dB.

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[*] *Dipl.-Ing. M. Merzkirch, Dr.-Ing. K. A. Weidenmann*
Institut für Werkstoffkunde I, Karlsruhe Institute of Technology Kaiserstr. 12, 76131 Karlsruhe, Germany
E-mail: matthias.merzkirch@kit.edu
Prof. Dr.-Ing. E. Kerscher
Lehrstuhl für Werkstoffkunde, Technische Universität Kaiserslautern Postfach 3049, 67653 Kaiserslautern, Germany

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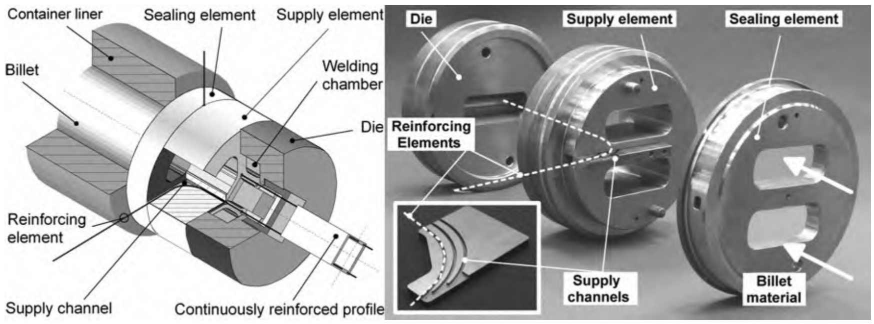

Fig. 1. Process principle (left) and tool design for feeding wires during profile extrusion (right).[1]

The two piezoelectric sensors (1 in Fig. 2, right) are placed onto the flat front faces at the top and the bottom of the specimen. Additionally, a stiff polymer foam is used to fix the sensors (2 in Fig. 2, right). With the help of two sensors a linear localization along the specimen axis is possible.[5,6] Vacuum grease was used to assure a good acoustic conductance between the transducers and the specimen.[5–7]

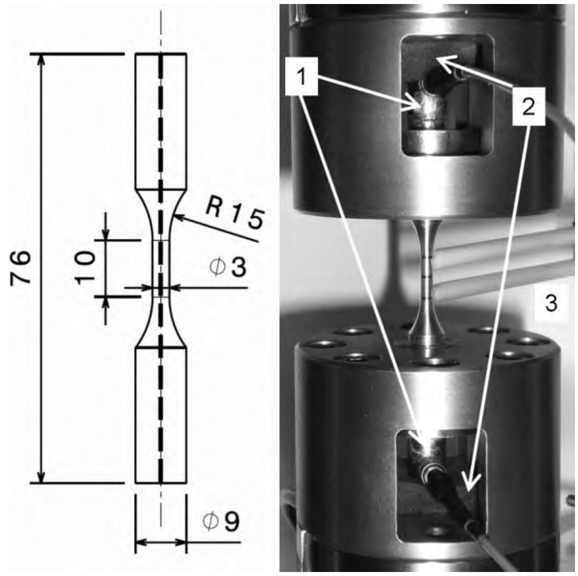

Fig. 2. Geometry of the specimen with position of the wire if reinforced (dashed line) (left) and experimental setup with strain measuring gauge and acoustic emission setup (right).

Results

Investigations of the Background Noise

In order to avoid or fade out the background noise preliminary investigations regarding the frequency spectra have been carried out.[2,5] Figure 3 (left) shows the frequency spectrum of a broadband sensor placed at the top of a reinforced specimen at the very beginning of the cyclic test. No damage could be registered with the strain measuring device. It can be seen that the highest peaks which result from the background noise of the testing machine, appear up to a frequency of about 150 kHz.

