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Strain Response Determination in Notched Specimens under Multiaxial Cyclic Loading by DICM

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Abstract. Focus of the contribution is to determine strain tensor's components in root of notched specimens by DICM. Three types of samples were examined with three types of notch: U, V and "fillet". The behaviour of these samples during low-cycle fatigue testing were examined. Specimens were subjected to five different types of loading, which caused uniaxial and also biaxial state of stress. The results are deformation responses in the notch of the each sample, which will serve to validate numerical results.

Introduction

Digital Image Correlation Method (DICM) belongs to the most progressive methods suitable for 3D full-field strain analysis of structural components [1,2]. In present time the DICM enables to find out deformations under uniaxial as well as multiaxial loading during fatigue testing [3]. Measurement of deformation, vibration or displacements take place in real time. The DICM is full field methodology of measurement of deformations or displacements. DIC is a non-contact optical method, which enable to determine primarily displacements even in 3D space. Application of DICM for strain determination inside the notch have clear advantages, because the usage of extensometer or strain gauges is excluded. Each specimen must be equipped by high contrast speckle pattern. Measuring set-up consists of two cameras with high-resolution, which are placed on tripod and controlled by appropriate software.

This contribution shows some interesting results of deformation response on cyclic loading in notch roots obtained by DICM. The samples were loaded on biaxial testing machine LabControl 100kN/1000Nm. Behaviour of specimens with three different types of notch was investigated: U-notch, V-notch and "fillet". Schemes of these notches are shown on Fig. 1. Specimens with these types of notch were exposed to cyclic loading in five modes: Tension--compression (path 1), torsion (path 2), tension-compression/torsion proportional (path 3), tension-compression/torsion non-proportional 90° out of phase loading (path 4) and 45° out of phase loading (path 5).

