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Evaluation of the fatigue damage development using ESPI method

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Fatigue damage process developing in structural materials under long-term cyclic loading is still an unsolved problem of modern engineering. Attempts to assess a degree of materials degradation under fatigue conditions on the basis of changes in the areas of local strain concentration determined by optical methods can be treated as the promising contemporary research direction of majority of scientific centers in the world. In most cases, fatigue damage has a local character and it is based on damage development leading to generation of cracks appearing around structural defects or geometrical notches. An identification of these areas and their subsequent monitoring requires a full-field displacement measurements performed on the objects surfaces. It seems that modern contemporary optical methods for displacement components measuring on the surfaces of structural elements or tested specimens are suitable for such purpose. Digital Image Correlation (DIC) and Electronic Speckle Pattern Interferometry (ESPI) are nowadays the most widely used testing methods in this area. Both of them enable capturing of displacement and strain components distributions. This paper presents an attempt to use the ESPI method for fatigue damage evaluation and its monitoring on specimens made of the aluminide coated nickel super-alloys. Flat specimens were subjected to cyclic loading. The fatigue tests were interrupted several times in order to perform a static loading during which the optical measurements were carried out. An analysis of the results captured by the ESPI system allowed indication of places of the greatest stress concentration and demonstration of the damage development process as a function of the increasing number of cycles.

Key words: fatigue, damage, super-alloy, Electronic Speckle Pattern Interferometry

1. INTRODUCTION

Experimental assessment of damage development in materials subjected to cyclic loading requires continuous monitoring of the displacement or strain responses into the loading programme applied [1-5]. The Electronic Speckle Pattern Interferometry method allows a determination of the displacement distribution on the specimens' surface, and thus, indication of strain and stress concentration spots appearing around structural defects or geometrical notches. Moreover, thanks to this technique an assessment of these spots evolution is possible in subsequent fatigue cycles until the dominant crack is formed and the specimen failure occurred.

2. ESPI METHOD (ELECTRONIC SPECKLE PATTERN INTERFEROMETRY)

Electronic Speckle Pattern Interferometry (ESPI) is an optical technique for displacement and strain measurements on the specimens surface. It is a type of the holographic interferometry based on the analysis of laser beam, distracted from the optically rough surface. The interference process involves two beams: the first one illuminates the specimens' surface, and as a reflected beam interferes with a second one - the reference beam. The interference results are recorded as speckled images using the CCD camera. Through the subtraction process of the speckle interferograms (before and after loading up to the selected levels), correlation fringes are obtained. Having them, a phase map can be generated (Fig. 1). It represents a distribution of displacement components in each direction, separately [1].

Final full-field stress and strain phase maps are created as the result of mathematical operations under the fixed boundary conditions (measurement area dimensions) and the material parameters (elastic modulus and Poisson's ratio).

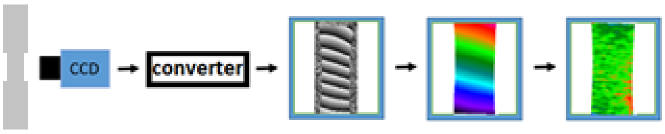

Fig.1. Scheme of subsequent steps during ESPI measurement [1]

Rys.1. Schemat kolejnych kroków podczas pomiaru metodą ESPI [1]

3. MATERIAL AND EXPERIMENTAL METHODOLOGY

Series of flat specimens (Fig.2) made of the coarse-grained, cast nickel alloy MAR247 coated by 40 μm heat resistant aluminide layer using CVD method, were tested under fatigue conditions.

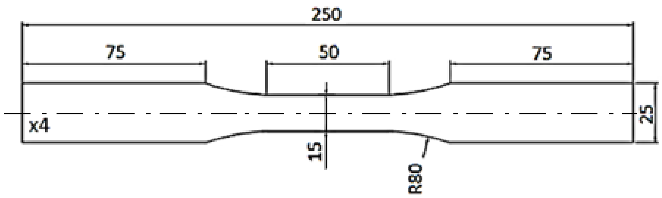

Fig.2. Geometry and dimensions of the fatigue specimen.

