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IDENTIFICATION OF FATIGUE CRACKS ON THE BASIS OF MEASURABLE CHANGES IN SYSTEM DYNAMICS

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Abstract: In order to obtain correct experimental results, fatigue strength tests carried out on the basis of a measurement setup using dynamic excitation generated by inertial force require test completion criterion to be specified. The paper presents the method applied to identify damage on the basis of an analysis of changes in registered acceleration amplitudes based on experimental studies, and an analysis of image of obtained fatigue fractures.

KEYWORDS: Fatigue cracks, mechanical system dynamics, acceleration measurement.

1 Introduction

Material defect due to fatigue damage occurring in it is one of the most frequent reasons for malfunctions of machinery and equipment components. Currently, the literature presents methods allowing detection of fatigue cracks and monitoring them with: strain measurement systems like extensometers [1], [2], ultrasonic sensors, and the analysis of acoustic emission of an object [3]. Degradation phenomena appearing in constructional materials depend on many factors. Among other parameters, the following reduce strength properties of materials due to the occurrence of damage in material structure during service: component shape, material type, load type and the state of stress. Due to multi-aspect nature of material fatigue phenomenon and considering continuously expanding level of knowledge in this regard, individual aspects of this phenomenon are currently under thorough investigation, including: the impact of load type [4], [5], cumulation of damage during random loads [6], [7], reduction of multiaxial state of stress to an equivalent uniaxial state of stress [8], [9], or else the impact of an average value of load [10], [11]. Are also known in the literature approaches which takes into account the grain structure and the content of respective alloying elements for the purpose of estimating the fatigue life [12]. In industrial durability tests more and more accelerated tests are performed [13]. This paper presents preliminary experimental study performed on the AA PA4.

2 Method

For the purposes of this work, a testing setup has been used (Fig. 1), in which fatigue tests are conducted using the method of dynamic excitation generated by inertial force. The measurement setup, and both analytical and simulation model have been extensively discussed in the work [14]. Degradation changes may occur in structural components as a result of the impact of loads, which vary in time. Defects in form of fatigue cracks may appear in these loading conditions in load-carrying section of a structural component. A defect occurring in load-carrying section affects the ability of a structural component to transfer the required loads, which may result in structural component damage. The tests were performed using specimens made of PA4 aluminum alloy, specimen geometry is shown in fig. 2.

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Fig. 1. Measurement setup [12]

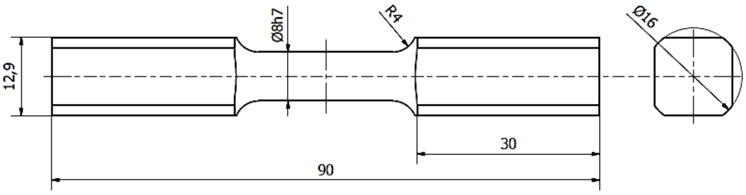

Fig. 2. The geometry of the specimen

While carrying out fatigue tests, one should precisely determine the state of an examined test component, which will be deemed damaged or destroyed. Formulation of the relationship between damage level and the change in testing setup response, monitored using accelerometers implemented in the setup, is the purpose set by the authors. The relationship between registered acceleration amplitudes in the mass loading (a_M) the setup and acceleration amplitudes registered in excitation axis (a_U) has been selected as the parameter that describes testing setup response to kinematic excitation (Fig. 3).

