Comparison of Acoustic Emission Signal and X-ray Diffraction at Initial Stages of Fatigue Damage

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Abstract

The contribution treats the evaluation of degradation processes appearing during the cyclic loading of the samples from Al alloys EN AW-2017/T4 and EN AW-6082/T6. Two NDT methods have been applied in this case, namely the acoustic emission (AE) and the X-ray diffraction used to detect the microstructural changes in the material during the fatigue damages as well as to report the microcracks appearing afterwards. These measurements have been completed with reports of changes to the loading (resonance) frequency coming from fatigue loading equipment.

Moreover, the article describes the records of AE signal coming from an AE analyser with full scan of signal as it has been newly developed. The main advantage of this type analyser (compared with AE measuring systems currently used) is continuous sampling and full (uninterrupted) signal saving data.

The acoustic emission registers the transition changes in the material during the damage accumulation. It is, of course, a problem to identify such changes. The structure monitoring by means of X-ray diffraction is a great contribution to identify the acoustic emission sources. The results as presented imply a correlation between the AE signal changes and the changes of so called mosaic blocks of material crystal structure detected by means of X-ray diffraction.

Introduction

The fatigue damage is mostly divided into some basic stages. It is the dislocation structure that passes changes featured by cyclic material hardening/softening at the beginning of the cyclic charging. During the next period, no material changes appear visually, however new processes provoked by continuous charging proceed inside the structure. This period is usually designated as the period of damage accumulation. At the end of this period, the damage becomes localized in the suitable (predisposed) sites. Micro-cracks appear and some of them start to join producing short cracks and finally the main crack creates.

As to the research of fatigue damage principles, the biggest attention is paid to the description of crack initiation at this time. As to the material property evaluation it is, however, quite important to follow the processes imminently preceding the appearance of the fatigue crack. These changes take place on the micro-structural level and the current investigation methods identify them only with great troubles.

Cyclical degradation process of aluminum alloys’ properties is noteworthy distinguished of such principles of iron alloys described at quite large. The imminent difference is in the difficulties with statement of fatigue threshold. For example damaging of AlMg alloys proceeds even with loading amplitudes that correspond to standard fatigue threshold of current ferrous materials and therefore reliable determination of fatigue threshold is very difficult. That is why a conventional fatigue limit is defined at these materials, which is on the level of $10^8$ loading cycles at least [1].

An Al alloy EN AW-2017/T4 has been used as an experimental material used to make the test specimens. Similarly to the materials (i.e. EN AW-6082, EN AW-7075) tested previously has
been featured by direction structural anisotropy arisen due to the extruding technology [2, 3] (see Fig. No. 1). Chemical composition of the alloys is shown in the table no.1.

![Fig. 1. Structural inhomogeneity (orientation) of EN AW-2017/T4 alloy](image)

![Fig. 2. Specimen geometry for the fatigue tests](image)

**Table 1. Chemical composition of used alloys EN AW-2017 and 6082 (wt %)**

<table>
<thead>
<tr>
<th>material</th>
<th>element</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN AW-2017</td>
<td></td>
<td>0.8</td>
<td>0.7</td>
<td>2.5</td>
<td>0.2</td>
<td>0.25</td>
<td>0.1</td>
<td>0.25</td>
<td>-</td>
<td>rest</td>
</tr>
<tr>
<td>EN AW-6068</td>
<td></td>
<td>1.01</td>
<td>0.17</td>
<td>0.067</td>
<td>0.66</td>
<td>0.84</td>
<td>0.16</td>
<td>0.030</td>
<td>0.032</td>
<td>rest</td>
</tr>
</tbody>
</table>

The test specimens for fatigue tests as shown with their geometry and dimensions are fund on the Fig. 2. It concerned directions LS, LT (in the extrusion direction) and TS and TL (transversal directions) – see Fig.1. Shallow notches are used for localisation of the crack starting point.

The fatigue tests have been realised with the testing electro-resonance RUMUL Cracktronic 160 maschine working on the principle of electromagnetic resonance and loading the specimen with four point bending. The resonance frequency of the mentioned specimens moved around 70 Hz with the bending tension 210 MPa (strength limit 340 MPa).