Rys.2. Geometria i wymiary próbki zmęczeniowej.

Fatigue investigations were carried out under force control using the MTS-810 hydraulic testing machine. In each test the maximum cyclic stress range and stress amplitude were equal to 600 MPa and 300MPa, respectively. Both these parameters were lower than the yield point of the material in question. In order to eliminate vibrations of the testing machine during optical measurements the loading process of the specimen was executed manually using a special device designed originally by the IPPT PAN workers. The loading programme is presented in Figure 3. As it is shown, the first cycle was conducted manually, and subsequently, a block of cycles under the frequency of 10 Hz was carried out using testing machine.

The process of cyclic loading was interrupted several times in order to perform displacement measurements by means of the ESPI camera. The experimental programme provided displacement measurements at the beginning of test and after 20000, 40000 and 50000 cycles. The number of cycles to failure was N_f=54315.

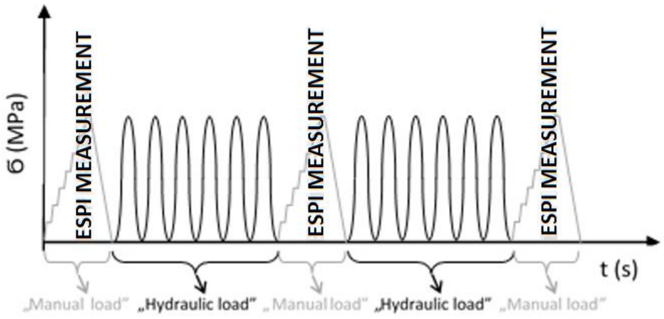

Fig. 3 Scheme of loading during the interrupted fatigue test.
Rys. 3 Schemat obciążenia podczas przerywanego testu zmęczeniowego.

4. RESULTS

ESPI observations carrying out at various stages of the fatigue degradation represent a status and dynamics of the damage development. They enable a determination of the areas of the greatest stress concentrations and reflect a local character of the fatigue damage initiation.

The field strain distributions along the Y axis corresponding to the acting stress direction in the specimen are presented in Figure 4. The figure shows strain distributions for different stages of the fatigue process, i.e. after: (a) first cycle; (b) 20000 cycles; (c) 40000 cycles, and (d) 50000 cycles. It has to be mentioned, that all these maps were obtained for different scales in order to ensure a more accurate documentation of the fatigue damage development. The same maps are presented in Figure 5, however, in this case the scale is unified in order to enable a direct comparison of the results achieved. The magnified view of the maps elaborated for the material after the first and last ESPI measurements are illustrated in Figure 6. As it is seen, the method enables identification of places where damage initiates. Figure 7 demonstrates a location of decohesion on the specimen gauge length, that well agrees with the largest displacement concentration occurring on the phase maps captured by means of the ESPI measurements.