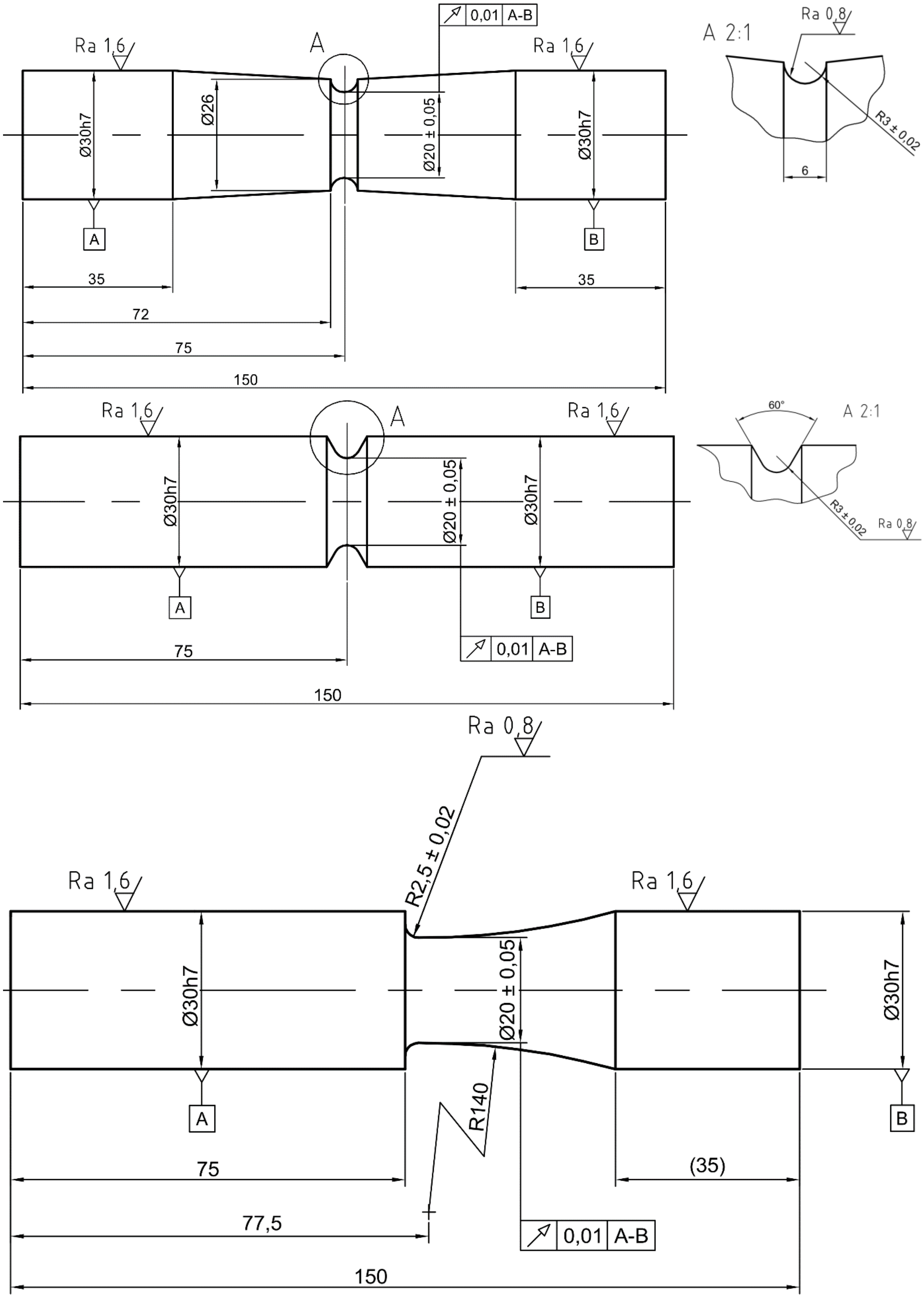

Fig. 1. Three types of notched specimens used for testing.

Experimental Setup

Specimens were made from the aluminium alloy 2124-T851. The deformations in notch root cannot be investigated by strain gauges because of strain gradient, therefore the DIC technology was applied. Mercury RT® system (2x2.3Mpx@40Hz) provided by Sobriety company was used (Fig. 2b). The optical contrast coating was created on each specimen (generally known as pattern).

The samples were loaded up to failure on the universal testing machine LabControl 100kN/1000Nm (Fig. 2a.). The testing machine is able to exert uniaxial (tension-compression) and biaxial (tension-compression-torsion with and without phase shift) state of stress inside the specimen. Fatigue tests were done in low-cycle fatigue mode and all of them were done under load control. Overall 15 tests and DIC measurements were carried out, 5 tests for each specimen type under 5 different load setting.

a) b)

Fig. 2. Photographs of used equipment: a) Biaxial testing machine LabControl 100kN/1000Nm, b) Mercury RT® system.

Frequency of all five loading cases was 0.5 Hz. Deformation responses on cyclic load were investigated on all specimens. Main attention was concentrated on determination of longitudinal, transverse and shear strains in root of a notch. With the aid of DIC apparatus first hundred cycles of test was recorded for afterwards processing.

Processing of measured data was done in software Mercury RT® and the basic GUI layout can be seen on Fig. 3.

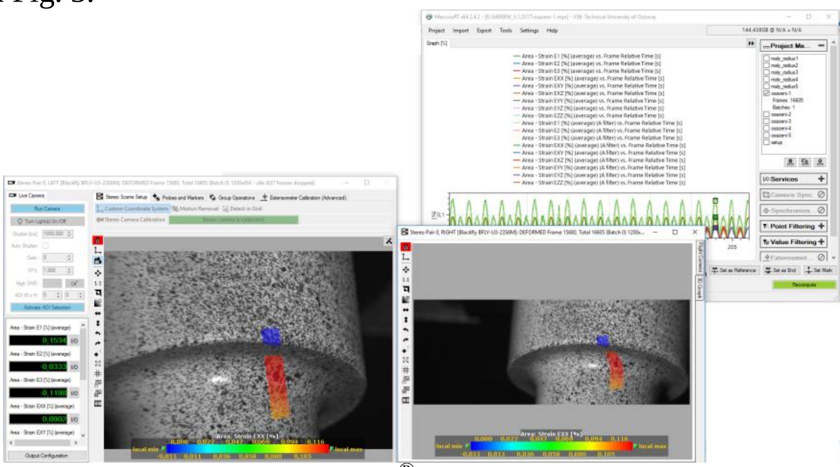

Fig. 3. Mercury RT® software GUI layout.

Software mentioned above enables, among other things, to configure the measuring cameras and to do their calibration. In the case of periodical loading the system is able to record and evaluate deformation response up to frequency of 40 Hz in full resolution of cameras. Into the area equipped by contrast coating an optical probe is subsequently placed (virtually in Mercury RT® software), which has to be aligned in both images (from two cameras). The testing machine was started together with the DIC measuring system. The data acquisition was done in real time and the calculation of desired outputs takes place in post-processing procedure.