Two piezoelectric sensors of AE made by DAKEL type MIDI (see Fig. 3 on right) have been used for AE detection during fatigue loading process. One has been placed near to he notch by means of mechanical fixing lug and the other one has been glutted to the specimen front. The signal coming from AE sensor is magnified by preamplifier and further lead by cable trace to the evaluation in measuring systems DAKEL – XEDO and DAKEL - IPL.

**Methods and testing operation conditions**

The test procedures have been divided into 3 phases. The first one concerned the test specimens in all directions up to the fracture without AE signal measurements. These specimens served to monitor the changes in structure (as produced by cyclic loading) and this by X-ray diffraction. The second phase concerned scanning the AE signal during the whole fatigue test up
to the fracture of the specimen. The system DAKEL – XEDO has been used for measurements. The main aim here was to measure the AE signal activity during the cyclic material loading when the microstructural changes and the microcracks occur. The last phase has concerned again measuring the AE signal however this time via measuring system DAKEL–IPL with fully continuous signal sampling. All measurements have been completed with noticed resonance frequency changes of the tested sample coming from the fatigue load apparatus RUMUL CRACKTRONIC.

The interval 5 thousand (EN AW-2017) and 10 thousand (EN AW-6082) cycles between each measurement has been fixed for monitoring the microstructural changes by means of X-ray diffraction [4, 5].

**Overview of experimental results**

The figures show examples of AE activity entries, completed with the diagram of loading frequencies for both materials. Particular entries show the cyclic softening (or hardening) stage, rise and development of the first micro-cracks and the course of main crack propagation. The plot of the loading frequency (above) indicates some changes in the period of damage cumulation but it is not very conclusive.

![Basic parts of the Cracktronic 8204/160 machine](image)

**Fig. 3. Basic parts of the Cracktronic 8204/160 machine**

**Fig. 4.** a) changes of loading frequency during a fatigue test of EN AW-6082/T6 alloy ($N_f$ app. $5.1 \times 10^5$ cycles), b) number of overshoots (counts–cnt) over the preset signal levels during a fatigue loading test of the same sample
The creation and propagation of fatigue crack is registered unambiguously. The higher AE activity confirms this result. It is however evident that the AE signal changes also in the period between these basic phases. Changes of AE signal before the final period gives the chance to see the beginning rise of first microcracks and other changes of microstructure.

Fig. 5. Plot of loading frequency and test machine power changes (upper) and AE signal - counts rate, RMS, cumul. AE events (bottom) - alloy EN AW-2017/T6 (N\textsubscript{f} app. 4,3.10\textsuperscript{5} cycles)

Fig. 6 Changes of basic parameters of AE events (peak amplitude, rise time, event duration) during the fatigue test of aluminium alloy EN AW-2017/T6

The change of AE activity is observed before crack initiation, too. Classical techniques of optical observation of surface do not provide any obvious reason for this phenomenon. On the basis of analogy with other observations it is possible to expect that the reason of AE activity can be for example the accumulation of energy sufficient for loosening of dislocations captured in structural obstacles. The reason of increased AE activity during the so called stable mode can be also the changes of material substructure – emphasizing of sub-seeds, mutual rotation of suitable areas in frame of individual seeds of material etc. can appear [4, 5].
Results of the acoustic emission signal measured by DAKEL – IPL analyser

The AE signal activity has been measured during the fatigue tests of the Al alloy EN AW-2017/T6 with analyser DAKEL – IPL. The sensors used have been the same as used for the DAKEL – XEDO measuring system. The exemple of results of AE signal measurement in the direction LS (see Fig.1) during the fatigue test under the bending tension 210 MPa is plotted on Fig. 9.
On Fig. 9, time changes of AE signal frequency in the interval 75-400 kHz (Figure b) and 460-750 kHz (Figure c) are compared – these are horizontal cuts by the 3D plot from Figure 9a. From the record of lower frequencies (a) it is possible to identify creation and propagation of fatigue crack. Changes of structure in the period before the creation of this crack are however not well visible. On the record of higher frequencies on Fig. c, we can see an evident change of the character of AE signal source in the period between 6th and 15th minute of loading. We suppose that in this period the above mentioned changes of microstructure occur. It is however very difficult to reliably identify the essence of these changes from AE signal and therefore it is necessary to use additional NDT procedures (at least at this stage of research).