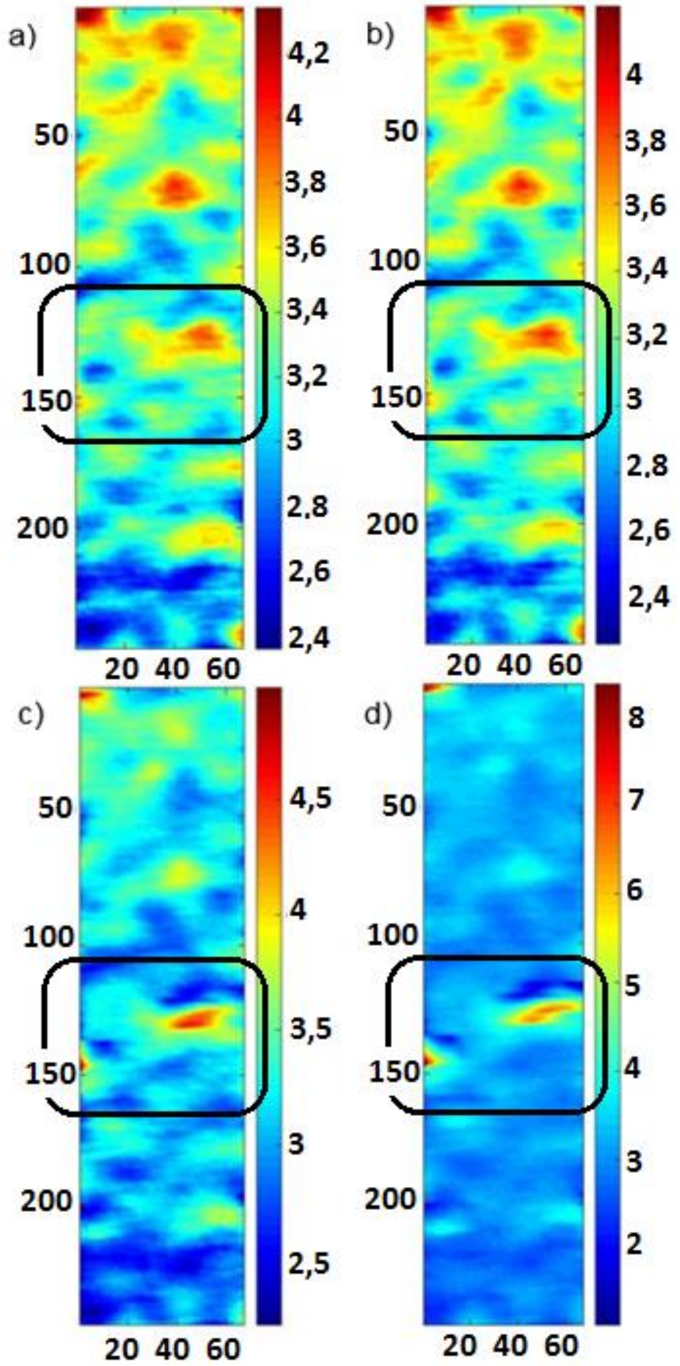

Fig. 4. The full-field strain distributions along Y axis corresponding to the stress direction. Measurements are performed: (a) during the first cycle, b) after 20000 cycles, c) after 40000 cycles, d) after 50000 cycles. The scale was automatically adjusted to the extreme strain value in each measurement.

Rys. 4. Całopolowy rozkład przemieszczenia w kierunku osi Y, zgodnym z kierunkiem działającej siły. Pomiar wykonano: a) w pierszym cyklu obciążenia, b) po 20000 cykli, c) po 40000 cykli, d) po 50000 cykli. Skala została dobrana automatycznie do ekstremalnych wartości odkształcenia w każdym pomiarze.