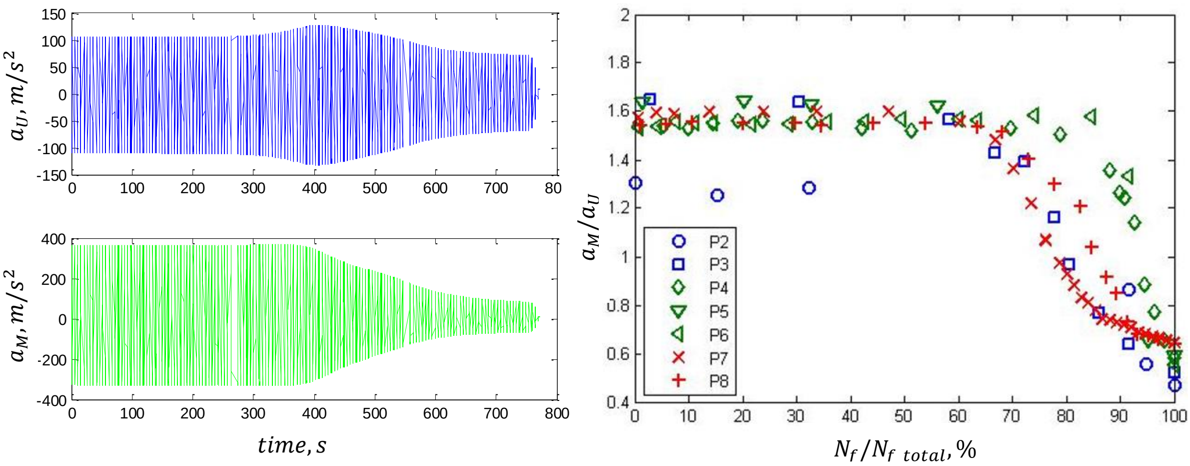

Fig. 3. a) The trajectory of acceleration amplitudes during fatigue test; b) comparison of a_M/a_U for a completed fatigue test series

Variability of testing setup dynamic response to excitation shall be linked with the damage in the test piece working section occurring in the setup. This provides the basis to describe the change in the moment of inertia of the section capable of load transfer in function of defect length. It has been assumed that only some of stretched parts of the cross section are damaged while bending the test piece and the crack is parallel to the neutral axis of the section (Fig. 4). The defects occurring in the test piece have been put to analysis while checking the parameter of change in testing setup rigidity by variable relationship of registered acceleration amplitudes in characteristic points of the setup.

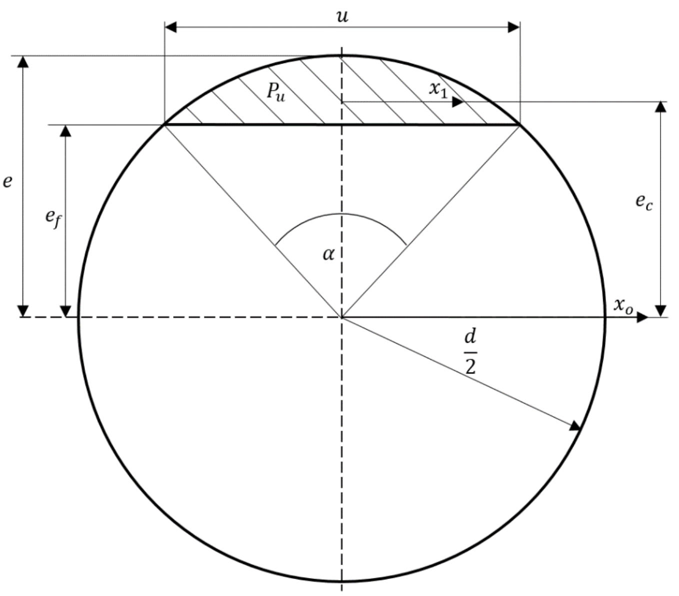

Fig. 4. Cross section model with fatigue failure used for consideration.

The distance of the distal fibers from the neutral axis of the bending section takes the form:

$$e_f = \sqrt{\left(\frac{d}{2}\right)^2 - \left(\frac{u}{2}\right)^2}\,, \qquad u \in R(0,d), \tag{1}$$

therefore, depending on the change in the crack length, the distance e_f will influence the change of the cross-sectional area of the damage P_u and will determine the value of the angle α.