The background noises were suppressed by using high pass frequency filters with a threshold frequency of 180 kHz. By loading a reinforced specimen until the first crack growth could be registered with the strain measuring gauge, Figure 3 (right) gives the frequency spectrum of the damage which shows remarkable signals between 180 and 300 kHz. Therefore resonant sensors Vallen VS600-Z1 with an increasing sensitivity from 180 kHz were chosen for the investigations of the cyclic behavior.[7]

Cyclic Behavior

Figure 4 shows the cyclic behavior of a reinforced specimen which was tested by stress amplitude of 175 MPa. This specimen had a number of cycles to failure of 79 510. The left side of Figure 4 shows four regions whereas region I is characterized by the cyclic hardening due to dislocation movement and pile-up, pointed by the decrease of the plastic strain amplitude $\varepsilon_{pl,a}$.[2]

Region II characterizes the saturation state before crack growth within the matrix material can be detected via the

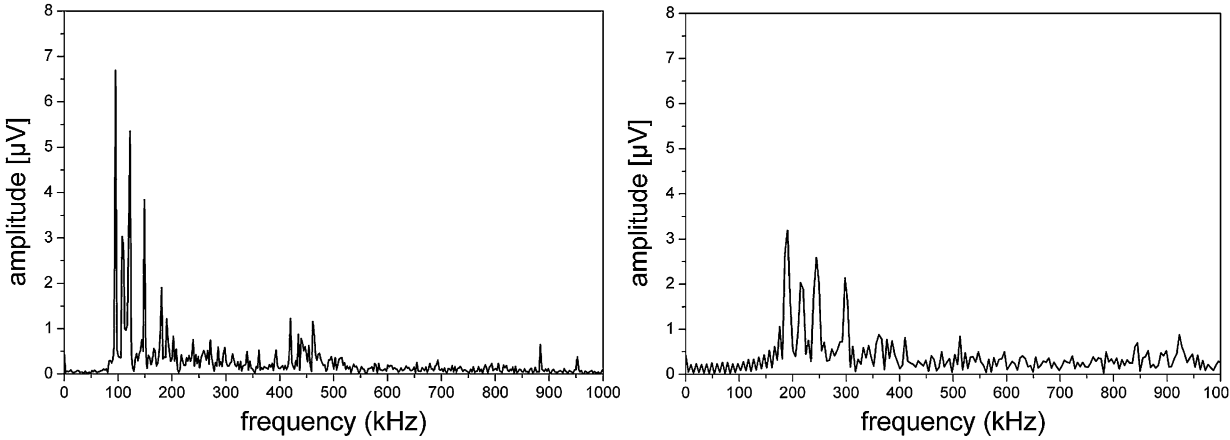

Fig. 3. Frequency spectra of reinforced specimen at the beginning of the test (left) and during damage (right, $\sigma_a = 175$ MPa).

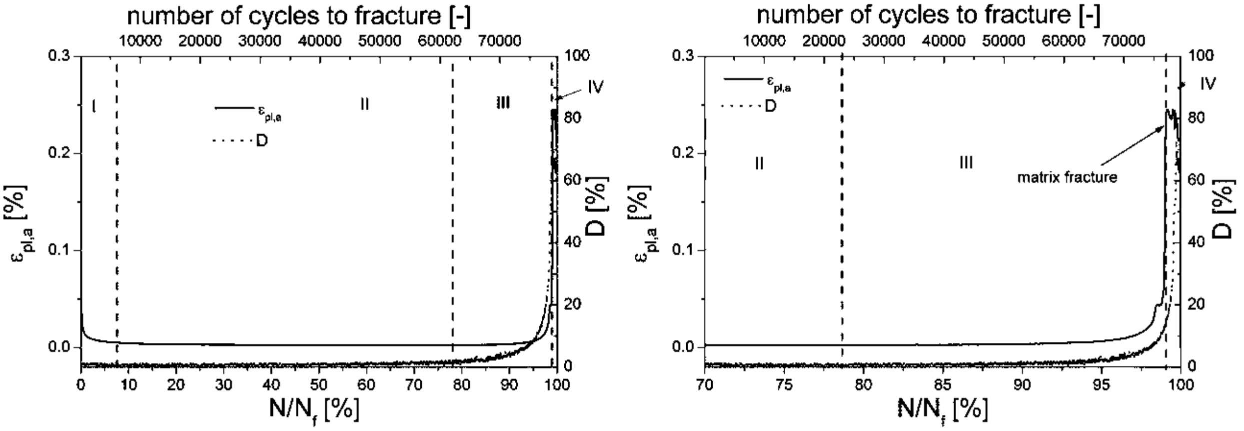

Fig. 4. Development of the plastic strain amplitude $\varepsilon_{pl,a}$ and the damage parameter D versus the number of cycles to fracture, overview (left), zoom (right) ($\sigma_a = 175$ MPa).