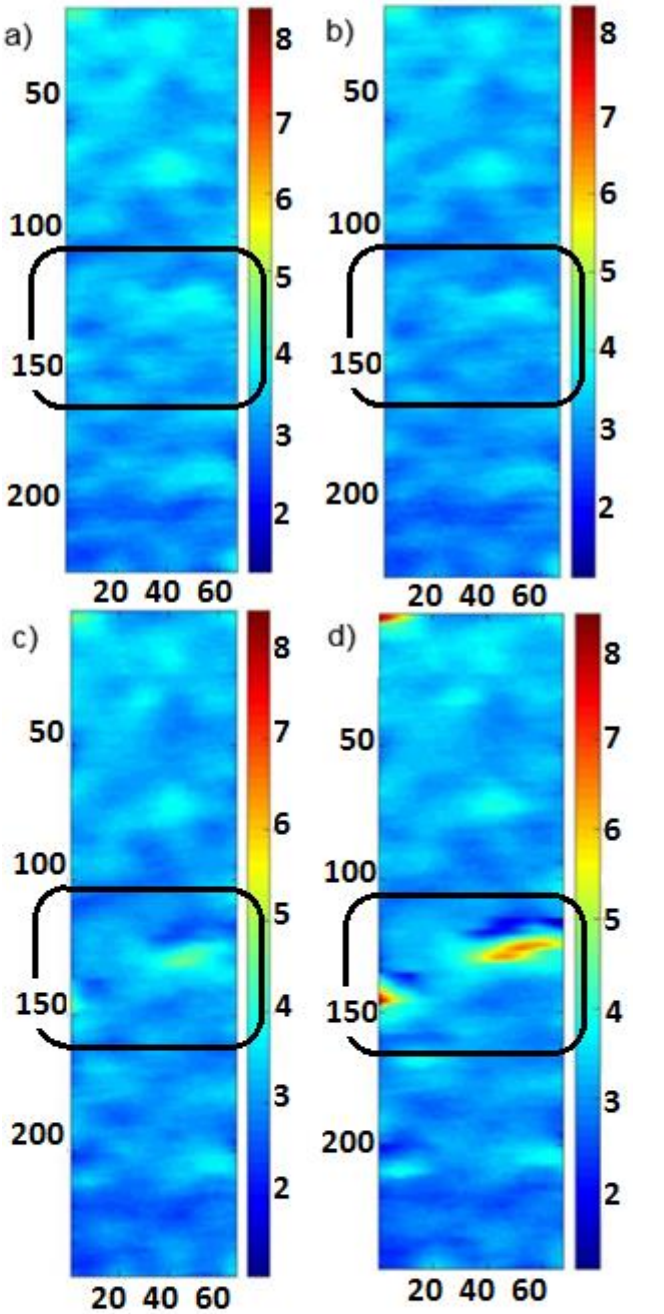

Fig. 5. The full-field strain distributions along Y axis corresponding to the stress direction. Measurements are performed: (a) during the first cycle, (b) after 20000 cycles, (c) after 40000 cycles, (d) after 50000 cycles. The scale is matched to the extreme strain magnitudes of all measurements: $\varepsilon_{MIN}=1,1*10^{-3}$, $\varepsilon_{MAX}=8,4*10^{-3}$.

Rys. 5. Całopolowy rozkład przemieszczenia w kierunku osi Y, zgodnym z kierunkiem działającej siły. Pomiar wykonano: a) w pierszym cyklu obciążenia, b) po 20000 cykli, c) po 40000 cykli, d) po 50000 cykli. Skala została dobrana do ekstremalnych wartości odkształcenia we wszystkich pomiarach: $\varepsilon_{MIN}=1,1*10^{-3}$, $\varepsilon_{MAX}=8,4*10^{-3}$

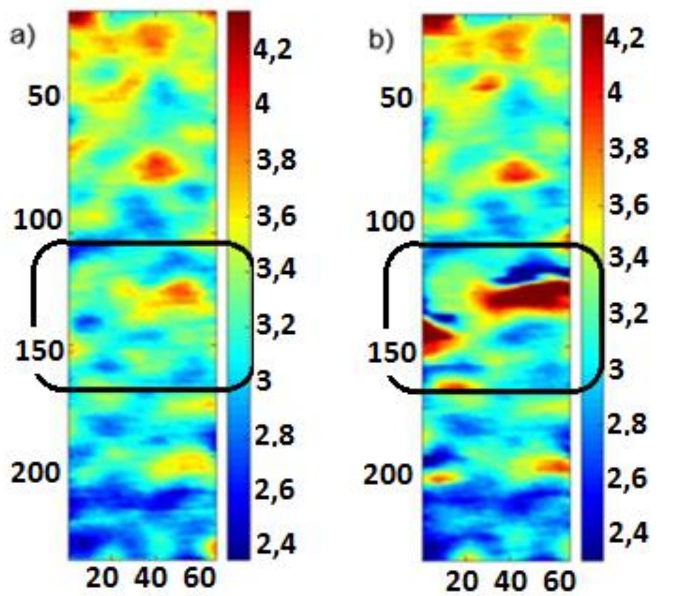

Fig. 6. The field strain distribution along Y axis corresponding to the acting stress direction. Measurements performed: (a) in the first loading cycle; (b) after 50000 cycles. Scale is matched to the extreme strain values in the first measurement.