Therefore:

$$\alpha = 2 \cdot \sin^{-1}\left(\frac{u}{d}\right), \tag{2}$$

and:

$$P_u = \left(\frac{\alpha}{360°}\right) \cdot \pi \cdot \left(\frac{d}{2}\right)^2 - \frac{u}{2} \cdot \sqrt{\left(\frac{d}{2}\right)^2 - \left(\frac{u}{2}\right)^2}\,. \tag{3}$$

Knowing the geometric form of the damage described as a section of circle, you can determine the moment of inertia with respect to the neutral axis of the cross section that does not carry the bending load (x_1):

$$I_{x_u} = \left(\frac{d^4}{256}\right) \cdot (2\alpha - \sin(2\alpha)) - \left(\frac{d^4}{144}\right) \cdot \frac{(1 - \cos(\alpha))^3}{\alpha - \sin(\alpha)}. \tag{4}$$

To determine the resultant moment of inertia of a circular cross section with fatigue failure, the moment of inertia of the segment representing the fatigue failure shall be presented in accordance with Steiner's theorem:

$$I_{xu_o} = I_{x_u} + P_u \cdot e_c^2\,, \tag{4}$$

where:

$$e_c = \frac{2d}{3} \cdot \frac{\sin^3\left(\frac{\alpha}{2}\right)}{\alpha - \sin(\alpha)}. \tag{5}$$

As a result, the moment of inertia of the load carrying cross-section can be expressed as:

$$I_{xf_o} = \frac{\pi d^4}{64} - \left(I_{x_u} + P_u \cdot \left(\frac{2d}{3} \cdot \frac{\sin^3\left(\frac{\alpha}{2}\right)}{\alpha - \sin(\alpha)} \right)^2 \right). \tag{6}$$

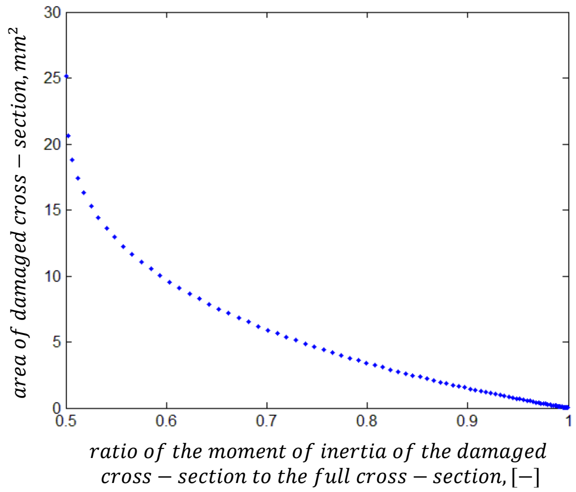

Fig. 5. The relationship between the increase of the damaged cross-section and the moment of inertia of the cross-section

The resulting fatigue failure, which decreases the moment of inertia of the damaged section described by the relation (6), also has an effect on the change in bending section index depending on the varying moment of inertia and the distance of the outermost fibers in cross-section:

$$W_{x_f} = \frac{I_{xf_0}}{e}. \tag{7}$$

The change in the working cross section resulting from the increase of the damage length (u) influences the position of the neutral axis in relation to the initial position. For this reason, the distance of the outermost fibers (e) takes the form:

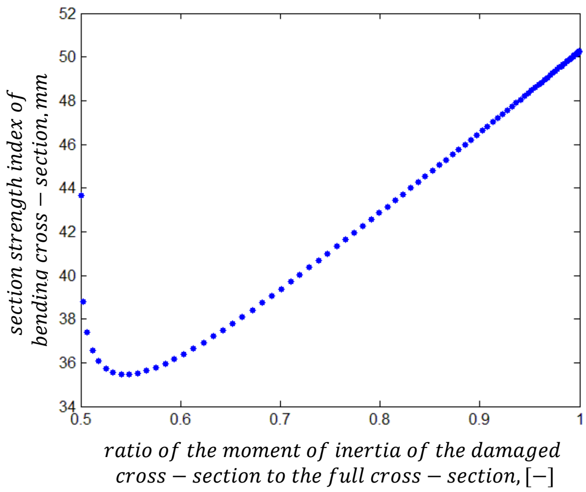

Fig. 6. Variation of the section strength index on bending with respect to the moment of inertia of the bending cross section

$$e = e_f + y_{sc}\ , \tag{8}$$

where:

y_{sc} – the difference between the position of the neutral axis of the circular cross-section and a cross section of modeled damage of length u

$$y_{sc} = \frac{\sum P_i \cdot y_i}{\sum P_i}, \tag{9}$$

where:

P_i – surface area of i-th component,

y_i – the distance of the neutral axis of the i-th component to the axis of the reference system.

What after the substitution and after ordering gives the following relationship:

$$y_{sc} = \frac{-\left(\frac{\alpha}{360°}\right) - \frac{d \cdot u}{6}\sqrt{d^2 - u^2}\,\frac{sin^3\left(\frac{\alpha}{2}\right)}{\alpha - \sin(\alpha)}}{\frac{\pi d^2 - d^2(\alpha - \sin(\alpha))}{4}}. \tag{10}$$

The above expression (10) is correct if the coordinate system has its origin in the middle of the circular cross-section. Figure 7 shows the change in the center of gravity of the cross-section as a function of the length of fatigue failure.

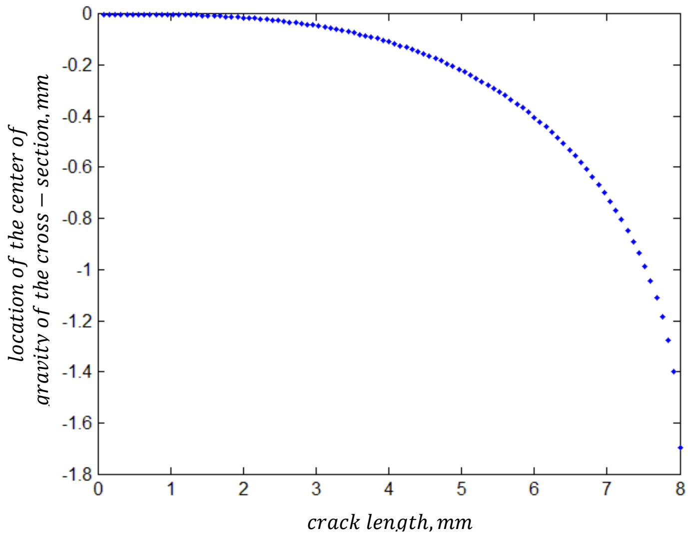

Fig. 7. Location of the center of gravity of the section relative to the crack length.

It is well known that bending fatigue cracks occur on both sides of the working section of the specimen (due to the fact that the greatest distortion values occur at the end of the fibers)

In Fig. 8, the distribution of deformations in the analyzed working section was presented, taking into account the damage of different lengths u in the range $0 \leq u \leq d$.