increase of the damage parameter *D* and of the plastic strain amplitude $\varepsilon_{\rm pl,a}$ marking the beginning of region III. At the end of region III the complete fracture of the matrix occurs and region IV is confined to the fatigue of the reinforcing element.[8] Furthermore from Figure 4 (right) it can be concluded that the damage parameter *D* is much more sensitive to crack growth than the plastic strain amplitude $\varepsilon_{\rm pl,a}$.

Comparison Between the Mechanical and Acoustic Parameters

Figure 5 shows the comparison between the mechanical parameter *D* and the acoustic parameter "accumulated counts" versus the relative number of cycles to fracture.[2,9–11] Counts are threshold crossings of an acoustic hit.[6,7,12] First damage is acoustically registered from about 80% of lifetime. It can be concluded that the dislocation reactions during the cyclic hardening are not registered with the above-mentioned settings of the frequency filters and the threshold of 22 dB.

There is an equivalent sensitivity of the acoustic emission data and the mechanical parameter *D*. Furthermore, the beginning of the detection of crack growth within the matrix is characterized by the increase of the counts density (comparable to hit density (hits/time)); see Figure 5, bottom left (hits/time $> 10^5$).[5,6]

The steep increase of the accumulated counts after matrix fracture is lead back to the bumping of the matrix crack surfaces during unloading of the specimen.[2,13] Therefore the parameter "counts per acoustic hit" is used to describe the fracture of the matrix material and the onset of fatigue of the reinforcing element; see Figure 5, bottom right (counts/hit $> 10^5$).

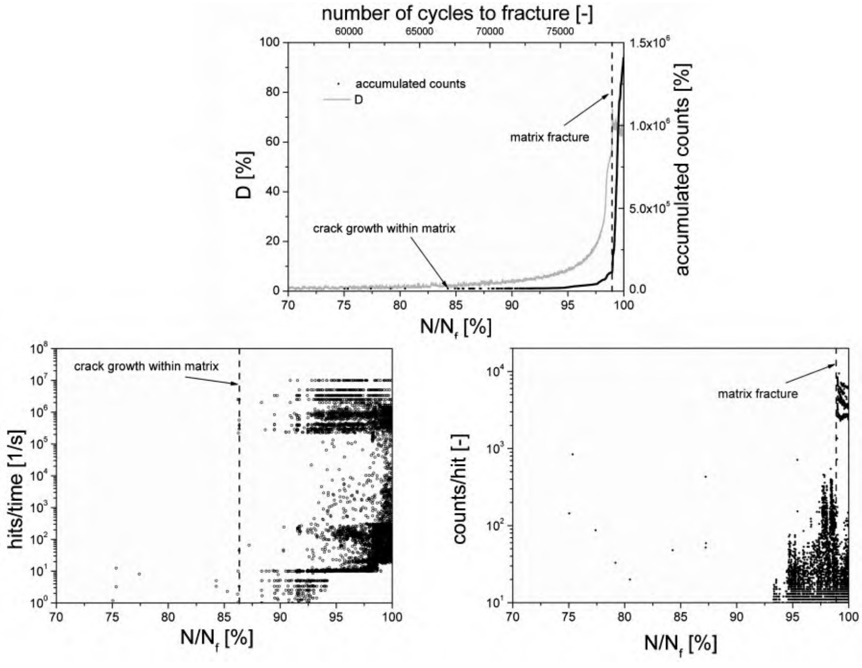

Fig. 5. Development of the damage parameter D and the accumulated counts (top) and the damage parameters hits/time (bottom left) and counts/hit (bottom right) over the number of cycles to fracture ($\sigma_a = 175$ MPa).