Theory of Digital Image Correlation Method

Digital image correlation method is modern non-contact technique for measuring contours as well as measuring displacements or deformations on surfaces of solid bodies. For 3D measuring two optical sensors are desirable (two high resolution cameras) in the same way as live organisms have two eyes. For 2D application one CCD camera is sufficient. DIC methodology is based on digital images processing in grayscale mode so the RGB format is not required. The DIC method is widely used for determination of Young modulus, Poisson's ratio or for capturing material elasto-plastic behaviour. Motion or displacement are derived from two images taken before and after the deformation occurs by minimizing the grayscale difference on these two images in a small area called subset. The correlation algorithm is based on minimizing the sum [4]

$$C = \sum[G_t(x_t, y_t) - G(x_t, y_t)]^2, \tag{1}$$

$$G_t(x_t, y_t) = g_0 + g_1\, G(x_t, y_t), \tag{2}$$

$$x_1 = a_0 + a_1\, x + a_2\, y + a_3\, xy, \tag{3}$$

$$y_1 = a_4 + a_5\, x + a_6\, y + a_7\, xy, \tag{4}$$

where g_0, g_1 are parameters of illumination, $(a_0, \dots, a_7)$ are parameters of affine transformation and (x, y) are coordinates of the point inside a subset.

Results

All specimens were subjected to low-cycle fatigue testing in five modes and each test was force-controlled. Values of applied force or torque were recorded by testing machine. From these records it is possible to depict five loading paths (according to Fig. 4), where on the horizontal axis are values of axial force and on vertical axis are values of torque.

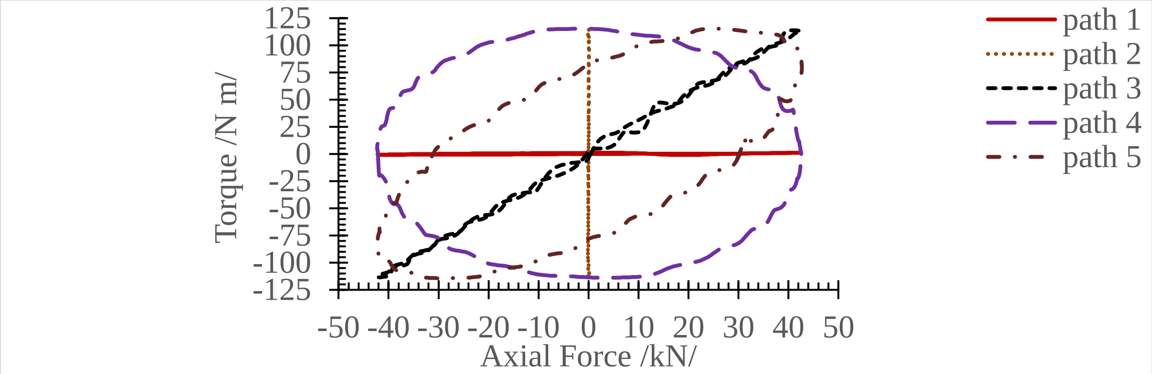

Fig. 4. Five loading paths.

In testing mode according to path 1 the specimen is subjected only to axial tension/compression load. Path 2 depicts loading by torque. Path 3 is combination of axial force and torque with no phase shift between them. Paths 4 and 5 are also combination with phase shift 45° and 90°. One cycle took two seconds for all testing modes. Our attention was aimed particularly on determination of longitudinal and shear strain in the tangential plane of the notch (Fig. 5a, Fig. 6a and Fig. 7a). Strain responses (near the hundredth cycle) are shown: For notch U in Fig. 5b, for notch V in Fig. 6b and for notch “fillet” in Fig. 7b.