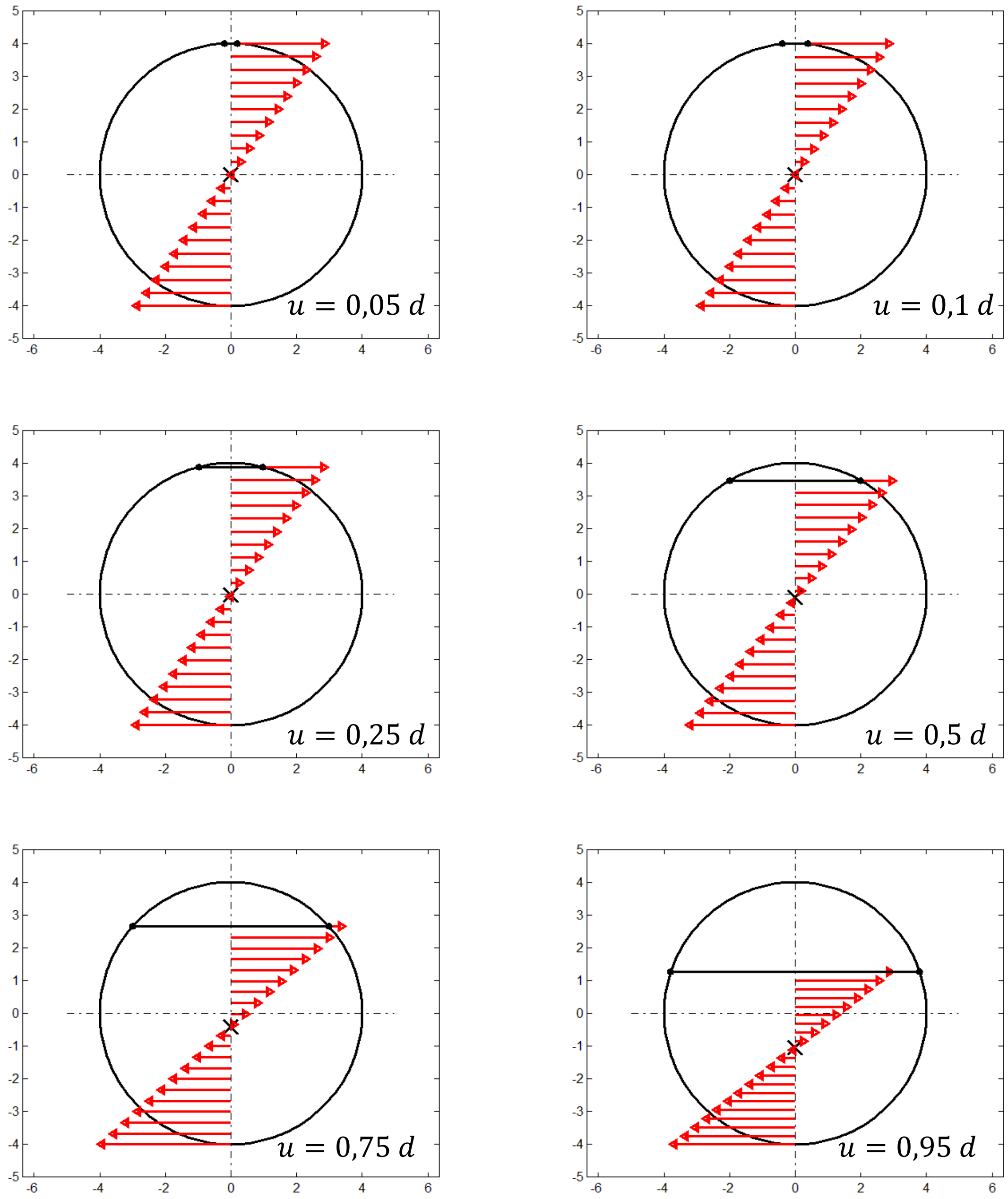

Fig. 8. Change the deformation distribution in the cross-section according to the crack length.

On the Fig. 9. is shown the obtained fractures of test pieces characterized by different degrees of damage. Obtained fractures have been put to image analysis in order to determine working section area, which has been damaged and is unable to transfer load.