Rys. 6. Polowy rozkład przemieszczenia w kierunku osi Y, zgodnym z kierunkiem działającej siły. Pomiar wykonano: (a) w pierszym cyklu, (b) po 50000 cykli obciążenia. Skala dopasowana do ekstremalnych wartości odkształcenia w pierwszym pomiarze.

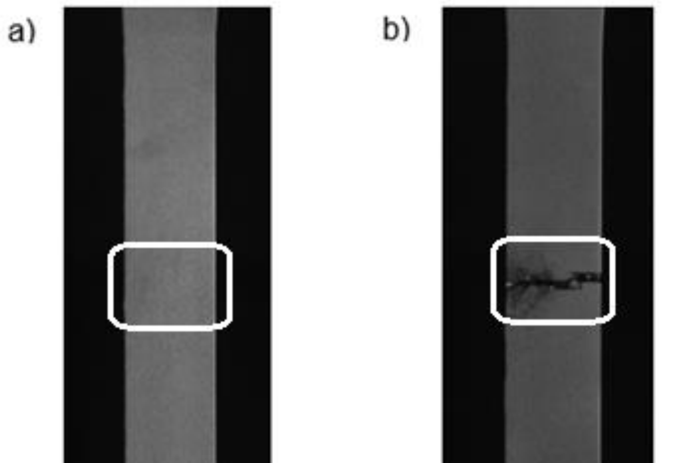

Fig. 7. Fatigue specimen photo: (a) before fatigue test; (b) after fatigue test (N_f= 54315 cycle)

Rys. 7. Widok próbki zmęczeniowej:(a) próbka przed obciążeniami zmęczeniowymi; (b) próbka po testach zmęczeniowych (N_f= 54315 cykli)

4. CONCLUSION

The paper was devoted to experimental analysis of the local fatigue damage development in the MAR247 alloy using the ESPI system. It has to be mentioned, that the other contemporary methods of the material degradation assessment are well known, however, their application for an accurate description of the local character of developing damage during fatigue is not possible as yet. Defectoscopic and optical full-field measurement methods of surface displacement enable determination of the area with the greatest stress concentration. Fatigue development in a homogeneous material, such as coarse-grained casting MAR247 alloy, exhibits the effect of strain localization in early stages of the cyclic loading. It is mainly caused by the relatively large number of the stress concentrators existing in the material structure. It has to be emphasized however, that using optical techniques, like the Electronic Speckle Pattern Interferometry or Digital Image Correlation, only the surface or subsurface defects can be successfully identified.

REFERENCES

[1] Kowalewski Z.L., Dietrich L., Kopeć M., Szymczak T., Grzywna P..: Nowoczesne systemy optyczne w badaniach mechanicznych – budowa, działanie, zastosowania. XXII Seminarium NIENISZCZĄCE BADANIA MATERIAŁÓW, Zakopane, March 16th-18th,2016, 5-36

[2] Grzywna P., Kukla D., Evaluation of strain distribution for the P91 steel under static load using ESPI system, ADVANCES IN MATERIALS SCIENCE, ISSN: 1730-2439, DOI: 10.2478/adms-2014-0019, Vol.42, No.4, 2014, 28-39

[3] Kukla D., Grzywna P., Karczewski R., Fatigue damage growth evaluation based on changes in the strain and eddy current parameters in the subsequent cycles load, PRZEGLĄD SPAWALNICTWA, ISSN: 0033-2364, Vol.5, 2014, 23-31

[4] Kukla D., Kowalewski Z., Grzywna P., Kubiak K., Assessment of fatigue damage development in power engineering steel by local strain analysis, KOVOVE MATERIALY-METALLIC MATERIALS, ISSN: 0023-432X, Vol.52, No.5, 2014, 269-277

[5] Rodríguez - Martín R., et al., Use of electronic speckle pattern interferometry in the detection of fatigue failure in high strength steels, Engineering Failure Analysis, Vol. 17 pp. 2010, 226-235

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