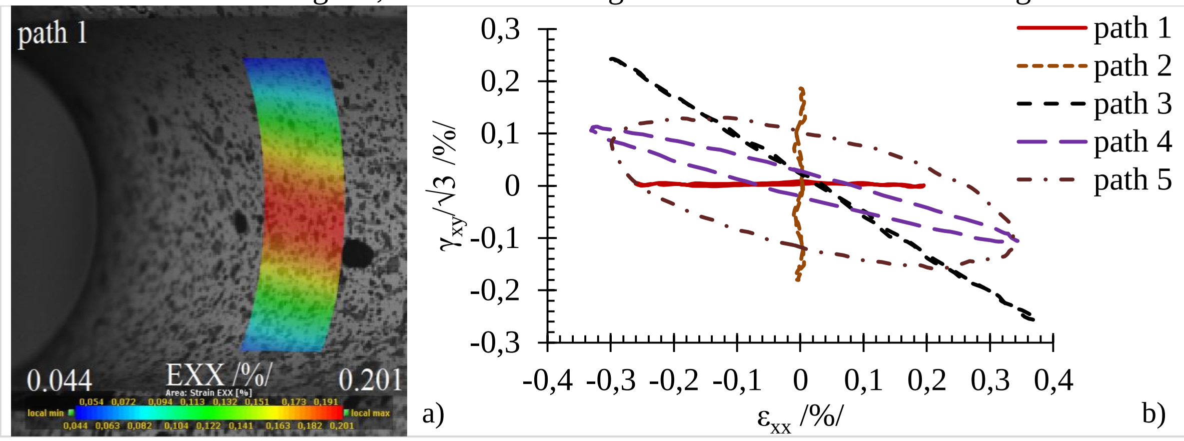

Fig. 5. Longitudinal strain distribution for path 1 (a) and strain responses in U-notch (b).

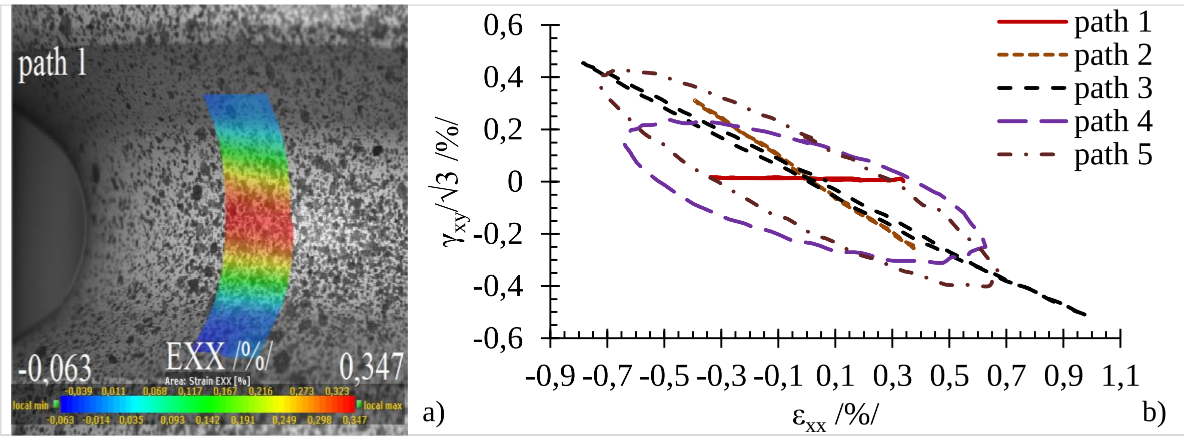

Fig. 6. Longitudinal strain distribution for path 1 (a) and strain responses in V-notch (b).

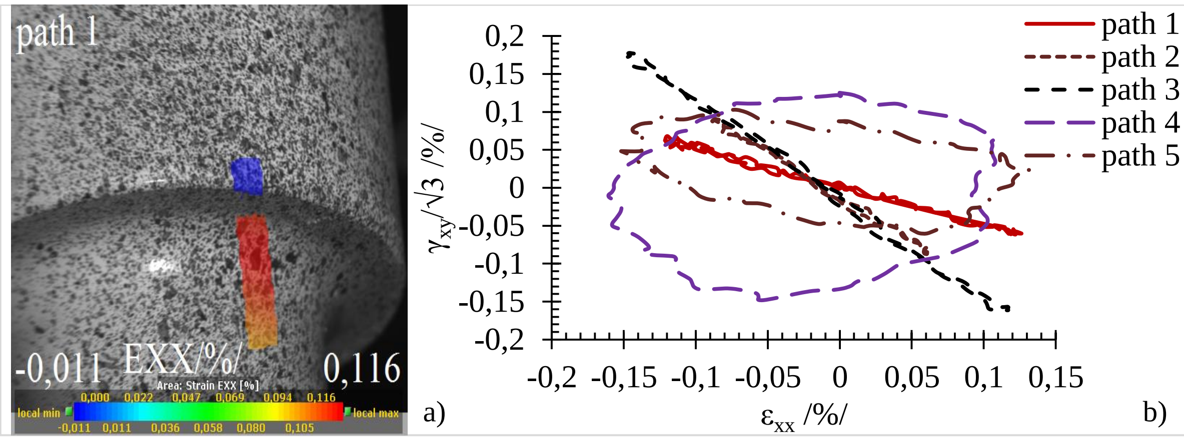

Fig. 7. Longitudinal strain distribution for path 1 (a) and strain responses in fillet-notch (b).