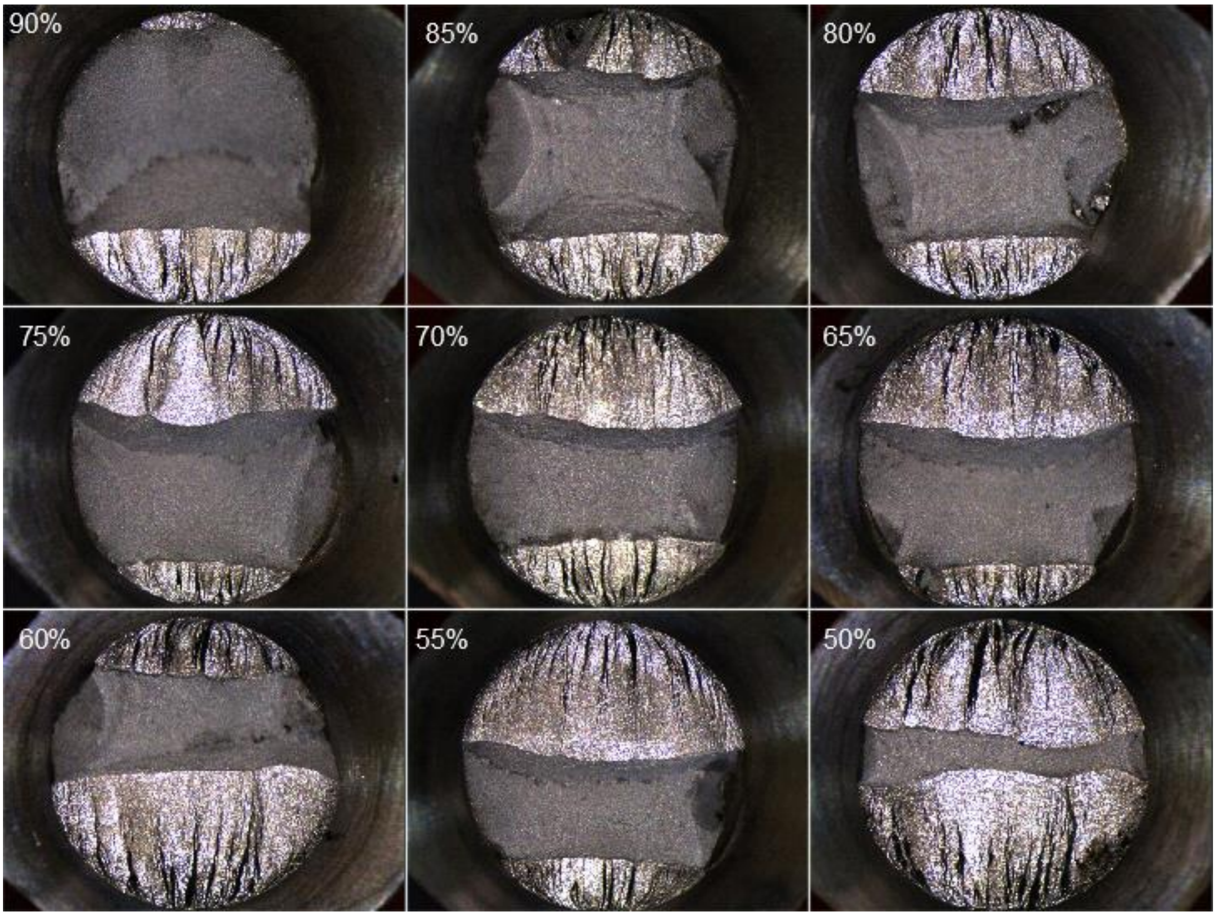

Fig. 9. Comparison of fractures in test pieces after fatigue tests showing different damage levels – the grip side of a test piece.

The discussed case of bending generates alternately compressive and tensile stresses on the opposite sides of the cross-section. Therefore, simultaneous two-side fatigue crack increments are observed for oscillatory loads. Observed drops in testing setup rigidity have been compared to the areas of damaged parts of the section. Obtained data provide grounds for determining the condition of fatigue test completion as a specific drop in the relation $a_M\ /a_U$ for the entire series of fatigue tests, which will correspond to a certain value of fatigue damage length being reached.

3 CONCLUSIONS

On the basis of the drop in the relation between acceleration amplitudes registered in characteristic areas of testing setup it is possible to determine the area of test piece working section, which has been damaged during fatigue test and does not transfer the load. Moreover, it allows determining the length of increasing fatigue damage. On the same grounds one can specify the moment of test completion – as the expected fatigue damage length according to the changes in registered acceleration amplitudes in characteristic points of the testing setup. Kinematic excitation allows efficient use of supplied energy and may be used in fatigue tests, especially during tests at higher frequencies.

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