Fig. 9. Records of the amplitude changes on selected frequencies in time (horizontal cut of the 3D spectral map): a) lower frequencies (75 – 400 kHz), b) higher frequencies (460 – 750 kHz).

**Overview of X-ray diffraction analysis**

X-ray diffraction analysis of loaded samples structure (Fig. 10) is based on the knowledge that in case of loading of wrought materials the redistribution of deformation strengthening occurs, which is caused by re-arrangement of dislocations.
By X-ray examination of the aluminum alloy EN AW-6082/T6 (results of EN AW-2017/T6 aren’t at disposition at this paper deadline), we have found that its microstructure, as characterized by the proportion $R$ of the large CSR’s (mosaic blocks, structural cells) greater than 10 $\mu$m, does change much under repeated stress [4]. In the first stage of loading, the CSR’s due to the introduced plastic strain disintegrate. As a result of this, the boundary surface of the cell aggregate extends, and, consequently, its energy finally increases enough to initiate its coarsening. The energy necessary to activate the growing of the larger blocks at the expense of the smaller ones is supplied by further cycling. But, during this growth, paracrystalline distortions emerge, which gradually accumulate in the interior of the widening cells, raising thus their volume energy. After next fatigue loading, the energy increases to such degree that the blocks begin disintegrate a new. Due to this disintegration, the paracrystalline distortions relax and the alloy energy drops [7, 8].

So, at a cyclic loaded Al alloy we found correlation between the increased acoustic emission activity and the growth of regions (so called mosaic blocks of the crystal structure) independently reflecting X-rays (Fig. 11) [7, 8]. Cyclic deformation, unlike unidirectional deformation, does not spread uniformly through a grain but tends instead to concentrate cycle after cycle in preferred zones. These dislocation sinks, which finally turn into micro-cracks, reduce the grain into a disoriented cell structure, which is readily proved by the so-called „diffraction imaging” or „grain by grain” X-ray diffraction technique [7, 8]. The interior of a cell, being relatively free of dislocations, scatters the x-rays coherently giving rise to a diffraction spot.

![Fig. 10. X-ray diffraction analysis: a) test specimen in the initial state - azimuth profile of the (200) Al diffraction line, b) results of the same test specimen after 60 000 loading cycles [4].](image)

![Fig. 11. Record of real change of x-ray K factor vs. time of fatigue loading for EN-AW 6082 alloy [6].](image)
the width of the peak of azimuth profile of diffraction line (200) alloy matrix in the half height of this peak; this coefficient represents the amount of disorientation of mosaic block structure. From the Fig. 11 are evident the cyclical changes of mosaic blocks, which appear at all the mentioned samples – on the given level of loading approximately in the area 60 and 110÷120 x 10³ loading cycles. These changes of microstructure can be the cause for local amplification of AE signal in the stage of damage accumulation.

Conclusion

The results of the all fields covering the acoustic emission signal measurement during the fatigue load to Al alloys and monitoring the structural changes in the material by means of the X-ray diffraction topography, show evidently the application of these non destructive methods on the field of basic research of the fatigue processes working in the material, so that both are a great contribution to respective knowledge.

The AE methods identified the changes in the material during the fatigue load, namely the process of accumulation of damages and the start of magistral crack propagation. Detailed information concerning the acoustic emission act parameters (like rise time, signal maximum amplitude etc) as they change during the test can be also a good contribution to this research. Unfortunately, we did not yet find the correlation between these parameters possible able to describe the changes occurring inside the material during the fatigue damage. We did not get yet the answer what changes occur during the process of damage accumulation. Therefore also we have made many X-ray diffraction measurements, namely in order to define what are how are the changes evoked in tested material structure by cyclic load Another figure shows, the disorientation of material structure mosaic blocks really changes during the cyclic loading in fact changes alternatively (grows and shrinks). The resonance frequency observances acquired by loading instrument CRACKTONIC appeared also to be a contribution as they have shown more complex information about the fatigue degradation of the material.

Acoustic emission brings information on macroscopic volumes of analyzed material, which is a big advantage when investigating structurally heterogeneous processes that occur under cyclic loading. Combining the results of the observation of AE and X-ray diffraction enables to extend our knowledge of fatigue processes.

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References