The results of that test at a stress amplitude of 175 MPa are representative for the complete S-N curve.

Correlation Between AE and Crack Growth

The acoustic damage parameters hits/time for crack growth and counts/hit for matrix fracture allow actualizing automatic damage monitoring. By passing a certain threshold for the mentioned parameters, the acoustic emission system brings the testing machine to interrupt the test, so metallographic investigations regarding the crack growth behavior can be carried out.

The search for the cracks within the matrix can be simplified by localization with the help of the two oppositely placed sensors. Due to reflections of the acoustic

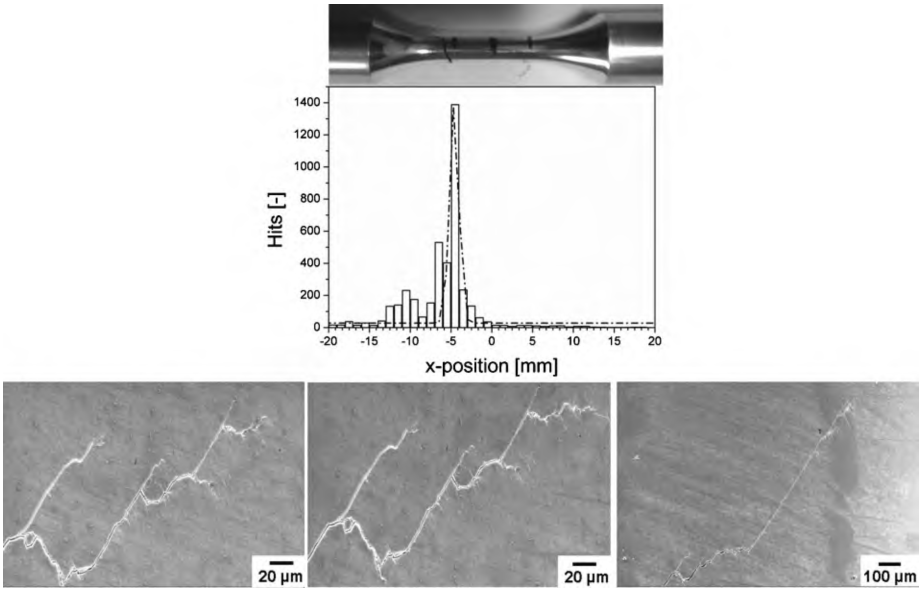

Fig. 6. Acoustic localization of the primary crack within the matrix (top), growth of the primary crack within the matrix (bottom – left: after 288 182 cycles, middle: 289 201, right: after 292 221 cycles).

waves at the interface between matrix and reinforcing element, an eccentric placement of the resonant sensors on the pure matrix material has been realized to improve the localization.[5–7]

Figure 6 (top) shows the localization of the fatigue crack within the matrix via acoustic hits recorded before matrix fracture. The following bumping of the crack surfaces during fatigue of the reinforcing element result in an increase of acoustic hits which cannot be located anymore due to the steep elongation of the specimen.

It can be concluded that the localization of the primary crack is relatively precise. At the bottom of Figure 6 the crack growth inside the matrix can be seen. The automatic damage monitoring started at about 97% of lifetime at a crack length of approx. 200 µm. With another 1,019 cycles, the crack length has increased of about 20 µm and about another 800 µm for the next approx. 3,000 cycles.

Conclusion and Outlook

Within this work, it could be shown that acoustic emissions analysis is feasible during cyclic loading of a composite extruded spring steel reinforced aluminum matrix material. With the help of specific high pass filters and the use of resonant sensors the acoustic sensitivity to crack growth was comparable to that of the capacitive strain measuring gauge. The AMSY 5 system even allows for an automatic damage monitoring by detecting the crack growth by crossing specifically defined parameters indicating crack growth within the matrix material and the fracture of it. Further investigations should focus on increasing the sensitivity of the acoustic emissions analysis by improving the frequency filters. Also the acoustic localization of damage evolution, with the use of two sensors, prior to the fracture of the matrix material should be improved by analyzing and classifying the recorded data.

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