Now the question is how to compare the behaviour of different samples under the loading? The simplest way is to determine an equivalent strain amplitude according to formula

$$\varepsilon_a^{eq} = max\left[\sqrt{\varepsilon_{x,i}^2 + \left(\frac{\gamma_{xy,i}}{\sqrt{3}}\right)^2}\right]. \qquad (5)$$

In more precise approach the value of ε_a^{eq} is calculated as the radius of envelope of each strain path. The calculated equivalent strain amplitudes for each geometry of specimen are pictured on Table 1 and visualised on Fig. 8.

Table 1. Values of equivalent strain amplitude for each geometry.

Specimen Geometry	ε_a^{eq} [%]				
	Path 1	Path 2	Path 3	Path 4	Path 5
U-notch	0.260734	0.186903	0.453987	0.359194	0.358940
V-notch	0.338717	0.509316	1.113471	0.674877	0.826682
Fillet-notch	0.139909	0.087370	0.177957	0.125172	0.089847

The highest values of equivalent strain occur in proportional combination loading. This behaviour is generally known. On the other hand the smallest values are presented in case of loading according to path 2 (torsional loading).

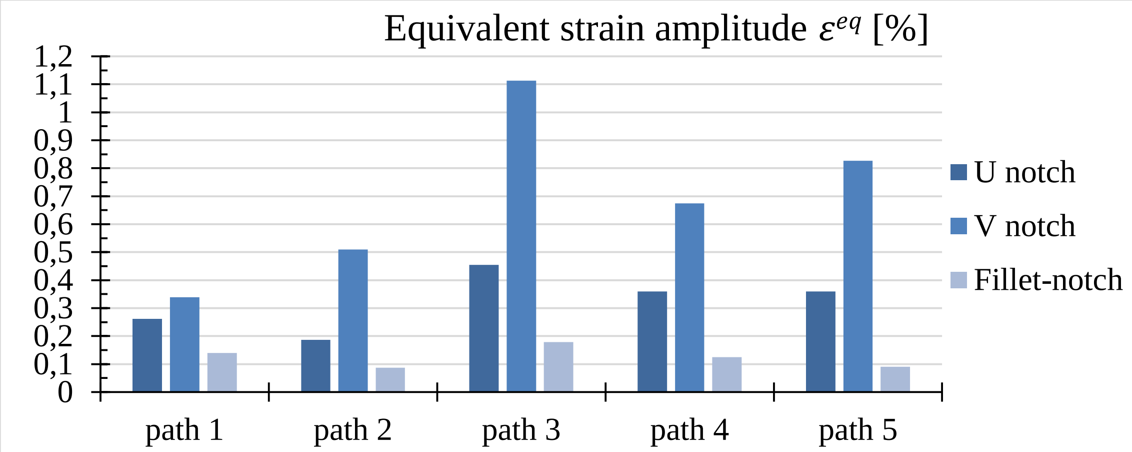

Fig. 8. Values of von Mises equivalent strain.

The second question is, if the measured values by DICM reflected reality. In order to prove that, some tests were performed on notch-free specimen and the deformations were measured by extensometer and by DICM. An acceptable correspondence was observed.

Conclusions

Objective of performed low-cycle fatigue tests was to determine complete strain tensor history in the root of notches by DICM as well as to investigate lifetime. Three types of specimen geometry were investigated: Specimen with notch U, V and fillet. Specimens were made from Aluminium Alloy 2124-T851. An application of strain gauges or extensometers in notch roots is problematic. The DIC methodology is good alternative here. DICM is contact less method and can stand to even large strains. Some basic characteristics of this modern optical method are stated above including a brief mathematical description. Specimens were subjected to the same five cyclic loading paths (Fig. 4), thus lifetimes can also be compared. The loading cases were without the mean value of stress, so there was no influence of mean stress on fatigue life.

Obtained data will be used for notch effect investigation in low cycle fatigue, for FEA verification and for evaluation of various Neuber-like methods.

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